Comparison of Northern Ireland radon maps based on indoor radon measurements and geology with maps derived by predictive modelling of airborne radiometric and ground permeability data.

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Abstract

Publicly available information about radon potential in Northern Ireland is currently based on indoor radon results averaged over 1-km grid squares, an approach that does not take into account the geological origin of the radon. This study describes a spatially more accurate estimate of the radon potential of Northern Ireland using an integrated radon potential mapping method based on indoor radon measurements and geology that was originally developed for mapping radon potential in England and Wales. A refinement of this method was also investigated using linear regression analysis of a selection of relevant airborne and soil geochemical parameters from the Tellus project. The most significant independent

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variables were found to be eU, a parameter derived from airborne gamma spectrometry measurements of radon decay products in the top layer of soil and exposed bedrock, and the permeability of the ground. The radon potential map generated from the Tellus data agrees in many respects with the map based on indoor radon data and geology but there are several areas where radon potential predicted from the airborne radiometric and permeability data is substantially lower. This under-prediction could be caused by the radon concentration being lower in the top 30 cm of the soil than at greater depth, because of the loss of radon from the surface rocks and soils to air.

Keywords

Airborne, Northern Ireland, Mapping, Modelling, Permeability, Radiometric, Radon

1. Introduction

In order to prevent the public receiving high exposures to radon, it is necessary to identify those areas most at risk. The potential for high indoor radon concentrations depends on multiple factors including the amount of radium-226 in the ground underneath buildings, and the permeability of the ground. As a result, indoor radon tends to be correlated with local geology (Appleton and Miles, 2005; Barnet et al., 2008; Kemski et al., 2009; Scheib et al., 2009). The probability of homes in Northern Ireland having radon concentrations above the UK Action Level (AL, 200 becquerels per cubic metre of air, Bq m^{-3}) is currently estimated on the basis of the results of radon measurements in homes, grouped by 1-km squares where there are sufficient results in the square, or interpolated from the nearest measurements for squares where there are too few results (Green et al., 2009). This approach does not take any account of the geological influence on indoor radon (Appleton and Miles, 2010). An integrated mapping method has been developed to use indoor radon results in conjunction with geological boundaries to map radon potential (RP_{irg}) with greater accuracy and detail than currently available for Northern Ireland (Miles and Appleton, 2005). This method is applied to indoor radon and geological data available in Northern Ireland and the results are compared with the 1-km grid square radon potential (RP_{ir}) map based solely on indoor radon measurements.

Both the 1-km grid and the integrated mapping methods can have significant uncertainties where indoor radon data are sparse. It is difficult to provide a consistent indication of the spatial variation of the likely reliability of the RP_{ir} and RP_{irg} maps although the density of indoor radon measurements is probably the best indicator (Green et al., 2009). Uranium concentrations in surface rocks and soils, estimated by airborne gamma spectrometry surveys of gamma rays from ^{214}Bi, and referred to as eU (equivalent uranium), have been used to inform radon potential mapping in many countries (Appleton, 2007; Smethurst et al., 2008). The integrated geological-grid square radon mapping of England, Wales and Scotland did not use airborne geophysics or soil geochemical data, because neither is universally available in GB. In Northern Ireland, the Tellus Project has produced new geochemical and geophysical maps designed to support mineral exploration, inform land-use planning and provide environmental baseline data (Young et al., 2007; Beamish and Young, 2009). The study reported here develops and applies to the whole of Northern Ireland the predictive modelling methods of a pilot study (Appleton et al., 2008) which used linear regression analysis of a selection of relevant Tellus airborne and soil geochemical parameters in an attempt to refine the radon map based solely on indoor radon data and geology. In this study, a range of national and terrain specific linear regression models are statistically validated against the radon map based on indoor radon and geology in order to assess whether radon potential maps derived by predictive modelling of ground permeability, airborne gamma-ray spectrometry and soil geochemical data could usefully inform future indoor radon measurement programmes.

2. Materials and methods

Appleton et al. (2008) describe the airborne gamma-ray spectrometry and soil geochemistry data from the Tellus Project, together with ground permeability information based largely on aquifer character (Ball et al., 2005; McConvey, 2005) and the approximately 23,000 indoor radon measurements available for Northern Ireland (Green et al., 2009). Uncertainties related to indoor radon measurements are documented by Hunter et al., (2005, 2009) and Miles and Appleton (2005). For the integrated radon mapping of Northern Ireland, the 1:250 0000 scale bedrock and superficial geology data (GSNI 1991, 1997) were simplified and then unioned and intersected with a 1-km grid, derived from the Irish National grid, using ArcGIS geoprocessing tools. Radon potential estimates were made for each 1km\bedrock\superfical (1kmBS) polygon initially following the method described in Appleton and Miles (2005). In cases where there were too few house radon results available for a bedrock\superficial (BS) geological combination to allow the spatial variation to be mapped using the method described by Miles and Appleton (2005), a number of different approaches were taken, dependent on the number of indoor radon measurements and their distribution (Table 1).

An average radon potential value is usually applied uniformly to those geological units with insufficient indoor radon measurements for the application of the combined geological-grid square mapping method. The possibility of mapping spatial variation of radon potential within these geological units was investigated by deriving a smoothed map of Tellus airborne eU within geological units, and then using the variation in the smoothed airborne eU data to map intra-geological variation in radon potential. Three units for which there are many indoor radon results and combined geological-1-km grid square mapping results available were used to test the method. However, it was concluded that corrected uniform mapping using smoothed eU data, when applied in a standard manner to units with few house radon results, is unlikely to produce any significant improvement in accuracy over the application of the average radon potential to the whole of the geological unit, so this method was not investigated further. For the relatively small number of BS polygons for which no indoor radon data is available, the radon potential was assessed by analogy with similar geological combinations (Table 1).

Radon mapping based on a least squares linear regression analysis approach using data including airborne gamma-ray spectrometry has been used in Central England (Scheib et al., 2006) and for a pilot study in the SE sector of Northern Ireland (Appleton et al., 2008).

