Exploring the Relationship between Social Deprivation and Domestic Radon Levels in the East Midlands, UK

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Abstract

The natural radioactive gas radon is widely present in the built environment and at high concentrations is associated with enhanced risk of lung-cancer. This risk is significantly enhanced for habitual smokers. Although populations with higher degrees of social deprivation are frequently exposed to higher levels of many health-impacting pollutants, a recent study suggests that social deprivation in the UK is associated with lower radon concentrations.

The analysis reported here, based on published data on social deprivation and domestic radon in urban and rural settings in the English East Midlands, identifies a weak association between increasing deprivation and lower radon areas. This is attributed to the evolution of the major urban centres on low-permeability, clay-rich alluvial soils of low radon potential. In addition, the predominance of high-rise dwellings in towns and cities will further reduce average exposure to radon in populations in those areas.

1 Introduction

Tobacco smoking, the primary cause of a range of diseases responsible for preventable morbidity and premature mortality, accounted for 79,100 deaths in England in 2015, with more than a third (28,560) of these deaths attributed to lung cancer (Department of Health, 2017). In England, lung cancer contributes 0.93 years (10%) of the life-expectancy inequality gap between the most and least deprived deciles (NHS, 2019). Although tobacco smoking remains the most significant risk factor for lung-cancer, being implicated in 86% of all lung-cancer deaths, environmental radon gas has been identified as posing the second-most significant risk. Case-control studies confirm increased lung-cancer prevalence in populations with raised radon levels in their homes (AGIR, 2009), with the risks from radon and smoking considered to be multiplicative (Gray et al., 2009).

Radon is a natural radioactive gaseous decay product of uranium and its daughter products, principally radium, occurring widely in the geological environment with geographically varying concentration, and its distribution in many soils and their underlying rocks is a key, but not exclusive, factor determining its concentration levels in the built environment. Studies have demonstrated the influence of numerous factors, including house type, building materials, foundations, ventilation and draught-exclusion, on domestic radon levels (Gunby et al., 1993; Demoury et al., 2013), leading to the development of a model suggesting that 25% of the total variation in indoor radon in England and Wales can be explained by bedrock and superficial geology (Appleton and Miles, 2010).

Within the United Kingdom (UK), considerable geographical variation of indoor radon concentration exists, with levels often in excess of 200 Bq.m^{-3}, the UK domestic Action Level. The Action Level has been established as the radon concentration above which householders are encouraged to take remedial action to reduce radon in their homes (AGIR, 2009). Figure 1 (McColl et al., 2018) shows the geographical distribution of homes with radon concentrations exceeding the Action Level, with contours at 1, 3, 5, 10 and 30% of homes exceeding this level, plotted at 5 km square resolution.

Figure 1 here

Figure 1: Geographical distribution of homes in England and Wales with radon concentrations exceeding the UK Action Level (McColl et al., 2018). Contours at 1, 3, 5, 10 and 30 $Bq.m^{-3}$.

Since the early 1990s there has been increasing concern that the location of hazardous industries and the spatial distribution of environmental pollutants have resulted in higher exposures to the more deprived populations. This led Jerrett et al. (2001) to postulate the 'triple jeopardy' of environmental inequality, poor socio-economic status and poor living environment and health, with many research groups now studying the principal pollutants of concern to evaluate this potential relation.

Briggs et al. (2008) analysed associations between Socio-Economic Status (SES) and five sets of environmental pollutants, including radon, measured in terms of proximity, emission intensity and environmental concentration. SES was quantified using the 2001 English Index of Multiple Deprivation (IMD), the UK Government methodology for assessing deprivation (Noble et al., 2004, and a strong positive association with IMD was demonstrated for air pollution, especially volatile organic compounds and NO_2, with weaker positive associations for pollutants such as SO_2 and NO_X and weak negative correlations for ozone and radon. More recently, Kendall et al. (2016) have suggested that greater social deprivation is associated with lower radon areas in the UK, lending support to the findings of Briggs et al. (2008). However, they used older data from the UK Childhood Cancer Study of the 1990s (UKCCI, 2000; 2002) and the Socio-Economic Categorisation of Draper et al. (1991).

Shortt et al. (2011), in developing their Multiple Environmental Deprivation index (MEDIx) and the associated Multiple Environmental Classification (MEDClass), identified a set of seven environmental factors having significant correlation with deprivation. They excluded a further set of six factors, including radon, the grounds for this being the relatively low (<4%) total exposure of the population to levels exceeding the Action Level, and differences in methodology and resolution across the four nations of the UK. Finally, Riaz et al. (2011) showed that urbanisation is an additional factor to consider when investigating deprivation and lung-cancer incidence.

Since the work of Briggs et al., new UK datasets for IMD and domestic radon have been published, with 3% higher population in the IMD dataset (DCLG, 2015), and 34% more measurements in the domestic radon dataset (Rees and Miller, 2017). Briggs et al. noted that their radon dataset did not have measurements for 78% of postcode sectors, although geological considerations suggested that radon levels in these postcode sectors were likely to be low.

The study reported here addresses a set of geologically-related Radon Affected Areas (RAAs) in the East Midlands of England, a region where radon levels have been studied intensively. The methodology considers deprivation, dwelling style, urbanisation and domestic radon concentration levels in small geographical areas, to investigate the relation between social deprivation and radon in more detail, using the most recent published UK data.

2 Method

2.1 Study Area

The area selected for study, shown in Figure 2, is a broadly rectangular region in the East Midlands straddling the radon-rich Jurassic escarpment, which crosses England from Somerset to Lincolnshire, including the counties of Northamptonshire and Rutland, together with parts of adjoining counties. This escarpment, developed by denudation, consists of an extended, steep scarp-slope with a corresponding gentle back-slope (dip-slope), formed of interbedded soft and hard inclined Jurassic age strata of mudstones, silt and sandstones, ironstones and limestones. While predominantly rural, with villages and small towns ranging in population from a few hundreds to a few thousands, it also contains the major urban areas of Leicester, Northampton, Wellingborough, Kettering, Corby, Bedford and Rugby.

Figures 2(a) and 2(b) here

(a) (b)

Figure 2: (a) Location of the study area in Central England
(b) Constituent counties.

2.2 Population-Based Data – Radon

The smallest geographical area in the UK for which domestic radon concentration data have been published is the postcode sector (ONS, 2017) and this is, therefore, the optimal geographic unit for high-resolution radon-based studies. The study area contains 231 postcode sectors (e.g. NN12 3), with populations ranging from 15 to 17,365 (mean 7,820, median 7,662, standard deviation 3,926). Since the UK postcode system is intrinsically address-based, a rural postcode sector may include a single small town or several villages, together with surrounding countryside areas, and inevitably covers a much larger area than its urban counterpart, as can be seen from Figures 4, 5 and 7.

Data on the percentage of houses found to be have domestic radon concentrations exceeding the Action Level in each postcode sector in the study area was taken from *Radon in Homes in England: 2016 Data Report* (Rees and Miller, 2017), published by Public Health England (PHE). The UK measurement programme places emphasis on measuring domestic radon levels in areas where the underlying geology is expected to lead to raised indoor radon levels. In the study area, 27% of postcode sectors had no data, and the percentage of houses over the Action Level in those sectors was assumed to be 0%.

2.3 Population-Based Data - Deprivation

The Indices of Multiple Deprivation (IMD) are measures of relative deprivation used to rank neighbourhoods across the UK. Deprivation is essentially defined as '*a lack of…*', and the Indices are constructed to provide multidimensional information on material living conditions in an area or neighbourhood based on a 'lack of' living necessities causing an unfulfilled social or economic need, relative to the rest of the country.

