Market tremors: shale gas exploration, earthquakes, and their impact on house prices

Article:

Gibbons, Stephen ORCID: 0000-0002-2871-8562, Heblich, Stephan and Timmins, Christopher (2021) Market tremors: shale gas exploration, earthquakes, and their impact on house prices. Journal of Urban Economics, 122. ISSN 0094-1190

https://doi.org/10.1016/j.jue.2020.103313

Journal of Urban Economics 122 (2021) 103313

Contents lists available at ScienceDirect

Journal of Urban Economics

journal homepage: www.elsevier.com/locate/jue

Market tremors: Shale gas exploration, earthquakes, and their impact on house prices[☆]

Stephen Gibbons[a], Stephan Heblich[b,*], Christopher Timmins[c]

[a] LSE, CEP, UK
[b] University of Toronto, CESifo, ifw Kiel, CEP, Canada
[c] Duke University, NBER., US.

ARTICLE INFO

JEL classification:
R1
Q5
Q4

Keywords:
Shale gas
Fracturing
Hedonic prices
Housing prices
Consumer expectation
Information
Media
United Kingdom

ABSTRACT

Shale gas has grown to become a major new source of energy in countries around the globe. While its importance for energy supply is well recognized, there has also been public concern over potential risks from hydraulic fracturing ('fracking'). Although commercial development has not yet taken place in the UK, licenses for drilling were issued in 2008, signalling potential future development. This paper examines whether public fears about fracking affect house prices in areas that have been licensed for shale gas exploration. Our estimates suggest differentiated effects. Licensing did not affect house prices but fracking the first well in 2011, which caused two minor earthquakes, did. We find a 3.9–4.7 percent house price decrease in the area where the earthquakes occurred. The earthquakes were too minor to have caused any damage but we find the effect on prices extends to a radius of about 25 km served by local newspapers. This evidence suggests that the earthquakes and newspaper coverage increased awareness of exploration activity and fear of the local consequences.

1. Introduction

The advent of cost-reducing technological innovations associated with hydraulic fracturing and horizontal drilling has propelled shale gas to become one of the most promising and viable new global sources of energy. With the discovery of large reserves around the world, shale gas can support global energy needs for decades. The US Energy Information Administration estimated in 2012 that United States natural gas resources will last for up to 87 years and the British Department of Energy and Climate Change suggested in 2013 that Britain has enough shale gas deposits to supply the UK for about 25 years. In the US, a shale gas boom has boosted property values, domestic energy supplies and the profits of producers (Boslett et al., 2016; Feyrer et al., 2017). At the same time, shale gas development has raised concerns about externalities (i.e., environmental, disamenity, and other costs borne by nearby landowners and other stakeholders besides the drilling company).[1] During the extraction process, large amounts of high-pressure water and additives are used to fracture the rock layer and release embedded shale gas. The water is transported by trucks, thus raising concerns about noise, road damage and accidents due to increased traffic (Balthrop and Hawley, 2017; Gilman et al., 2013; Muehlenbachs and Krupnick, 2014). Increased air pollution may result from this truck traffic and from drilling operations (Colborn et al., 2014; Caulton et al., 2014; Roy et al., 2014). Moreover, there is a risk of soil or water contamination caused by metals, radioactive and saline wastewater, or by the added chemicals used to treat the wells (Olmstead et al., 2013; Warner et al., 2013; Fontenot et al., 2013). More recently, there have also been rising concerns about seismic activity induced by gas exploration (Koster and van Ommeren, 2015; Cheung et al., 2018; Ferreira et al., 2018; Metz et al., 2017). In the US, these costs may be compensated to some degree, with many US households owning the rights to their underlying minerals and receiving offsetting lease payments.

To our knowledge, this is the first paper to study fracking outside the US. Specifically, we look at the impact of prospective hydraulic fracturing for shale gas in the UK. The UK – and in fact all other countries –

[☆] We thank Lin Fan and Esther Lho, for excellent research assistance and seminar participants at the University of Amsterdam, the University of Bristol, the 2016 SERC meeting, the 2017 RES in Bristol, and the 2017 EUEA meeting in Copenhagen for useful comments. This work was part-funded by the Economic and Social Research Council (ESRC) through the Applied Quantitative Methods Network: Phase II, grant number ES/K006460/1 and grant number ES/M010341/1 to the Centre for Economic Performance at the LSE..

[*] Corresponding author.
E-mail addresses: s.gibbons@lse.ac.uk (S. Gibbons), stephan.heblich@utoronto.ca (S. Heblich), christopher.timmins@duke.edu (C. Timmins).

[1] Bartik et al. (2019) still report a positive net-effect for the US.

https://doi.org/10.1016/j.jue.2020.103313
Received 6 August 2018; Received in revised form 3 December 2020
Available online 22 December 2020

differ in two important ways from the US in that (i) there is no royalty-based compensation for the costs of shale gas extraction as all subterranean petroleum is owned by the Crown since the 1934 Petroleum Act,[2] and (ii) commercial shale gas extraction has not yet begun, although *Petroleum Exploration and Development Licenses* (PEDLs) grant the right to explore for shale gas or coal bed methane. Licenses awarded in the UK in 2008 mention shale gas exploration projects for the first time.[3] This change allows us to take a closer look at individuals' expectations (and fears) about shale gas development.

To assess expectations, we employ regression methods and look at whether the new information provided by licensing (i.e. PEDLs assigned in 2008) was capitalized in house prices. Buying a house is a significant financial commitment and buyers will likely consider the expected costs and benefits of shale gas extraction. While our setup does not allow us to disentangle the expected costs and benefits separately, we aim to obtain unbiased estimates of the expected *net local effects* of potential future shale gas extraction. To this end, we exploit detailed information on every house transaction in the years before and after the 2008 round of licensing. This allows us to compare changes in house prices in the licensed area to changes in the prices of comparable houses outside that area in a difference-in-differences procedure. The approach controls flexibly for all time-invariant local attributes (observed or unobserved) that might be correlated with licensing and house prices. Moreover, the design also controls for all time-varying characteristics through the use of control locations. These control areas are chosen such that they are likely to be similar to the licensed areas in terms of the unobservables that determine the supply of licenses (and potentially prices). These control group definitions are: (i) areas bordering the newly licensed areas; (ii) areas that are not close to the newly licensed areas, but are licensed for exploration in a future round of licensing in 2014, (iii) areas that were already licensed before 2008 and so were locations where any net costs and benefits would be already capitalised; and (iv) areas where geological surveys suggest shale gas deposits. Comparison of impacts using control areas close to the treatment areas in (i) and further away from the treatment areas in (ii) allows us to assess whether our estimates are threatened by spillovers from treatment to proximate control areas and violation of the Stable Unit Treatment Value Assumption (SUTVA).[4] We further address the possibility that licensed areas may have experienced trends different from those in non-licensed areas with a triple-difference strategy in which we compare license areas where license holders explicitly mentioned shale gas exploration to license areas where shale gas exploration was not mentioned explicitly.

Our estimates show that licensing itself did not affect house prices. Only when exploratory hydraulic fracturing caused seismic activity do we observe statistically significant negative effect on house prices. After Cuadrilla – one of the companies involved in UK shale gas exploration – hydraulically fractured the first well in the UK near Blackpool, two small earthquakes of magnitude 2.3 and 1.5 on the Richter scale were detected by the British Geological Survey in February and May 2011. These were very minor earthquakes, of a magnitude which would not have caused any structural damage, although some residents reported noticeable shaking of windows and furniture.[5] Earthquakes of this magnitude are not uncommon in the UK, but subsequent investigations and a well-publicized report, showed that these earthquakes were very probably caused by hydraulic fracturing. Focusing on those areas where hydraulic fracturing likely caused seismic disruption in 2011, we see a pronounced negative effect on house prices. Depending on the control group specification, we estimate negative house price effects that range between 3.9 to 4.7 percent following the incidents in 2011. Distance decay specifications show that the effects are centered on the earthquake site and decay rapidly with distance, but there are residual impacts in licensed areas up to 25km away. Importantly, this 25km radius largely overlaps with the circulation area of local newspapers from the earthquake area and additional estimations suggest that the house price drop after the earthquake occurs along the (fuzzy) border of the newspaper area. These border effects demonstrate the important impact of information transmission on expectations in property markets; in particular, econometric evidence of property market impacts out to the edge of a boundary determined by newspaper circulation highlights the important role of media in hedonic modeling. Moreover, these media effects are not fleeting – we show that the shock to house prices in the earthquake region persisted after 2011, suggesting that fear of fracking-induced seismic activity is not a temporary phenomenon.

Our paper addresses topics relevant to different strands of the literature. Most relevant is the literature on the property value impacts of seismicity induced by oil and gas operations. These papers include Koster and Van Ommeren (2015), Metz et al. (2017), Ferreira et al. (2018), and Cheung et al. (2018). Koster and Van Ommeren (2015) look at earthquakes induced by conventional gas development in the Netherlands; the other papers focus on wastewater injection arising from shale gas development in Oklahoma. All of these papers find a reduction in house prices of 2–5% resulting from induced seismicity.[6]

Our paper is also relevant for the literature analyzing the external costs of shale gas development (Gopalakrishnan and Klaiber, 2013; James and James, 2014; Muehlenbachs et al., 2015). Other work has found mixed results with respect to these costs, sometimes finding evidence of net benefits (Bennett and Loomis, 2015; Delgado et al., 2016; Weber et al., 2016; Boslett et al., 2016). In the US context, property value impacts of shale gas development may be mixed because of the substantial royalty payments that can be accrued by property owners who choose to lease their land. In the UK, mineral rights reside with the crown, making the situation similar to the case of "split estate" in the US, where rights have been severed from the property by a previous owner. A number of papers have studied the impact of shale gas development on split estates, generally finding evidence of negative effects (Kelsey et al., 2012; Fitzgerald et al., 2014; Weber and Hitaj, 2015; Brown et al., 2019).

Finally, we relate to a stream of literature that examines the impact of new information, e.g. about nearby toxic releases, on housing market transactions (Moulton et al., 2012; Mastromonaco, 2015; Ma, 2019).

---

[2] While individual homeowners in the UK will not receive royalty payments from shale development as they do in the US, the UK Onshore Oil and Gas Industry's *Community Engagement Charter* promises approximately £100,000 as a community benefit per well site where hydraulic fracturing takes place, plus one percent of the future production revenue (Walsh et al., 2011). Moreover, the industry commits to make a voluntary one-off payment of £20,000 for the right to use deep-level land for each unique horizontal well that extends by more than 200 m. These payments are voluntary but the government reserves powers to make these payments compulsory if firms fail to volunteer.

[3] Exploration implies drilling a test well to get accurate estimates of the recoverable shale resources. If firms want to go beyond the exploration stage and actually frack a well, this will require the landowners' consents, planning permissions from the local community, permits from the environmental agencies, positive reviews form the Health and Safety Executive, and permission from the Department of Energy and Climate Change (see DECC 2015b for details). Note that the 2015 Infrastructure Act provides automatic access to deep-level land below 300m for the purpose to exploit petroleum or deep geothermal energy by hydraulic fracturing. As a result, operators do not need access rights from every individual landowner whose land is drilled under at a depth below 300m.

[4] Our main concern is selective siting. Concerns that licensing had heterogeneous effects on home buyers' perceptions of the probability to experience fracking in the future across the four control groups are not supported by google trends data as we will discuss in Section 4.

[5] http://www.bbc.co.uk/news/uk-england-12930915

[6] A related literature has examined the housing market impact of naturally occurring earthquakes Brookshire et al. (1985); Naoi et al. (2009); Singh (2019) and disasters such as nuclear accidents (Huang et al., 2013; Coulomb and Zylberberg, 2016), floods (Gallagher, 2014; McCoy and Zhao, 2018), and wildfires (McCoy and Walsh, 2018; Garnache and Guilfoos, 2018).

Particularly relevant for the interpretation of the newspaper effects is Bernstein et al. (2019) which presents evidence for climate risk discounts in house prices as a response to (global) news about sea level rises for a subset of informed investors. Bakkensen and Barrage (2017) rationalize this in a model with heterogeneous buyers who value this new information differently. Snyder and Strömberg (2010) show that local variation in press coverage affects citizens' knowledge.

In the remainder, Section 2 provides background information on shale gas development in the UK, followed by a detailed data description in Section 3 and a description of the estimation method in Section 4. We present our results on the 13th licensing round in Section 5, discuss the house price impacts of expected seismic activity in Section 6, and draw conclusions in Section 7.

2. Shale gas development in the UK

Gas and oil exploration in the UK is licensed by the government every few years at the so called Onshore Oil and Gas Licensing rounds. In these licensing rounds, 10km × 10km blocks of land are offered for potential exploration and development. Exploration and production (E&P) companies can apply for a license to drill exploration wells in one or more of these blocks (with only one well per block). These *Petroleum Exploration and Development Licenses* (PEDLs) allow the holder to "search for, bore and get hydrocarbons" subject to access rights, planning permission, environment and health & safety permits. Historically, these licenses were granted for conventional oil and gas exploration. However, the rise of new horizontal drilling technologies that propelled the shale gas boom in the US led the *Department of Energy and Climate Change* (DECC) to identify areas in the east and south of England as having potential for shale gas development in 2007. Subsequently, in the 13th licensing round in 2008, unconventional gas exploration using hydraulic fracturing technology became a new option. By 2014, the only companies that had drilled shale gas exploration wells were Cuadrilla Resources, IGas and Third Energy but there has been no commercial extraction.