In this study we investigate the relationship between radon potential (RP_{irg}; i.e. estimated % of dwellings above the UK Action Level of 200 Bq m^{-3} (%>AL) estimated by lognormal modelling using LnGM and LnGSD of grouped natural log transformed indoor radon data), and the independent variables (a) airborne eU, eTh (estimated ^{232}Th) and K values, (b) ground permeability and (c) soil K, U, Th, Zr, Y, Ca, Si, Al and Fe concentrations. Indoor radon statistics (%>AL) used for linear regression modelling are based on the natural logs of indoor radon concentrations because indoor radon data are generally log-normally distributed when grouped by geology and grid square. Arithmetic means (AM) of geology\grid square grouped airborne gamma spectrometry eU, eTh, K and soil chemistry data were used for the linear regression modelling because these data usually have distributions that are closer to normal than lognormal (Appleton et al, 2010). Central estimates of the distributions of the grouped data are required for the linear regression modelling.

There is an approximately linear relationship between GM of geologically and spatially grouped indoor radon data and AM eU (Scheib et al, 2006; Appleton et al., 2008; Appleton et al., 2010). For geologically and spatially grouped data the linear relationship between GM indoor radon and %>AL calculated by lognormal modelling is statistically significant but is not, of course, perfect due to the number of other factors which impact on indoor radon concentrations.

The scheme used to attribute a permeability value to each bedrock\superficial geological combination is different to that described in Appleton et al (2008). Interval values of 1, 2, 3 or 4 representing estimated low, medium, high or very high permeability were assigned to bedrock and superficial geology units based on information in Ball et al., 2005. The scale ranges are 1 to 3 for superficial geology and 1 to 4 for bedrock; 4 being assigned to the highly permeable Carboniferous limestone bedrock. The permeability value attributed to each bedrock\superficial combination in a particular 1km grid square depends on the thickness of the superficial deposits. The bedrock permeability value was used where bedrock is at the surface or the superficial deposits are <1m thick (because building foundations generally go down to bedrock when the superficial cover is very thin). The permeability rating for the superficial unit is used when the superficial deposits are >3 m thick and the average of the bedrock and superficial permeability values is used when the superficial deposits are relatively thin (1-3 m). For 5km grid square – geology grouped data, permeability is not either categorical or interval variables in the conventional sense (i.e. values are not all 1, 2, 3 or 4; Figure 1) and for this reason permeability is treated as a continuous rather than a categorical variable.

For this study, three datasets were constructed to allow regression modelling of the parameters to be investigated for the whole of Northern Ireland:

(1) Data for 1km\bedrock\superficial (1kmBS) polygons with 30 or more radon measurements (range 30-310, median 59) and 10 or more airborne data values (13-102, median 59). The regression modelling was carried out for all the data (106 1kmBS polygons) and also separately for the SE sector (79 1kmBS polygons) and the western sectors (24 1kmBS polygons) of Northern Ireland.

(2) Data for bedrock\superficial (BS) combinations with 10 or more radon measurements (range 10-3,111, median 35; 79 BS combinations have 30 or more radon measurements, 20 have 20-29 and 39 have 10-19 radon measurements). The regression modelling was carried out for (i) all the data and also separately for (ii) the SE sector, (iii) Palaeozoic terrain in the SE sector, (iv) Palaeozoic and Palaeogene intrusives in the SE sector, (v) the western sector, (vi) Carboniferous terrain in the western sector and (vii) Proterozoic terrain in the western sector. The main geological terrains are illustrated in Figure 2.

(3) Data grouped by 5km grid-square and bedrock\superficial (5kmBS) combinations with 10 or more radon measurements in order to encompass some of the spatial variation within geological units. 144 5kmBS combinations have 30 or more radon measurements, 53 have 20-29 and 166 have 10-19 radon measurements. Least squares linear regression modelling was carried out for (i) all the data and also separately for (ii) the SE sector, (iii) Palaeozoic terrain in the SE sector, (iv) Palaeozoic – Hawick Group terrain in the SE sector, (v) Palaeozoic and Palaeogene

intrusives in the SE sector, (vi) Carboniferous terrain in the western sector and (vii) Proterozoic terrain in the western sector.

For the BS and 5kmBS data groupings, regression analysis was carried out using (i) the indoor radon data, (ii) the AM airborne eU, eTh and K values calculated from the 5 airborne data points located nearest to each house location, (iii) the AM soil K, U, Th, Zr, Y, Ca, Si, Al and Fe concentrations for the 1kmBS polygon in which each house is located, calculated from the nearest 5 soil samples located on the same BS combination, and (iv) the average permeability for the 1kmBS polygon. This data was used to ensure that the indoor data, airborne data and soil data have approximately the same spatial supports. In this study, each house location was given the geographical coordinates for the centre of the 1kmBS polygon in which it is located in order to maintain the confidentiality undertaking given to house owners.

In general terms, the estimated values of independent variables y^i at location x_j are constructed from values within a vicinity $V(x_j)$ of an indoor Rn datum $C(x_j)$. The dependent variable is the RP. As described in Appleton et al. (2008) this is defined in units U_k, $RP(U_k)$, derived from the indoor measurements in the units U_k by lognormal modelling (Miles and Appleton, 2005).

The general regression model is:

$$RP(U_k) = c + \Sigma\, b^i * y^i(U_k) + \varepsilon,$$

where the upper index i counts the independent variables, lower index j counts the data within unit U_k, and the lower index k counts the spatial units described above (BS and 5kmBS). This approach was not used for the 1kmBS data grouping because very few 1kmBS polygons in a geological terrain contain 10 or more indoor radon measurements.

The multiple linear regression model where both eU and permeability are the independent variables is: RP_{irg} (%>AL) = c + a*eU + b*Permeability + Є. When eU is the only independent variable then the regression model is: RP_{irg} (%>AL) = c + a*eU + Є.