Deprivation data has been published by the UK Government Department for Communities and Local Government (DCLG) since the late 1990s in tabulations of increasing sophistication. The most recent issue for England and Wales, (DCLG, 2015), reporting updated assessment of deprivation with revised analysis and some boundary revisions, was used for the present study.

In England and Wales, deprivation is reported in seven domains: Income, Employment, Education, Health, Crime, Barriers to Housing & Services, and the Living Environment. The smallest units for which data are available are Lower-layer Super Output Areas (LSOAs), with the most recent iteration dating from the 2011 UK census. There are currently 32,844 LSOAs in England, with an average population of 1500. To calculate the IMD Score, each LSOA is assigned a Deprivation Score under each of the seven headings, these being then amalgamated to provide the relevant single Multiple Deprivation score. These LSOA Scores are then ranked in descending order to generate the IMD Ranking, (Smith et al., 2015a, 2015b), which currently ranges from 1 (most deprived) to 32,844 (least deprived). The IMD Ranking tabulations also allocate LSOAs to 10 equal-sized deciles. Middle-Layer Super-Output Areas (MSOAs) are larger areas, combining around four LSOAs and matching local authority boundaries where appropriate.

UK postcode geography was originally developed specifically to meet the needs of the postal system and does not generally map conformably with local government geographies. A procedure is therefore required to synthesise the average deprivation score for any given postcode sector from the deprivation data for the LSOAs encompassed within it. An appropriate methodology, using population weighted summation and averaging, has been described (Smith et al., 2015a), and this was applied to each postcode sector in the study area. The calculated IMD Scores range from 5.05 (least deprived) to 85.36 (most deprived), with mean and median scores of 18.11 and 13.0 respectively.

2.4 Rural-Urban Classification

Under the UK Government Rural-Urban Classification (RUC) scheme (Bibby and Brindley, 2013), initially introduced in 2001 with the current version based on the 2011 Census, LSOAs are assigned one of four Urban or six Rural categories. The classification for England and Wales is shown in Figure 3.

Figures 3(a) and 3(b) here

Figure 3: Rural-Urban Classification (RUC) of 2011 Census areas in England and Wales. (Bibby and Brindley, 2013). Contains public sector information licensed under the Open Government Licence v3.0.

2.5 Processing and Analysis

Radon, Deprivation and Population data were tabulated and plotted on maps created using the ArcGIS 10.5 mapping software supplied by ESRI[a], using postcode sector boundary data obtained from the UK Data Service[b]. Associations between radon potential, IMD score and postcode sector population density were investigated using correlation analysis. Spearman's rank correlation was used because the relationships are not necessarily linear but show varying degrees of monotonicity.

3 Results

3.1 Population

As noted in the Methods section, postcode sector populations vary considerably, so it is appropriate to consider postcode population density (i.e. the number of residents per square kilometre) when considering any impact of population. The postcode sector population density distribution across the study area at the 2011 census is shown in Figure 4.

Figure 4 here

Figure 4: Population density in postcode sectors across the study area. Population data from 2011 Census (ONS, 2011).

[a] ESRI, 380 New York Street, Redlands, CA 92373-8100, USA.
[b] UK Data Service, University of Essex, Wivenhoe Park, Colchester, Essex, CO4 3SQ

3.2 Radon

Figure 5 shows the percentage of existing houses in each postcode sector with radon concentrations exceeding the Action Level, taken from the PHE Radon Data Report (Rees and Miller, 2017). Three major areas of high radon potential can be identified in the study area, all associated with the Jurassic escarpment that runs diagonally across Northamptonshire from south-west to north-east. Two of these high-radon areas are predominantly rural, one situated around the borders of the county with neighbouring Oxfordshire and Warwickshire in the south-west, and the other around the county borders with Rutland, Lincolnshire and Cambridgeshire in the north-east. A third, largely urban, high-radon area encompasses much of the town of Northampton itself, with outliers around Wellingborough and Kettering to the east and Brixworth to the north.

Figure 5 here

Figure 5: Percentage of homes with radon levels over the Action Level by postcode sector. Radon data from Rees and Miller (2017)

Figure 6 plots the variation of radon potential with postcode sector population density, the data for Urban, Rural and Mixed classifications being distinguished by the point and line symbols and colours, as indicated in the figure caption. The elliptical zones indicate the 90% confidence intervals in the data (around the centroids) and show the relative senses of the correlations for Urban, Rural and Mixed classifications. The correlations are significant at >95% for the Urban and Rural data (Urban, $\rho = -0.263$, $p = 0.002$; Rural, $\rho = -0.332$, $p = 0.004$).

Although the plotted points exhibit visible scatter, the ellipses show clear orientations (of their major axes) which distinguish the underlying association of (a) relatively low radon potential over the range of population densities for the Urban postcode sectors and (b) relatively low population density over the range of radon potentials for the Rural postcode sectors. The correlation is less significant for the Mixed data ($\rho = -0.436$, $p = 0.136$) and the ellipse is closer to circular, reflecting the mixed nature of the data in these postcode sectors. The higher radon potentials occur mainly in rural areas with lower population densities.

Figure 6 here

Figure 6: Radon potential and population density for Urban, Rural and Mixed postcode sectors. Inset expands details for data in the lower 25% of the ranges for all three classifications.
Urban (C1): +, solid line, red
Mixed (D1): o, dotted line, black
Rural (E1): x, dashed line, blue

3.3 Deprivation

The deciles for the 2015 Index of Multiple Deprivation (IMD) ranking for each postcode sector in the study area were calculated using the methodology outlined in Section 2 and the algorithm of Smith et al. (2015a).

Figure 7 here

Figure 7: Social deprivation deciles in the study area.

The results are shown graphically in Figure 7, where 1 is the most deprived decile, and 10 is least deprived. The study area contains postcode sectors covering the whole range of deciles, with the most deprived areas (decile 1) being found in the centres of Leicester, Bedford, Northampton and Corby, the least deprived postcodes (decile 10) being rural areas around Market Deeping in southern Lincolnshire, Olney in Buckinghamshire and Broughton Abbey in Leicestershire. The mean decile for the study area is 6.23, suggesting an average deprivation slightly less than the average for the whole of England.

Figure 8 plots the variation of IMD Score with postcode sector population density, the data for Urban, Rural and Mixed classifications being distinguished by the point and line symbols and colours, as in Figure 6. As previously, the elliptical zones indicate the 90% confidence intervals in the data (around the centroids) and show the relative senses of the correlations for Urban, Rural and Mixed classifications. The correlations are significant at >90% for the Urban and Rural data (Urban, $\rho = 0.383$, $p \ll 0.001$; Rural, $\rho = -0.197$, $p = 0.092$).

For the Rural data, the ellipse shows a relatively tight grouping at low IMD scores and low population densities. For the Urban data, the ellipse shows a wider grouping including relatively high values of both IMD score and population density. The correlation for the Mixed data is less significant ($\rho = 0.371$, $p = 0.192$) and the ellipse shows an intermediate association between IMD score and population density, although closer to the Rural data than the Urban, reflecting the absence of both the higher population densities and higher IMD scores associated with the Urban postcode sectors.

Figure 8 here

Figure 8: IMD Score and population density for Urban, Rural and Mixed postcode sectors. Inset expands details for data in the lower 7% of the population density range, primarily for Rural and Mixed classifications..

