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The Price of Indoor Air Pollution:
Evidence from Risk Maps and the Housing Market

Edward W. Pinchbeck* Sefi Roth† Nikodem Szumilo‡ Enrico Vanino§

Abstract

This paper uses the housing market to examine the costs of indoor air pollution. We focus on radon, a common indoor air pollutant which is the leading cause of lung cancer after smoking. For identification, we exploit a natural experiment whereby a risk map update in England induces exogenous variation in published pollution risk levels. We find a significant negative relationship between changes in published pollution risk levels and residential property prices. Interestingly, we do not find a symmetric effect for decreasing risk. We also show that the update of the risk map led higher socio-economic groups (SEGs) to move away from affected areas, attracting lower SEG residents via lower prices. Overall, our results demonstrate that indoor air quality has material economic effects on the housing market and provide novel policy-relevant insights into how the market responds to information on environmental risks.

Keywords: indoor air pollution; neighbourhood sorting; house prices; risk information; radon.

JEL codes: Q53, H23, R21, R28.

*University of Birmingham

†London School of Economics and IZA

‡University College London - Corresponding author: n.szumilo@ucl.ac.uk.

§University of Sheffield

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1 Introduction

The adverse impacts of ambient pollution and its associated costs have received substantial public policy attention in the last few decades. Nevertheless, the health and economic consequences of indoor pollution are often overlooked. This is surprising given that the population in developed countries spends approximately 90% of their time indoors (Klepeis et al., 2001), and the documented substantial health implications from exposure to indoor pollution. More specifically, the World Health Organisation (WHO) estimates that indoor pollution is responsible for 2.7% of the global burden of disease and 3.8 million deaths every year. In Europe alone, it is estimated that a minimum of 99,000 deaths are attributed to indoor air pollution but experts suggest that the exact number is likely to be much higher (Holgate, 2017). Importantly, indoor pollution is not simply a by-product of ambient pollution, as there are numerous indoor sources of pollution including cooking, smoking and substances of natural origin such as radon. In fact, according to the US Environmental Protection Agency (EPA) the indoor concentrations of some pollutants are in many cases 2 to 5 times higher than those typical outdoor. As such, focusing on reducing ambient pollution concentrations without addressing the indoor environment would fail to provide adequate protection to the public against overall pollution exposure.

Assessing the economic effects of indoor pollution is challenging for several reasons, even compared to other non-market goods. First, large data samples on indoor air pollution are rarely available. Second, exposure to indoor pollution may be associated with unobserved factors that are also correlated with human health and well-being (e.g. income, diet and smoking). Finally, monetizing the total cost of exposure to indoor pollution is remarkably difficult, as exposure can lead to a wide range of observed or unobserved health and wellbeing costs.[1] This paper exploits a unique opportunity to overcome these challenges and examine the following research questions: What is the willingness to pay to avoid indoor air pollution? Which socio-economic groups are most affected by it? And what are the consequences of providing information to the public about indoor pollution risk?

We address these questions by looking at how an exogenous variation in the information provided by governmental sources about the level of indoor pollution risk is linked with variation in residential property prices in England. We focus on radon, an odourless, colourless and tasteless common indoor air pollutant which is formed by the natural decay of uranium from rocks and soil. Radon is considered to be the largest source of exposure to natural ionising radiation, which damages human lungs and causes lung cancer. Globally, exposure to radon at homes and workplaces is estimated to cause tens of thousands of deaths each year, making it the most important cause of lung cancer after smoking

[1] Indoor pollution can affect a wide range of outcomes including mortality, morbidity, cognitive performance and educational outcomes (Duflo et al., 2008; Künn et al., 2019; Stafford, 2015; Gilraine, 2019; Roth, 2019).

(WHO, 2009; US-EPA, 2013). The main risk factors for getting lung cancer from radon depend on the level and duration of exposure, and whether the individual is a smoker or has smoked in the past. However, it is important to note that while smoking is an important risk factor, exposure to radon is also the number one cause of lung cancer among non-smokers. Due to increased awareness of these deleterious effects on health, radon exposure has become an increasingly important environmental concern for policymakers. Consequently, the US, EU and China have developed new radon policies for buildings and residents, and in many cases have commissioned radon maps of increasing accuracy and spatial granularity to increase awareness about this issue (Gruber et al., 2013; US-EPA, 2013; Zielinski et al., 2006). Nonetheless, there is very limited evidence on how effective those policies are in informing market participants about radon risk, and more generally about the economic cost of radon.[2]

We conduct our analysis using a unique data set that combines information on the universe of residential property transactions in England with detailed maps of radon risk provided by Public Health England that classifies radon risk into six categories of increasing risk, of which all but the first are classified as "radon affected areas".[3] To overcome endogeneity concerns, we exploit a quasi-experimental radon risk variation resulting from the publication of an updated radon risk map in England in 2007, which did not incorporate changes in actual levels of radon, but simply new developments in risk modelling techniques. Our setting is also advantageous because since 2002 the UK standard conveyancing searches undertaken on behalf of house buyers must include information about radon risk based on the latest map.[4] The combination of arguably exogenous variation and information disclosure to home buyers provides us with a unique opportunity to estimate the effects of pollution risk information in

[2]Our focus on radon is also advantageous from an empirical perspective. Unlike other common pollutants (such as particulate matter), outdoor concentration of radon is typically very low (as it dilutes quickly), and it is generally not consider as a health risk. This feature of radon is what makes it an ideal pollutant to use in our study, as it enables us to ensure that we estimate only the willingness to pay to avoid indoor air pollution and not ambient pollution or some combination of the two.

[3]The six categories of risk are based on the estimated percentage of houses in the grid square above the action level of 200 becquerels per cubic meter (Bq m^3): 0-1% (risk free area), 1-3%, 3-5%, 5-10%, 10-30% and >30%.

[4]These conveyancing searches are enquiries with public authorities that a specialist property lawyer or a licensed conveyancer makes to provide buyers with more information about the property that they plan to buy. These searches include enquiries that are sent to Local Authorities, which are the main units of local government in the UK. One part of the searches is the CON29 form: a standard set of questions set by the government, the Law Society and the Local Government Association. CON29 contains required and optional questions. Radon gas is on the required part, whereas flooding is on the optional part. The radon question asks if the property is in a "radon affected area", which is defined as any risk category higher than category one. There is no explicit requirement to report the specific category in which the property is, although the conveyancer can find this out from other sources. Importantly, conveyancing searches are required to obtain a mortgage. They are not required for cash buyers but will usually be undertaken. As a robustness test, we confirm that our main analysis yields similar results when using a sub-sample of properties with only mortgage buyers.

housing markets.

Our baseline specifications examine the effect of radon risk category changes on house prices using a repeat-sales approach. The principal measure of radon we use is the reclassification from the first category, i.e. reclassification into a "radon affected area". We find a highly significant negative relationship between changes in radon risk and changes in residential property prices. The results from our preferred specifications suggest that an upward reclassification of a property, from being in a radon risk-free category to being in a radon affected category, reduces property prices by about 0.8%. These results are economically significant and are similar to the estimated effects found in studies that measure the impact of flooding risk or earthquake risk on property prices (Bosker et al., 2018; Naoi et al., 2009). In contrast, we find no evidence that downwards reclassifications of radon risk (i.e. lower radon risk) affect house prices. A possible explanation for these asymmetric results might be the fact that buyers are responsible for conducting the conveyancing search, which includes information about the current radon risk level, and that sellers might not be informed of the latest radon risk reclassification of their area. However, we are unable to make strong claims about this because there are substantially less data points for which radon risk levels fall.

We next test whether radon risk induces sorting. We find that it does, and more specifically we show that the share of higher educated, home owning and higher social status residents decreases in response to upward radon risk reclassification. Once again, we find no effect of downward reclassification. These findings have two important implications. First, they suggest that radon risk disproportionately affects lower socio-economic groups in our society, creating a source of environmental injustice, in line with previous theoretical predictions (Hausman and Stolper, 2021). Second, it means that our previous estimates are "local", in the sense that they reveal the Willingness To Pay (WTP) of the specific buyers who are purchasing houses affected by radon and not the average buyer (see Greenstone (2017), Gamper-Rabindran and Timmins (2013) and Davis (2004) for more details). Therefore, we propose and apply a new theoretical framework, following Bayer et al. (2007) and utilising results from Besley et al. (2014), that uses transaction probabilities to account for sorting in order to calculate the average WTP. We also present several robustness tests and placebo exercises that provide further support to our empirical analysis and validate our estimates.

Our study provides several important contributions to the literature and to policy-making more broadly. First, despite the growing body of work on the capitalization of ambient air pollution (Chay and Greenstone, 2005; Currie et al., 2015), the paucity of direct measurements of indoor air pollution mean we are among the first to provide an hedonic estimate of the economic impact of indoor air pollution. To the best of our knowledge, the only other revealed-preference estimates of WTP for indoor air quality improvements are inferred from the demand for air purifiers in China (Ito and Zhang, 2020). The authors of this study develop a novel framework to estimate WTP for indoor air quality improvements from information on the air purifier's effectiveness in reducing indoor particulate matter and the price elasticity of demand. Although we lack home-specific measures of indoor air pollution, the risk categories in our data are arguably a very close approximation to this ideal, because they are derived from the underlying measurements and because they are very granular. Furthermore, even though radon is linked with significant health risks by the epidemiological literature, it has not yet received much attention in economics and our paper addresses this gap as well. In fact, the only two exceptions are a paper by Smith and Johnson (1988) which studied how households form risk perceptions using a survey of households' responses to information about risks associated with radon in Maine, and a paper by Howe and Shreedhar (2020) that evaluated if a 'Healthy Home Checklist' postcard nudges households to purchase a radon test in Ottawa.