These regression equations were used because the objective of the study was to compare maps modelled from the independent variables (eU, permeability etc.) with conventional radon maps used in the UK which show the %>AL, rather than GM or AM indoor radon. As detailed below, the least squares linear regression modelling appears to show that permeability is generally not a significant independent variable for the terrain specific modelling, or when it is significant, it controls a relatively small proportion of the variation (compared with eU).

Whilst a multiplicative model (C ~ (Ra) * (Perm) * (other factors)) may be more appropriate based on theoretical physics, we have used the simpler additive model (RP_{irg} = c + a*eU + b*Permeability + Є) because (1) because the aim was to model RP_{irg} rather than C (concentration of indoor radon); (2) there is a linear relationship between RP_{irg} and GM indoor radon for data grouped by geology; (3) grouped eU, eTh and soil data have near-normal distributions; and (4) the multiplicity of other unquantifiable factors involved. A similar approach was used by Appleton et al. (2010).

Spearman rank and Pearson correlation coefficients between the dependent variable (i.e. the radon potential (RP_{irg}) estimated from indoor radon data grouped by geology and spatial unit) and possible independent variables (airborne spectrometric, soil chemistry and ground permeability) were used to identify those independent variables with the strongest linear relationship with RP_{irg}. For each data set (1kmBS, BS and 5kmBS), we used stepwise linear regression or, more commonly, repeated the linear regression analysis after removing independent variables from the model if the b-coefficients (regression coefficients; slopes) were not significant and/or the ANOVA p-value for an independent variable was >0.05, in order to produce modelled estimates of radon potential (RP_{mod}). The K, U, and Th soil variables were omitted from all data sets to avoid multicollinearity as they have high positive correlations with the equivalent airborne variables.

The goodness of fit between RP_{irg} (Figure 3) and RP_{mod} predicted using a range of linear regression models (Table 2), was evaluated by (a) visual comparison of the maps (Figures 3, 8-11), and (b) calculation of the mean squared deviation (MSD, Eq. (1)) and Bias (Eq. (2) for 1kmBS data grouped by BS:

$$MSD = \frac{1}{n}\sum_{i=1}^{n}\left(RP_{mod} - RP_{irg}\right)^{2} \qquad (1)$$

$$Bias = \sum_{n}\left(RP_{mod} - RP_{irg}\right)/n \qquad (2)$$

Only those 1kmBS polygons with >9 airborne eU measurements were included in the MSD and bias calculations.

The provisional data smoothing reported by Appleton and Miles (2008) was extended to include all those geological combinations with >79 indoor radon measurements. However, it was concluded that the use of the relationship between eU and RP_{irg} for individual BS combinations as a method for modelling RP is probably not a statistically valid or practical option because of the (1) negative correlations for some BS combinations; (2) lack of statistically significant correlations for other BS combinations; (3) many BS combinations do not fulfil the criteria for this type of data analysis. This approach was therefore not investigated further.

3. Results and discussion

3.1 Radon map based on indoor radon data and geology

Comparison of a provisional geology-grid square radon potential map with the published 1-km grid map produced by the Health Protection Agency (HPA; Green et al., 2009) revealed a number of differences which were investigated. The majority of apparently anomalous areas on the provisional RP_{irg} map were caused by high indoor radon associated with a geological combination in the SE and W sectors of Northern Ireland influencing relatively isolated occurrences of the same geological combinations in the NE sector of N. Ireland, where there are relatively few indoor radon measurements. When the indoor radon data for the NE sector of Northern Ireland was processed separately, it was found that the high RP_{irg} for the majority of the geological combinations did not extend from the SE and W sectors to the NE sector. The revised RP_{irg} map is illustrated in Figure 3.

Comparison of the published 1-km grid map (Figure 4) with the geology-grid square radon map of Northern Ireland (Figure 3) revealed a number of differences reflecting the characteristics of the two mapping methods. There are situations where the RP_{irg} is likely to be more accurate than the 1-km grid radon potential (RP_{ir}) map, for example, in County Fermanagh where high radon potential closely associated with the Carboniferous limestone (Figure 5) is amplified over a relatively wide area on the 1-km map (Figure 6) because the geographical extent of the high radon potential is not constrained on this map by the geological boundaries of the Carboniferous limestone.

Comparison of the geology-grid square radon map (Figure 3) and the simplified geological map (Figure 2) confirms the close association of moderate and high RP_{irg} with (1) Carboniferous limestone in the western sector of Northern Ireland, especially in County

Fermanagh, (2) Late Caledonian and Palaeogene acid intrusive rocks of the SE sector in County Down and County Armagh, (3) Hawick Group greywackes in the SE sector and (4) the Neoproterozoic Argyll and Southern Highland Group psammites, semipelites and meta-limestones in the western sector of Northern Ireland. The RP_{irg} map (Figure 3), which delineates the spatial variations in radon potential both between and within geological units, was used as the standard against which radon maps produced by predictive modelling of the airborne gamma-ray spectrometry, soil geochemistry and ground permeability data were compared.

3.2 Selection of independent variables for linear regression models

3.2.1 1kmBS data set

Spearman rank correlation data (Table 3) suggest that only permeability, soil Al and soil Fe are likely to be significant ($p<0.05$) independent variables for linear least squares regression models for this data grouping. Soil Al and Fe are negative correlations with RP_{irg} while permeability is positive. Stepwise and repeated linear regression indicated that eU and permeability are significant independent variables which respectively explain 22%, and 5% of the total variance. Identification of eU and permeability as significant independent variables may reflect the statistically significant (p 0.05) Pearson correlation coefficients between RP_{irg}, eU and permeability, although Pearson coefficients between RP_{irg} and eTh, Kair (K determined by airborne gamma ray spectrometry), and soil K, U, Th, Al, and Fe are also significant. The disparity between the Pearson and Spearman coefficients is likely to reflect the impact of a small number of 'outliers' in this data grouping in which data for all geological units are considered together.