Urban (C1): +, solid line, red
Mixed (D1): o, dotted line, black
Rural (E1): x, dashed line, blue

The radon potential, IMD score and postcode sector population density data, as shown in Figures 6 and 8 considered together, suggest associations between (a) relatively low radon potentials over the full range of IMD scores for the Urban data, and (b) low IMD scores over the full range of radon potentials for the Rural data.

Figure 9 plots the variation of IMD score with radon potential to show these associations, the data for Urban, Rural and Mixed classifications being distinguished by the point and line symbols and colours as in Figure 6. As previously, the elliptical zones indicate the 90% confidence intervals in the data (around the centroids) and show the relative senses of the correlations for Urban, Rural and Mixed classifications. The correlation for the Rural data is significant at >90% ($\rho = 0.240$, $p = 0.078$) but the correlations for the Urban and Mixed data are much less significant and essentially null-hypothesis (Urban, $\rho = -0.033$, $p = 0.697$; Mixed, $\rho = -0.309$, $p = 0.305$). Therefore, Figure 9 needs to be interpreted with caution.

Whilst the ellipses show clear orientations (of their major axes) which illustrate the suggested associations between radon potential and IMD scores, the association is only significant for the Rural data. Consideration of the centroids, as shown in the inset, shows that the centroid for the Urban data lies on the ellipse for the Rural data and, although the centroids for the Rural and

Mixed data lie within all three ellipses, this indicates that the centroids for the Urban and Rural data are distinct at this confidence level. Also, the centroid for the Mixed data has an IMD score in line with the Rural data and a radon potential in line with the Urban data. A possible explanation for this is the tendency to build new houses on the peripheries of existing Urban areas with lower radon potentials, resulting in Mixed urban-rural areas, and a majority of such new housing comprises bigger detached houses associated with lower IMD scores. However, whilst more data are required to fully resolve the associations, the analysis does confirm that higher radon potentials occur mainly in Rural areas with lower IMD scores.

Figure 9 here

Figure 9: Radon levels and social deprivation in Urban, Rural and Mixed postcode sectors. Inset shows the centroids (as large symbols) for the data from the postcode sectors, data-points indicated by small symbols for clarity.
Urban (C1): +, solid line, red
Mixed (D1): o, dotted line, black
Rural (E1): x, dashed line, blue

3.4 Housing Type

The 2011 UK Census classifies residential accommodation into six types, three for houses (detached, semi-detached and terraced) and three for apartments (purpose-built, commercial and converted/shared). In this study, the relationship between IMD and RUC is considered at Medium-Layer Super Output Area (MSOA) level, as both of these parameters are available at this level with adequate sample size and without further processing. The study area contains 308 MSOAs, of which 216 were classified as Urban, 50 were Semi-Rural and 42 were Rural. The distribution of apartments and detached houses in the study area is shown in Figure 10.

Figures 10(a) and 10(b) here

(a) (b)

Figure 10: Distribution of house types in 2011 across the study area.
(a) all Apartments, (b) Detached Houses.

Figure 11 plots the distribution of detached houses and apartments as a percentage of housing stock in the MSOAs in the study area, grouped by RUC, the data for Urban, Rural and Semi-Rural MSOAs being distinguished by the shadings and colours (consistent with Figures 6, 8 and 9) as indicated in the figure caption. These clearly demonstrate the variation between the Urban and Rural MSOAs with regard to both types of housing. While Urban areas are characterised by MSOAs with apartments forming up to 20% of the housing stock, in Rural MSOAs, apartments comprise no more than 4% of the housing stock. Detached houses in both Urban and Rural MSOAs are distributed over the full range up to around 80%. The incidence of detached houses in Urban MSOAs peaks at around 10% of the housing stock, the corresponding peak in Rural MSOAs occurring at around 50-60% of the housing stock. These distributions illustrate the generally higher housing densities in Urban postcode sectors (and correspondingly lower densities in Rural sectors). Apartments are of particular interest in this analysis as internal radon levels generally decrease with height above ground level (Gunby et al., 1993). Semi-Rural MSOAs are more similar to Rural than Urban MSOAs with regard to the distribution of both types of housing, reflecting the concentration of the highest-density housing types (such as apartments) in the Urban postcode sectors. More detailed statistics are presented in Table 1.

Figures 11(a) and 11(b) here

Figure 11: Distribution of detached houses in the housing stocks of Urban (C1), Semi-Rural (D1) and Rural (E1) MSOAs
(a) all apartments, (b) detached houses
Red, downward shading: Urban (C1)
Black, horizontal shading: Semi-Rural: (D1)
Blue, upward shading: Rural (E1)

Rural Urban Classification	C1: Urban *Urban City and Town*		D1: Semi-Rural *Rural Town and Fringe*		E1: Rural *Rural Village and Dispersed*	
Total MSOAs	216		50		42	
	Detached house or bungalow	*Apartment*	*Detached house or bungalow*	*Apartment*	*Detached house or bungalow*	*Apartment*
Mean	26.11%	5.84%	47.17%	1.99%	53.94%	1.44%
Minimum	1.56%	0.06%	25.07%	1.99%	53.94%	1.44%
Maximum	71.02%	82.88%	63.62%	0.29%	35.91%	0.36%
Stand. Dev.	17.20%	8.28%	9.31%	6.30%	70.20%	3.65%

Table 1: Statistical analysis of housing stock distribution by Rural-Urban Classification.

4 Discussion

The results presented in Figure 9 confirm that areas of lower deprivation are, in general, associated with higher radon levels, suggesting that areas of higher deprivation are associated with lower radon levels. This replicates the findings of Briggs et al. (2008) and Kendall et al. (2016). Briggs et al. (2008) used radon data from 2004 and IMD data from the 2001 UK Census, while Kendall et al. (2016) used deprivation data from a case-control study of 6000 participants from 2000 (UKCCI, 2000; 2002), and deprivation data using SES methodology for electoral wards from 1988 (Draper et al., 1991). This association is, therefore, consistent over several decades and independent of methodology. As shown above, the association is weakly significant and other factors may be more significant.

Miles and Appleton (2005) suggest that 25% of the variation in UK indoor radon concentration levels is due to underlying geology, somewhat higher than a previous estimate of 6% (Gunby et al., 1993). In Switzerland, Kropat et al. (2013) found significant associations between indoor radon concentration and a number of factors, including radon detector type, building construction characteristics (foundation type, year of construction and building type), altitude, average outdoor temperature during measurement and underlying lithology, but warned that spatial distribution of samples could strongly affect the associations. More recently, Hahn et al. (2015) reported that of the fourteen geological formation categories in north central Kentucky, USA, four were associated with high average radon levels, ranging from 100 $Bq.m^{-3}$ to 300 $Bq.m^{-3}$, with two of these having median radon values exceeding the 4.0 $pCi.L^{-1}$ (148 $Bq.m^{-3}$) EPA action level for radon.

Comparison of Figures 1, 2a and 3 shows that many major English conurbations, among them Greater London, Leeds-Bradford, Greater Manchester, West Midlands and Tyneside, are all in low-radon areas. This is not surprising, as major towns in England were established at strategic points with access to the sea or at major communications intersections and, as Briggs et al. (2008) suggest, urban development has tended to concentrate in lowland, often alluvial, sites where radon levels are low.