Second, consistent with approaches in other countries and other domestic policies (e.g. on energy efficiency), the UK Government radon policy centres on increasing information availability to allow markets to price environmental risks. Our paper provides critical insights into how the market responds to this information, complementing a growing literature on the effects of access to pollution information that has so far solely focused on ambient pollution (Cutter and Neidell, 2009; Zivin and Neidell, 2009; Barwick et al., 2019), and to the empirical literature on the role of information on environmental risks and on consumer choices more broadly (Hastings and Weinstein, 2008; Jessoe and Rapson, 2014; Wichman, 2017; Bakkensen and Barrage, 2017; Bakkensen and Ma, 2020). Importantly, our distinctive setting enables us to purely estimate the effect of information shock as the underlying risk (actual pollution level) has not changed. This is unique because most papers in the literature study an exogenous shock to the amenity itself (e.g. flood risk) and the price or other responses to this change are a composite of the change in the amenity itself and its salience.

Third, our work also speaks to the literature on environmental justice, which denotes various channels through which environmental costs and poverty or race may be correlated, including household sorting (or "coming to the noise/nuisance") and selective siting of polluting facilities (Banzhaf et al., 2019; Hausman and Stolper, 2021). The evidence on the extent to which sorting drives the observed correlations in this literature is mixed, in part reflecting considerable empirical challenges (Banzhaf et al., 2019). We contribute to this literature by showing that different socio-economic groups sort in response to radon risk change.

Fourth, our study contributes to the existing hedonic literature on air pollution by overcoming two important and common empirical limitations. More specifically, the institutional set up we study determines that information on property-level radon risk is made available to buyers through standard conveyancing searches. This addresses an important concern regarding prior research studying the impact of air pollution on property prices, which are less certain about market participants awareness of pollution levels. Recent evidence on the effects of environmental information disclosure on house prices and other outcomes suggests this is an important concern (e.g Pope, 2008; Moulton et al., 2018). Additionally, we propose and utilise a new theoretical framework to estimate the average willingness to pay in the presence of sorting.

Finally, our paper demonstrates that the stakes are high for policymakers working on indoor air pollution. Due to its geology, the UK has relatively low levels of radon compared to those found in other countries, notably the US and China.[5] Despite this, our estimates imply that if unmitigated by remedial measures the presence of radon in our setting would reduce the total market value of residential properties in England by as much as £5.8 billion.[6]

The rest of the paper is structured as follows: the next section provides background information about radon risk and risk information policy in the UK; section 3 presents the data and our study design; section 4 discusses the empirical strategy; section 5 presents the main results of our analysis; section 6 proposes and utilises a new theoretical framework to account for sorting and estimate the average WTP, while section 7 concludes.

2 Background on radon and the UK

2.1 Background on radon

Radon is a colourless, odourless and tasteless gas which is formed by the natural decay of uranium that occurs in all rocks and soil. Once escaped from the ground into the air, it decays and produces radioactive particles which tend to concentrate in enclosed spaces. The amount of radon in houses, schools and workplaces depends on a variety of factors including the amount of uranium in the underlying rocks and soil, the available routes for radon to enter the building, and the rate of exchange

[5] According to the EPA, approximately 1 out of every 15 houses in the US have elevated levels of radon.

[6] This range is obtained by multiplying the average impact of being reclassified to a radon affected area (0.8%) by the number and average value of all houses in the housing stock classified to be in radon affected areas according to the latest and most accurate radon maps available (25x25 meter grid).

between indoor and outdoor air (WHO, 2009). Radon is usually measured in becquerels per cubic meter (Bq m^3) or in picocuries per liter (pCi/L). In the UK and in many other countries, a radon level of 200 (Bq m^3) or above is classified as "Action Level", which means that householders are advised to take actions to reduce radon through remediation works (e.g. by installing a radon sump). The average radon level in UK houses is 20 (Bq m^3), but there is significant variation across geographical areas and some dwellings have yielded readings of more than ten thousand Bq m^3 (PHE, 2018).

According to the medical literature, radon can affect the human body as radioactive elements are inhaled and enter the lungs where they emit radiation. This radiation (mainly alpha particles) is absorbed by nearby tissues which can lead to lung cancer. Early epidemiological studies evaluated this link empirically among miners, and established that exposure to high levels of radon is associated with an increased risk of lung cancer (Radford and Renard, 1984; Howe et al., 1986; Tirmarche et al., 1993). Later studies have examined the relationship between residential exposure to radon and lung cancer in the general population. This strand of the literature, which relies on pooled large scale epidemiological studies, provides robust evidence that residential exposure to radon is linked with a significant number of lung cancers in China, North America and Europe (Lubin et al., 2004; Krewski et al., 2005; Darby et al., 2006). While there is a small theoretical risk that radon exposure can also cause cancer to other organs, there is currently no strong empirical evidence to support this hypothesis (AGIR, 2009).

Approximately 1,100 lung cancer deaths a year in the UK and 21,000 in the US are attributed to exposure to elevated levels of radon. Although these numbers are considerably lower than deaths attributable to smoking, radon is the most important cause of lung cancer after smoking (US-EPA, 2013; Gray et al., 2009). The main risk factors for getting lung cancer from radon depend on the levels of radon exposure and whether the individual is a smoker or has smoked in the past. For example, if 1,000 people who smoke were exposed to a radon level of around 0.5 Bq m^3 over a life time, about 150 of them could get cancer compared to 36 people among a group of 1,000 people who have never smoked and were exposed to the same level of radon. Nevertheless, it is important to clarify that non-smokers are still at significant risk from radon exposure, and according to the EPA radon is the number one cause of lung cancer among non-smokers. There are several methods for radon prevention and mitigation at dwellings, such as increasing under-floor ventilation, installing radon sump systems, and sealing floors and walls. The appropriate remedial strategy depends on several factors including radon levels, sources and the type of floor. Importantly, none of the techniques can guarantee complete eradication of radon, and often a combination of strategies is required to reduce the risk. This is important given the fact that measuring radon concentration is a complex process, as readings can vary between rooms, over times of day, months of the year or even with phases of the moon. Costs of these remedial techniques vary significantly, but as a rough guideline the approximate costs range between £200 and £2000 according to Public Health England. However, in practice a high proportion of affected properties, both in the UK and in other countries, do not have any remediation measure in place (Zhang et al., 2011). This could be due to non-monetary costs of installation (hassle costs), budget constraints for lower socio-economic groups, or low awareness of the health risks related to radon.

2.2 History of radon information and policy in the UK

Developments in understanding the health risks of ionizing radiation after the Second World War led to investigations of radon levels in UK houses in the 1970s and 1980s. These initial local measurement schemes developed into a systematic measurement program which tried to identify areas and houses exposed to the risk. The concept of "radon affected areas" was introduced in the 1990s and defined as areas where 1% of houses were above a pre-specified action level. In 1993 several parts of the UK were designated as affected areas and in 1996 the first complete nation-wide map of radon was published. The map was based on over 250,000 measurements, and denoted radon risk in 5km grid squares using five categories of risk based on the percentage of houses in the grid above the action level: 0-1% (risk free area), 1-3%, 3-10%,10-30% and >30%. The measurements in each dwelling were made with two detectors over a period of three months and were calculated using temperature corrections to enable to produce accurate annual estimates.[7]

A second radon map was issued in November 2002 and was in use from 2003. This map (the "2003 map") updated the 1996 map based on additional measurements (over 400,000). It also included an additional risk category, as the 3-10% category was split into 3-5% and 5-10%. Additional measurements allowed mapping the affected areas of the South West of England in a $1km^2$ grid. A third iteration of the radon map was then released in November 2007 (the "2007 map"), as shown in Figure 1 presenting the evolution of these maps. This updated map incorporated further improvements to probability models, which now included not only measurements but also geological information as input variables (Miles et al., 2007).[8] Importantly, two versions of this 2007 map were created from

[7]Houses included in the measurement program were selected based on progressive measurements of areas where initial reading were high and on geological data.

[8]Specifically Miles et al. (2007) state that, "The previous maps published separately by the NRPB and BGS grouped domestic radon results either by grid square or by geological unit, before applying lognormal modelling. Both of these mapping methods ignore some part of the geographical variation in radon potential: grid square mapping ignores variation between geological units within grid squares, and geological mapping ignores variation within areas sharing combinations of geological characteristics. It was realised by the HPA and BGS that combining the two methods could

the same underlying data. The first (the "25m 2007 map") was a map using a 25x25 meter grid for the whole of England. Unlike the earlier maps, this version was not available to the public or to local government organisations free of charge, but required a fee to be accessed (a paid subscription for institutions including government organisations). However, a second publicly available version of the 2007 update was released, which indicated radon risk in 1km grid squares (the "1km 2007 map"). This $1km^2$ map was created by taking the maximum category of radon risk in all the 25 meter squares within each 1km square.[9]

Radon information can be obtained by individuals in two main ways. First, maps are available online for download, so potential buyers could in theory find this information themselves. However, since it is unlikely that the average buyer would actively search for such information online,[10] we believe (and later document) that the main source of radon information that buyers receive is via the set of questions submitted to Local Authorities (LAs) by specialist property lawyers or licensed conveyancers on behalf of their clients when a property is traded or a development application is made.[11] These are known as Local Authority searches and the specific form used to make enquiries is known as CON29. CON29 contains a standard set of questions which are jointly agreed by the government and the Law Society. Part of the form indicates required questions (CON29r) and another part contains optional questions (CON29o). Information about radon has been a part of this process since 1994 and it was made compulsory in July 2002 (it was previously optional). Conducting Local Authority searches is a formal requirement for mortgage lenders, so we can be sure that all mortgaged buyers receive radon information (representing around 70% of all transaction in the UK according to the ONS). While cash-buyers are not required to do so, we expect most will as the searches are inexpensive and solicitors will recommend them. The information about radon is based on risk categories, but the CON29 is only strictly required to state if a property is in a radon affected area (any category other than category 1) and not its actual risk category.[12] Buyers obtain CON29 information only at a relatively late stage in the buying process, since the LA searches are performed after an offer is accepted, but before final sales price is agreed and the deposit (usually 10% of the final sales price) is paid. Frequently, the

give more accurate mapping than either separately. The two organisations cooperated to develop a joint geological/grid square mapping method. This atlas is the outcome of applying this method to radon mapping in England and Wales, and supersedes the previous atlas of radon potential in England and Wales".