3.2.2 BS data set

The Spearman rank correlation data (Table 3) suggest that eU, eTh, Kair, permeability and soil K, U, Th and Y are likely to be the most significant independent variables. Pearson correlation coefficients for these variables are also significant ($p<0.05$). Stepwise linear regression showed that eU and permeability are significant and respectively explain 53% and 2% of the total variance. For the SE sector of N. Ireland, eU explains 73% and eTh 7% respectively of the RP_{irg} variation. The relationship between eU and RP_{irg} for some individual BS combinations and groups of combinations is illustrated in Figure 7.

3.2.3 5kmBS data set

The Spearman rank correlation data (Table 3) indicate that eU, eTh, permeability, soil U, Th, K, Y, Al and Fe may be significant independent variables as do the Pearson coefficients. Stepwise and repeated linear regression of these variables showed that only eU and permeability are significant, explaining 24% and 4%, respectively, of the RP_{irg} variance.

Only eU, eTh, Kair and soil Y appear to be significant positive independent variables for the Proterozoic in the West sector (Table 3) but stepwise regression indicates that none of the variables are statistically significant. A model based on eU, eTh and Kair shows that although eU is the most significant it is not statistically significant (p 0.09) and explains only 3% of the total variance of RP_{irg}.

Spearman rank (Table 3) and Pearson correlation coefficients suggest that eU, eTh, Kair, and soil K, U, Th and Y may be significant independent variables for the Palaeozoic terrain in the SE sector. In contrast, stepwise regression indicates that eU and Kair are the only significant independent variables and these explain 28% and 5%, respectively of the total variance of RP_{irg} .

For the Carboniferous terrain in the West sector, Spearman correlation statistics (Table 3) suggest that eU is likely to be the only significant independent variable but stepwise least squares linear regression indicates that eU and permeability are significant independent variables which explain 31% and 18%, respectively, of the total variance of RP_{irg}. Pearson correlation coefficients suggest that soil U, Th, Y, Fe and permeability may be significant in addition to those indicated by the Spearman rank correlation data.

eU, eTh, Kair and soil U, Th, Y and LoI are likely to be the most significant positive independent variables for the Palaeozoic and Palaeogene intrusives in the SE sector (Table 3). However, regression analysis indicates that only eU, Kair, permeability and soil Th are significant and of these only eU explains a substantial (47%) proportion of the variance. Kair, permeability, and soil Th each account for only 4-5% of the total variance and are not included in the model for this terrain. When eU is the sole independent variable, it explains 58% of the total variance in RP_{irg} .

3.3 Radon potential maps derived using linear regression modelling of Tellus data

Visual comparison of the results of radon potential maps derived from linear regression modelling (for model definitions see Table 2) with RP_{irg} indicates that (i) the 1kmBS RP_{mod} (Figure 8) substantially underestimates radon potential throughout most of Northern Ireland and overestimates RP for the Gala Group in the SE sector; (ii) the BS-eUperm model (Figure 9) over estimates RP for most of the area underlain by the Gala and Hawick Groups in the SE sector as do the BS-eU, 5kmBS-eUperm (Figure 10) and 5km-eU models; (iii) model

5kmBS-mix (Figure 11), in which a range of linear regression models are applied to different geological terrains, provides the best visual agreement with the RP_{irg} map (Figure 3).

The MSD and Bias between RP_{mod} and RP_{irg} values for the four main models is compared with the average RP_{irg} in Table 4. Only data from 1kmBS polygons with >9 airborne data points were used to compile Table 4. In general there are only subtle differences between MSD's and Bias's for the four models although when only the major bedrock units are considered (i.e. those with >100 1kmBS polygons), the 5kmmix model produces the lowest MSD and Bias values for the Argyll, Moine, S. Highland Group and Neoproterozoic mafic intrusives. The only high positive bias values for a bedrock geological unit covering a significant area are associated with the Mourne Mountains Granite complex (Table 4), which has a relatively high RP_{irg} (15.6%).

When the impact of superficial geology is considered separately (Table 5), the average bias is most negative (i) for areas covered by peat where high soil moisture and organic content will tend to depress eU values and hence RP_{mod}, and (ii) for areas where bedrock is covered by permeable glacial sand and gravel units, which may be explained by radon loss resulting in low quantities of radon daughters, and hence low ^{214}Bi, low eU and low RP_{mod}.

4. Conclusions

The RP_{mod} map produced from Tellus data using separate linear regression models for different geological terrains provides the best visual agreement with the RP_{irg} map. Also the lowest bias values were generally obtained when terrain specific regression models were used. However, radon potential maps produced using the Tellus data appear to underestimate radon potential especially where the highest radon potential is indicated on the integrated

RP_{irg} radon map. For example, there are several areas underlain by Argyll Group metasediments, Gala Group greywackes, Hawick Group greywackes (e.g. Lecale peninsula), the Newry Granodiorite and Carboniferous limestone where the RP estimated from the Tellus data is substantially less than that shown on the RP_{irg} map. This underestimation may be because airborne eU values (calculated from ^{214}Bi, a daughter product of radon, ^{222}Rn) are in some cases reduced where the radon concentration is lower in the top 30 cm of the soil than at greater depth, as a result of the loss of radon from the surface rocks and soils to air.

Areas have been identified where RP may be higher or lower than indicated on the RP_{irg} map. Only 13% of the variation of indoor radon can be explained by geology in Northern Ireland whereas geology explains 69% of the variation of airborne eU data and 83% of the variation of soil U data (based on average eU and soil U values calculated from the five eU or three soil U values located nearest to each of the 23 040 indoor radon measurement locations). So it is not entirely surprising that the agreement between the $D200_{irg}$ and $D200_{mod}$ radon maps in Northern Ireland is less than perfect. In contrast, 24% of the variation of indoor radon in England and Wales and 27% in Scotland is explained by geology (Appleton and Miles, 2010).