Historically, inland settlements would have developed at the crossing points of rivers, where alluvial silts and muds would have been deposited. Such deposits, if clay-rich, as most will be, are less permeable and tend to act as a barrier to radon. Swelling clays, such as montmorillonites, bentonites or smectites, tend to adsorb water as the inter-layer bonds are weak, rather than let water pass through. Similarly, soil gases tend to be blocked by such clays. Such soils are often referred to as expansive soils and have a significant potential for volume change (Powrie, 2002). In the Northampton region, many soils are derived from Jurassic rocks and contain bentonite clays (Dudek et al., 2006). The soils in the area are loamy (a mixture of sand, silt and clays), clayey (more than 25% clay) floodplain soils with naturally high groundwater, surrounded upslope by more freely draining slightly acid loamy soils. Slowly-permeable, clay-rich loamy soils occur In the Corby region. If these expansive soils dry out, they can crack, providing pathways for gas. Climate change suggests a shift in patterns of rainfall across the UK, with some regions becoming drier and others wetter. Expansive soils can crack buildings and their foundations by swelling and contracting, a common problem in some regions in the London area underlain by London Clay deposits that contain bentonites, providing further pathways for gas.

It is likely that people who are more deprived will live in poorer accommodation and carry out less maintenance on their homes. Gunby et al. (1993) studied some aspects of houses potantially affected by this observation, and noted that 1.7% of the radon could be attributed to decreases in ventilation arising from double glazing, and 0.3% to draught-proofing.

An additional factor reducing radon exposure in urban areas is the predominance of multi-storey buildings and apartments. On average, radon levels decrease by 70% in each successively higher storey (Gunby et al., 1993). Assuming an average of four storeys, Denman et al. (2013) estimated that average radon exposure to apartment block occupants was around 45% that of occupants of a two-storey house. These authors also noted that, in 2009, apartments comprised 38% of all dwellings in London, but only 9% in the East Midlands; at similar radon levels, the population in London would be exposed, on average, to 83% of the radon exposure in the East Midlands. The corresponding apartment density for the study area is 4.6%, although it must be noted that while the study area forms part of the administrative East Midlands area, it does not include the Nottingham-Derby conurbation. However, the presence of significantly more apartments in urban areas could explain at least some of the variation of radon exposure with deprivation. With the higher percentage of apartments in London and other major urban areas, this would be a somewhat more significant factor in the national datasets of Briggs et al. (2008) and Kendall et al. (2016).

Although the 2015 IMD includes seven separate contributors to deprivation, radon, as an indoor hazard, can only influence deprivation domains relating to living and working accommodation. Only two of the deprivation domains, Living Environment and Barriers to Housing and Services, include aspects of housing, and both of these also include other pollutants and social factors. Analysis was therefore restricted to the overall IMD.

As already noted, Kendall et al. (2016) used a precursor of IMD, the SES of Draper et al. (991), which contains five factors. This makes direct comparisons impossible. In addition, IMD ranking, by its nature, does not permit longitudinal study of changes in deprivation and there have also been a number of changes in the geographical definition of MSOAs between the 2001 and 2011 Censuses.

Taken together, these factors mean that it is difficult to study changes in deprivation over time and, in particular, it becomes problematic to consider changes in rural deprivation. In his study of South Northamptonshire, Sherwood (1984) noted that villages in Northamptonshire experienced a population decline of 26% between 1880 and the 1930s, but have subsequently seen significant immigration of high-income ex-urban households and extensive new house building. Commenting on the social status of such villages, he noted "*Superimposed upon a predominantly elderly demographic structure with a strong orientation to agriculture, these parishes are gaining a veneer of new, younger, high-status households living in substantial dwellings built in small numbers and at low densities*". This growth is a result of the advent of the motor car, facilitating driving into nearby towns for work, or even commuting to London by train, and villages could be assigned to zones, depending on their distance from a large conurbation and the quality of rail or road links. By 1981, at least 50% the working population of the majority of wards in South Northamptonshire worked outside the district, with a quarter of wards having over 70% working away.

The trend in house-building and net migration to villages continues. For example, Brixworth, a large village in Northamptonshire had a population of 1,173 in 1931 (Fletcher, 1937), while the 2001 census recorded a parish population of 5,162, increasing to 5,228 at the 2011 census (ONS, 2011), with current building of new estates expanding the village further. In this scenario, it would be expected that the average IMD Score would decrease as the population grows. It is also true that pockets of rural deprivation would be small, consisting of a few families in a village, and this is unlikely to be detected even in the small LSOA areas. Such changes over time and, of course, also changes in the degree of deprivation in the urban environment, could be expected to have little direct impact on the relationship between IMD Score and radon, being most likely to affect the degree of scatter.

One area where it is important to take into account variations in the levels of deprivation is in the epidemiological assessment of the health risks of radon. The studies showing environmental inequalities and 'triple jeopardy', and those showing that those living in areas of higher deprivation smoke more, all demonstrate reduced life expectancy among the more deprived. The NHS Long Term Plan (NHS, 2019) states *"While life expectancy continues to improve for the most affluent 10% of our population, it has either stalled or fallen for the most deprived 10%".* In addition, smoking and radon together increase the risk of lung-cancer. Thus lung-cancer incidence will be higher and life expectancy lower in urban areas, even though radon exposure will be lower. These factors need to be taken into account when studying the risks of radon to the population.

The current UK policy for reducing the risk of radon is to encourage householders who live in radon affected areas to test their homes for radon; if the measured concentration exceeds the Action Level, householders are advised to remediate their homes, usually by installing a sump-and-pump system under the foundations. Previous studies have shown that householders are not always willing to pay the cost of this work, that only around 15% do so and that those with lower incomes are less likely to pay (Zhang et al., 2011). In addition, people in such categories are more likely to be tobacco smokers, so it is evident that current initiatives to reduce radon exposure are not reaching those most at risk. However, other studies have shown that smokers are more likely to live in urban areas (Department of Health, 2011; 2014), where radon is lower, and so the issue of 'willingness to pay' may not be as significant on a nationwide scale as might be thought.

5 Conclusions

This study shows a small, weakly significant decrease in deprivation score associated with potential domestic radon exposure. This is consistent with the previous UK studies of Briggs et al. (2008) and Kendall et al. (2016), both of which used older datasets and different methodologies and study areas. This is, in part, due to the higher incidence of multi-storey accommodation in urban areas relative to rural areas, which results in a lower average radon exposure to occupants than traditional housing. In addition, since the major centres of urbanisation in England and Wales are generally situated in areas of lower radon potential, we suggest that it is not appropriate to regard the weak association between deprivation and potential domestic radon exposure as a causative link. However, it is important to consider the association in epidemiological studies of radon exposure, as deprivation is linked with a shorter life-span, and other confounding factors such as tobacco smoking, and conclude that encouraging smoking cessation is a higher priority than radon remediation in urban areas.