[9] A comparative example of these two set of maps for the Sheffield Local Authority District is provided in Figure A1 in the Appendix.

[10] Analytics from Google Trend show a limited and stable number of online searches in the UK about radon maps through this period, even around the release of updated maps. Also see section 5 for more analysis on this subject.

[11] Local Authorities are the main unit of local government in the UK.

[12] Specimen of a standard CON29 form could be found on the UK Law Society website: https://www.lawsociety.org.uk/en/topics/property/con29-forms. Figure A2 in the Appendix shows an example of the demand and answer about radon provided in a standard CON29 form.

final sales price differs from the accepted offer to reflect information disclosed to the buyer about previously unknown characteristics of the property (lack of required documents, environmental hazards, revealed extensive work required, presence of Japanese knotweed, etc.), as in England an offer does not become legally binding until contracts are exchanged. In addition, the results of the conveyancing searches are not transmitted to the sellers, who might be informed about their outcomes only by buyers.

The transmission of information contained in the radon maps to home buyers is an important consideration in our empirical work. In late 2002 copies of the 2003 map were provided to all Local Authorities (LAs) in the country, and contemporaneous guidance issued by the National Radon Protection Board (NRPB) indicated that the map should be used by LAs to answer enquiries by conveyancers about whether houses were in radon affected areas. For the 2007 map update, things are more complicated as Local Authorities had a choice about which map to use. Around half of the Local Authorities in the country have elected to licence the more spatially detailed 25x25 meter version of the map for part or all of the period since it was released, while the other half have elected to use the freely available $1km^2$ version of the 2007 map. In our empirical work we will define house level radon information based on the version of the 2007 map the associated LA had at the time of the house sale, and further exploit the two map versions for robustness checks.[13]

3 Data and Study Design

Our final dataset combines information on house sales, radon risk and various socioeconomic characteristics from several administrative sources. Data on house sales come from the Land Registry, which contains all housing transactions in England between the years 1995-2018. From this source,

[13]Besides the radon maps and the CON29 form, there are two further institutional details which are somewhat related. First, newly built houses are subject to radon policies. The general policy since 1990 has been that houses with radon levels above $200Bqm^3$ are advised to apply preventive measures and all new buildings in affected areas have to apply these measures (National Radiological Protection Board, 1996). Second, a Home Information Packs (HIP) policy, in place from late 2007 to May 2010, required house sellers or their representatives to disclose a number of documents and pieces of information to buyers about the house before a sale, including an Energy Performance Certificate, local authority searches, title documents, guarantees, etc, as well as to state if the house is in a radon affected area as identified by the Health Protection Agency. While the HIP policy could signal a mechanism for sellers to learn of radon risk changes to their house, in practice this assumption could be tenuous as it would require that (a) the HIP contains accurate and up to date radon information from a new LA radon search, and (b) the seller carefully checking the HIP radon question. The first condition is undermined because the regulations do not specify which map should be used, and by evidence from a survey that found five out of six HIPs contained “inaccurate, incomplete or missing information” (”Home Information Packs: a short history”, House of Commons Research Paper 10/69). The second also seems improbable given that the vast majority of sellers would be unaware of the 2007 radon map update (or even that radon maps are periodically updated), and hence unlikely to carefully check through a 100 page document for this information.

we take over 2.4 million transactions that took place during our 2003-2011 study period. This is the population of all repeated transactions of the same property which is a sub-sample of the population of all 6.48 million transactions in England in this period. Our data on radon risk comes from radon maps provided by Public Health England (PHE) which are the publicly available maps and the 25 meter square map provided by the British Geological Survey. The public maps are presented in Figure 1. Notably, the three maps include revisions of the radon level in numerous locations with the vast majority of revisions increasing the level of radon risk (see Table 1).

In order to focus our study on areas where we can be certain that buyers received information about radon and what map was used to provide it, we only consider transactions in which the first sale occurred between January 2003 and October 2007 and the second sale between 2008-2011.[14] The full database consists of 601,6554 pairs of transactions, as shown in Table 1, where for each property we observe two transactions, one before the map update and one after.

There are 6 radon categories in each map, and house level changes can theoretically be in any of the 36 possible combinations. However, as shown in Table 1, in practice about 72% of dwellings in our sample stay in the same category (n=435,090). Of those that do move categories (n=166,565), more than 64% start in category 1 and move up, while only 13% start in a category higher than 1 and move down one or several categories. Moreover, some combinations of starting and ending category are very thin, especially when we condition on area fixed effects. We therefore collapse the dimensionality of this problem by focusing on particular start/end category combinations that are well-populated, notably moving to and from a radon affected classification (i.e. categories above 1), as shown in Figure 2 where we map the spatial distribution of areas reclassified as radon-affected, those reclassified as being radon-free, and those unaffected by the reclassification between the 2003 and the 2007 maps. This strategy also better reflects the information provided to buyers about properties radon-risk through the CON29 forms. To create our final sales dataset, we first geocode each property using the AddressBase database from the Ordnance Survey. This gives us the exact location of each house, which enables us to assign a radon risk category to each transaction from the radon risk maps. By using ancillary data which tell us the periods when Local Authorities had a subscription to the 25x25 meter grid version of the 2007 radon map, we ensure the radon risk in our data matches the radon information buyers receive from the CON29 form.[15] Note however that where CON29 information comes from the $1km^2$

[14]Starting our sample period in 2003 implies that we use two iterations of radon maps and we focus only on sales when radon questions were compulsory in the CON29 form. With the most recent radon map issued in November 2007, we drop the final 2 months of 2007 because it is unclear which map was used. We choose to end the sample period in 2011 as this is the last year for which we have rich demographic information from the Population Census.

[15]We obtained this information about map usage from The British Geological Survey.

map, individuals can purchase information from the 25 meter square map which may indicate a lower, but not higher, radon category (the $1km^2$ map gives the local maximum of the 25x25 meter tiles). This implies we may sometimes have "false positive" radon affected classifications in the $1km^2$ map.

Besides this property-level dataset, we also create several area level datasets. For balancing checks and to test for sorting, we obtain micro-neighbourhood information on socioeconomic characteristics such as education, age and ethnicity from the 1991, 2001, and 2011 Censuses. The spatial units we use are Output Area (OA), the smallest census geography in the UK, with an average of around 100 residents.[16] We measure the radon level in each area by assigning the median radon risk for all houses in the same neighbourhood. Finally, to examine the effect of radon on transactions, we also create two panel datasets for the period 2003-2011 at the level of (i) the radon map grid square tile and (ii) the Output Area.[17]

Table 2 presents summary statistics for all property transactions in our dataset. The first two columns, considering all transactions, show that cross-sectionally transaction prices in radon affected areas do not appear to be statistically different from those in radon-free areas, although the mean house price is slightly lower for transactions in categories higher than one. The next three columns consider only repeated sale transactions, showing that prices of properties where radon did not change grew faster than in places where radon risk changed (either upwards or downwards). Figure 3 provides another insight into the evolution of prices, comparing properties that were reclassified from radon free to radon-affected areas with unaffected properties before and after the reclassification. As evident from the figure, reclassified properties experienced a sizable reduction in price growth following the reclassification in October 2007, compered to properties which were not reclassified. Naturally, these comparisons are very general as they do not account for confounding factors. In the next section we provide detailed explanation of possible confounders and how our empirical strategy overcomes them.

4 Empirical Strategy

Following the standard hedonic approach to modelling house prices, we begin with the following simple equation:

$$ln(P_{it}) = \beta R_{it} + \rho X_i + \epsilon_{it} \quad (1)$$

[16] OAs are the smallest of a hierarchy of nested Census geographies. They sit within Lower Layer Super Output Areas (LSOAs) which in turn are nested within Middle Layer Super Output Areas (MSOAs).

[17] More information provided in Appendix A.2.

Where P_{it} denotes the transaction price of property i in year t, R_{it} is the level of radon risk category for the transacted property given by the map used by the Local Authority at the time of the transaction, X_i is a vector of time invariant property characteristics, and ϵ is an idiosyncratic error term.

The usual identification problem is that radon risk levels can be correlated with both the features of the house and with property price. For example, geological conditions could affect the level of radon risk but also the amenity value of the location or construction materials used to build houses. As such, estimating equation 1 would yield a biased estimate in the presence of unobserved correlated factors. To overcome this problem we take advantage of the popular approach in the real estate literature and adopt a repeat-sales approach (Cannaday et al., 2005). More specifically, if the same property is transacted also in year τ (where $\tau > t$), we can write a first-difference model of the following form:

$$ln\left(\frac{P_{i\tau}}{P_{it}}\right) = ln(P_{i\tau}) - ln(P_{it}) = \beta \Delta R_{i\tau t} + \epsilon_{i\tau t} \tag{2}$$

The repeat-sales approach removes all time-invariant characteristics and focuses our identification on changes in radon risk levels within the same property over time. The approach is particularly compelling in our context because geological conditions and actual radon levels do not change over time, yet the estimates of the radon risk do due to map updates. As radon only affects humans through the impact on their health, β captures the impact of the health risk associated with radon on prices. Since time varying unobserved correlated variables remain a potential threat for causal identification, we allow for house prices to change over time by including a fixed effect θ for the first and second years, τ and t, and quarters, κ and q, which effectively strips out any time effects in log price changes and seasonal price effects:

$$ln\left(\frac{P_{i\tau}}{P_{it}}\right) = ln(P_{i\tau}) - ln(P_{it}) = \beta \Delta R_{i\tau t} + \theta_t + \theta_\tau + \theta_q + \theta_\kappa + \epsilon_{i\tau t} \tag{3}$$

Furthermore, we also adjust for local housing cycles by allowing each area to have its own trend in prices between periods τ and t. We define areas in one of two ways, one based on administrative geography and the other using an arbitrary spatial grid. For the former, our units are Census Middle-Layer Super Output Areas (MSOAs), which have populations of between 7,000 and 10,000 people. For the latter, we group homes together by rounding the centroid of the full postcode - which typically contain between 15 and 100 homes - to a 1km grid. This postcode grid has the advantage of yielding a tight spatial grouping that does not fully overlap with the radon map grid or administrative units and is used in our main estimates. Finally, we separate areas according to which version of the 2007 map (25x25 meter or $1km^2$) was in use by the Local Authority at the time of the second sale, which effectively means our identifying variation comes from comparing sales of homes that become radon affected or not under the same version of the map.[18] Specifically, our main specification takes the following form:

$$ln\left(\frac{P_{i\tau}}{P_{it}}\right) = ln(P_{i\tau}) - ln(P_{it}) = \beta \Delta R_{i\tau t} + \theta_{rt} + \theta_{r\tau\mu} + \theta_q + \theta_\kappa + \epsilon_{i\tau t} \quad (4)$$

Where θ_{rt} and $\theta_{r\tau\mu}$ interact year of sale and area r fixed effects (postcode grid or MSOA), and in the latter case with an indicator which denotes whether the parent Local Authority had a contract to use the 25 meter square map. Therefore, our identification is based on changes in radon risk levels within the same property over time after accounting for all time-invariant characteristics of the property and factors common to the local area.