The 14th Onshore Oil and Gas Licensing Round was launched on 28 July 2014 and closed on 28 October 2014. According to the *Oil & Gas Authority* (OGA), "a total of 95 applications were received from 47 companies covering 295 Blocks. Following scrutiny of each applicant's competency, financial viability, environmental awareness and geotechnical analysis, and following the decision not to award licenses in Scotland and Wales, 159 blocks were taken forward for further consideration." On 17 December 2015, the OGA announced that 159 license blocks were formally offered under the 14th round. We do not look at the house price impacts of this licensing round in our main specification but utilize the areas offered as a control group for areas offered in the 13th licensing round in one part of our estimation strategy. Fig. 1 maps existing license blocks from previous licensing rounds (Panel A), newly licensed blocks in the 13th licensing round in 2008 (Panel B) and blocks that were formally offered to firms in the most recent 14th licensing round in 2014 (Panel C).

Shale gas development is considered a promising energy strategy in the UK for several reasons. First, it can contribute to energy security, reducing the UK's reliance on offshore gas and imported gas. Second, it is thought to support the UK's attempted transition to a low-carbon economy as it emits less CO_2 than oil or coal. If shale gas replaced these alternative energy sources it could have a positive effect on the UK's carbon footprint. Third, developments in the US show that commercial drilling can have significant economic benefits not only with respect to possible independence from fossil fuel but also for the local communities where the drilling sites are located. DECC (2013) suggests that "UK shale gas production would be a net benefit to public finances, could attract annual investment of £3.7 billion and support up to 74,000 jobs directly, indirectly and through broader economic stimulus." Given reports about booming fracking regions in the US, the prospect of an economic stimulus might have stimulated house price growth in licensed areas.

One important difference to the US is that home owners in the UK cannot expect royalty payments because mineral rights are owned by the Crown.[7] However, there are potentially some direct local payments. The *UK Onshore Oil and Gas Industry* (UKOOG) agreed in their 2013 Community Engagement Charter to pay £100,000 to local communities situated near exploratory well sites regardless of whether or not recoverable deposits are found. On top of that, they promised 1 percent of production revenues to communities during the production stage, which may amount to £5-10m per well over a period of 25 years. Finally, the industry confirmed a voluntary one-off payment of £20,000 per horizontal well to local communities in return for the right to use deep-level land that extends by more than 200 m. We do not expect these schemes to be capitalized in house prices during our study period for three reasons. First, we look only at housing transactions up to 2014 and fracking related events in 2008 and 2011 which occurred before these payments were offered. Secondly, only one well has been fracked and a few additional wells drilled in the UK during this period, and the first (and as far as we can see only) payment of £100,000 made was in August 2017 by Cuadrilla (see below). Thirdly, the expectation of future payments may not be capitalized in house prices because they are not formally guaranteed (though such payments could be made compulsory if companies fail to volunteer) and because they are paid to the community instead of the individual landowner. For community payments to be capitalized in house prices, house buyers would probably need more information about the exact benefits of community projects.

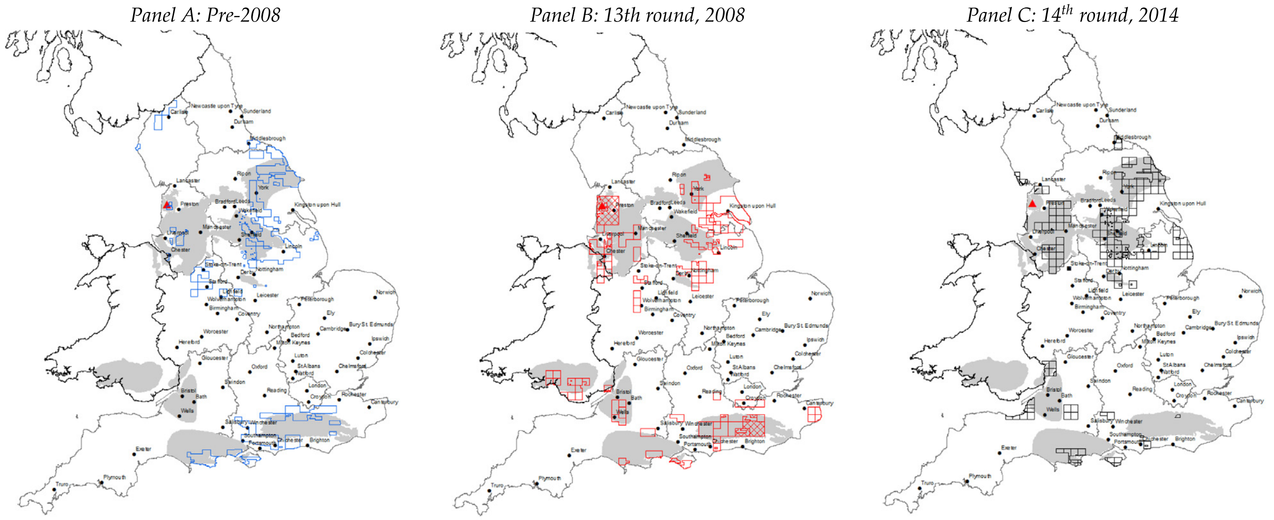
Cuadrilla was the first company to receive a license for shale gas exploration along the coast of Lancashire (the hatched red area in the north-west of Figure 1). In August 2010, they started hydraulically fracturing the well Preese Hall 1, which is located near Blackpool. This was the first time that a well had been fracked with modern, high-volume techniques in the UK. On 1 April 2011, the *British Geological Survey* (BGS) reported an earthquake of magnitude 2.3 on the Richter scale near Preese Hall 1. Following this event, Cuadrilla installed local seismometer stations around the exploration well that did not observe any further seismic activity. On May 26th, Cuadrilla resumed hydraulic fracturing and only 10 hours later, the BGS reported another earthquake of magnitude 1.5 on the Richter scale. Following these events, Cuadrilla announced on 31st May 2011 a halt due to unstable seismic activity (De Pater and Baisch, 2011). Cuadrilla then commissioned a series of geomechanical studies to investigate the connection between the seismic events and the hydraulic fracturing operations.

The reports concluded that the observed seismic activity "was caused by direct fluid injection into an adjacent fault zone during the treatments, but that the probability of further earthquake activity is low" (Green et al., 2012). A subsequent official UK government report acknowledged that hydraulic fracturing caused the seismic activities.[8] Despite that, the report did not recommend stopping further operations but rather called for careful monitoring of seismic activities around frack-

---

[7] The UK case where property rights are not in private hands also applies to other countries in Europe. Looking more closely into the prevalence of one or the other regime, it turns out that the US case where private individuals own most subsurface minerals is unique Gaille (2015). The differences in mineral ownership originate from the civil law and common law system and later amendments. Ironically, the US legislation dates to historical UK legislation because the crown did not reserve any subsurface minerals in its original land grants which then carried through to the colonies' grants to settlers. The 1934 Petroleum Act changed the legislation and ruled that the Crown should own the subterranean petroleum rights in the UK. US legislation did not change. For a review of the historical origins of the legal differences, we refer the reader to Campbell (1956).

[8] Appendix Fig. A1 illustrates the relationship between the water volume used for fracking the well and the observed seismic activity in a diagram published by the BGS.



Panel A: Pre-2008

Panel B: 13th round, 2008

Panel C: 14th round, 2014

Fig. 1. PEDL blocks from onshore oil and gas licensing rounds. The figures show PEDL blocks that were licensed in licensing rounds before 2008 (Panel A), in the 13th licensing round in 2008 (Panel B), and blocks that were formally offered in the 14th round in 2014 (Panel C). Cross-hatched areas in Panel B indicate blocks where shale gas development was mentioned in the license application and the red triangle indicates Preese Hall 1 where the earthquake happened. Shaded areas indicate regions with shale gas potential according to the British Geological Survey (BGS). Note that Output Areas are not perfectly nested in license blocks which leads to small differences. We do not consider Scotland in the north.

ing wells. Subject to stricter rules, the Secretary of State announced on 13 December 2012 that exploratory hydraulic fracturing for shale gas could resume in the UK. However, there were no further wells being fracked during this licensing period, partly because local communities delayed or blocked the planning permission process. Subsequently, after our study period, Cuadrilla fracked two other wells in Lancashire, in 2018 and 2019, both of which resulted in similar earthquakes to those in 2011. For a more detailed discussion of the politics of shale gas and the anti-fracking movement, see Keeler (2015), and for a recent summary of fracking in England see Davies (2019).

3. Data

Housing transaction data were taken from the *Land Registry Price Paid Data* provided by the UK government for England and Wales. The data go back to 1995, but we restricted the data to the period between the first quarter of 2005 and the second quarter of 2014 for the purpose of this research. The data include information on the sales price, four property types – detached, semi-detached, terraced or flat/maisonette – whether the property is new, and whether it is sold on freehold or leasehold basis. Housing transactions are mapped into 2001 Census Output Areas and aggregated to mean output area-by-quarter cells.[9] Output Areas (OA) are Census geographical zones with approximately 110–140 households. We exclude from the sample, Output Areas in the top quartile of the population density distribution and in major and minor conurbations, because these concentrated areas are likely inner-city areas which are fundamentally different (possibly in unobservable ways) from the rural areas where drilling tends to happen. We further drop all observations that are in the top and bottom percentiles of transaction prices. This leaves us with a panel of quarterly sales at the level of 92,663 Output Areas. The panel is unbalanced because we do not observe sales for every Output Area in every quarter. Appendix Table A1 provides descriptive statistics of our data separated by license area, period, and the respective control groups.

We supplement the land registry data with property sales data from the Nationwide building society, which covers about 15 percent of the transactions reported in the land registry database. The sample is not random since it is limited to buyers who need a mortgage but it allows us to test the effect of additional house characteristics including floor area, the number of bathrooms and bedrooms, housing tenure and whether the house comes with a garage or not. Further socio-economic characteristics at the output area level are taken from the 2001 Census.

Information on the areas licensed under the 13th and 14th licensing round are published by the UK Oil and Gas Authority. These data include detailed information on the licensing blocks, the proposed exploration, and the companies that hold licenses. The data further include information from the British Geological Survey on areas whose geology renders them promising for shale gas development. We use these data to determine whether Output Areas are within the licensed area and whether the license covers shale gas development.

We complement the administrative data with a number of control variables that account for the geographic location of an output area. These involve interactions between year and four elevation categories ($0 < e \leq 25m$; $25m < e \leq 50m$; $50m < e \leq 100m$; $e > 100m$), the log of distance to the coast, and the log of distance to the next center with 1,000, 10,000, and 50,000 inhabitants. These interactions capture time variation in the importance of terrain differences and the amenity value of being close to the coast or close to urban centers.

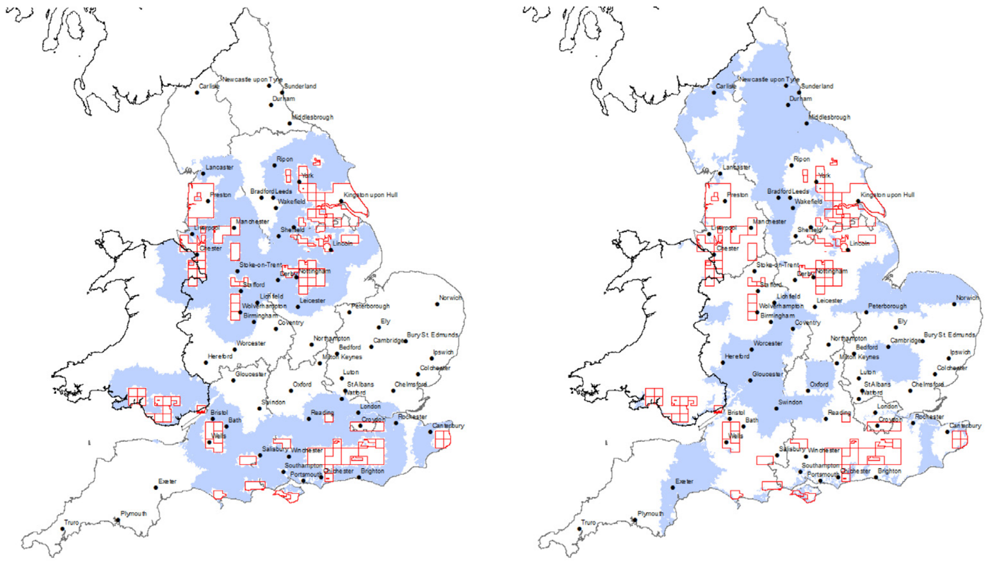
Finally, we collect information on the circulation areas of the following six local newspapers: *Blackpool Gazette, Blackpool Reporter, Fleetwood Weekly News, Garstang Courier, Lancashire Evening Post*, and *Lytham St. Annes Express*. We define local newspapers as those with a circulation area which covers the Preese Hall 1 well site and define their coverage area as all postcode sectors in which at least 100 copies are sold around 2011 (postcode sectors are postal zones with around 7,000 residents on average). Appendix Fig. A3 shows the circulation areas for all six newspapers.