6 Acknowledgements

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Declarations of interest

None

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Figure and Table Captions

Figure Captions

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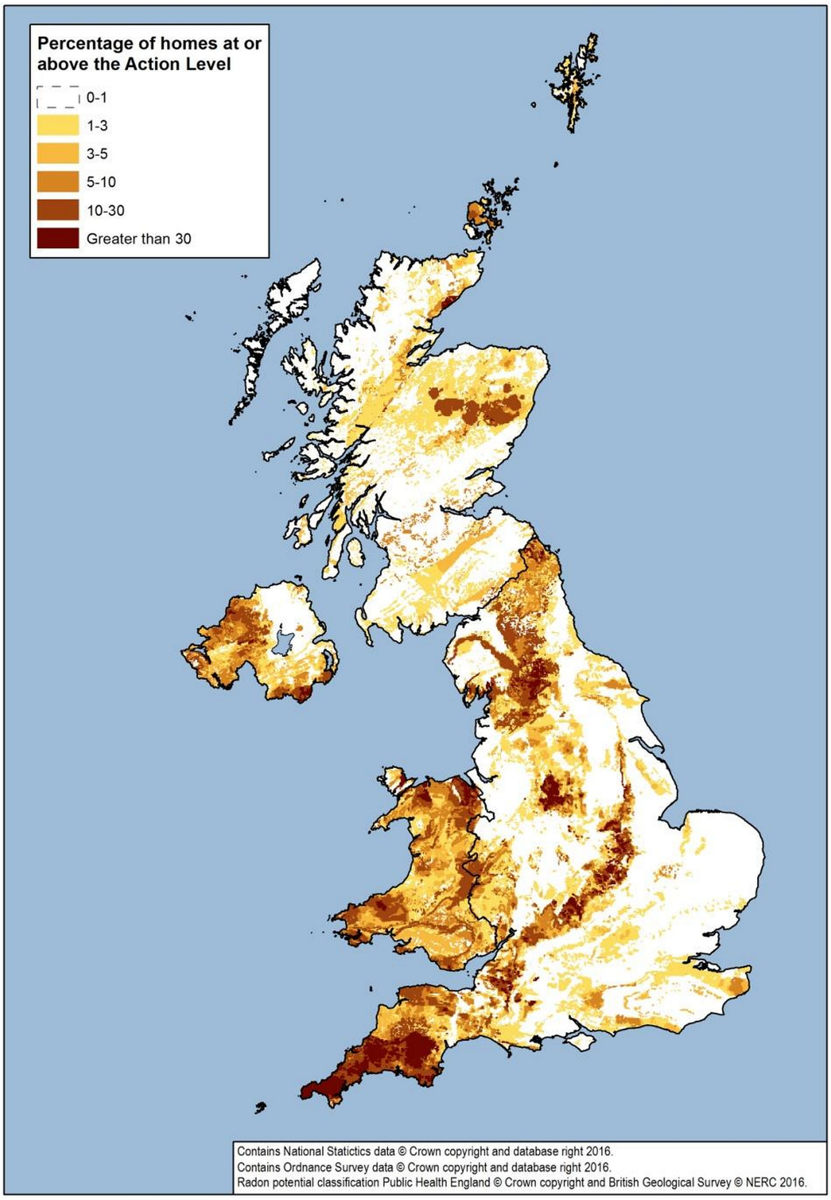

Figure 1: Geographical distribution of homes in England and Wales with radon concentrations exceeding the UK Action Level (McColl et al., 2018). Contours at 1, 3, 5, 10 and 30 Bq.m^{-3}.

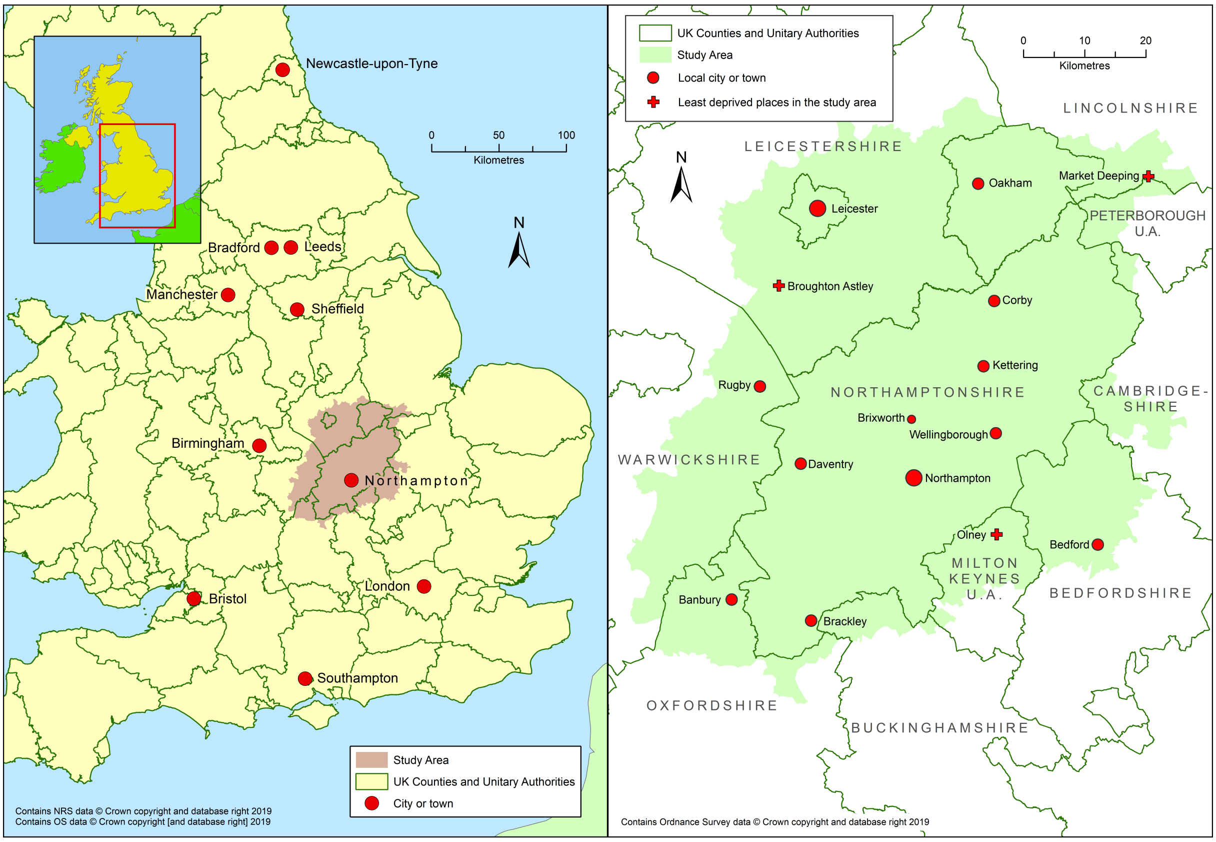

Figure 2: Location of the study area in (a) Central England and (b) its constituent counties.