Whilst the integrated geological-grid square radon mapping method, as applied in this study, is currently the most accurate method for defining radon Affected Areas in Northern Ireland, it is suggested that additional indoor measurements should be made in those areas where Tellus data indicate that the radon risk appears to be relatively high or low compared with the RP_{irg} map (Figure 3). The RP_{mod} map (Figure 11) may be particularly valuable as a predictor of radon potential in those areas where there are currently very few indoor radon measurements. In addition, the greater spatial accuracy of new 1:10 000 scale digital geological maps, which are being produced as part of the Tellus 2 project might increase the confidence level of the data analysis reported here. A range of alternative regression methods including the generalised linear model (GLM) could be evaluated (see for example Bossew et al., 2010) but these may well produce essentially the same results, as indicated in previous studies by Appleton et al.(2010) who compared the results of least squares, Theil's and weighted total least squares regression. Least squares regression analysis studies between indoor radon and a range of independent variables including soil gas radon, gamma-ray spectrometry, soil and rock uranium data are being carried out as part of a project to produce a geogenic radon map of Europe (e.g. Kemski et al., 2010).

Radon mapping based on targeted in-house measurements would normally be more cost-effective than using an airborne survey carried out only for the purpose of producing radon potential maps. As a consequence, airborne radiometric survey data should be used for radon mapping only if the data is collected as part of a multi-disciplinary, multi-detector survey such as the Tellus project in Northern Ireland (Young and Earls, 2007). Radon maps based on the airborne radiometric data from such surveys would be a valuable by-product that could be used to help target future in-house radon measurement campaigns.

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Table 1 Methods used for calculating the estimated percentage of dwellings above 200 Bq m^{-3} in each 1kmBS polygon for the integrated geology-grid square radon potential (RP_{irg}) map

No. radon measurements in BS group	No. of polygons	Description of method used to estimate RPirg (%>200 Bq m^{-3})
>79	38319	RP_{irg} based on GM and GSD of nearest 30 radon measurements or all measurements in a polygon if >30; Bayesian GSD corrected for measurement uncertainty
25 – 79	13679	RP_{irg} based on GM of nearest 10 measurements; GSD is average of national GSD and Bayesian GSD corrected for measurement uncertainty
10 – 24	9704	RP_{irg} based on GM of all data in the same BS group in N Ireland; GSD is average of national GSD and Bayesian GSD corrected for measurement uncertainty
<10	6869	RP_{irg} based on GM of all data in the same BS group in N Ireland and national GSD (2.27)
0	2816	Assessment of RP_{irg} based on analogy with similar geological combinations for which radon data are available

Table 2 Least squares linear regression models for 1kmBS, BS and 5kmBS data sets

Model name	Data grouping	LS linear model
1kmBS	All NI data for 1km-BS polygons with >30 IRn and >9 airborne	(2.76*eU)+(1.11*PERM)-3.85
BS-eUperm	All NI data grouped by BS with >30 IRn	(6.94*eU)+(1.14*PERM)-6.14
BS-eU	All NI data grouped by BS with >30 IRn	(7.13*eU) -4.03
5kmBS-eUperm	All NI data grouped by 5km grid square and BS with >30 IRn	(5.85*eU)+(1.95*PERM)-7.6
5kmBS-eU	All NI data grouped by 5km grid square and BS with >30 IRn and >9 airborne	(5.79*eU)-3.68
5kmBS-mix	Use 5KmBS-eU apart from terrains detailed below	
	Data for Proterozoic terrain in western sector	(5.98*eU)-1.17
	Data for Silurian in western sector	(6.26*eU)-2.25
	Data for Carboniferous terrain	(9.38*eU)+(1.77*PERM)-9.5
	Data for Ord. Gilnahirk Gp. Sandstone and Moffatt Shale and Sil. Gala Group in SE sector	(5.49*eU)-6.10
	Data for Palaeozoic and Palaeogene intrusives in SE sector apart from Mourne Mountains Granite Complex	(10.1*eU)-8.1

Abbreviations: NI = Northern Ireland; IRn = indoor radon, PERM = permeability

Table 3 Spearman rank correlation coefficients between RP_{irg} and variables available for linear regression analysis

	1kmBS	BS	5km BS	5kmBS W. sector	5km Proterozoic. in W. sector	5km Carb. in W sector	5km Palaeozoic in SE sector	5km Palaeozoic and Palaeogene intrusives in SE sector
Kair*	-0.04	**0.40**	0.10	**0.18**	**0.20**	-0.01	**0.21**	**0.30**
eTh	0.06	**0.52**	**0.21**	**0.30**	**0.21**	0.00	**0.48**	**0.41**
eU	0.13	**0.48**	**0.22**	**0.30**	**0.20**	**0.33**	**0.42**	**0.50**
K	0.15	**0.33**	**0.15**	0.10	-0.03	0.14	**0.17**	0.20
U	0.01	**0.30**	**0.22**	-0.07	0.08	0.15	**0.54**	**0.33**
Th	0.08	**0.50**	**0.34**	**0.23**	0.00	0.26	**0.57**	**0.36**
Zr	-0.09	0.11	0.10	0.07	-0.15	-0.03	-0.06	0.20
Y	-0.02	**0.24**	**0.14**	0.05	**-0.20**	0.19	**0.42**	**0.45**
LoI**	0.03	0.04	0.06	0.08	0.13	0.06	-0.10	**0.32**
Ca	0.02	-0.11	0.05	-0.04	0.00	-0.07	0.15	0.07
Si	0.18	-0.08	-0.01	-0.07	-0.03	-0.06	0.13	**-0.40**
Al	**-0.34**	0.00	**-0.22**	-0.01	-0.17	0.18	**-0.23**	**-0.35**
Fe	**-0.30**	-0.08	**-0.21**	-0.05	**-0.27**	0.30	-0.09	0.12
Perm.	**0.20**	**0.29**	**0.23**	**0.23**	-0.02	0.19	-0.04	-0.13
No.	106	138	361	157	97	40	146	40

Perm. = permeability; *Kair = K estimated from airborne gamma ray spectrometry; **LoI = Wt. loss on ignition at 450°C; **bold** coefficients significant ($p < 0.05$).