4. Estimation strategy

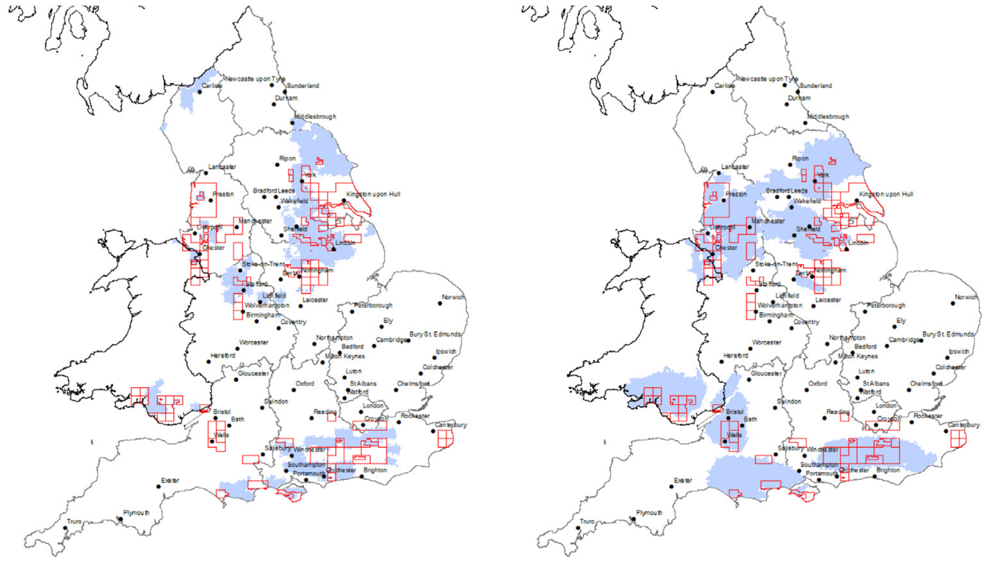
Our aim is firstly to estimate if and by how much house prices are affected when the area in which a house is located is licensed for shale gas exploration and is thus exposed to potential future shale gas development. There are two fundamental challenges to this exercise: (i) licensing might not occur randomly and (ii) PED licenses are not limited to unconventional shale gas exploration.

---

[9] Licensing status does not vary by individual property but location.


Panel A: 20km buffer

Panel B: Offered 14th Round w/o 20km Buffer


Panel C: Licenses issued pre-2008

Panel D: Geology

Fig. 2. Control Group Specifications. The Figure shows the four different control group definitions. The red outlines indicate blocks that were licensed under the 13th round in 2008 and the shaded areas mark the respective Output Areas that comprise the control group.. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

We start with the concern that places offered, chosen and licensed for oil and gas exploration are selected for their potential productivity and may therefore differ from unlicensed areas on many dimensions. The licensing decisions may also be influenced by planning considerations and the potential impacts on local residents. Both of these considerations imply that house prices may be different in licensed and unlicensed areas, for reasons other than a causal effect of licensing on prices. To address these problems and assess how licensing an area has affected house prices, our baseline approach involves regression-based difference-in-differences (DiD) methods that compare the average change in property prices before and after the 13th licensing round to the average house price change in a comparison group. To make this comparison group more similar to the areas licensed for gas exploration, we consider four geographical definitions to determine control areas where the trend should closely resemble that in licensed areas. We think of this exercise as a cross-validation where each control group provides insights into the relative importance of potential sources of bias. The four control areas are mapped in Fig. 2, Panels A-D.

Our first control group in Panel A is composed of areas that are proximate to the licensed areas but not inside those areas. Specifically, we draw a 20km buffer around all licensed areas and restrict our estimations to the area that is licensed and the surrounding 20km.[10] The strategy should reduce potential effects from unobserved heterogeneity between license areas and the control group. One concern with this strategy is that areas that are licensed for shale gas development may affect bordering areas negatively (e.g., if expectations about future truck traffic were to spill over into neighboring communities); alternatively, spillovers might be positive if shale gas is expected to stimulate the local economy and create new jobs (Feyrer et al., 2017). Expectations that licensing could extend outward from the currently licensed area might also lead to spatial spillovers. To account for that, we consider a second specification where we use the area that was offered under the future 14th licensing round but we exclude all areas that overlap with the 20km buffer used in specification (1). Note that we restrict the end of our observation period to mid-2014 when the 14th licensing round started. The corresponding area covered by this control group is mapped in Panel B. Panel C presents a control group specification where we use all existing license areas. Prior to the advances in drilling technology that made hy-

---

[10] Unreported specifications where we use smaller distance buffers lead to very similar results.

draulic fracturing lucrative, license holders engaged in conventional oil and gas exploration. With the rise of hydraulic fracturing technologies, existing PED licenses could also be used for unconventional shale gas exploration. However, while a license grants exclusivity to the holder within the licensed area, it does not imply a right to drill a well. Initial seismic investigations can be undertaken but further steps towards exploration and exploitation require consent from the national authority DECC and an additional planning permission from the relevant *Mineral Planning Authority* (MPA). One can therefore think of the already licensed areas as regions where some consent for oil and gas development has been granted. Using them as a control group therefore accounts for unobserved effects that are specific to areas that get licensed. While PED licenses allow shale gas exploration (conditional on consent from the national and local authorities), exploration will only happen in areas with the right underlying geology. To account for that, we exploit the exogenous assignment of geology to create a fourth control group that allows us to compare licensed and non-licensed areas with the same underlying geology that is promising for shale gas development (Panel D). Information on geological features that are promising for shale gas development stems from the British Geological Survey. This strategy accounts for unobserved license area effects and it also accounts for geological specificities. For instance, if the underlying shale rock implied better (or worse) natural amenities we would face a bias if these amenities had time-varying effects that were captured in house prices.

The second concern arises because PED licenses also cover conventional gas exploration methods which have been used for almost 50 years and are less likely to be of concern in terms of the potential for groundwater contamination, air pollution, and other local disamenities. As a result, combined estimations that consider licenses for conventional and unconventional exploration jointly may be biased towards zero. To account for that, we exploit additional information provided by DECC on the type of exploration project to identify a separate effect for areas where shale gas exploration was explicitly mentioned in the license (s) with $s \subseteq l$. This is not to say that areas where shale gas was not explicitly mentioned are excluded from shale gas exploration but we expect individuals to be less informed about it.

Lastly, we want to distinguish two events, the 2008 licensing round where fracking has become an option and the fracking-induced earthquake that happened in a subset of shale gas licensed areas (e) with $e \subseteq s$ in the third quarter of 2011.[11] To incorporate this information, we rely on a triple-difference model with two events, licensing and earthquake, across the three geographical treatment areas: PED licensed areas (l); PED license areas where the license mentions shale gas (s); and PED license areas where the license mentions shale gas and the earthquake occurred (e). One beneficial feature of the triple-difference model is that it controls for license-area-specific trends. For instance, if licensed areas were environmentally less attractive or economically less vibrant, we would expect them to follow a different house price trend. As a result, we rely less on the choice of control groups.

While our main concern is selective siting, one may be concerned that the choice of different control groups comes at the cost of increased heterogeneity among home buyers. To the extent that these are time-invariant differences, this would be covered by the fixed effects. A remaining concern is that licensing might have changed home buyers' perceptions of the probability to experience fracking in the future deferentially in the control groups. In this case, each control group would give us a different estimate depending on how much the 2008 licensing event shifted individuals' expectations about future fracking events in the control groups. We believe this concern is of second order importance because google trend shows virtually no interest in fracking before the earthquake event (see Appendix Fig. A2). Put differently, fracking was not considered a disamenity in 2008 and therefore, we have no reason to believe that it had different effects on individuals' expectations. After the earthquake event, expectations might have changed deferentially but this does not affect our estimate of the earthquake or shale-license effect because our triple-difference specification controls for trends in other licensed areas.

We estimate variations of the following equation between the first quarter (Q1) of 2005 and the second quarter (Q2) of 2014:

$$\begin{aligned} lnP_{it} = {} & \alpha_i + \kappa_t + \sum_{j\in(l,s,e)} \rho_j \cdot License_{i,j} \times \mathbb{1}_{t>Q1,2008} \\ & + \sum_{j\in(l,s,e)} \gamma_j \cdot License_{i,j} \times \mathbb{1}_{t>Q2,2011} + X_{it}\delta + \epsilon_{it} \end{aligned} \tag{1}$$

The dependent variable is the log of the mean property transaction price observed in Census Output Area i in quarter t. Across all specifications, we include output area-specific constants (α_i) that absorb time-invariant area characteristics and quarter-by-year specific constants (k_t) to allow for flexible time trends.[12]

The coefficients ρ_j on the interaction of an indicator for the three types of geographical treatment areas ($License_{i,j}$) with an indicator for the period after the licensing event ($\mathbb{1}_{t>Q1,2008}$) quantifies the average house price effect after licensing across the three geographical treatment areas. Similarly, coefficient γ_j quantifies the average house price effect after the earthquake in the third quarter of 2011 ($\mathbb{1}_{t>Q2,2011}$) across the three geographical treatment areas. Note that the components of the interaction terms and all other interactions are controlled for by the output area and time fixed effects. When we estimate Eq. 1, we start with a simple difference-in-differences model for post-2008 licensing effects and then gradually augment our model.[13]

X_{it} is a matrix of covariates including sets of control variables for the proportion of sales of detached, semi-detached, and terraced houses or flat/maisonette.[14] Beyond that, we interact year dummies with (i) four elevation groups ($0 < e \leq 25m$; $25m < e \leq 50m$; $50m < e \leq 100m$; $e > 100m$) to capture time-varying terrain differences (this might be a concern if shale-geology is correlated with surface geology); (ii) the log of distance to the coast as well as the log of distance to the next center with 1,000, 10,000, and 50,000 inhabitants to allow for changes in the valuation of proximity to the coast or centers; and (iii) indicators for 10 regions to allow for differing and flexible house price trends across regions over time.[15] These controls along with the output area fixed effects, should capture unobserved geographic differences that simultaneously affect the (un)attractiveness of an area and the availability of shale gas. Across all specifications, standard errors are clustered on the ward level.[16]

5. Results

5.1. Baseline

Table 1 presents our baseline specifications for the four control group definitions described above. Panel A uses as a control group a 20km

---

[11] Note that the third quarter of 2011 is the first quarter after the second earthquake lead to a temporary freeze in all fracking activities.

[12] In the robustness checks, we compare this to an alternative specification where we deflate house prices with an annual price index instead of flexible time trends.

[13] Put differently, we start with $\rho_s, \rho_e, \gamma_l, \gamma_s, \gamma_e = 0$.

[14] We will present additional specifications were we use property transaction data from Nationwide Building Society that allow us to control for further house attributes.

[15] The regions are North East, Yorkshire and the Humber, North West, East Midlands, West Midlands, East Anglia, South East, South West, Wales, London.

[16] Wards are sub-authority areas from electoral geography. In our sample without restrictions to a specific control group, we observe on average 13 census output areas per ward. Alternative specifications where we allow for common shocks within larger spatial units do not change our results. We present specifications where we cluster standard errors on the level of travel to work areas in the robustness checks. In our sample, the average travel to work area nests 477 census output areas.

Table 1
Baseline Estimations.

	(1)	(2)	(3)	(4)	(5)	(6)	(1)	(2)	(3)	(4)	(5)	(6)
	Panel A: 20km Buffer						**Panel B: Offered 14th Licensing Round without 20km Buffer**					
After 2008 * License Area	-0.008***	0.004**	-0.008***	0.004**	-0.004**	0.002	0.008***	0.011***	0.008***	0.010***	0.004*	0.003
	(0.003)	(0.002)	(0.003)	(0.002)	(0.002)	(0.002)	(0.003)	(0.003)	(0.003)	(0.003)	(0.002)	(0.002)
After 2011 * License Area					-0.007**	0.004*					0.007**	0.014***
					(0.003)	(0.002)					(0.003)	(0.003)
After 2008 * License Area*Shale	-0.031***	-0.021***	0.004	-0.009**	0.038***	-0.003	-0.031***	-0.028***	0.001	-0.015***	0.038***	0.004
	(0.006)	(0.004)	(0.005)	(0.004)	(0.006)	(0.006)	(0.006)	(0.005)	(0.005)	(0.004)	(0.006)	(0.006)
After 2011 * License Area*Shale					0.052***	0.003					0.052***	0.005
					(0.006)	(0.006)					(0.006)	(0.006)
After 2008 * License Area*Earthquake					-0.067***	-0.010					-0.068***	-0.032***
					(0.007)	(0.007)					(0.007)	(0.008)
After 2011 * License Area*Earthquake			-0.095***	-0.035***	-0.122***	-0.039***			-0.086***	-0.043***	-0.122***	-0.046***
			(0.005)	(0.005)	(0.007)	(0.007)			(0.005)	(0.006)	(0.007)	(0.008)
Observations	1,187,630	1,187,630	1,187,630	1,187,630	1,187,630	1,187,630	756,248	756,248	756,248	756,248	756,248	756,248
R-squared	0.815	0.817	0.815	0.817	0.815	0.817	0.799	0.802	0.799	0.802	0.799	0.802
Geo and Region Controls	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y
	Panel C: Licenses issued pre-2008						**Panel D: Geology**					
After 2008 * License Area	-0.004	0.004	-0.004	0.004	-0.004	0.002	0.010***	0.005*	0.010***	0.005*	0.001	-0.000
	(0.004)	(0.003)	(0.004)	(0.003)	(0.003)	(0.003)	(0.004)	(0.003)	(0.004)	(0.003)	(0.003)	(0.002)
After 2011 * License Area					-0.001	0.002					0.018***	0.010***
					(0.003)	(0.003)					(0.004)	(0.003)
After 2008 * License Area*Shale	-0.031***	-0.021***	0.003	-0.006	0.038***	-0.003	-0.029***	-0.023***	0.004	-0.011***	0.039***	-0.007
	(0.006)	(0.005)	(0.005)	(0.004)	(0.006)	(0.006)	(0.007)	(0.004)	(0.006)	(0.004)	(0.006)	(0.006)
After 2011 * License Area*Shale					0.052***	0.000					0.045***	-0.002
					(0.006)	(0.006)					(0.006)	(0.006)
After 2008 * License Area*Earthquake					-0.067***	-0.005					-0.066***	-0.003
					(0.007)	(0.008)					(0.007)	(0.008)
After 2011 * License Area*Earthquake			-0.092***	-0.048***	-0.122***	-0.047***			-0.092***	-0.037***	-0.125***	-0.041***
			(0.005)	(0.006)	(0.007)	(0.008)			(0.006)	(0.006)	(0.007)	(0.008)
Observations	517,580	517,580	517,580	517,580	517,580	517,580	513,063	513,063	513,063	513,063	513,063	513,063
R-squared	0.825	0.828	0.826	0.828	0.826	0.828	0.818	0.821	0.818	0.821	0.818	0.821
Controls	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y