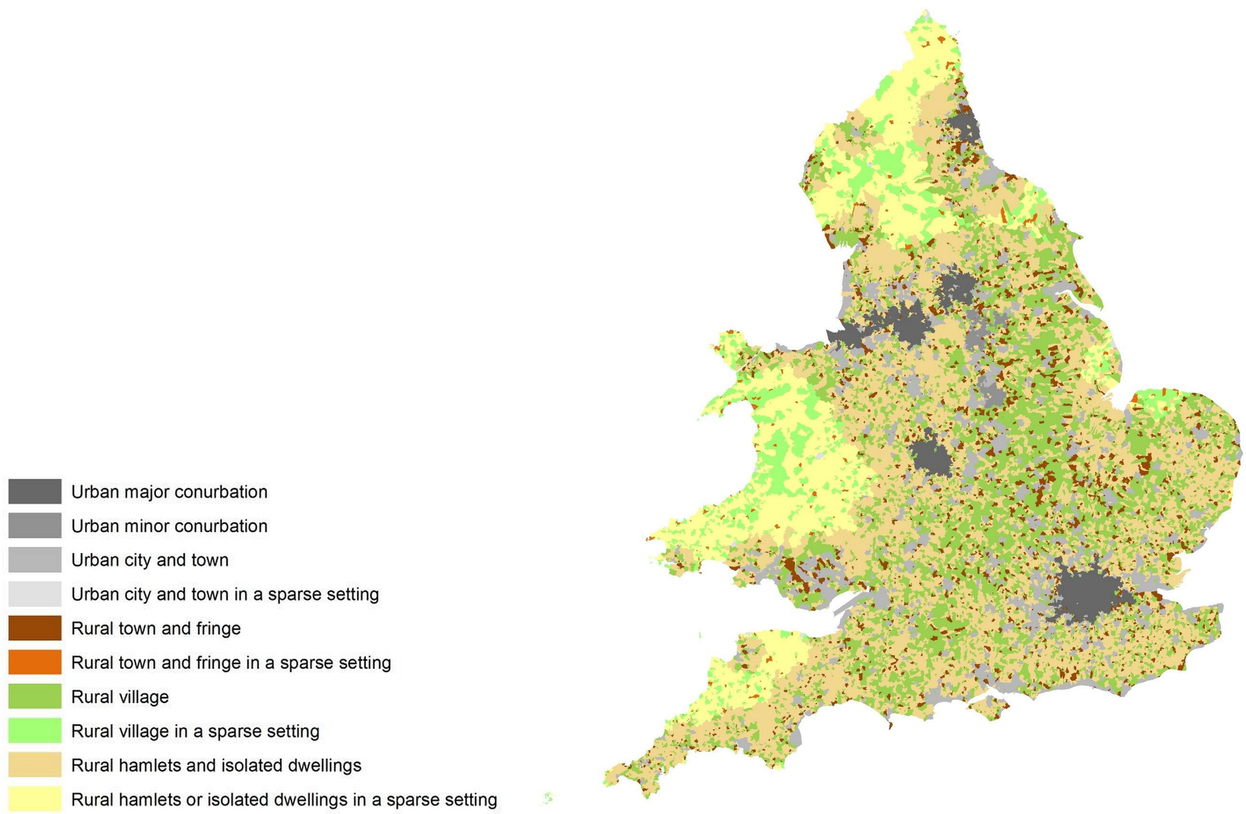

Figure 3: Rural-Urban Classification (RUC) of 2011 Census areas in England and Wales. (Bibby and Brindley, 2013). Contains public sector information licensed under the Open Government Licence v3.0.

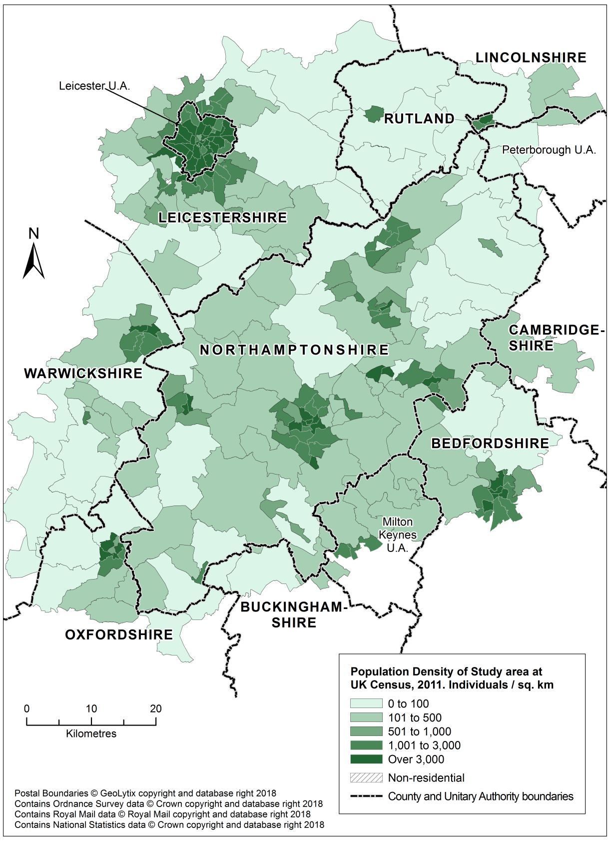

Figure 4: Population density in postcode sectors across the study area. Population data from 2011 Census (ONS, 2011).

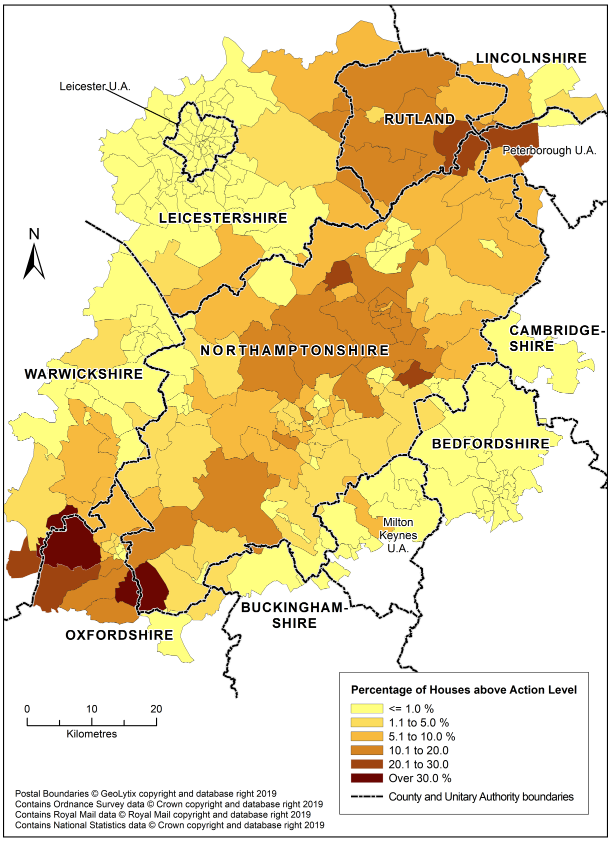

Figure 5: Percentage of homes with radon levels over the Action Level by postcode sector. Radon data from Rees and Miller (2017).

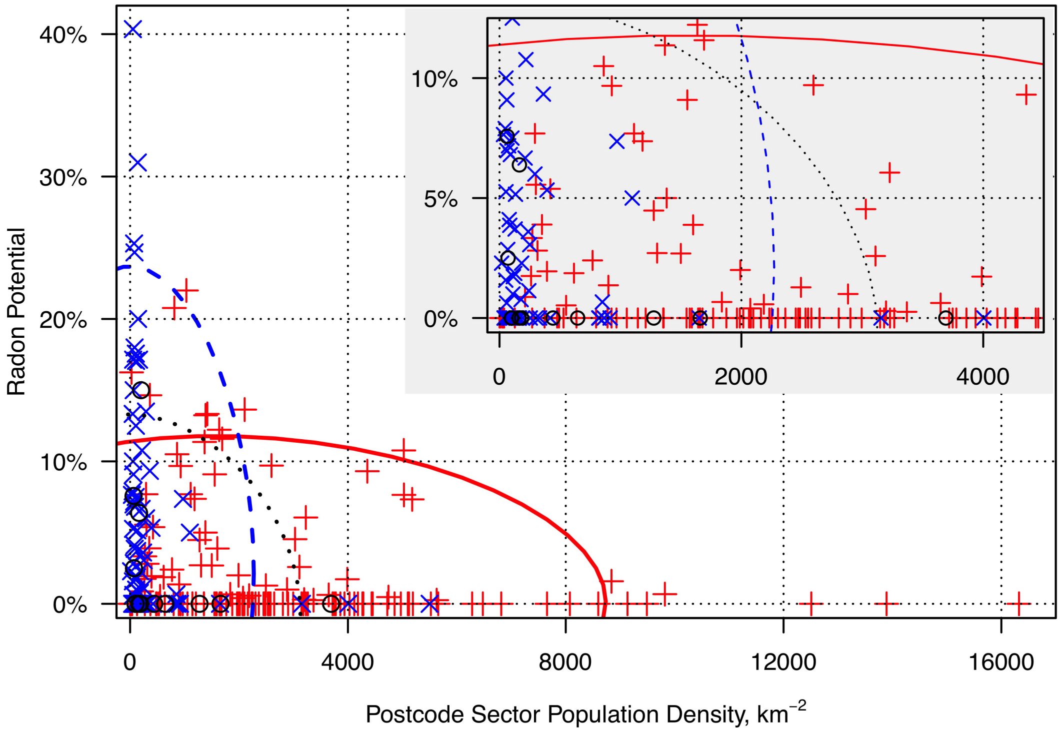

Figure 6: Radon potential and population density for Urban, Rural and Mixed postcode sectors. Inset expands details for data in the lower 25% of the ranges for all three classifications.