Importantly, for equation 4 to reveal a causal estimate we have to assume that without the treatment changes in house prices in the treatment group would have followed the same trend as in the control group. We test this assumption in two ways, first we assess if the two groups followed the same trends before the treatment. In Fig. 3, price indices of the two groups are plotted against time and clearly follow the same trends before 2008. Second, in section 5.3 we test the parallel pre-trend assumption more formally and find no evidence that it is violated. Besides this, we can also evaluate whether the main treatment in our analysis (radon level going from "risk free" to "radon affected" relative to remaining "risk free") is correlated with potential determinants of house prices. Only if our treatment is plausibly uncorrelated to these factors, we can use our estimated price effects to calculate the average willingness to pay (see section A3 in the Appendix). To do so, we obtain data for micro neighbourhood level characteristics from the 2001 and 1991 Censuses and regress these on an indicator for radon level going from "risk free" to "radon affected" under the 2007 map change, together with area fixed effects and some time invariant spatial controls, restricting the attention to places that were classified as being radon risk free in the initial period. Our regressions take the form:

$$y_j = \gamma R_j^+ + \theta_{r\mu} + \rho X_j + \epsilon_j \quad (5)$$

where y_j represents a share variables for 2001, or a change in the share variables between 1991 and

[18]Note that the radon map version is not collinear with the fixed effects, as map use changes over time and can also vary within postcode grids. As the $1km^2$ map reflects a local maximum, radon designations may have different implications under the different maps; these controls thus ensure we are comparing like with like. These controls also mitigate effects of false positive radon classifications in the $1km^2$ map which arise because people can purchase the 25 meter square map. False positives may be particularly prevalent in postcode grid cells where both maps are used and, as conditional treatment variance is higher in the 25 meter square map, ignoring the map version tends to increase the weight our estimator puts on these false positives. Our results are materially unchanged if we instead drop all observations in postcode grid-year cells that contain both version of the map in which case this control is obsolete.

2001 for Census Output Areas (OA) j, while R_j^+ is an indicator for (median) radon level going from "risk free" to "radon affected" under the 2007 map change, $\theta_{r\mu}$ is an interaction between the area r fixed effect and an indicator μ denoting whether the associated Local Authority had a contract to use the 25 meter square map at any time after the 2007 map was released, and X_j includes distances to the labour market centre, the nearest coast, and nearest rail station. The additional controls capture trends correlated to geology but also to long term gentrification (they drop out of equation 4 as they are time-invariant).

In the first column of Table A2 we find that most area characteristics are uncorrelated with our radon measure when we use our preferred $1km^2$ postcode grid local area fixed effects. There are some exceptions to this. In particular, we find that the share of workers in high income professional and managerial occupations is correlated to radon, although the magnitude of the effect is small. The same holds true for education (which is unsurprising given that this is highly correlated with the occupation measure ($\rho = 0.83$)), age and ethnicity. However, this is not necessarily a concern, since our main identification strategy eliminates time-invariant sources of bias. Reassuringly, in the second column we find no significant correlations between radon risk increases and changes in the share variables between 1991 and 2001 for characteristics that are available in both Censuses, except for age and ethnicity but the magnitudes of these coefficients are very small. Moreover, later in the paper, we test for the presence of price trends correlated to our treatment locations (using periods in which there were no changes in radon maps) and find no evidence of trends correlated to our treatment. Besides this, we also test whether radon risk is correlated with ambient air pollution which has been shown to affect house prices in numerous studies (e.g. Chay and Greenstone (2005)) and can therefore pose a risk for causal interpretation. More specifically, we examine the correlation of OA level ambient air pollution measured by PM10 and OA level radon risk.[19] In Table A1 columns (1) and (2) we regress levels of PM10 on levels of radon risk in 2003 and 2008 with TTWA fixed effects. Column (3) repeats this for changes in both measures of air pollution. The results are statistically insignificant and the coefficients are very small, indicating that ambient air pollution is not correlated with either levels or changes in radon risk in our data. In addition, later on in Table 5 we test if any other possible local trends could be correlated with changes in radon, by conducting a placebo test examining the impact of the change in radon maps introduced in 2007 on transaction pairs in which both first and second sales happen before the publication of the 2007 map. In line with previous tests, we find no effect,

[19] The information on ambient air pollution (PM10) comes from the Department for Environment Food and Rural Affairs (DEFRA). To generate PM10 measures we keep stations that have less than 10% missing values for these years and we assign pollution level to OA by linking it with the three closest monitoring stations to each OA centroid. We then use the mean value of those three measurements weighted by the inverse squared distance between the monitoring station and the OA centroid.

corroborating once more the random distribution of our treatment.

To claim that the price effect reflects the willingness to pay to avoid radon we require several additional assumptions. First, housing market participants (buyers and sellers) must be aware of the radon risk and take it into account when making buying and selling decisions. For example, if buyers are unaware of higher radon risk in a property, they will not ask for a discount and our estimates should be zero. While this fundamental assumption is being made implicitly in all papers that rely on the hedonic technique, it is not frequently discussed or addressed explicitly.[20] We believe that our unique context enables us to ease concerns regarding a violation of this crucial assumption as buyers receive information about radon risk levels when buying properties. More specifically, buyers receive information on radon risk levels as it is included in the conveyancing process through the local authority search (CON29), which is based on the same radon risk data that we use in our study. Interestingly, while the owner should have known what the radon risk was at the time of the first transaction, they will not necessarily be aware of updates to radon risk in their area. Therefore, if new data reveal that the radon risk in an area is reduced, a rational buyer might not pass this information to the seller and we would not expect to see an effect on property prices, as information about the map updates is not widely advertised and sellers do not typically pay for conveyancing searches ahead of sales.

Second, in order to claim that the estimated effect is the price households attach to indoor air pollution risk, we have to measure changes in air pollution risk observed by households. One possible concern is that radon remedial measures may introduce a misalignment between the level of risk observed in our data and by buyers, since we cannot observe if properties have remedial measures in place. For example, a change in the level of risk which in our data is between categories 2 and 6 could be less consequential for the buyer if the house is equipped with radon mitigation devices. Mindful of this issue, in the majority of specifications we will focus on properties for which the first transaction occurred when the contemporary map indicated no risk of radon. These houses had no, or at least very small, incentives to install radon mitigation devices before the update of the map. Furthermore, in our downwards movements analysis we exclude properties that were new at the first sale, as newly-built houses in radon-affected areas are advised to install radon protection during construction, and we cannot observe whether they did and what these are. Another possible source of measurement error is that owners can measure the actual level of radon in their houses and may thus have different information than reflected on the map. For example, if the seller tests the house that has been reclassified into a high risk area and the test shows no pollution, our measure of risk would be biased. We will address

[20]There are several exceptions to this, including early work by Kask and Maani (1992). See Pope (2008) for a recent example of an environmental application that examines the effect of information disclosure.

this concern in Section 5.3.

Third, we must also be assured that the institutional features of our setting do not potentially drive a wedge between our estimates and the value that households truly place on radon risk. We address various concerns, including those relating to inaccuracy of radon information in our later robustness checks.

Finally, it is important to note that the hedonic model only reveals the marginal willingness to pay (WTP) of the marginal buyer. This means that, in order to interpret our "direct" hedonic estimates as the average WTP of the population, we would have to make a number of assumptions, including that there is no sorting based on radon (Greenstone, 2017; Ekeland et al., 2002; Gamper-Rabindran and Timmins, 2013; Davis, 2004). In the next sections we will test this assumption directly and in Section 6 we will propose and apply a new theoretical framework to estimate this policy relevant parameter in a context with sorting.

While we obtain the impact on house prices from our central empirical approach above, we also conduct a number of ancillary regressions. To estimate the effect of radon risk on sorting, we utilise the following cross-sectional specification:

$$y_j = \gamma_1 R_j^+ + \gamma_2 R_j^- + \theta_{r\mu} + \theta_\eta + \rho X_j + \epsilon_j \tag{6}$$

This is similar to the balancing estimation described in equation 5, albeit here the dependent variables are the change in shares between the 2001 and 2011 Censuses. Moreover, because here we wish to examine the effect of moving to and from a radon affected classification, we add places that move down to a radon-free classification in our sample and include fixed-effect for the initial 2003 radon category (θ_η). This implies that estimates can be interpreted as the average change in the outcome when radon changes, relative to remaining in the same initial radon category.

5 Results

5.1 Main Results

We begin our empirical investigation by examining whether upwards and downwards movements in house level radon risk categories affect property prices using first difference estimations.[21] In all cases

[21] For clarity of exposition we present upwards and downwards changes in separate regressions but collapsing them into a single regression yields effectively identical results.

we control for whether a house was new at the previous sale, and cluster standard errors on the radon grid square, which is the spatial scale at which radon varies. Recall that radon category 1 is denoted as a "radon risk free area" in the local authority search (CON29), whereas all other categories are denoted as being in "an area that is affected by radon". Commensurate with the institutional set up, Table 3 examines whether moving to and from category 1 affects house prices. In the first two columns of this table the fixed effects are derived from the 1km postcode grid, and in the last two MSOAs. These specifications control for changes in local amenities such as school quality, public transport or ambient air pollution, but also for changes in the composition of the neighbourhood (i.e. sorting), which helps identify the direct impact of map changes on affected houses (Ekeland et al., 2002).