The table reports results from fixed effects regressions of log price on an interaction between an indicator for time which either indicates the post-license period (after 2008) or the post-earthquake period (after 2011) and an indicator for (i) licensed areas, (ii) areas licensed for shale gas exploration, or (iii) areas licensed for shale gas exploration where the earthquake happened. All regressions are conditional on quarter-by-year fixed effects, house controls, and output area fixed effects. Even column numbers additionally control for region-by-year fixed effects and geographic characteristics (elevation categories, distance to coast and centers) interacted with year dummies. Panel A uses all output areas within a buffer of 20km around the licensed areas as control group. Panel B uses the 14th licensing round areas as control group but exclude the 20km buffer around the licensing area. Panel C uses all Output Areas that were licensed under previous rounds as control group. Panel D uses Output Areas where the underlying geology makes shale gas development more likely to happen. Output areas in the top quartile of the population density distribution and minor and major urban centers are excluded from all specifications. The time horizon is Q1/2005-Q2/2014. Standard errors are clustered on the ward level. *** p<0.01, ** p<0.05, * p<0.10

buffer around the area licensed under the 13th licensing round. The control group in Panel B is the area under consideration for the 14th licensing round minus the 20km buffer in Panel A. In Panel C, we present specifications with areas that were licensed under previous rounds as a control group. Finally, in Panel D, we use information on the underlying geology to distinguish between areas where shale gas development is more or less likely to happen.[17]

We present two specifications of our regressions. The first one contains a baseline set of controls that merely accounts for flexible time trends (quarter-by-year dummies), output area fixed effects, and basic house attributes (share of four property types, share of new properties and the share of properties sold as freehold) and a second one where we additionally control for geographic control variables interacted with year dummies to allow house prices to vary with the geographic location of an output area (four elevation categories, log of distance to the coast, distance to the next center with 1,000, 10,000, and 50,000 inhabitants). We include these geographic control variables, because the geology that makes shale gas development more likely and makes areas susceptible to earthquakes, may also give rise to desirable environmental amenities which affect house price trends (distance to coast and attractive scenery). Finally, we add region-by-year effects to allow for flexible price trends across ten broad regions. For example, this will account for different price trends in the Weald Basin south of London where the Jurassic shales were expected to hold some shale gas.

Our baseline specification in columns 1 and 2 is a simple difference-in-differences, where the coefficient of interest tells us whether licensed areas experienced a house price drop in the post-period from the second quarter of 2008 till the second quarter of 2015. Among licensed areas, we distinguish all licenses granted in 2008 (*License*), a subset of licenses where shale gas development was mentioned (*Shale*) and within the latter group those areas where the earthquake happened (*Earthquake*). The estimated coefficient on licensed areas after 2008 is small and ranges between a positive effect of 1.1 percent and a negative effect of 0.8 percent across Panels A–D. By contrast, we see a persistently negative effect after 2008 for those regions where shale gas development was mentioned. The effects indicate negative house price effects between 2.9 and 3.1 percent. In column 2, we extend our set of control variables and we find similarly small house price effects between 0.4 and 1.1 percent in the licensed areas overall and negative house price effects between 2.1 and 2.8 percent in the areas where shale gas development was mentioned.

In columns 3 and 4, we split the after-period up and allow for a different effect in licensed areas after the first instance of hydraulically fracturing a well in the UK resulted in two earthquakes. Doing so shows that the negative effect in areas where shale gas development was mentioned is driven by the one area where shale gas development took place and caused seismic activities. Accounting for the full set of controls, those areas where the first hydraulic fracturing attempt caused two earthquakes in 2011 faced a negative house shock after 2011 that ranges between 3.5 and 4.8 percent while the effect in licensed areas and licensed areas where shale gas was mentioned is negligible.

Finally, in columns 5–6, we present our preferred specification where we additionally include after-2008 interactions for the earthquake regions and after 2011 for the non-earthquake regions. The specification in column 6 with the full set of controls suggests that the negative house price effects were predominantly driven by the time after the seismic incidents in 2011 and it is restricted to the earthquake region. Our estimates suggest that house prices in the earthquake area fell after 2011 by 3.9–4.7 percent.

There are a few potential concerns with the pattern of coefficients in these results. First, the inclusion of control variables has a pronounced effect on the coefficient of interest. To shed more light on this, Appendix Table A4 shows specifications where we include the control variables one by one. Looking at the coefficient of interest, it turns out that the inclusion of output area fixed effects and quarter-by-year trends hikes up the R^2 but the estimated earthquake effect does not change much compared to the baseline specification without controls. We observe the same for the inclusion of house controls and flexible geographic controls. Only the inclusion of region-by-year controls decreases the size of the effect. Given the North-South divide in the English housing market, the sensitivity of the estimates is to be expected. House prices in the south are systematically higher and on different trends, so we have to account for this heterogeneity in the control group. Therefore, Appendix Table A5 presents an alternative specification where we condition the baseline on region-by-year fixed effects. We then add the output area fixed effects and other control variables, calculating the bias-adjusted treatment effect for the earthquake areas after 2011 as suggested in Oster (2019) to verify that the parameter estimate is not unduly sensitive to the inclusion of these controls.[18] Our estimated coefficients are very similar to the bias-adjusted treatment effect and we conclude that unobserved heterogeneity is not a major concern. We further observe a slight price-uplift in the licensed areas overall in 2011, although this coefficient is small and only significant in panels B and D after including all controls. Given the absence of any credible explanation for the earthquake generating benefits in other licensed areas, we suspect this coefficient is simply capturing a spurious price trend. Lastly, there is some indication that house prices in the earthquake area might have started to fall after 2008 which could point to a negative effect of drilling and fracking that is independent of the seismic activities. However, since this interpretation is only supported by Panel B we do not consider it conclusive.

For ease of interpretation, we summarize the effects from the full specification in Column 6 for the four control group specifications and the after-2008 (light bars) and after-2011 (dark bars) period in Fig. 3. The figures illustrate a pronounced and fairly similar earthquake effect after 2011 while there is no evidence of negative effects in licensed areas or shale areas. Unlike the other Panels, Panel B suggests a pronounced negative house price effect of 3.2 percent in the earthquake areas, pointing to some difference between our control region specifications. However, this does not affect our conclusions that seismic activity was the main driver of the sharp drop in house prices after 2011.[19]

Overall, these results suggest that shale gas exploration was only perceived as a disamenity as a result of the earthquake, and in the areas where the earthquake took place. Another interpretation is that the earthquake raised people's awareness of shale gas exploration and the potential risks – but only in proximity to the location where the incident happened. In line with the interpretation that the earthquake raised people's awareness of fracking, Appendix Fig. A2 shows that Google searches for the terms "fracking" and "shale gas" in England only started when the earthquake triggered massive media attention.[20] In the following, we will test the robustness of our findings and take a closer look at the effect in proximity to the earthquake location in an attempt to understand the underlying drivers.

---

[17] Appendix Table A3 presents an alternative specification where we choose no sample restriction and Appendix Table A2 presents an specification where we omit all non-licensed areas. In unreported specifications, we also considered a matched sample. Non of these variations changes our results significantly.

[18] The bias-adjusted treatment effects compare the post-2011 coefficient for earthquake areas in the baseline in column 1 with the corresponding coefficient from a model with additional controls (the respective column), scaled by the change in R^2. The exact formula is $\beta^* \approx \tilde{\beta} - \delta[\mathring{\beta} - \tilde{\beta}]\frac{R_{Max} - \tilde{R}}{\mathring{R} - \tilde{R}}$. Following Oster (2019) we assume $\delta = 1$ and $R_{Max} = 1.3 \times R_{spec4}$ where R^2_{spec4} is the R^2 from the fully specified model in column 4 of each Panel.

[19] Appendix Table A6 presents the results from our preferred specification in Table 1, column 6 in levels instead of logs.

[20] Unfortunately, there is no spatial variation in Google searches before the end of our observation period in 2014. Looking at search results after 2014, we observe the highest interest in "fracking" or "shale gas" in large cities and Clayton-le-Woods which is located inside the earthquake regions.

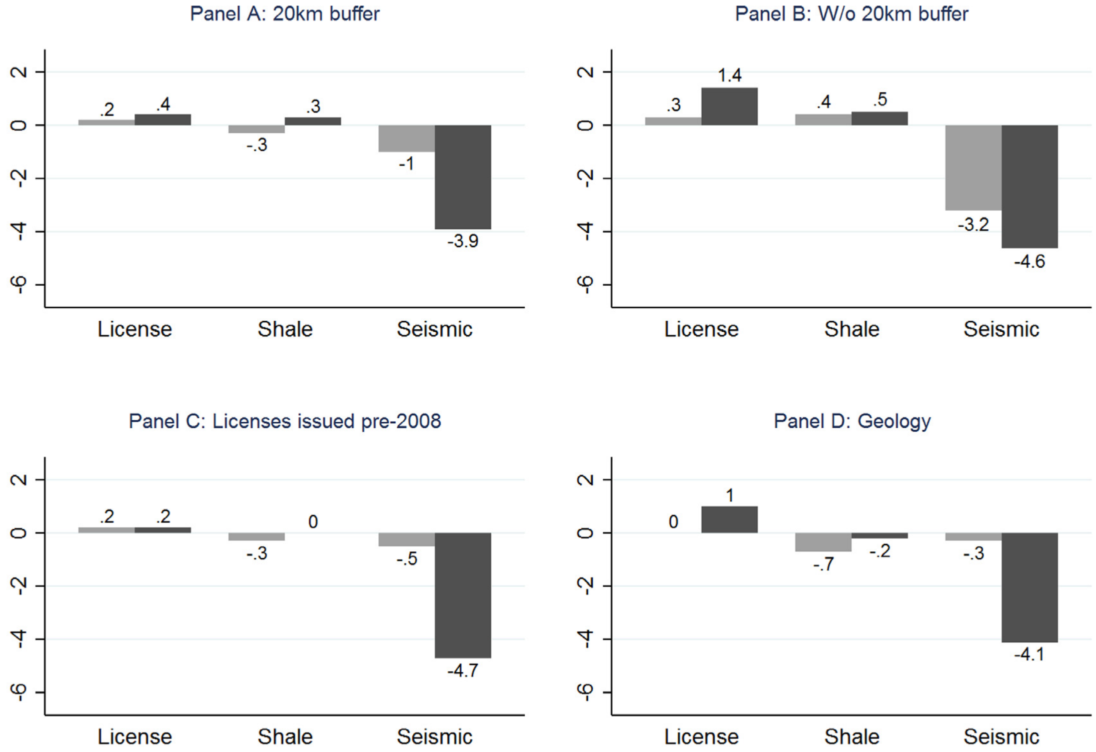


Fig. 3. Estimated Effects. The Figure shows the estimated effects for the coefficients in Table 1, Columns 6. Light bars (on the left) refer to interactions with an after-2008 dummy and dark bars (on the right) to interactions with the after-2011 dummy. The three areas are licensed areas, licensed areas where shale gas development was mentioned, and finally the one region where fracking activities caused two earthquakes (seismic)..

5.2. Robustness

We will now consider a number of additional specifications to probe the robustness of our preferred findings. The results are displayed in Table 2. In column 1, we deflate house prices with a price index for the ten regions used to calculate region-trends with 2008 as base year. In column 2, we include socio-demographic characteristics from the 2001 census interacted with a 4^{th}-order polynomial of year-trends to allow for time-variant differences between Output Areas that are not captured by the output area fixed effects, the limited number of time-variant house characteristics or the region-trends. Specifically, we include controls for the proportion of individuals without basic high school qualifications, the proportion of highly qualified individuals with a university degree, the proportion of individuals born in the UK, the proportion of individuals of white ethnicity, the proportion of employed individuals, the proportion of individuals who live in social housing, and a measure of the size of the output area.

In column 3, we control for an interaction between the Output Areas' XY-coordinates and a flexible 4^{th}-order polynomial of year-trends and in column 4, we interact the house characteristics with year-dummies to allow them to vary over time. Finally, in column 5, we present the baseline specification but cluster the standard errors on the level of 76 travel-to-work areas.