Urban (C1): +, solid line, red

Mixed (D1): o, dotted line, black

Rural (E1): x, dashed line, blue

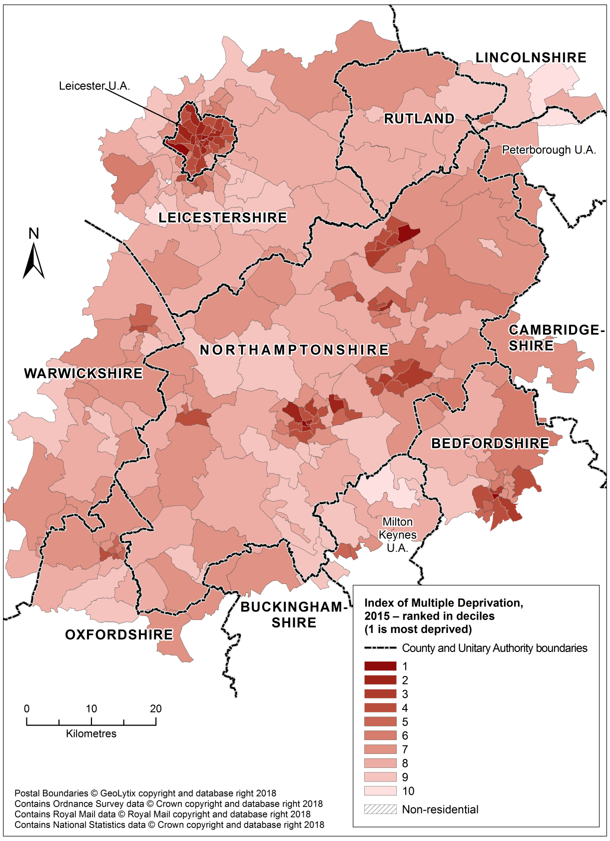

Figure 7: Social deprivation deciles in the study area.

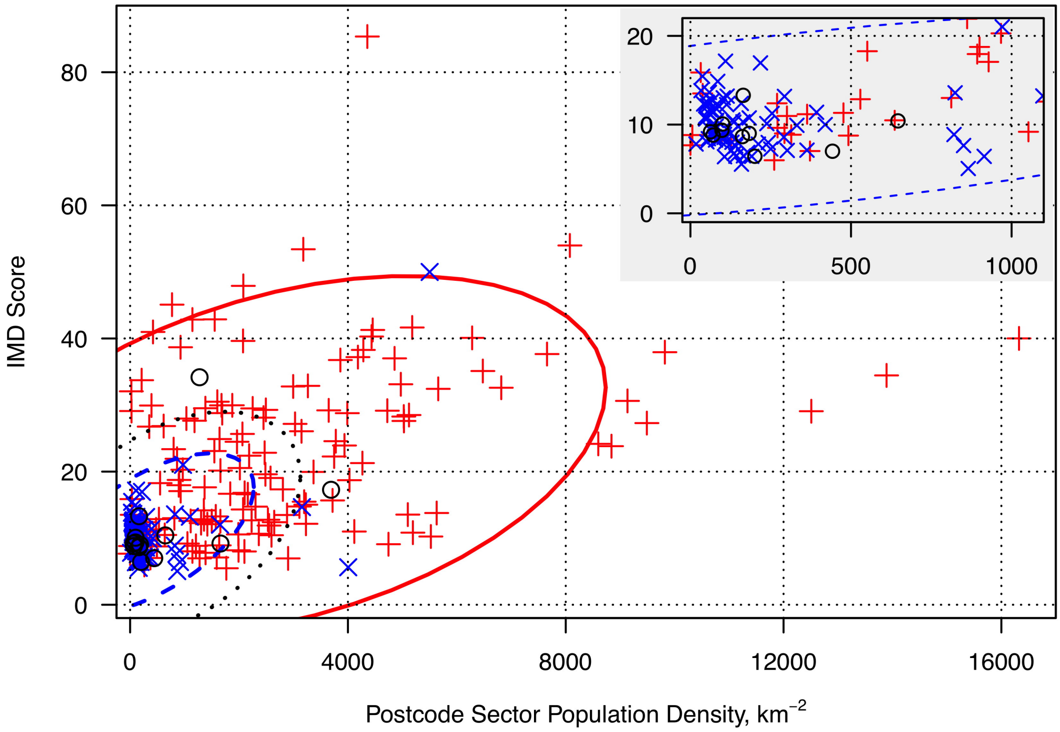

Figure 8: IMD Score and population density for Urban, Rural and Mixed postcode sectors. Inset expands details for data in the lower 7% of the population density range, primarily for Rural and Mixed classifications.

Urban (C1): +, solid line, red

Mixed (D1): o, dotted line, black

Rural (E1): x, dashed line, blue

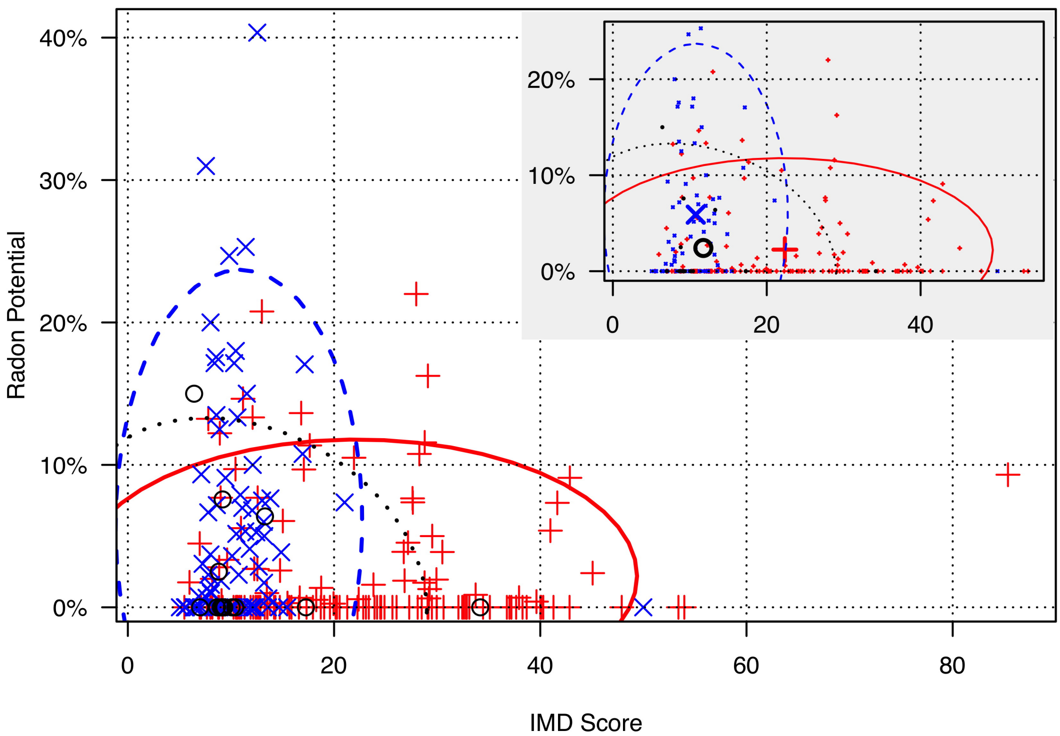

Figure 9: Radon levels and social deprivation in Urban, Rural and Mixed postcode sectors. Inset shows the centroids (as large symbols) for the data from the postcode sectors, data-points indicated by small symbols for clarity.