In panel A, we test for upwards risk reclassifications, using samples composed of sales that stay in category 1 (the baseline category), and houses that move from category 1 to other, by definition higher, categories. In column 1, we examine moves from category 1 (risk free) to the lowest category classified as affected by radon (category 2). Despite the relatively small increase in radon risk between categories 1 and 2, this upward risk reclassification decreases house prices by 0.86%. In column 2 we expand the sample to include properties that start in category 1 but move to higher risk categories. The estimated parameter is slightly smaller in magnitude, but statistically indistinguishable from our estimate in column 1.[22]

Given that the updating of the maps led to reclassifications of properties downwards as well as upwards, we test downwards moves in panel B of Table 3. Our approach relies on comparing houses that stay in a given category with others that move from the same category to category 1. However, we acknowledge that our estimation sample is much smaller than for upwards moves, which limits the strength of the conclusions we can draw. In column 1, we examine the effect of moving from category 2 to category 1 relative to staying in category 2. We obtain a small positive coefficient that is not significantly different from zero. In column 2 we expand the sample to any house that moved to category 1 or stayed in the same radon-affected category, identifying the average downward effect by adding the baseline radon category into the interactive fixed effects. Again, the estimate is statistically insignificant and the coefficient is even smaller, implying that conditional on our 1km postcode grid trends in prices, a house reclassified from a radon affected to a radon-free area does not command a statistically significant price premium.

[22] As we discuss further below, it may be that the smaller magnitude of the coefficients when we add higher risk categories follows from unobserved radon remedial works in higher risk category houses. In many later regressions we will focus solely on properties that move from category 1 to category 2 for this reason.

This suggests an asymmetry in price responses to radon risk, which is consistent with buyers and sellers acting on information about higher radon risk but not acting on information about lower radon risk. One possible explanation for this is the asymmetry in radon information between buyers and sellers. As mentioned above, buyers receive radon risk information from conveyancing searches, but sellers will not necessarily be fully aware of the latest radon risk classification in their area, as map updates are not widely advertised and sellers do not typically pay for conveyancing searches ahead of sales.[23] Hence, with information mostly coming from the buyer-side, only upwards movements in radon risk classification get priced in. Nonetheless, we acknowledge the limitations imposed by our data here and moreover that there are other possible mechanisms that could lead to this finding. For example, a persistent sorting effect or a stigma effect could lead to similar results (McCluskey and Rausser, 2003; Ioannides and Zabel, 2003).

In columns 3 and 4 of Table 3, we use MSOA rather then the 1km grid fixed-effects. Reassuringly, the estimates remain similar to the findings in the first 2 columns of Table 3 in terms of statistical significance and the magnitude of the coefficients. Again, we find that upward changes in risk significantly affect house prices, but downward changes do not. Since using geographical trend controls at different levels of local aggregation (1km grid and MSOA level) yield very similar results in conjunction with our preference towards the more restricted 1km grid fixed effects strategy, we adopt the coefficients from columns 1 and 2 as our main results and use them in our subsequent analysis.

5.2 Sorting

In this section we investigate the possibility that changes in radon risk information may lead to taste-based sorting of residents across properties for two main reasons. First, testing for sorting might help us to shed light on issues related to environmental justice (e.g. Banzhaf et al., 2019; Hausman and Stolper, 2021). Second, it is unclear whether our estimates above can be classified as the average willingness to pay to avoid radon of the average buyer, since it requires the strict assumption that buyers do not sort based on radon (Greenstone, 2017; Gamper-Rabindran and Timmins, 2013; Davis,

[23] We have looked at the media coverage on Radon in the United Kingdom over the 6 months before and after the changes in the 2007 map using data from the market-leading online news aggregation platform Factiva. In particular, we restricted our search to UK sources and used the keyword ‘radon’ in our search. We did not find evidence for meaningful changes in the media coverage on the topic of radon at and around the time of the publication of the new map in November 2007. Nevertheless, it is important to mention that there were some explicit coverage of this new map by The Times and the Daily Post, and it was also very briefly mentioned in the Sunday Sun. Overall, this exercise suggests that the radon map change was not extensively covered by the media and support the notion that the information on the new radon risk levels are mainly coming from conveyancing searches.

2004).

In Table 4 we test whether residents sort in response to changes in radon risk using census data by regressing changes in Output Area characteristics between the 2001 and 2011 Census on our main radon treatment variables (collapsed at the Output Area level), conditional on our preferred 1km postcode grid fixed effects.[24] The table shows that the share of people with characteristics normally correlated with higher house prices, such as education , or wealth (as proxied by owning an house), decreases in response to upward radon risk reclassification (Ioannides and Zabel, 2003; van Ham and Manley, 2009). We also find no strong evidence that the ethnic composition (as proxied by the share of white people) changes in areas that are newly affected by radon, which is interesting in light of the recent discussion around racial gaps in pollution exposure in the U.S (Tessum et al., 2019; Colmer et al., 2020). Overall these findings lead us to two important conclusions. First, radon risk falls disproportionately on lower socio-economic[25] groups, as they move into affected areas in search for a price discount, an example of environmental injustice that results from sorting. In fact, despite radon risk being mitigable to some extent, the risk could fall disproportionately on lower SEGs if they do not install remedial measures. Evidence from surveys show that lower SEGs are not as aware of the risks of radon (Zhang et al., 2011). Our findings are also in line with the theoretical predictions of Hausman and Stolper (2021), claiming that environmental inequities can arise even from uniform limitations to perfect information when all individuals are equally uninformed, producing disproportionate pollution exposure and welfare loss for low-income households, mostly because of sort according to known pollution. In addition, the installation of remedial measures by households in lower SEGs could be limited by more stringent budget constraints. Second, we are unable to support the assumption of no sorting as a consequence of the reclassification, and we therefore interpret our previous estimates as "local" in the sense that they reflect the difference between the WTP of the ex-ante and ex-post marginal buyers after the property have been reclassified. In other words, it is the market price of indoor air pollution risk in the housing market, under supply determined by the pre-determined housing stock and the natural experiment, while demand is determined by preferences of the population. However, since we are also interested in the average willingness to pay for avoiding radon, in Section 6 we develop a new theoretical framework to estimate this policy relevant parameter.

[24] Note that the use of 2001 does not exactly mirror our house price results because reporting radon to home buyers became compulsory in 2002 and new radon maps were issued in November 2003 and 2007. These results here will capture the composite effect of these changes rather than just the 2007 map change, and we interpret them as about the link between radon and sorting rather than specifically about the effect of the 2007 map.

[25] We define SEGs by education which in England is highly correlated to other measures such as social class or occupation. For example, as noted earlier the correlation of share educated and share professional and managers is very high.

5.3 Robustness and Heterogeneity Tests

In this section we provide a set of robustness tests to evaluate the soundness of our main empirical result, and heterogeneity analysis across several dimensions of house and area characteristics. We begin by conducting a placebo test which examines the impact of the change in radon maps introduced in 2007 on transaction pairs in which both first and second sales happen before the publication of the 2007 map, the period between August 2002 and October 2007. This approach checks if local trends are correlated with changes in radon, including long-term trends induced by sorting. The result of this test is presented in the first column of Table 5. Reassuringly, we find no effect, which demonstrates that our treatment effect cannot be attributed to any other long-term trends that are correlated to changes in radon.

In column (2) of Table 5, we assess if our estimates are affected by measurement error, as previously discussed in Section 4. To address this issue, we take advantage of the fact that most house radon measurements in the UK are recorded by PHE (the government agency which subsidises radon measurements). Our strategy is to replicate our main analysis but restricting the focus only to areas where fewer than 1% of houses have had measurements taken by PHE. Our estimate in in column (2) is highly significant and almost identical to our baseline results, demonstrating that house radon measurement are unlikely to be a major source of bias in our estimates. This finding thus provides further reassurance that our main results are robust to mis-measurement that may arise as a consequence of a dwelling having an evaluation of radon risk independent of the publicly-available radon maps.

In column (3) of Table 5, we test whether our results are robust to using a house-level fixed-effect panel rather than a first difference estimating approach, and find that they are (Davis, 2004). Although the house fixed-effect has the advantage of using more information, we generally prefer to rely on the first difference approach as it gives us more flexibility in dealing with radon as a categorical variable and provides a clearer match to our theoretical model.

Next, we focus on houses purchased with a mortgage, since cash buyers are not strictly required to request an environmental search for their house (CON29). In this case, it is possible that the buyer would not receive information about radon risk. To test if this is affecting our results, we use a sub-sample of transactions financed by the mortgage provider Nationwide Building Society. To assess if transactions with mortgages are different from the rest of the sample, we add a dummy variable denoting having a mortgage from Nationwide and interact it with the treatment variable. The results presented in column (4) of Table 5, indicates a statistically indistinguishable but smaller effect for mortgaged homes which suggests that our results are unlikely to be biased by mis-measuring the information that cash buyers receive.

We report further robustness checks in the Appendix. We start by using an alternative identification strategy based on the spatial boundary discontinuity design (BDD) akin to Gibbons et al. (2013) exploiting boundaries of radon grid tiles. As lease term is unobserved yet critical to house value in the cross-section, we focus on freehold transactions within 300m of the boundary between radon affected (category 2) and radon free (category 1) areas.[26][27][28] To further strengthen the identification, we also control for third-order polynomials in distance from the boundary, which account for possible spatial trends in house prices closer to boundaries.[29] The results of our BDD regressions are presented in Table A3 in the Appendix. The first column shows cross sectional results across the BDD sample with distance to the boundary polynomials as well as TTWA and time period fixed effects. In the second column we add property characteristics to the sample to ensure that our results are not biased by changes in characteristics of the housing stock at the boundary. In the third column, we add Output Area characteristics from the 2001 Census as control variables (the same as in our sorting table 4) to control for cross sectional differences in housing market characteristics. Finally, we extend our bandwidth to 500m and show that our key coefficient remains close to our other results. Overall, our BDD analysis yields results which are very similar to our first-difference estimates. However, the results are clearly less precisely estimated than our main results in Table 3. This seems logical given the smaller sample size, less precise controls for unobserved property characteristics and the fact that not all sellers were informed about radon when they purchased their properties. [30]

[26]Since some areas consist of only one tile, we use 300m as a bandwidth of roughly one third of a tile's length/height, but get similar results with other bandwidths.