The results of these modified specifications are very similar to those described in Table 1. For the 20km buffer in Panel A, we find negative house price effects between 3.0 and 4.2 percent; in Panel B, they range between a negative effect of 3.5 and 4.6; in Panel C we find negative house price effects between 3.6 and 4.7 percent; and in Panel D, the house price drop varies between 3.1–4.1 percent. Clustering the standard errors at a very conservative level increases the standard errors slightly but our results remain highly significant. Overall, the robustness checks give us a most conservative estimate of a 3.0 percent reduction and a least conservative effect of 4.7 percent.

So far, our regressions have relied on data from the Land Registry database. This is the most comprehensive dataset on property transactions available but it comes with a fairly limited number of house-level control variables. To assess whether unobserved property characteristics bias our estimates, we present two checks. First, we used data from Koster and Pinchbeck (2018) who employ a fuzzy matching procedure based on address and house characteristics to add house characteristics reported in Energy Performance Certificates (EPC) to the land registry data. The control variables include indicators for the wall type, log size of the house, the number of rooms, a fireplace indicator, the overall energy efficiency rating, the floor level, and the number of floors. Second, we looked at property transactions from the Nationwide Building Society, which includes a more comprehensive set of housing characteristics and so allows us to control more carefully for physical structure. However, this dataset covers only about 15 percent of all transactions reported in the register data. Accordingly, we are more interested in the sign and existence of the effects than the exact magnitude.

Using the land registry data enhanced by additional house characteristics, the negative effect increases significantly and now ranges between 6.4 and 8.6 percent in license areas that experienced the earthquake. This is likely due to the fact the that the matched houses are not a random sample of the population. For example, we see that newly built houses are over-represented. Repeating our analysis on the Nationwide data yields consistently negative but slightly smaller results that range between -1.2 and -3.0 percent in license areas that experienced the earthquake. However, as might be expected from the even smaller sample, the individual coefficients are generally less precisely measured and more sensitive to the choice of control group and specification. The full results using these two datasets are shown in Appendix Table A7.

Despite our comprehensive set of control variables, it may be the case that highly localized shocks are correlated with our different licensing treatments. To account for that, and absorb an extended set of unobserved and potentially biasing local effects, we use Bai's (2009) in-

Table 2

Robustness Tests

	(1) Deflated	(2) Census Cont.	(3) XY-Trend	(4) Char.-Trend	(5) Cluster TTWA	(1) Deflated	(2) Census Cont.	(3) XY-Trend	(4) Char.-Trend	(5) Cluster TTWA
	Panel A: 20km Buffer					***Panel B:14th Licensing Round w/o 20km Buffer***				
After 2008 * License Area	0.000	0.000	0.002	0.001	0.001	-0.001	-0.002	0.003	-0.000	-0.001
	(0.002)	(0.002)	(0.002)	(0.002)	(0.003)	(0.003)	(0.002)	(0.003)	(0.003)	(0.006)
After 2011 * License Area	0.005**	0.004*	0.004**	0.004*	0.004	0.016***	0.012***	0.011***	0.014***	0.014***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.006)	(0.003)	(0.002)	(0.003)	(0.003)	(0.005)
After 2008 * License Area*Shale Gas	-0.002	-0.004	-0.002	-0.004	-0.004	0.007	0.005	0.009	0.005	0.005
	(0.006)	(0.006)	(0.006)	(0.006)	(0.005)	(0.007)	(0.006)	(0.007)	(0.006)	(0.007)
After 2011 * License Area*Shale Gas	0.001	0.002	0.005	0.005	0.003	0.002	0.001	0.003	0.005	0.005
	(0.006)	(0.005)	(0.006)	(0.006)	(0.008)	(0.006)	(0.005)	(0.006)	(0.006)	(0.006)
After 2008 * License Area*Earthquake	-0.012	-0.002	-0.012	-0.005	-0.005	-0.039***	-0.027***	-0.039***	-0.032***	-0.033**
	(0.007)	(0.007)	(0.008)	(0.007)	(0.011)	(0.008)	(0.008)	(0.008)	(0.008)	(0.016)
After 2011 * License Area*Earthquake	-0.030***	-0.034***	-0.041***	-0.039***	-0.039***	-0.035***	-0.038***	-0.042***	-0.046***	-0.045***
	(0.007)	(0.007)	(0.007)	(0.007)	(0.013)	(0.008)	(0.007)	(0.008)	(0.008)	(0.011)
Observations	1,187,630	1,187,630	1,187,630	1,187,630	1,187,630	756,248	756,248	756,248	756,248	756,248
R-squared	0.815	0.818	0.817	0.996	0.817	0.798	0.803	0.802	0.996	0.802
	Panel C: Licenses issued pre-2008					***Panel D: Geology***				
After 2008 * License Area	0.001	0.001	0.001	0.002	0.002	-0.005**	-0.004*	-0.004	-0.005*	-0.005
	(0.003)	(0.002)	(0.003)	(0.003)	(0.005)	(0.002)	(0.002)	(0.002)	(0.002)	(0.004)
After 2011 * License Area	0.003	0.001	0.002	0.002	0.002	0.011***	0.009***	0.011***	0.011***	0.011*
	(0.003)	(0.003)	(0.003)	(0.003)	(0.004)	(0.003)	(0.003)	(0.003)	(0.003)	(0.006)
After 2008 * License Area*Shale Gas	-0.002	-0.003	-0.007	-0.005	-0.005	-0.007	-0.006	-0.005	-0.007	-0.007
	(0.006)	(0.006)	(0.007)	(0.006)	(0.006)	(0.007)	(0.006)	(0.007)	(0.007)	(0.006)
After 2011 * License Area*Shale Gas	-0.003	-0.001	-0.002	0.000	-0.000	-0.002	-0.005	-0.002	-0.002	-0.002
	(0.006)	(0.005)	(0.006)	(0.006)	(0.006)	(0.006)	(0.005)	(0.006)	(0.006)	(0.008)
After 2008 * License Area*Earthquake	-0.004	0.009	0.002	0.004	0.003	0.002	0.006	-0.005	0.003	0.002
	(0.008)	(0.008)	(0.009)	(0.008)	(0.013)	(0.008)	(0.008)	(0.008)	(0.008)	(0.014)
After 2011 * License Area*Earthquake	-0.036***	-0.039***	-0.047***	-0.046***	-0.047***	-0.040***	-0.030***	-0.041***	-0.040***	-0.040***
	(0.008)	(0.007)	(0.008)	(0.008)	(0.011)	(0.008)	(0.007)	(0.008)	(0.008)	(0.012)
Observations	517,580	517,580	517,580	517,580	517,580	513,063	513,063	513,063	513,063	513,063
R-squared	0.826	0.829	0.828	0.996	0.828	0.821	0.822	0.821	0.996	0.821
Controls	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

The table reports results from fixed effects regressions of log price on an interaction between an indicator for time which either indicates the post-license period (after 2008) or the post-earthquake period (after 2011) and an indicator for (i) licensed areas, (ii) areas licensed for shale gas exploration, or (iii) areas licensed for shale gas exploration where the earthquake happened. All regressions are conditional on quarter-by-year fixed effects, house controls, region-by-year fixed effects and geographic characteristics (elevation categories, distance to coast and centers) interacted with year dummies. Panel A-D use the sample restrictions from the baseline results in Table 1. Output areas in the top quartile of the population density distribution and minor and major urban centers are excluded from all specifications. The time horizon is Q1/2005-Q2/2014. Standard errors are clustered on the ward level and in column 6 on the travel to work area level. *** p<0.01, ** p<0.05, * p<0.10

teractive effect methods as suggested by Gobillon and Magnac (2016).[21] Reassuringly, we see that flexibly accounting for heterogeneous local shocks leads to qualitatively similar results.

In a last exercise, we conduct balancing tests that explores whether other observable house characteristics in an Output Area changed around the time that our treatment areas were licensed in 2008. Our main concern would be that the observed price change is being driven by the sale of lower quality houses rather than by the expectation of shale gas development. As discussed in Appendix A1.2, we find no indication for such a bias and the few small changes we observe cannot possibly account for the price reductions seen in our main estimates.

6. Extensions

6.1. Distance decay effects around preese hall 1 well

To better understand the extent of the observed effect around the Preese Hall 1 site where the earthquake happened, we now turn to a set of distance decay models. Fig. 4 shows distance rings set to steps of 5km from the well that induced the earthquake. We can see that a maximum distance of 35km includes parts, but not all, of the Bowland Basin (shaded area) which, according to a 2013 study by the British Geological Survey (Andrews, 2013), holds significant shale gas resources. Their gas-in-place assessment suggests 37.6 trillion cubic meters (tcm) and potentially recoverable resources of 1,800–13,000 billion cubic meters (bcm) at a recovery factor of 8–20% which is common for the US. To put this into perspective: DECC suggest an annual UK gas consumption of 70 bcm for 2014 (DECC, 2015a). Holding gas consumption constant, this would cover at least 25 years. The importance of the Bowland Basin for UK shale gas development is further underlined by the fact that it is the only area where shale gas exploration wells have been fracked. Our distance decay estimations therefore serve two functions. Firstly, if the estimated price reductions are caused by the Preese Hall 1 earthquakes, we would expect to see the price effects declining rapidly with distance from the drill site. Secondly, any effects at higher distance radii may say something about the extent to which the 2011 seismic events spread fear of fracking into the Bowland Basin area.

Following Linden and Rockoff (2008), we start with a series of local polynomial regressions of house price effects on distance to Preese Hall 1 within an area of 40km, split in a period before (dashed line) and after (solid line) the earthquake in 2011. We further distinguish between areas with (black) or without (grey) the right geological conditions for fracking. The left panel of Fig. 5 shows the results of this exercise. We see a pronounced difference between the pre- and post-period within an area of 20km. After that, the difference gets smaller and finally disappears at a distance of about 25km from Preese Hall 1. We use this insight in the following distance decay estimations and compare the 30–35km bin to 5km rings between 0–30km from Preese Hall 1. Formally, we estimate the distance decay effect using a slightly modified version of the estimation equations introduced above:

$$lnP_{it} = \alpha_i + \kappa_t + \sum_r \tau_r \cdot Dist_{ir} \times \mathbb{1}_{t>Q2,2011} + X_{it}\delta + \epsilon_{it} \quad (2)$$

For distance rings $r \in [0,5), [5,10), [10,15), [15,20), [20,25), [25,30)$. The [30,35) km ring serves as reference group. In this estimation, τ_r will tell us the effect of the earthquake shock on house prices in the six different distance rings thus revealing any distance decay patterns.

To facilitate interpretation, we present the results of our distance decay regressions in a graph. The right panel of Fig. 5 shows results where we measure changes in house price effects following the 2011 seismic incidences relative to a pre-period from 2005 to 2011 in the distance rings described above. All estimates are reported with 95% confidence intervals and standard errors are clustered at the ward level. In line with the results from local polynomial regressions, we see negative house price effects up to the 20-25km bin. After that, the effect becomes statistically insignificant and slightly positive. Regression tables with the estimated coefficients can be found in Appendix Table A10, Column 1.

These figures suggest that there are distinct local impacts, but extending over a wider range than might be expected if the price effects represented a fear of direct impacts from the fracking or earthquakes at Preese Hall 1. At the same time, the effects are unlikely to represent a general fear of fracking in the Bowland Basin since Bowland Shale stretches over a much wider area of North West England (see the shaded area in Fig. 4). One way to rationalize the extent of the effect is that local media in the earthquake area circulated more information about fracking and its potential risks. Closer inspection of the local media market reveals that local newspapers are the only media outlet that could explain localized variation in access to information about fracking and earthquakes: local radio stations in this area are too diffuse and they extend well beyond the area within which we find price effects in our distance-decay estimates; there was no local television station in the area at this time; and access to online media is again not limited to the region. Consequently, we focus on local newspapers' circulation areas (see Fig. 4) and look at the difference between price effects just inside a zone covered by newspapers local to the Blackpool area, and price effects outside this zone. The local newspaper coverage zone is explained above in the Data section.

Visual inspection of the circulation area displayed in Fig. 4 suggests that the newspaper area largely overlaps with the area where we find house price effects (the newspaper coverage partly extends beyond 25km, but the majority of the 25-35km area is outside their circulation). To assess a potential newspaper effect more formally, we estimate a set of boundary regressions where we compare an area inside the newspaper circulation area to a control group that is geographically close but outside the circulation area. Specifically, we estimate:

$$lnP_{it} = \alpha_i + \kappa_t + \Psi \cdot Newspaper_i \times \mathbb{1}_{t>Q2,2011} + X_{it}\delta + \epsilon_{it} \quad (3)$$

where the treatment group $Newspaper_i$ comprises Output Areas within a buffer zone of 10km (or 5km or 2km) on the inside of the newspaper circulation boundary. On the outside of the boundary, we drop an area of 10km (or 5km or 2km) to allow for some fuzziness around the boundary and then define the control group as output areas within the next 10km (or 5km or 2km) ring outside the circulation area. The sample in each regression is restricted to the treatment and control group defined in this way. In the 10km sample, we additionally control for potential heterogeneity in locations that are further away from the boundary by interacting distance to the boundary with an after-2011 dummy. In specifications with more narrow bands, we cannot separately include this interaction.

The results of this specification are presented in Table 3. For all specifications, we find a negative and highly significant difference between the area with and without newspaper coverage suggesting that houses inside the area which have access to local newspapers experience a 2.6 to 5.9 percent house price drop after the 2011 earthquake relative to the control ring outside the circulation area. An event study within the 10km sample (column 5) further shows a pattern that supports the interpretation that more information about the earthquake or about fracking in general as a consequence of the earthquake is a main driver of the observed effect.[22] We do not find any evidence of relevant house price differences around the border before the earthquake. The year 2011 is the omitted category and from 2012 on, houses within the newspaper

---

[21] We refer to Appendix A1.1 for a more detailed introduction of this method.