Table 4 MSD and Bias between RP_{mod} and RP_{irg} for main linear regression models listed in Table 2

		MSD				BIAS				
Bedrock	n.	1km BS	BS-eUperm	5kmBS-eUperm	5kmBS-mix	1km BS	BS-eUperm	5kmBS-eUperm	5kmBS-mix	RP_{irg}
Oligocene clays	704	2	4	7	2	-0.9	-0.9	-1.8	-0.7	0.0
Antrim Lava Group	5873	2	6	8	5	-1.0	-2.0	-2.3	-2.0	0.0
Mourne Mountains Granite Complex	239	231	351	266	263	-5.9	8.9	4.7	4.3	15.6
Palaeozoic felsic intrusives	106	74	50	61	52	-4.4	-2.2	-3.7	-2.6	5.1
Palaeozoic mafic intrusives	250	6	26	18	18	-0.9	0.8	-0.5	0.4	1.4
Slieve Gullion felsic Intrusion	100	78	57	57	71	-5.7	-0.6	-2.2	0.4	9.1
Cretaceous chalk and greensand	274	1	4	3	7	-0.2	-0.6	-0.3	-1.8	0.6
Mercia Mudstone Group argillites	371	2	7	7	5	-0.7	-0.2	-1.3	-0.1	0.2
Sherwood Sandstone Group	928	1	5	4	3	0.1	1.0	0.5	0.1	0.5
Namurian mudstones	306	2	4	4	7	-0.7	0.4	-0.8	-0.1	0.7
Dinantian-Namurian lmst., sltst., and mdst.	169	2	4	3	6	-0.9	0.2	-0.2	0.2	1.7
Dinantian-Namurian mdst., sltst., sdst., lmst.	513	3	9	11	19	-1.3	-1.7	-2.4	-3.1	0.4
Dinantian-Namurian sdst., sltst., mdst.	414	3	9	10	21	-1.4	-2.2	-2.7	-3.7	0.4
Dinantian-Namurian sdst.	185	2	5	6	11	-1.0	-1.1	-1.5	-1.9	0.8
Dinantian lmst., sltst., and mdst.	468	11	10	11	14	-2.1	-1.0	-1.6	-1.0	2.8
Dinantian lmst.	1419	20	20	20	25	-2.4	-1.1	-1.6	-0.9	3.5
Dinantian mdst., sltst., sdst., lmst.	1130	2	4	4	7	-0.7	0.6	-0.7	0.1	0.7
Dinantian mdst.	460	2	5	4	8	-0.7	0.8	-0.7	0.3	0.6
Dinantian sdst., sltst., mdst.	1129	2	6	7	11	-0.7	0.1	-0.8	-0.5	0.6
Dinantian sdst.	697	8	10	11	16	-1.6	-1.1	-1.9	-1.8	1.5

		MSD				BIAS				
Bedrock	n.	1km BS	BS-eUperm	5kmBS-eUperm	5kmBS-mix	1km BS	BS-eUperm	5kmBS-eUperm	5kmBS-mix	RP_{irg}
Upper Devonian sdst., sltst., mdst.	561	1	5	3	3	-0.5	1.0	-0.4	1.0	0.5
Middle Devonian congl., sdst.	408	32	30	32	36	-4.2	-3.3	-3.7	-4.3	4.9
Newry Granodiorite Complex 3	118	31	34	30	27	-2.0	2.0	0.7	0.1	4.8
Newry Granodiorite Complex 2	181	9	15	14	9	-0.2	2.3	1.7	0.6	2.2
Newry Granodiorite Complex 1	297	33	41	39	31	-0.9	2.4	1.5	0.6	3.3
Lower Devonian sdst.	149	2	4	5	3	-1.1	-0.1	-1.0	-0.6	1.3
Silurian Gala Group gwck. and shale	3097	3	17	9	4	0.7	3.5	1.9	0.1	0.4
Silurian Hawick Group gwck. and shale	932	61	64	55	58	-3.0	2.1	0.0	0.8	5.7
Upper Ordovician Moffatt Shale	135	1	11	4	3	-0.1	2.7	1.0	-0.6	1.0
Ordovician Gilnahirk Gp. Sdst.	321	1	8	4	4	-0.1	1.9	0.4	-1.0	0.5
Ordovician Tyrone Plutonic Gp. Gabbro	212	111	118	124	86	-7.7	-7.6	-8.0	-5.6	7.7
Lower Ordovician lava	311	30	39	42	20	-4.7	-5.0	-5.5	-2.5	4.1
Argyll Group – metalmst.	408	54	46	50	39	-3.9	-2.2	-2.7	-1.2	5.4
Argyll Group psam. and semipelite	2647	24	25	27	16	-3.1	-2.6	-3.0	-1.1	3.6
Argyll Group quartzite	116	12	15	15	8	-2.9	-2.3	-2.6	-0.6	3.4
Moine psam.	128	20	22	23	12	-3.5	-2.9	-3.3	-1.2	3.9
Southern Highland Gp psam. and pelite	837	12	16	17	14	-1.0	-0.1	-0.5	0.8	1.9
Neoproterozoic mafic intrusions	152	82	71	83	50	-6.1	-5.4	-6.2	-3.1	6.2

Abbreviations: n. = number of 1kmBS polygons with >9 airborne data values; cong. = conglomerate; gwck. = greywacke; lmst. = limestone; mdst. = mudstone; psam. = psammite; sdst. = sandstone; slst. = siltstone; mdst

Table 5 Average Bias ($RP_{mod} - RP_{irg}$) for bedrock and where bedrock is covered by major superficial geology units

Superficial geology	No. of polygons	Average Bias	Average RP_{irg}
Peat	3794	-3.3	1.6
Permeable glacial sand and gravel	2001	-1.4	3.4
Impermeable alluvium	2708	-0.5	1.8
Glacial till (diamicton)	13241	-0.3	1.3
Bedrock	5066	-0.8	2.7