[27]We use the $1km^2$ gird, in locations/periods that did not have access to the 25x25 meter grid map, and transacted between 2007 and 2012.

[28]Freehold of a property means that the buyer owns it outright in perpetuity, including the land it is built on. This is the most common mode of ownership of real property in the UK, the Commonwealth and most European countries, in contrast to leasehold, in which the property reverts to the owner of the land after the lease period expires.

[29]Formally, we estimate the treatment effect given by β in the boundary sample in the following equation:

$$ln(P_{it}) = \beta RA_{it} + D_i + T_t + TTWA_i + \epsilon_{it} \tag{7}$$

where P_{it} denotes the transaction price of property i in period (quarter) t, RA_{it} is a dummy variable that equals one if the property is on the side of the boundary that is affected by radon, D_i is a vector of distance to the boundary polynomials up to the third order, T_t is a time period (quarter) fixed-effect, $TTWA_i$ is the Travel to Work Area local labour market fixed-effect, and ϵ is an idiosyncratic error term.

[30]Compared to our first-difference specification, BDD has some notable shortcomings. First, it focuses on a smaller sample, as we can only use transactions close to boundaries. Second, it cannot show if the estimated effect is attributable to increasing or decreasing radon risk. Third, it is only suitable for large grids ($1km^2$ and $5km^2$) and cannot be used with the most accurate map (25 meter square). Nonetheless, a cross-sectional BDD approach is very useful as a robustness

In our last set of robustness tests we explore the assumption that prices react to radon information given to buyers by Local Authorities through the CON29 form. More specifically we leverage that we know which version of the 2007 radon map - the 25x25 meter or the $1km^2$ grid - is being used by a LA to provide radon risk information at the time of the second sale, and we run tests to check that it is the information which is indeed driving house price changes. In column 1 of Table A4 we first separate out the treatment variable for the two different versions of the map and estimate the effect for each group.[31] We find that the impact of radon reclassification to "radon affected" is the same regardless of which version of the map is being used to provide this information. In column 2 we restrict attention to sales where CON29 is based on the 25 meter square map and test if a radon treatment defined using the $1km^2$ grid information affects prices. We find that it does not. However, more reassuringly, when information on radon changes from both $1km^2$ and 25x25 meter grids are included in the same regression in column 3, only the latter matters for transactions that have access to it. In columns 4 and 5 we conduct similar tests to those performed in columns 2 and 3 but this time we restrict attention to sales where CON29 is based on the $1km^2$ grid map and test if a radon treatment defined using the 25x25 meter grid information affects prices. Again, we find that only the estimate for the $1km^2$ grid is statistically significant. This provides further convincing evidence that the effects we estimate stem from information transmitted in the CON29 form.

A related issue is that the accuracy and consistency of radon information buyers receive could influence the way that information about risk translates into prices. One source of potential inaccuracy is Home Information Packs (HIPs). These were in place throughout the majority of our second sale sample time frame and the limited evidence available suggests that HIPs may have contained at least some degree of inaccurate information (although not necessarily about radon). As our main results compare homes that stay radon-unaffected with those that become affected under the map change, if we assume that HIPs contained radon information from the earlier map then buyers of newly radon-affected homes would get conflicting information from the HIP and the later results from their own solicitor (via the CON29 form). If so our estimate may underestimate the effect of radon risk to the extent that buyers become mistrustful of the radon information in the CON29 form and price this in. To assess whether this is a threat to our identification in Table A5 we report additional regression specifications. Column 1 replicates our main estimate which includes pairs with second sales in the

check of our main strategy, as it is based on different identification assumptions. Specifically, it assumes that while the information about being affected by radon is discontinuous at the boundary of a grid tile, all other determinants of house prices are continuous.

[31] Note that we use $1 \rightarrow 2$ radon treatment for this test. Using the $1 \rightarrow Any$ treatment yields qualitatively similar results, but these are estimated with less precision.

interval 2008-2011 inclusive. In column 2 we alter the sample to those pairs where the second sale takes place in 2011 or 2012, which should eliminate any effect of HIP misinformation as HIPs were abolished in 2010. We find the coefficient is essentially unchanged to column 1. A second test is underpinned by our belief that potential inaccuracies in radon information in general (either in HIPs or indeed local authority searches) would be very likely to be reduced after the 2007 map became fully embedded in the system. We therefore find it reassuring in column 3 that estimate is identical when we exclude second sales in the first year following the map change. Overall these tests lead us to conclude that buyers' mistrust of radon information, while potentially an important qualifier, is in practice not a meaningful factor in this specific context.

Finally, we investigate heterogeneity using models that employ our preferred 1km grid fixed-effects. In Table 6 our approach is to estimate the baseline model in column 2 of Table 3, but including separate radon treatment terms for different groups of observations (e.g. flats and houses) while simultaneously controlling for time effects for the groups, as well as the interaction between the group variable and a new build indicator. In column (1) we examine price effects for flats and houses, where we find the effects on houses to be very considerably larger and the effects on flats to be insignificant. This likely reflects heterogeneity with respect to distance to the ground because in column (2) we find very large negative effects of radon for basement flats. In column (3) and (4) we find that effects are generally slightly larger in London and in urban conurbations than elsewhere. While these results may be suggestive of heterogeneity, it is important to note that we do not have sufficient evidence to reject the null that the coefficients are equal in all columns, except for the first where we find the difference between flats and houses is statistically significant (F-test p-value = 0.04).

The heterogeneity we observe in these latter results could plausibly reflect differences in risk updating. Our priors are that more educated and wealthier residents may update their beliefs more than other residents. We lack the micro-data necessary to make strong claims in this respect. However, when we estimate separate effects for different quantiles of neighbourhood education and home-ownership, we obtain mixed results as shown in Figure 4. We are therefore unable to draw strong conclusions about whether there is differential updating of beliefs about radon risk in this setting.

6 Identifying WTP

As different households have different preferences, average WTP is not observed directly in housing transactions data as houses are purchased by the highest bidders (see Section A3 in the Appendix for details). However, we develop a strategy that allows us to estimate WTP from the impact of radon on both transaction prices and the number of transactions that occur at those prices. The idea is that if the transaction price is the market-clearing price, the probability of a transaction at that price can help us to reveal the WTP of an average treated owner. We briefly summarize the idea below, and section A3 explains in more detail this idea with a simple theoretical model and translates it into an empirical strategy.

At the very basic level, a house is sold if the value it delivers to the owner is lower than the value it delivers to the highest bidder. Both of these values are determined by the same household problem (outlined in section A3), and the results differ due to different budgets and preferences. Based on the evidence that our treatment is orthogonal to characteristics of owners, we can assume that the distribution of preferences of the treated owners is random (reflecting different characteristics of households). At the same time, the sorting mechanism suggests that the composition of preferences of the highest bidders is likely to be endogenous to prices and the corresponding characteristics of properties in the housing stock. For example, properties affected by radon attract buyers who do not care about radon. The discount they can negotiate on radon affected houses depends on how much households who want to avoid radon are willing to pay to avoid it. Owners of affected houses can choose to sell at market prices or to tolerate radon risk. The likelihood of an average owner deciding to sell after being informed that their house has been reclassified as affected by radon, and that the market value of their house has decreased by the average radon discount, reveals their willingness to pay to avoid radon.

In Section A2, we find that the probability of a transaction increases by only 0.0026%. This is a very small change over the mean transaction probability of 0.087% before the treatment. Not surprisingly, after plugging it into our model we conclude that the impact of sorting is very small, and that the hedonic estimate of 0.86% (or £1,760) is very close to the average WTP of 0.89% (or £1,816). It is worth noting that the result is driven by the fact that the change in transaction probability is very small, and that parameters of our model make very little difference. Importantly, the fact that the change in transaction probability is small does not imply that households do not sort, but simply that the impact this has on prices is negligible. Thus, the estimated discount of prices and increase in transactions seem to be mainly driven by the WTP to avoid radon-related health risks rather than sorting of different socio-economic groups into the neighbourhood.

7 Conclusion

We are among the first to provide evidence on the economic effects of indoor air pollution. By focusing on radon and the housing market, we are able to address many of the key challenges in the existing air pollution literature and provide compelling evidence that market participants react to information about indoor air pollution related to radon. Our results show that prices of houses affected by exogenous increases in radon risk decrease significantly. Our preferred specifications place the magnitude of the estimate at around 0.8%. We also find that changes in radon risk cause sorting and corresponding changes in characteristics of residents of the affected areas. Specifically, we show that residents from higher SEGs move out of places that are newly affected by radon, and that people from lower SEGs move in. These results thus highlight how sorting leads to the disproportionate exposure of lower SEGs to indoor air pollution. Although beyond the scope of our paper, we note that this environmental injustice may be exacerbated if individuals in these SEGs are less able to adopt radon remedial measures, for example because of credit or informational constraints.[32]

Our results prove to be robust to multiple tests, but they are still limited by the institutional setting and data availability. Most notably, while we find no evidence that reclassifying a house from a radon-affected to a radon-free category increases prices, we are unable to conclusively determine whether this is due to sellers being unaware of changes to radon levels (unlike the buyers), or due to a relatively small sample size. For similar reason, we are unable to exploit changes in the magnitude of radon risk in affected houses to understand how households react to changes in risk more generally. One particular question that we are unable to definitively answer is whether we can interpret our estimates as directly reflecting households valuation of the health risks of radon exposure.[33] This is because in our context a series of issues, including the ability of household to install remedial measures to mitigate risks and uncertainty around radon risk information quality, may drive a wedge between our estimates and households valuations.[34] That said, we do find it instructive to compare our estimates with both the implied value of health risks from radon, as well as the financial costs of installing radon remediation measures. Using the results discussed above, our estimated coefficient for moving up from

[32]This seems plausible because surveys suggest the main reason for households not remediating radon is cost. See Appendix D of the report of the Independent Advisory Group on Ionising Radiation https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/335102/RCE-11_for_website.pdf.