[22] We also estimated a variant of Eq. 2 and found some evidence that the price effects linked with the newspaper coverage were negative only within the area of shale-gas bearing geology. This finding supports the idea that local news coverage disseminated information about the fracking events, which depressed prices specifically in the areas at risk for future shale gas development. These results are, however, rather sensitive to the sample definition and specification so we do not report them in detail.

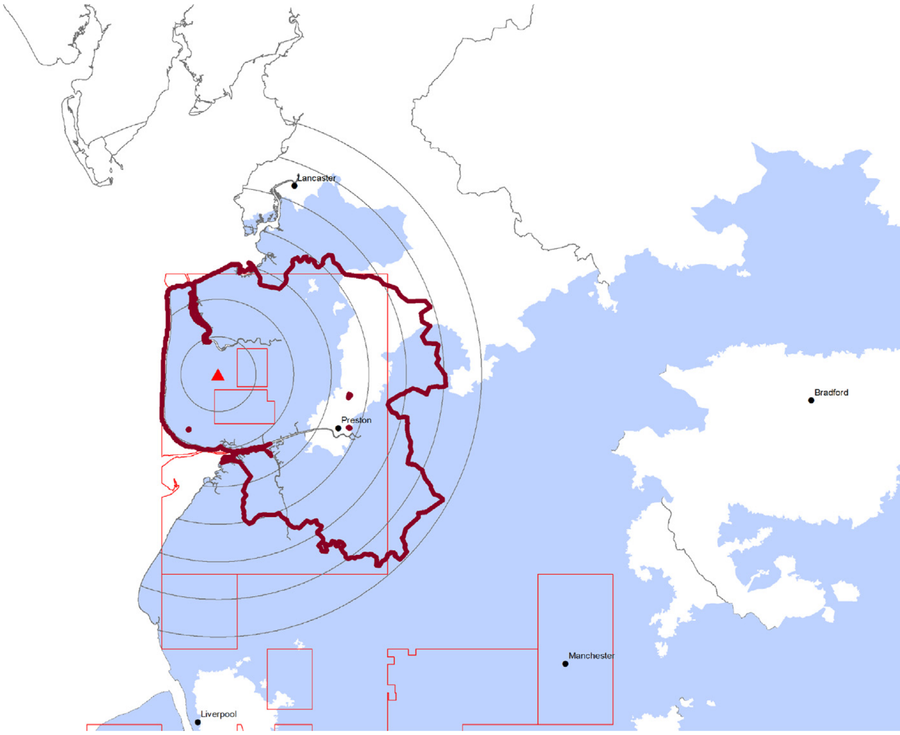
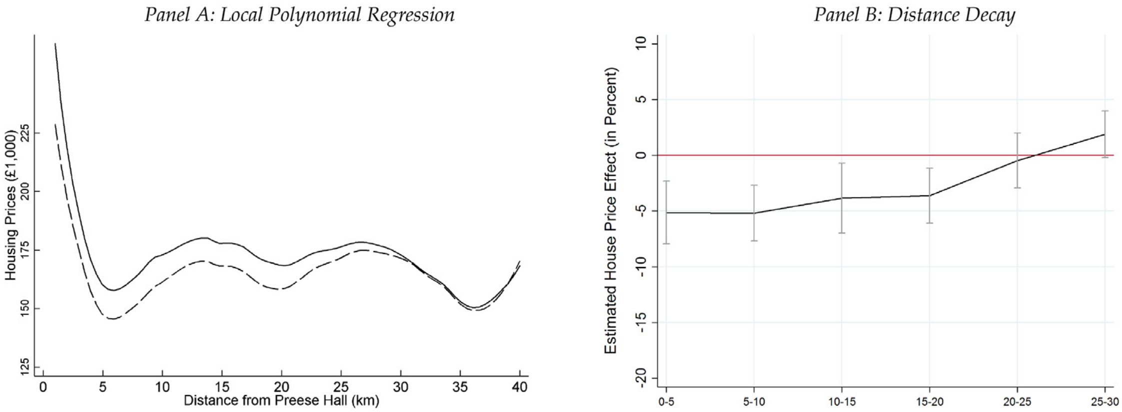


Fig. 4. Distance Rings around Preese Hall 1. The figures show the location of Preese Hall 1 (red triangle) and 5km distance rings around it. The rings go up to a distance of 35km from the well. The red blocks indicate areas licensed under the 13th licensing round in 2008 and the shaded area indicates the extent of the shale under the NW England Bowland Basin. The thick red polygon indicates the circulation area of local newspapers. Local newspapers are defined as those six newspapers that have a circulation area which covers the Preese Hall 1 well site and we define their coverage area as all postcode sectors in which at least 100 copies were sold.. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)


Panel A: Local Polynomial Regression

Panel B: Distance Decay

Fig. 5. Distance Decay around Preese Hall 1. Panel A shows the results from local polynomial regressions of house prices (in 1,000-£) on distance from Preese Hall 1 distinguishing between the period before (solid) and after (dashed) the earthquake incidence in 2011. Panel B shows the estimated coefficients τ_r from Eq. 2 for the 5km distance rings between 0-30km shown in Fig. 4 enclosed by 95%-confidence intervals. The omitted category is the bin (30,35]..

circulation ring sell for 3.0–3.4 percent less than houses in the control ring.

In summary, the boundary regressions provide suggestive evidence that the observed distance decay effect could be driven by differences in local media coverage. This finding would be in line with a large body of literature on the political economy of mass media.[23] However, in the absence of detailed information on newspaper content, these results remain suggestive.

6.2. Placebo estimations

This section presents a series of placebo estimations which provide further support for our interpretation that the observed effects are driven by the fracking-induced earthquake and the subsequent coverage in local newspapers. In a first placebo exercise, we look at locations across the UK that experienced earthquakes of similar magnitude (a range between 1.5 and 2.3) the year before the fracking-induced earthquake happened, i.e. between 2010/Q1 and 2011/Q1. This leaves us with 22 earthquakes of similar magnitude between 2010/Q1 and 2011/Q1.[24] In Fig. 7, Panel A, earthquake locations are indicated by a star symbol. Looking at the effects of seismic activity that is not caused by fracking will help us understand whether the occurrence of an earthquake per se is considered a disamenity that is reflected in house prices. In a second placebo check, we estimate distance decay effects around 61 conventional wells drilled between 2011/Q1 and 2014/Q2.[25] These locations are indicated by a square symbol in Fig. 6, Panel B. If there was any

---

[23] Prat and Strömberg (2013) summarize the literature on the political economy of mass media and Snyder and Strömberg (2010) show that local variation in press coverage affects citizens' knowledge.

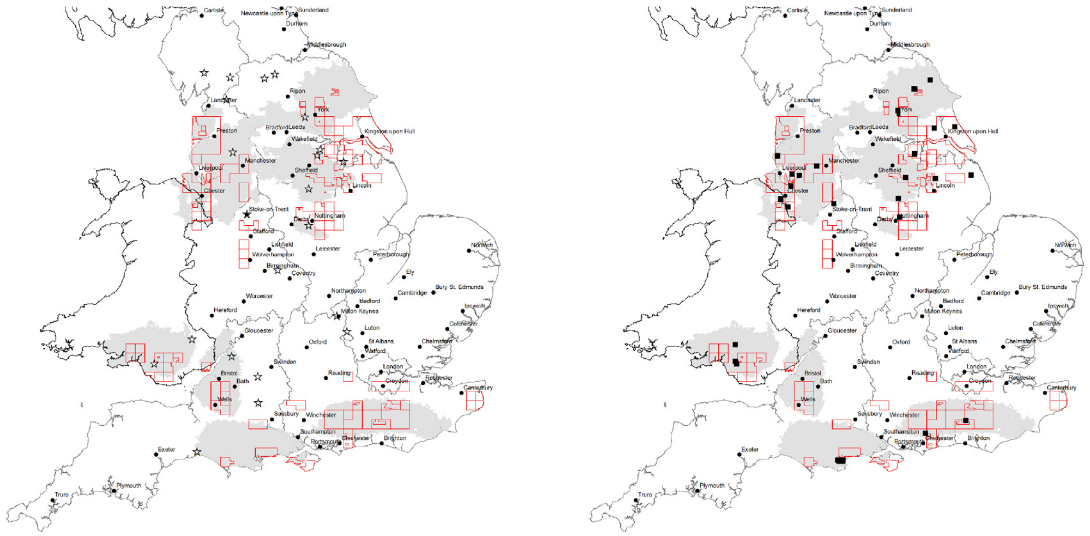
[24] Data on the magnitude and location of earthquakes are published by the British Geological Survey in the *Bulletin of British Earthquakes* for 2010 and 2011.

[25] Information on well drilling is published by DECC.

Table 3
Newspaper Regressions.

	(1) 10km	(2) 10km	(3) 5km	(4) 2km	(5) 10km / Event Study
After 2011*Newspaper	-0.059***	-0.038***	-0.036**	-0.026*	
	(0.010)	(0.014)	(0.015)	(0.014)	
I(year=2005)*Newspaper					0.035**
					(0.014)
I(year=2006)*Newspaper					0.055***
					(0.012)
I(year=2007)*Newspaper					0.057***
					(0.019)
I(year=2008)*Newspaper					0.032*
					(0.019)
I(year=2009)*Newspaper					0.016
					(0.013)
I(year=2011)*Newspaper					0.014
					(0.013)
I(year=2012)*Newspaper					-0.030*
					(0.018)
I(year=2013)*Newspaper					-0.029**
					(0.014)
I(year=2014)*Newspaper					-0.034*
					(0.019)
Observations	45,648	45,648	42,212	20,336	45,648
R-squared	0.747	0.747	0.742	0.747	0.747
Distance to boundary	N	Y	N	N	N
Controls	Y	Y	Y	Y	Y

The table reports results from fixed effects regressions of log price on an interaction between an indicator for time which either indicates the post-earthquake period (after 2011) and an indicator for the dissemination area of local newspapers. The sample in each regression comprises output areas within a k km wide buffer inside the newspaper circulation area and adjacent to the boundary (newspaper treatment) and output areas within a k km wide buffer outside the newspaper circulation area, but separated from the boundary by k km (controls). All regressions are conditional on quarter-by-year fixed effects, house controls, region-by-year fixed effects and geographic characteristics (elevation categories, distance to coast and centers) interacted with year dummies. Column (2) additionally interacts the log distance to the boundary with an after-2011 dummy. Output areas in the top quartile of the population density distribution and minor and major urban centers are excluded from all specifications. The time horizon is Q1/2005-Q2/2014. Standard errors are clustered on the ward level.*** p<0.01, ** p<0.05, * p<0.10


Panel A: Placebo Earthquake

Panel B: Placebo Drill

Fig. 6. Placebo Locations. The shaded areas mark areas with geology that is suitable for shale gas development and the red outlines indicate areas that were licensed in 2008. In Panel A, stars indicate the 22 areas that experienced an earthquake of magnitude 1.5-2.3 between 2010/Q1 and 2011/Q1. In Panel B, the 61 squares indicate wells that were drilled for conventional oil and gas development between 2011/Q1 and 2014/Q2.. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

disamenity related to drilling a well (but not fracking it), this regression should reveal it.

Fig. 7, Panel A shows the estimated coefficients of the placebo earthquakes using regression equation (5). The only difference is that we include an additional set of distance ring-by-year dummies to flexibly account for different house-price trends around earthquake locations. Further note that we drop all Output Areas within 35km of Preese Hall 1 and that we do not consider the intensity of an output area's earthquake exposure – i.e. an output area is treated after the first earthquake has happened in a given distance and we do not account for additional earthquake shocks in subsequent periods in the same distance bin. Regression tables with the estimated coefficients can be found in Appendix Table A10, column 2.

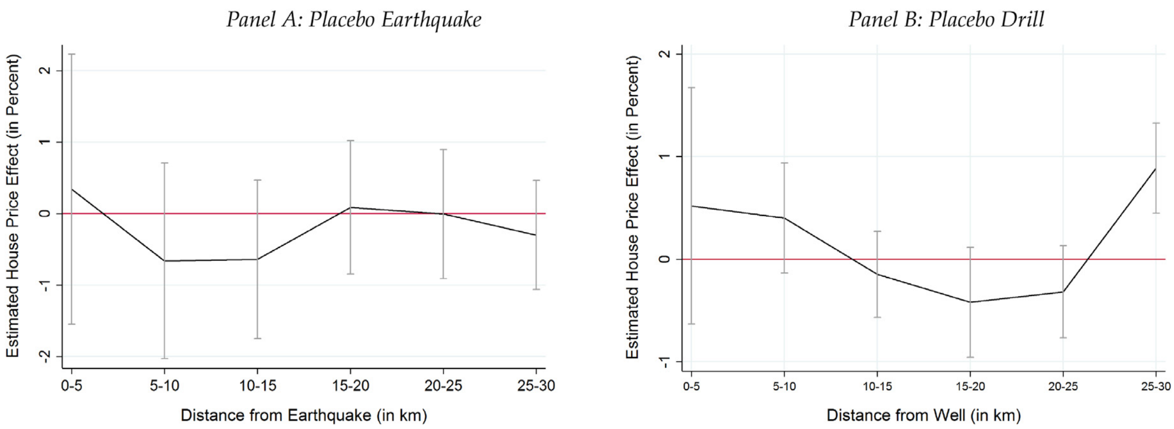


Fig. 7. Placebo Estimations. The Figure shows the estimated coefficients τ_r from Eq. 2 for placebo earthquake and placebo drill locations enclosed by 95%-confidence intervals. The omitted category is the bin (30,35]..