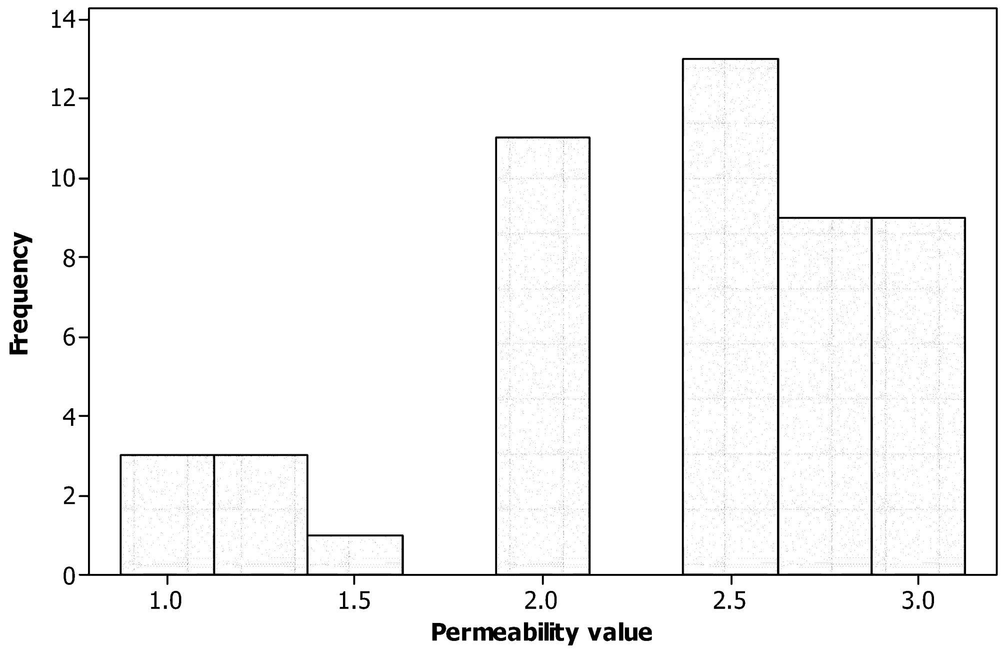

Figure 1 Histogram of permeability values for data grouped by 5km grid square and geology for Palaeozoic and Palaeogene intrusives in the SE sector of Northern Ireland (not including the Mourne Mountains Granite Complex)

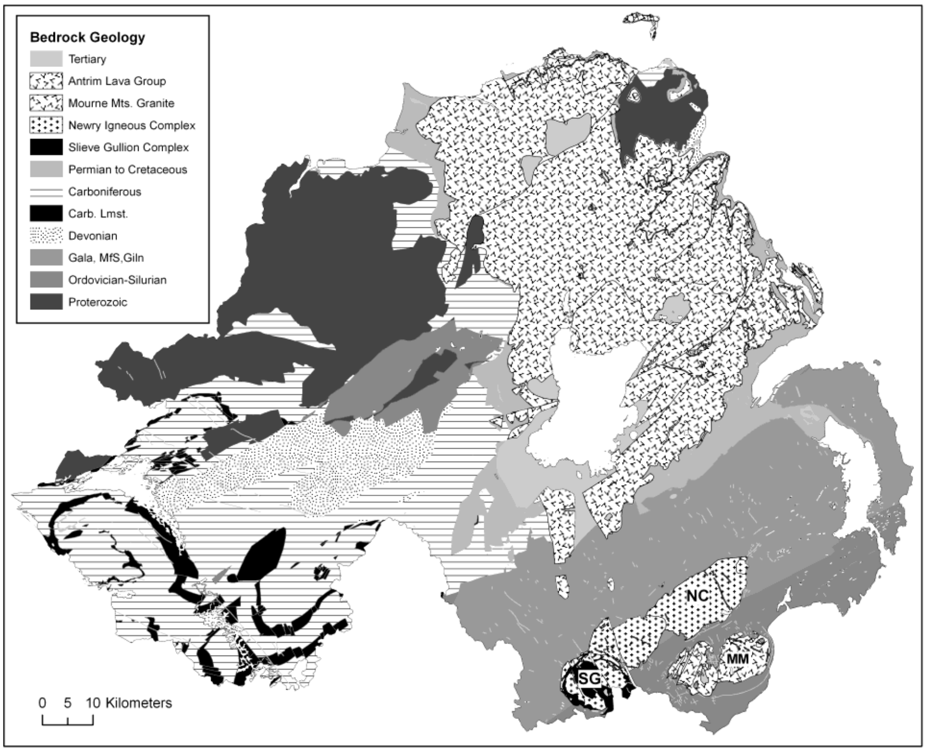

Figure 2 Simplified bedrock geology of Northern Ireland. MM – Mourne Mountains Granite; SG – Slieve Gullion Complex; NC – Newry Igneous Complex