[33]Related work in the literature (Davis, 2004; Sunstein and Zeckhauser, 2011; Dessaint and Matray, 2017) has typically found that market participants seemingly overreact to health risk.

[34]Note that our robustness checks do provide some reassurance that information inaccuracies do not drive our findings. While we cannot rule out the possibility that buyers may anticipate regulations that oblige them to incur full remediation costs before re-selling the house, we are not aware this issue has ever been proposed or mentioned, and moreover the regulation of similar risks (like flood risk) has been consistently based on information disclosure rather than mandatory remediation in our setting.

category 1 to category 2 in column 1 panel A of Table 3 implies a change in house prices of roughly £1,760. Based on a necessarily assumption heavy approach, we estimate that moving from category 1 to category 2 would yield an increase in risk with a present value of between £800 and £1,400 per household on average which is in the same ballpark.[35] A further relevant comparison is to the typical cost of installing radon mitigation systems. These are usually between £200 and £2000 according to Public Health England, and hence are also very similar to our main estimates. Whether remediation costs bound our estimated price discounts from above or below is a question we leave to future work.

We also provide new evidence on how the housing market reacts to information about environmental risks. We show that mandatory information provision has a strong effect on household choices and that, at least in the case of radon, prices react to the information about the risk even when the actual level of risk is the same. Therefore, alternative policy initiatives could be more efficient in order to provide health risk information to the population, while preventing the depression of the housing market value. For instance, CON29 forms could provide more detailed information, in particular distinguishing between the different radon categories and relative risk levels, and also disclosing all radon measurements done at the property level, especially in radon-affected areas. This would provide more advice and support to homeowners, and might also increase remediation rates. Following the suggestions made by Gray et al. (2009), an effective intervention would require the combination of two policies. First, extending the existing policy requiring measurement and basic preventive measures in all new residential properties from high radon level areas to the entire UK would be highly cost effective, reducing exposure levels and providing precise information to buyers. Secondly, a campaign of mass testing to precisely measure the exposure to radon for all residential properties in high radon level areas would be highly beneficial. This approach would solve once for all the information mismatch problem in affected areas at a limited cost of around £15 per test. Property-level low radon concentrations would be favourably reflected in the price of houses located in radon-affected areas, while documented high levels could increase the likelihood of remediation measures installed by homeowners.

[35] To compute this we use the cumulative risks of lung cancer at different radon concentrations (category levels) by smoking status, from Table 4.3 of the Health Protection Agency report "Radon and Public Health: Report of the independent Advisory Group on Ionising Radiation" https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/335102/RCE-11_for_website.pdf. We calculate the implied monetary values of lung cancer risk in each using a value of a statistical life of £5 million. This VSL is of course arbitrary, but it is within the typical range used in the US. The comparison of a transformed VSL to the reduced-form price effect relies on mean risk and variance as sufficient statistics (Cordoba and Ripoll, 2016). To assign risk values to households we assume households contain 2.3 people, that 10% are smokers (according to the UK Office of National Statistics, 14.7% of people aged 18 years and above are smokers https://www.ons.gov.uk/peoplepopulationandcommunity/healthandsocialcare/healthandlifeexpectancies/bulletins/adultsmokinghabitsingreatbritain/2018), and that adults represent 70% of the population.

Overall, our analysis highlights the importance of considering the extent and distribution of indoor air pollution costs alongside those of ambient air pollutants. Given the significant amount of time that we spend indoors, and the relatively little policy and research attention to this subject, we argue that much more focus should be directed towards this issue in future work.

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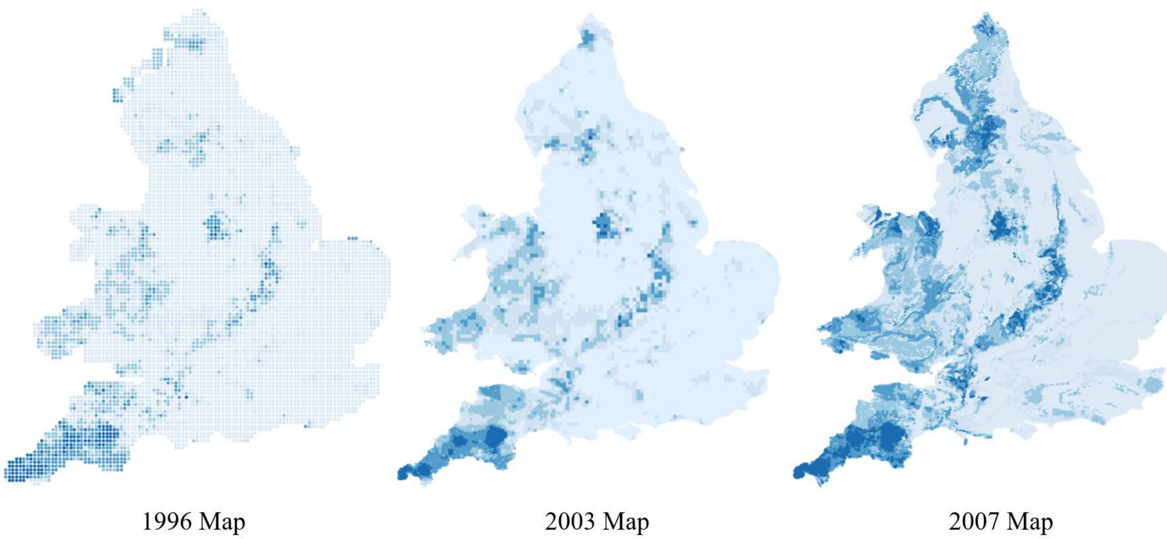
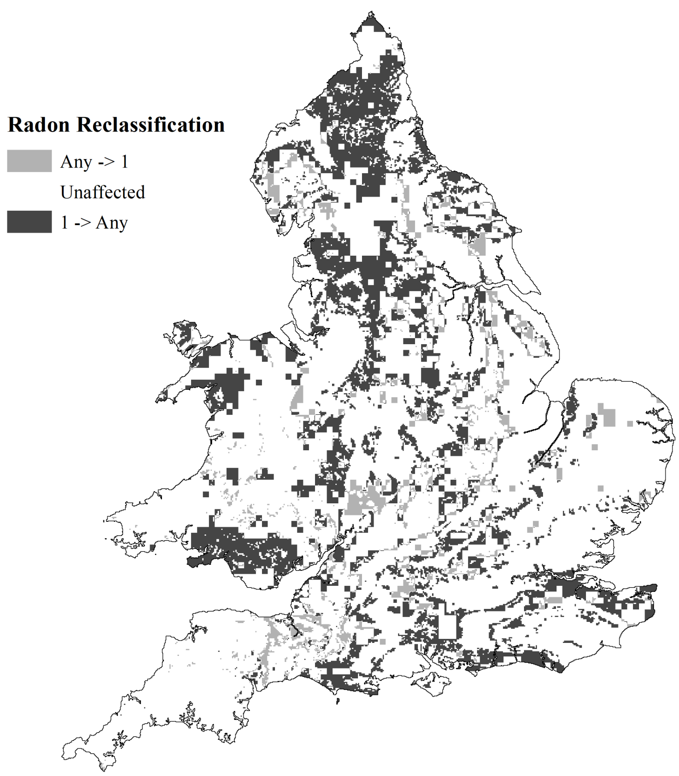
8 Tables and Figures

Figure 1: Radon Maps



Notes: The maps give the level of radon risk from 1 to 5 in the first map and from 1 to 6 in the other two with darker blue corresponding to higher levels of radon.

Figure 2: Areas reclassified between "radon-free" and "radon-affected" from the 2003 to the 2007 maps.



Notes: Areas in black are reclassified from "radon-free" in 2003 to "radon-affected" in 2007. Areas in grey are reclassified from "radon-affected" to "radon-free". Areas in white have not been affected by the reclassification.

Table 1: Summary statistics: Repeated transactions with changing radon levels.

	Radon 2nd sale						
Radon 1st sale	1(Radon-Free)	2	3	4	5	6	Total
1(Radon-Free)	411,262	81,918	12,826	9,036	3,950	455	519,447
2	20,012	16,584	5,999	6,125	4,520	496	53,736
3	1,826	2,154	1,714	2,537	2,857	652	11,740
4	587	411	416	874	3,561	1,112	6,961
5	139	187	133	688	3,404	3,801	8,352
6	0	1	0	2	161	1,255	1,419
Total	433,826	101,255	21,088	19,262	18,453	7,771	601,655