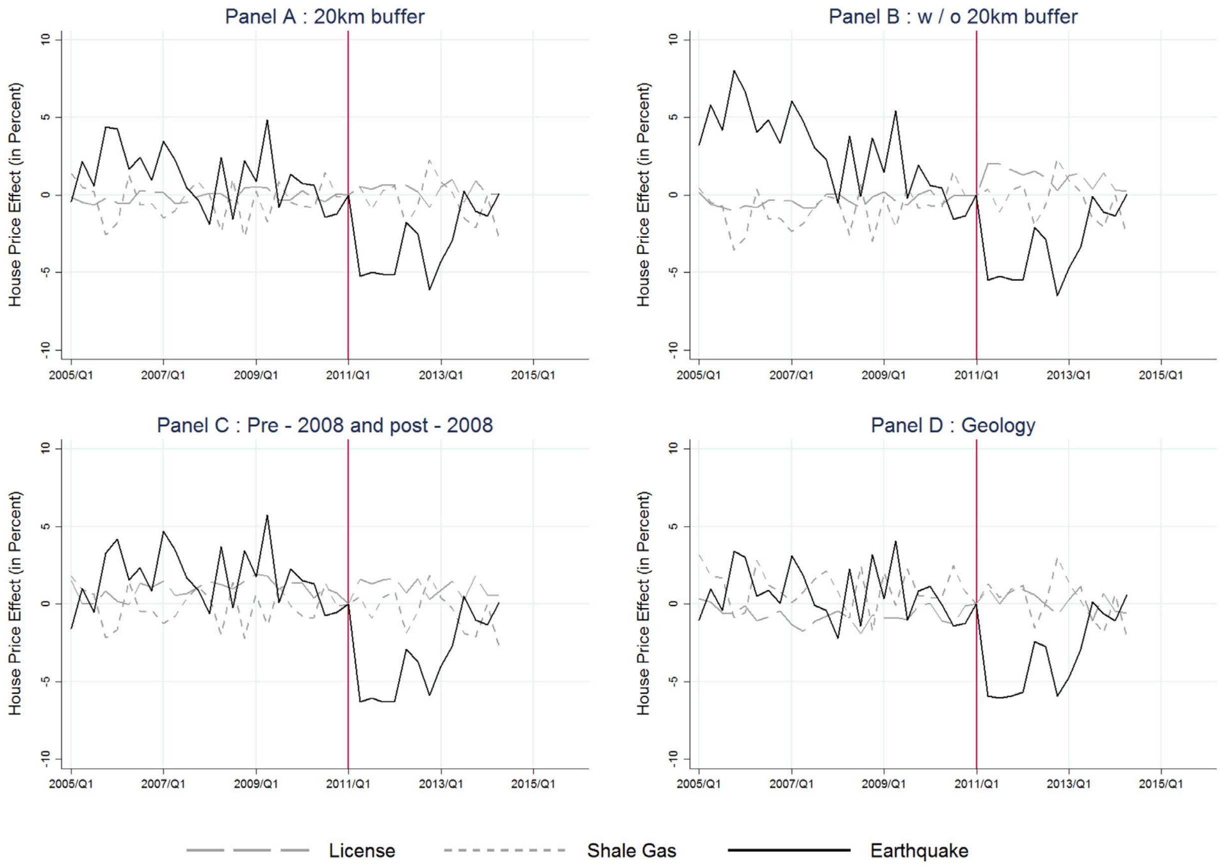


Fig. 8. Event study. The Figure shows the estimated effects of the event time indicators in Eq. 4. ω_t refers to licensed areas (long-dashed line), π_t to licensed areas where shale gas development was mentioned (short-dashed line), and η_t to the earthquake region (solid line). The omitted period is 2011/Q1..

There is no indication of a negative house price effect related to the earthquakes. This is not surprising since an earthquake of magnitude 1.5-2.3 can hardly be felt. This placebo exercise suggests that the post-fracking-earthquake effect we identify is not driven by a general fear of earthquakes. It is more likely that the earthquakes and media attention surrounding them made the risks associated with fracking more salient, and it is the fear of these risks that is capitalized in house prices.

In Panel B, we repeat the regression specification used in Panel A for conventional gas drilling sites. Regression tables with the estimated coefficients are presented in Appendix Table A10, Column 3. Again we find no indication of a negative house price effect related to well-drilling activities. If anything, there is a mildly positive (though highly insignificant) effect in close proximity. This second placebo exercise suggests that well-drilling activities for conventional oil and gas exploration do not raise any fear and we do not see any house price reaction. Taken together, these two placebo exercises support our interpretation of the effect around Preese Hall 1. The observed effect is either driven by a fear of future seismic activities induced by fracking or a general fear of future fracking which was fueled by numerous media reports after the earthquake in 2011.

6.3. *Event study estimation*

One assumption underlying our difference-in-differences estimations is that the different control groups will describe how the treated regions would have developed in the absence of licensing. To shed more light on the price trends before and after the beginning of our treatment period, we present an event study with 2011 as base year and interactions between the different license area definitions in the pre-period (2005/Q1-2010/Q1) and the post-period (2011/Q2–2014/Q2). 2011/Q1 is the omitted category.

The estimation equation for these dynamic effects is a modification of equation (4). Instead of interacting the license, shale gas and earthquake dummies with after-2008 and after-2011 dummies, we now interact them with quarter-by-year-indicators, D_t, in the pre- and post-periods:

$$
\begin{aligned}
lnP_{it} = \alpha_i + \kappa_t &+ \sum_{t \neq Q1,2011} \omega_t \cdot License_i \times D_t \\
&+ \sum_{t \neq Q1,2011} \pi_t \cdot ShaleLicense_i \times D_t + \\
&+ \sum_{t \neq Q1,2011} \eta_t \cdot Earthquake_i \times D_t + X_{it}\delta + \epsilon_{it} \qquad (4)
\end{aligned}
$$

We present the result of the event study for all four specifications in Fig. 8. The long-dashed line represents the event time indicators ω_t for the licensed areas, the short-dashed line the event time indicators π_t for the licensed areas where shale gas development was mentioned, and the solid line represents the event time indicators η_t for the earthquake region.

From the graph, we do not see a pronounced trend in the license (long-dashed grey line) and shale gas group (short-dashed grey line) over time.[26] By contrast, the earthquake group (solid black line) experienced a significant drop in house prices after the seismic activity in 2011.[27] Importantly, this effect is persistent for at least two years before it starts recovering. However, closer inspection of the shale gas time series (short-dashes) shows that shale areas face decreasing house prices around the same time and if we summed up the effect in the earthquake area and the areas with shale gas licenses we would see the overall negative effect continue (see Appendix Fig. A4), suggesting that fear of fracking and potentially related risks like increased seismic activity is not a temporary phenomenon. In the pre-period, we do not see a strong indication of a trend before 2010, maybe with the exception of Panel B where there is some indication of a decreasing price effect.[28] However, since we find broadly similar results for all four control group definitions, there is no reason to suspect that this potential pre-trend affects our estimations in the post-period. Around 2010, we see the beginning of a dip in the earthquake region which might indicate some disamenity from drilling and fracking activities before the earthquake. However, note that this small initial dip is not significant and thus indicative at best.

7. Discussion and conclusion

Research for the US shows that the shale gas boom has boosted property prices but there are also rising concerns about negative externalities linked to the extraction process. In this study, we turned our focus to the UK, where commercial shale gas development has not started, though reports at the beginning of our study period about substantial shale gas reserves had sparked hopes for a shale gas boom. At the same time, much of the media attention has been on the potential adverse local impacts. In the 2008 oil and gas licensing round, fracking became an option and some development licenses explicitly mentioned shale gas development as a goal. We use the issuing of these licences to test whether the prospect of future share gas development and its associated risks affected property values. Our estimations suggest that on average, areas that were licensed for conventional and unconventional oil and gas exploration in 2008 did not experience any house price effects. Looking at those areas where shale gas development was mentioned in the license, we still do not find any evidence that this information was capitalized in house prizes. Only when exploratory hydraulic fracturing caused seismic activity in a subset of shale licensed areas in 2011, do we observe a house price drop of up to 5 percent.

Further investigation suggests that local newspapers are likely contributing to this effect. Areas within the circulation area of local newspapers from the fracking region show stronger house price effects than a control group just outside their circulation area. We cautiously interpret these results as initial evidence for the role of media in the formation of house price expectations. Newspaper reports about the tremors and the British Geological Survey's subsequent investigations kept the topic in people's minds and might have raised fears about future developments. This interpretation would be in line with recent work by Bernstein et al. (2019) and Bakkensen and Barrage (2017) but we advise caution because we lack detailed information about the quantity and content of newspaper reports on fracking.[29] We hope to see future work that will look more closely into the relationship between newspaper information and house price expectations. In the light of our work, it would be interesting to understand whether newspapers inform potential house buyers about relevant risks that should be reflected in their willingness to pay or whether they raise individuals' fears thus leading to exaggerated reactions.

A long line of theoretical literature on hedonic models and empirical applications has shown that the estimated (net) price effects can be interpreted as home-buyers' *marginal willingness to pay* to avoid exposure to shale gas development in the vicinity of their homes once they have learned about the potential risks.[30] This interpretation requires some quite strong assumptions and approximations, but if applied in our case it implies that an average household in the earthquake area would be willing to pay between £310 and £374 (in 2008-prices) per year, depending on the specification in Table 1 and Table 2, Column 6, to avoid areas where fracking could induce seismic activity. We use the smallest (0.039) and largest (0.047) estimated difference-in-difference-in-difference coefficients to determine the bounds of these back-of-the-envelope calculations.[31] Given 22,749 housing transactions in the period after the earthquake (i.e., between the third quarter of 2011 and the second quarter of 2014), we arrive at a cumulative house price loss relative to control areas that ranges between £141 and £170 million (in 2008-prices) using the triple-difference coefficients. We can think of

---

[26] The table with detailed coefficients and standard errors is available from the authors upon request.

[27] Overall, the estimates for the earthquake group show a higher variability between quarters due to the smaller number of observations.

[28] To facilitate visual inspection, Appendix Fig. A5 separates the price trends for the four sample definitions and the three treatment groups and graphs them along with 95%-confidence intervals.

[29] We contacted the local newspapers but they do not have electronic archives that would allow us to quantify the number of articles on fracking-related topics. However, the people we contacted said unanimously that there was a strong increase in articles about fracking.

[30] Rosen (1974) provides the seminal theoretical analysis. The challenges to recovering information on underlying consumer preferences from empirical analysis were lately discussed in Heckman et al. (2010), Bishop and Timmins (2011) and Yinger (2015). Recent empirical applications include, to name just a few: valuations of air quality (Chay and Greenstone, 2005; Bajari et al., 2012), water quality (Walsh et al., 2011; Leggett and Bockstael, 2000), school quality (Black, 1999; Gibbons et al., 2013), crime ((Gibbons, 2004; Linden and Rockoff, 2008; Pope, 2008a), or airport noise (Andersson et al., 2010; Pope, 2008b).

[31] The implicit assumption is that the other estimated effects in license and shale areas are potentially spurious trends. If these trends were not spurious, we would compare the effect of the earthquake in licensed shale areas relative to non-licensed areas. Put differently, we would sum up the coefficients on License Area, Shale and Earthquake after 2011 which would give us coefficients between 0.027–0.045 (i.e. effects between 2.7–4.5 percent). In this case, the average household in the earthquake area would be willing to pay between £219 and £365 (in 2008-prices) per year to avoid areas where fracking induced seismic activity.

these numbers as lower bounds because fear of fracking-induced seismic activity does not just affect houses that were sold in that period. It also devalued houses that were not sold, and it may even have devalued land without houses. The 2011 census suggests that there were 145,018 households in the earthquake area, which implies that the house price loss could have been more than 6 times larger. Moreover, our distance decay specifications suggest that this effect was not limited to areas where the earthquake happened.

These local cost calculations naturally raise a question about benefits. As discussed above, we do not think that house prices capitalized expectations about local benefits from an economic upswing or community payments since this was an exploratory stage with commercial fracking still being in the distant future. The more general potential benefits of shale gas exploration and extraction–lower gas prices and lower CO_2 emissions relative to other fossil fuels–would not affect our estimates, since these benefits are national or global so have no impact on local relative house prices. We refrain form speculating about the scale of these more general benefits relative to the local costs in Britain, because quantifying the benefits is itself a major challenge and the estimates available are wide ranging depending on the assumptions made. Moreover, as of November 2019, the UK Government announced “an indefinite suspension” of fracking, after new attempts caused additional tremors and the Oil and Gas Authority concluded that it is not possible to predict the likelihood of their occurrence or magnitude. Evidently the Government’s conclusion was that the risks outweighed the benefits and so a big fracking expansion in the UK is now unlikely.

Declaration of Competing Interest

The authors declare that they do not have any financial or nonfinancial conflict of interests

Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jue.2020.103313.

References

Andersson, H., Jonsson, L., gren, M., 2010. Property prices and exposure to multiple noise sources: hedonic regression with road and railway noise. Environmental & Resource Economics 45 (1), 73–89.