Urban (C1): +, solid line, red

Mixed (D1): o, dotted line, black

Rural (E1): x, dashed line, blue

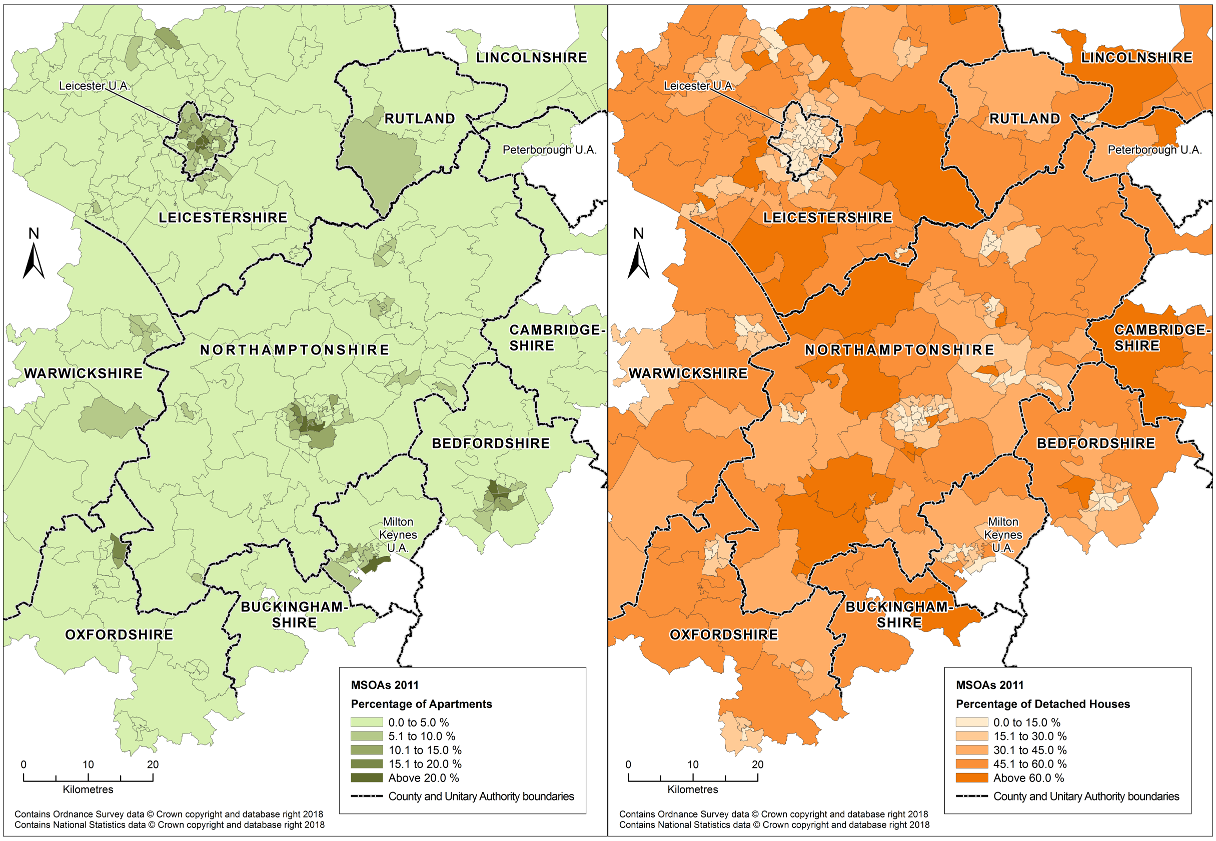

Figure 10: Distribution of house types in 2011 across the study area.
(a) all Apartments, (b) Detached Houses.

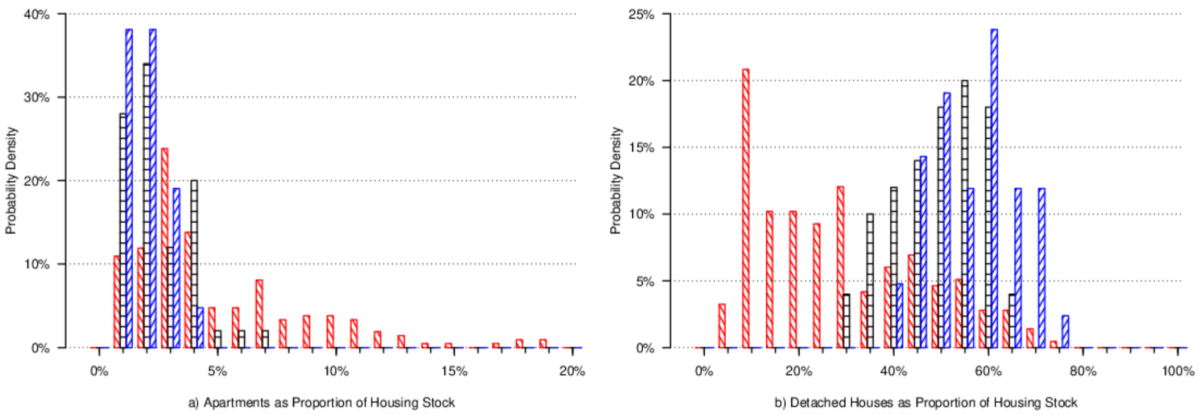

Figure 11: Distribution of detached houses in the housing stocks of Urban (C1), Semi-Rural (D1) and Rural (E1) MSOAs.
(a) all apartments, (b) detached houses
Red, downward shading: Urban (C1)
Black, horizontal shading: Semi-Rural: (D1)
Blue, upward shading: Rural (E1)

Table Captions

Rural Urban Classification	C1: Urban *Urban City and Town*		D1: Semi-Rural *Rural Town and Fringe*		E1: Rural *Rural Village and Dispersed*	
Total MSOAs	216		50		42	
	Detached house or bungalow	*Apartment*	*Detached house or bungalow*	*Apartment*	*Detached house or bungalow*	*Apartment*
Mean	26.11%	5.84%	47.17%	1.99%	53.94%	1.44%
Minimum	1.56%	0.06%	25.07%	1.99%	53.94%	1.44%
Maximum	71.02%	82.88%	63.62%	0.29%	35.91%	0.36%
Stand. Dev.	17.20%	8.28%	9.31%	6.30%	70.20%	3.65%

Table 1: Statistical analysis of housing stock distribution by Rural-Urban Classification.