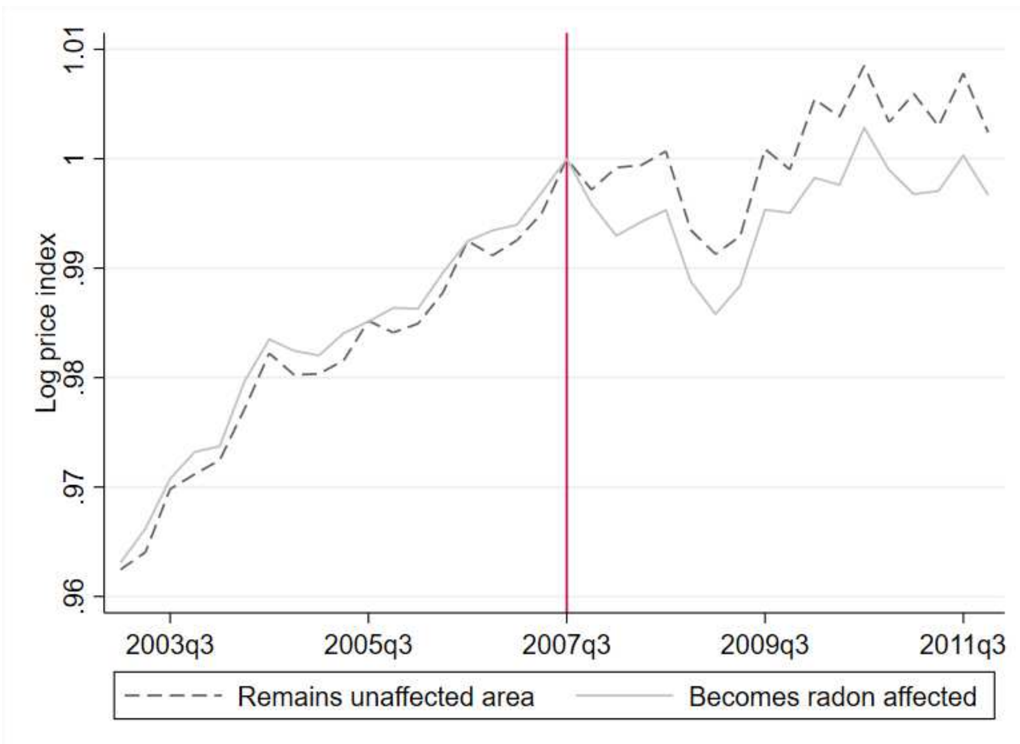
Notes: the table gives the number of repeated transactions for the estimation sample, which includes only those homes with a first sale in the period Aug 2002 to October 2007 and a second sale in the period January 2008 to December 2011. Data on transactions comes from Land Registry and on radon levels from PHE.

Table 2: Summary statistics: Average prices of house prices and changes in radon.

		(1)	(2)	(3)	(4)	(5)
		Radon-Free	Radon-Affected	Δradon=0	Δradon>0	Δradon<0
Price	Mean	198,846	187,706			
	St. Dev.	194,031	161,697			
Change in Price	Mean			35,542	23,965	23,328
	St. Dev.			119,963	61,005	68,215
N		7,095,851	1,993,193	435,093	139,845	26,717

Notes: the table gives the number of individual transactions in columns 1-2 and repeated transactions with no change in radon risk, upwards change, and downward change in columns 3-5 respectively. The data is the estimation period which means that only first transactions after July 2002 and second transactions between 2008 and 2012 are included. Data on transactions comes from Land Registry and on radon levels from PHE. Radon-Free indicates radon category 1; Radon-Affected indicates all higher categories.

Figure 3: Average price for radon-affected reclassified and unaffected properties before and after the reclassification.



Notes: the figure shows the evolution of prices, comparing properties that were reclassified from radon free to radon-affected areas with unaffected properties before and after the reclassification in October 2007.

Table 3: Radon Risk Reclassification and House Prices

	(1)	(2)	(3)	(4)
	Grid FX		MSOA FX	
	X={2}	X={All}	X={2}	X={All}
Panel A: $1 \rightarrow X$	-0.0086+	-0.0076+	-0.0078+	-0.0063+
	(0.0022)	(0.0020)	(0.0020)	(0.0018)
N	449563	473873	449763	473134
R^2	0.498	0.498	0.414	0.413
Panel B: $1 \rightarrow X$	0.0038	0.0032	-0.0001	-0.0023
	(0.0067)	(0.0064)	(0.0059)	(0.0056)
N	26449	32387	26457	32364
R^2	0.506	0.519	0.416	0.428

Notes: Standard errors in parentheses, clustered at 1km radon grid. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$, †$p < 0.001$. All regressions include interactions of years of sale with area (postcode grid or MSOA) indicators as well as quarter of first and second sale fixed effects. Panel A tests for upwards risk moves, using samples composed of sales that stay in category 1 (radon free) and houses that move from category 1 to radon risk categories. In columns 1 and 3, we examine moves from category 1 to the lowest category classified as affected by radon (category 2). Columns 2 and 4 include houses that start in category 1 but move to any higher risk categories. Panel B repeats the same process for downwards risk moves.

Table 4: Radon Risk and Sorting

	(1) A Level or higher	(2) Degree Education	(3) Own house Outright	(4) Own house Any	(5) Ethnic White
$1 \rightarrow Any$	-0.0042†	-0.0020**	0.0017	-0.0042***	-0.0010
	(0.0011)	(0.0009)	(0.0011)	(0.0013)	(0.0011)
$Any \rightarrow 1$	-0.0007	-0.0005	0.0054	-0.0014	-0.0008
	(0.0028)	(0.024)	(0.0038)	(0.050)	(0.0025)
N	134107	134107	134107	134107	134107
R^2	0.375	0.308	0.361	0.343	0.653

Notes: Standard errors in parentheses, clustered at the 1km radon grid level . ** $p < 0.05$, *** $p < 0.01$, $\dagger p < 0.001$. The table reports results from regressing changes in Output Area characteristics between the 2001 and 2011 Census on our main radon treatment variables (collapsed at the Output Area level), conditional on our preferred 1km postcode grid fixed effects. The first row presents the results of moving from "radon-free" to "radon-affected" categories. The second row shows the results of moving from "radon-affected" categories to the "radon-free" risk category. Column headings denote micro-neighbourhood characteristics as shares of population; (1) with A levels or higher as the highest level of education, (2) with Degree education as the highest level of education, (3) owning their houses outright, (4) owning their houses outright or with a mortgage, and (5) identifying as white.

Table 5: Placebo and Robustness Tests

	(1)	(2)	(3)	(4)
	Placebo	Radon Tests	Panel House FX	Mortgage
	$\Delta ln(price)$	$\Delta ln(price)$	$ln(price)$	$\Delta ln(price)$
$1 \rightarrow Any$	-0.0000	-0.0082†	-0.0049***	-0.0086†
	(0.0018)	(0.0021)	(0.0019)	(0.0022)
$1 \rightarrow Any$ with Mortgage				-0.0004
				(0.0090)
N	566845	450994	2438192	449563
R^2	0.400	0.498	0.966	0.498

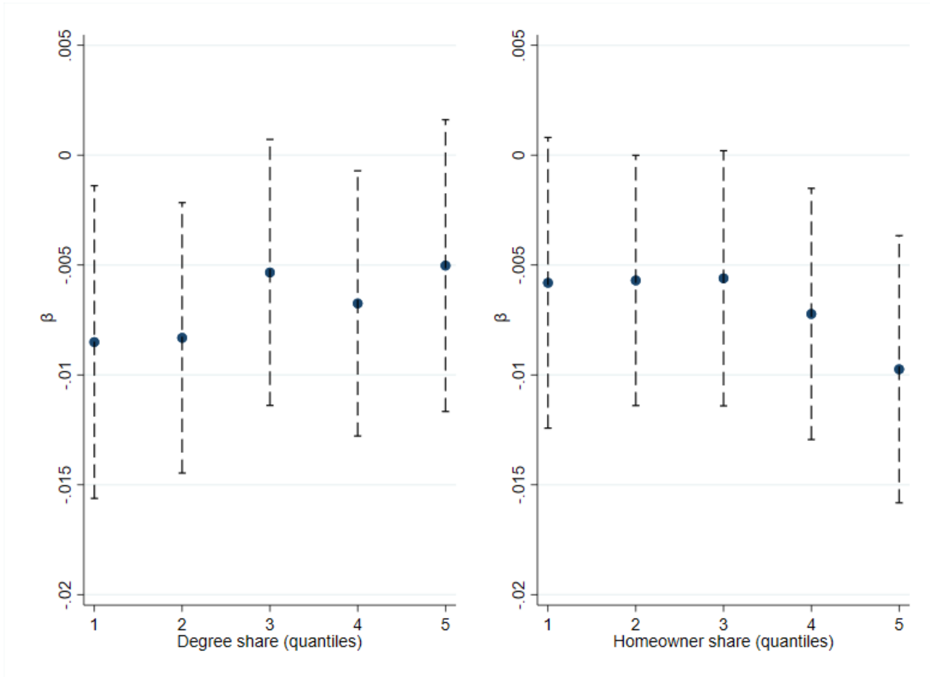
Notes: Standard errors in parentheses clustered at the 1km radon grid. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$, $\dagger p < 0.001$. All results in this table are based on an upward move from "radon-free" to "radon-affected" categories. The results in column 1 are based on pairs of transactions that occurred before the 2007 map change. The placebo change in radon applied to those pairs is based on the future radon change the house subsequently experienced. Column 2 gives results of a reclassification from no radon to any other category (again equivalent to table 3 in areas where no more than 1% of houses have been tested for radon risk by PHE. Column 3 reports results from a panel OLS regression with property fixed-effects. In column 4 we include a $1 \rightarrow 2$ with Mortgage dummy variable that equals one if the transaction is funded by a Nationwide mortgage and receives the treatment.

Table 6: Heterogeneity Results

	(1) Flats $\Delta ln(price)$	(2) Basement $\Delta ln(price)$	(3) London $\Delta ln(price)$	(4) Conurbations $\Delta ln(price)$
$1 \rightarrow Any \times X = 0$	-0.0079+	-0.0075+	-0.0071***	-0.0058**
	(0.0021)	(0.0020)	(0.0023)	(0.0026)
$1 \rightarrow Any \times X = 1$	-0.0022	-0.0304*	-0.0089**	-0.0095***
	(0.0029)	(0.0166)	(0.0039)	(0.0031)
N	473873	473873	473873	473873
R^2	0.50	0.49	0.49	0.49
F test p-value	0.04	0.16	0.69	0.37

Notes: Standard errors in parentheses clustered at the 1km radon grid. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$, †$p < 0.001$.The table estimates our baseline model as in column 2 of Table 3 but includes separate radon treatment terms for different groups of observations while simultaneously controlling for time effects for the groups, as well as the interaction between the group variable and a new build indicator. In columns (1-4) we examine price effects on flats and houses, basement flats, and properties in London and urban conurbations respectively. The F-tests examine the null that the coefficients are equal.

Figure 4: Effects of radon by neighbourhood education share and home ownership share.



Notes: The figure estimate separate effects for different quantiles of neighbourhood education and home ownership.