Andrews, I., 2013. The Carboniferous Bowland Shale Gas Study: Geology and Resource Estimation. British Geological Survey for Department of Energy and Climate Change. London, UK.

Bai, J., 2009. Panel data models with interactive fixed effects. Econometrica 77 (4), 1229–1279.

Bajari, P., Fruehwirth, J., Kim, K.i., Timmins, C., 2012. A rational expectations approach to hedonic price regressions with time-varying unobserved product attributes: the price of pollution. American Economic Review 102 (5), 1898–1926.

Bakkensen, L.A., Barrage, L., 2017. Flood Risk Belief Heterogeneity and Coastal Home Price Dynamics: Going Under Water? Working Paper. National Bureau of Economic Research doi:10.3386/w23854.

Balthrop, A.T., Hawley, Z., 2017. I can hear my neighbors’ fracking: the effect of natural gas production on housing values in tarrant county, tx. Energy Econ. 61 (C), 351–362.

Bartik, A.W., Currie, J., Greenstone, M., Knittel, C.R., 2019. The local economic and welfare consequences of hydraulic fracturing. American Economic Journal: Applied Economics 11 (4), 105–155. doi:10.1257/app.20170487.

Bennett, A., Loomis, J., 2015. Are housing prices pulled down or pushed up by fracked oil and gas wells? a hedonic price analysis of housing values in weld county, colorado. Society & natural resources 28 (11), 1168–1186.

Bernstein, A., Gustafson, M.T., Lewis, R., 2019. Disaster on the horizon: the price effect of sea level rise. J. financ. econ. 134 (2), 253–272. doi:10.1016/j.jfineco.2019.03.013.

Bishop, K., Timmins, C., 2011. Hedonic Prices and Implicit Markets: Estimating Marginal Willingness to Pay for Differentiated Products Without Instrumental Variables. NBER Working Papers. National Bureau of Economic Research, Inc.

Black, S.E., 1999. Do better schools matter? parental valuation of elementary education. Q. J. Econ. 114 (2), 577–599.

Boslett, A., Guilfoos, T., Lang, C., 2016. Valuation of expectations: a hedonic study of shale gas development and new york’s moratorium. J. Environ. Econ. Manage. 77 (C), 14–30.

Brookshire, D.S., Thayer, M.A., Tschirhart, J., Schulze, W.D., 1985. A test of the expected utility model: evidence from earthquake risks. Journal of political economy 93 (2), 369–389.

Brown, J.P., Fitzgerald, T., Weber, J.G., 2019. Does resource ownership matter? oil and gas royalties and the income effect of extraction. Journal of the Association of Environmental and Resource Economists 6 (6), 1039–1064.

Campbell, N.J.J., 1956. Principles of mineral ownership in the civil law and common law systems. Tulane Law Rev. 31 (2), 303–312.

Caulton, D.R., Shepson, P.B., Santoro, R.L., Sparks, J.P., Howarth, R.W., Ingraffea, A.R., Cambaliza, M.O.L., Sweeney, C., Karion, A., Davis, K.J., Stirm, B.H., Montzka, S.A., Miller, B.R., 2014. Toward a better understanding and quantification of methane emissions from shale gas development. Proceedings of the National Academy of Sciences 111 (17), 6237–6242. doi:10.1073/pnas.1316546111.

Chay, K., Greenstone, M., 2005. Does air quality matter? evidence from the housing market. Journal of Political Economy 113 (2), 376–424.

Cheung, R., Wetherell, D., Whitaker, S., 2018. Earthquakes and house prices: evidence from oklahoma. Reg. Sci. Urban Econ. 69 (C), 153–166.

Colborn, T., Schultz, K., Herrick, L., Kwiatkowski, C., 2014. An exploratory study of air quality near natural gas operations. Human and Ecological Risk Assessment: An International Journal 20 (1), 86–105.

Coulomb, R., Zylberberg, Y., 2016. Rare events and risk perception: Evidence from Fukushima accident. Working Paper.

Davies, G., 2019. Fracking for Shale Gas in England. National Audit Office.

De Pater, C.J., Baisch, S., 2011. Geomechanical study of Bowland Shale Seismicity. Synthesis Report. Cuadrilla Resources Ltd., Lancashire, U. K..

DECC, 2013. Developing Onshore Shale Gas and Oil - Facts about ‘Fracking’. Technical Report. DECC, London.

DECC, 2015. Digest of United Kingdom Energy Statistics. Technical Report. DECC, London.

DECC, 2015. Onshore oil and gas exploration in the UK: regulation and best practice. Technical Report. DECC, London.

Delgado, M.S., Guilfoos, T., Boslett, A., 2016. The cost of unconventional gas extraction: a hedonic analysis. Resource and Energy Economics 46, 1–22.

Ferreira, S., Liu, H., Brewer, B., 2018. The housing market impacts of wastewater injection induced seismicity risk. J. Environ. Econ. Manage. 92 (C), 251–269.

Feyrer, J., Mansur, E.T., Sacerdote, B., 2017. Geographic dispersion of economic shocks: evidence from the fracking revolution. American Economic Review 107 (4), 1313–1334. doi:10.1257/aer.20151326.

Fitzgerald, T., et al., 2014. Importance of mineral rights and royalty interests for rural residents and landowners. Choices 29 (4), 1–7.

Fontenot, B.E., Hunt, L.R., Hildenbrand, Z.L., Carlton Jr., D.D., Oka, H., Walton, J.L., Hopkins, D., Osorio, A., Bjorndal, B., Hu, Q.H., Schug, K.A., 2013. An evaluation of water quality in private drinking water wells near natural gas extraction sites in the barnett shale formation. Environmental Science & Technology 47 (17), 10032–10040. doi:10.1021/es4011724.

Gaille, S.S., 2015. How can governments accelerate international shale development? Energy Law Journal 36 (1), 95–112.

Gallagher, J., 2014. Learning about an infrequent event: evidence from flood insurance take-up in the united states. American Economic Journal: Applied Economics 6 (3), 206–233. doi:10.1257/app.6.3.206.

Garnache, C., Guilfoos, T., 2018. When Your View Goes Up In Flames: Effect of Wildfires on Real Estate Prices. Working Paper.

Gibbons, S., 2004. The costs of urban property crime. The Economic Journal 114 (499), F441–F463. doi:10.1111/j.1468-0297.2004.00254.x.

Gibbons, S., Machin, S., Silva, O., 2013. Valuing school quality using boundary discontinuities. J. Urban Econ. 75, 15–28.

Gilman, J.B., Lerner, B.M., Kuster, W.C., de Gouw, J.A., 2013. Source signature of volatile organic compounds from oil and natural gas operations in northeastern colorado. Environmental Science & Technology 47 (3), 1297–1305. doi:10.1021/es304119a.

Gobillon, L., Magnac, T., 2016. Regional policy evaluation: interactive fixed effects and synthetic controls. Rev. Econ. Stat. 98 (3), 535–551.

Gopalakrishnan, S., Klaiber, H.A., 2013. Is the shale energy boom a bust for nearby residents? evidence from housing values in pennsylvania. Am. J. Agric. Econ. 96 (1), 43–66.

Green, C., Styles, P., Baptie, B., 2012. Preese Hall Shale Gas Fracturing: Review and Recommendations for Induced Seismic Mitigation. Induced Seismic Mitigation Report.. Working Paper.

Heckman, J., Matzkin, R., Nesheim, L., 2010. Nonparametric identification and estimation of nonadditive hedonic models. Econometrica 78 (5), 1569–1591.

Huang, L., Zhou, Y., Han, Y., Hammitt, J.K., Bi, J., Liu, Y., 2013. Effect of the fukushima nuclear accident on the risk perception of residents near a nuclear power plant in china. Proceedings of the National Academy of Sciences 110 (49), 19742–19747.

James, A., James, J., 2014. A canary near a gas well: Gas booms and housing market busts in Colorado. Working Paper.

Keeler, J.T.S., 2015. The Politics of Shale Gas and Anti-fracking Movements in France and the UK. In: Wang, Y., Hefley, W. (Eds.), The Global Impact of Unconventional Shale Gas Development: Economics, Policy and Interdependence. In: Natural Resource Management and Policy, 39. New York and Heidelberg: Springer, pp. 43–74.

Kelsey, T.W., Metcalf, A., Salcedo, R., 2012. Marcellus Shale: land ownership, local voice, and the distribution of lease and royalty dollars. Working Paper.

Koster, H.R., van Ommeren, J., 2015. A shaky business: natural gas extraction, earthquakes and house prices. Eur. Econ. Rev. 80, 120–139.

Koster, H.R., Pinchbeck, E.W., 2018. How do Households Value the Future? Evidence from Property Taxes.. Working Paper.

Koster, H.R., Van Ommeren, J., 2015. A shaky business: natural gas extraction, earthquakes and house prices. Eur. Econ. Rev. 80, 120–139.

Leggett, C.G., Bockstael, N.E., 2000. Evidence of the effects of water quality on residential land prices. J. Environ. Econ. Manage. 39 (2), 121–144.

Linden, L., Rockoff, J.E., 2008. Estimates of the impact of crime risk on property values from megan’s laws. American Economic Review 98 (3), 1103–1127.

Ma, L., 2019. Learning in a hedonic framework: valuing brownfield remediation. Int. Econ. Rev. (Philadelphia) 60 (3), 1355–1387. doi:10.1111/iere.12389.

Mastromonaco, R., 2015. Do environmental right-to-know laws affect markets? capitalization of information in the toxic release inventory. J. Environ. Econ. Manage. 71 (C), 54–70.

McCoy, S.J., Walsh, R.P., 2018. Wildfire risk, salience & housing demand. J. Environ. Econ. Manage. 91, 203–228.

McCoy, S.J., Zhao, X., 2018. A city under water: a geospatial analysis of storm damage, changing risk perceptions, and investment in residential housing. Journal of the Association of Environmental and Resource Economists 5 (2), 301–330.

Metz, N.E., Roach, T., Williams, J.A., 2017. The costs of induced seismicity: a hedonic analysis. Econ. Lett. 160 (C), 86–90.

Moulton, J.G., Sanders, N.J., Wentland, S.A., 2012. Toxic Assets: How the Housing Market Responds to Environmental Information Shocks. Working Paper.

Muehlenbachs, L., Krupnick, A., 2014. Infographic: shale gas development linked to traffic accidents in pennsylvania. Resources 185.

Muehlenbachs, L., Spiller, E., Timmins, C., 2015. The housing market impacts of shale gas development. American Economic Review 105 (12), 3633–3659.

Naoi, M., Seko, M., Sumita, K., 2009. Earthquake risk and housing prices in japan: evidence before and after massive earthquakes. Reg. Sci. Urban Econ. 39 (6), 658–669.

Olmstead, S.M., Muehlenbachs, L.A., Shih, J.-S., Chu, Z., Krupnick, A.J., 2013. Shale gas development impacts on surface water quality in pennsylvania. Proceedings of the National Academy of Sciences 110 (13), 4962–4967. doi:10.1073/pnas.1213871110.

Oster, E., 2019. Unobservable selection and coefficient stability: theory and evidence. Journal of Business & Economic Statistics 37 (2), 187–204. doi:10.1080/07350015.2016.1227711.

Pope, J., 2008. Fear of crime and housing prices: household reactions to sex offender registries. J. Urban Econ. 64 (3), 601–614.

Pope, J.C., 2008. Buyer information and the hedonic: the impact of a seller disclosure on the implicit price for airport noise. J. Urban Econ. 63 (2), 498–516. https://doi.org/10.1016/j.jue.2007.03.003.

Prat, A., Strömberg, D., 2013. The Political Economy of Mass Media. In: Acemoglu, D., Arellano, M., Dekel, E.E. (Eds.), Advances in Economics and Econometrics: Tenth World Congress. In: Econometric Society Monographs, 2. Cambridge University Press, pp. 135–187. doi:10.1017/CBO9781139060028.004.

Rosen, S., 1974. Hedonic prices and implicit markets: product differentiation in pure competition. Journal of Political Economy 82 (1), 34–55.

Roy, A., Adams, P., A., R., 2014. Air pollutant emissions from the development, production, and processing of marcellus shale natural gas. Journal of the Air & Waste Management Association 64 (1), 19–37.

Singh, R., 2019. Seismic risk and house prices: evidence from earthquake fault zoning. Reg. Sci. Urban Econ. 75, 187–209.

Snyder, J., Strömberg, D., 2010. Press coverage and political accountability. Journal of Political Economy 118 (2), 355–408.

Walsh, P., Milon, J.W., Scrogin, D.O., 2011. The spatial extent of water quality benefits in urban housing markets. Land Econ. 87 (4), 628–644.

Warner, N.R., Christie, C.A., Jackson, R.B., Vengosh, A., 2013. Impacts of shale gas wastewater disposal on water quality in western pennsylvania. Environmental Science & Technology 47 (20), 11849–11857. doi:10.1021/es402165b.

Weber, J.G., Burnett, J.W., Xiarchos, I.M., 2016. Broadening benefits from natural resource extraction: housing values and taxation of natural gas wells as property. Journal of Policy Analysis and Management 35 (3), 587–614.

Weber, J.G., Hitaj, C., 2015. What can we learn about shale gas development from land values? opportunities, challenges, and evidence from texas and pennsylvania. Agricultural and Resource Economics Review 44 (2), 40–58.

Yinger, J., 2015. Hedonic markets and sorting equilibria: bid-function envelopes for public services and neighborhood amenities. J. Urban Econ. 86, 9–25.