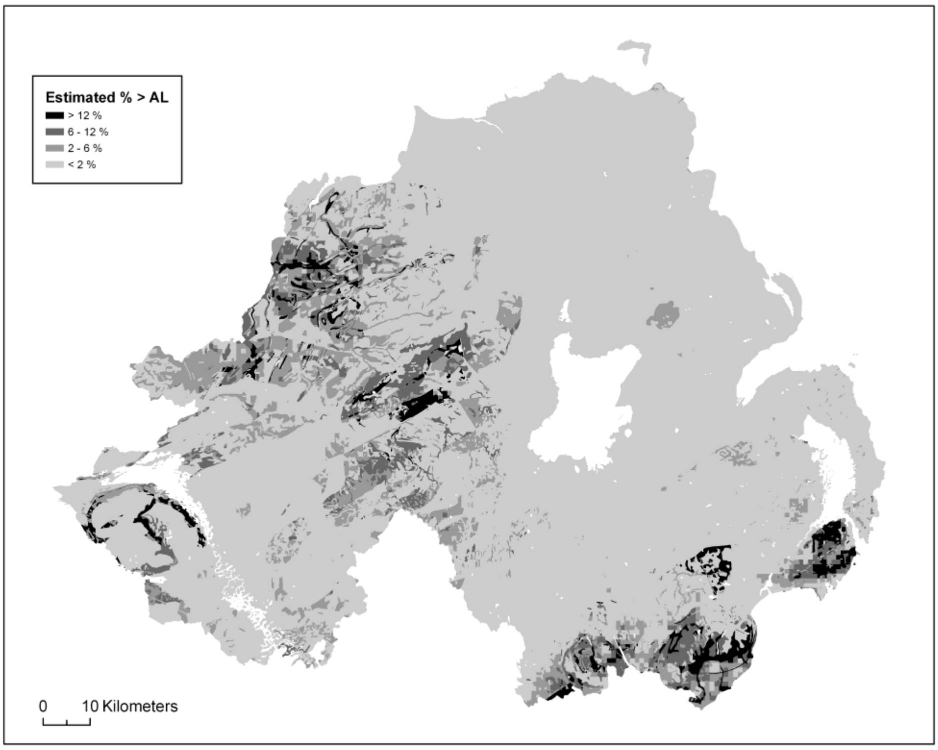

Figure 3 Radon potential (RP_{irg}) map based on geology and indoor radon

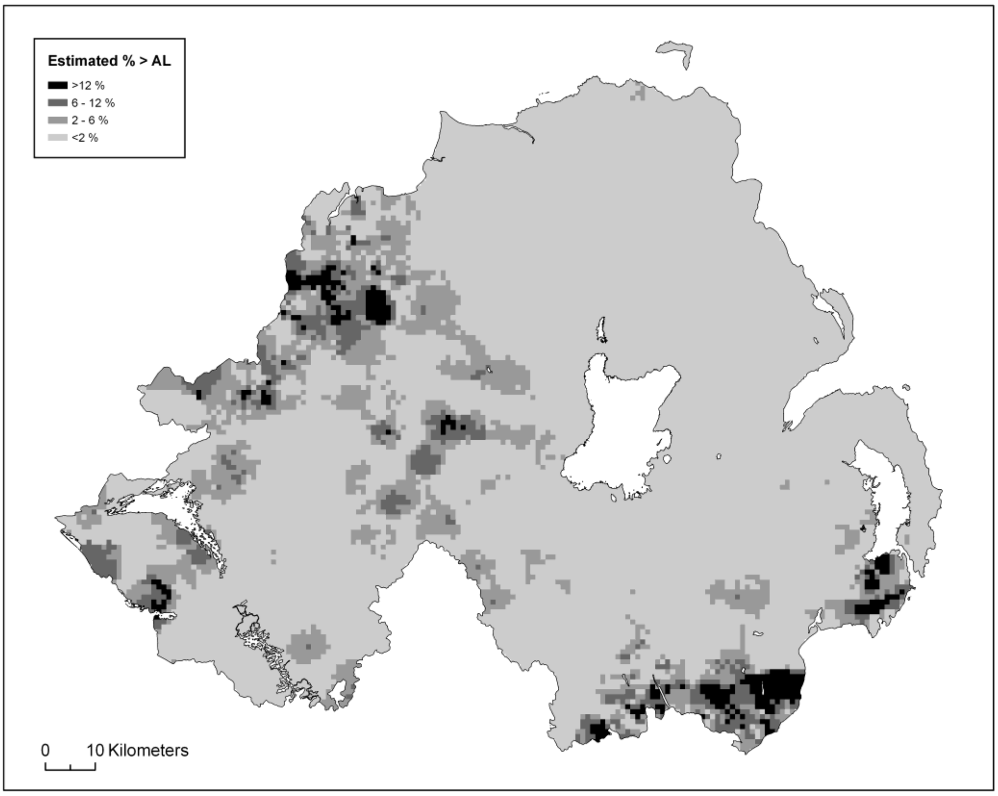

Figure 4 HPA 1-km grid radon map (adapted from Green et al., 2009)

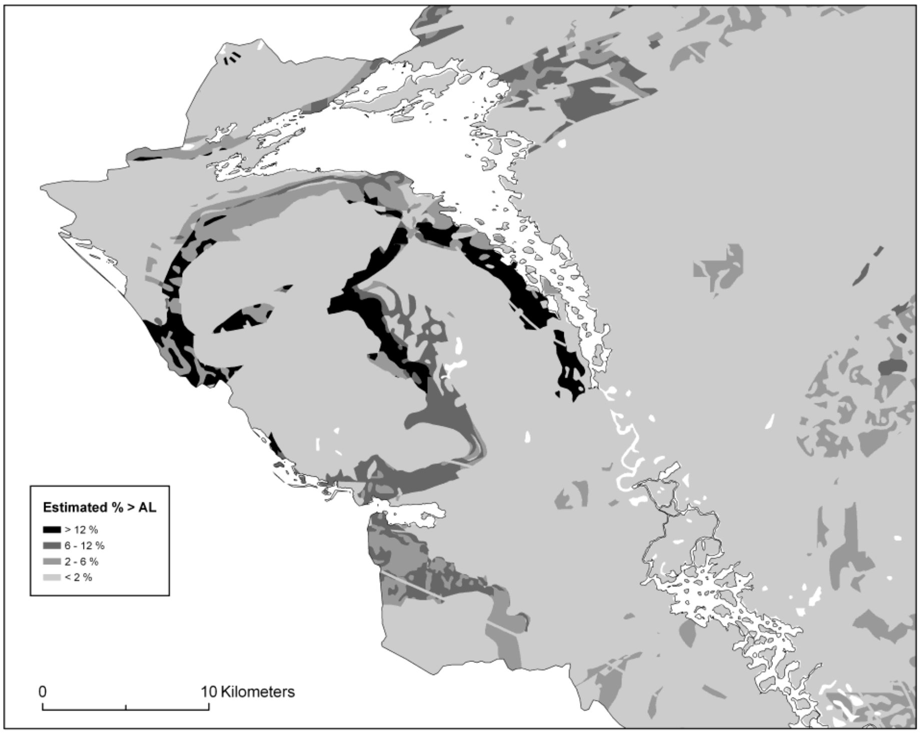

Figure 5. Radon potential (RP_{irg}) map of part of County Fermanagh (extract of Figure 2)

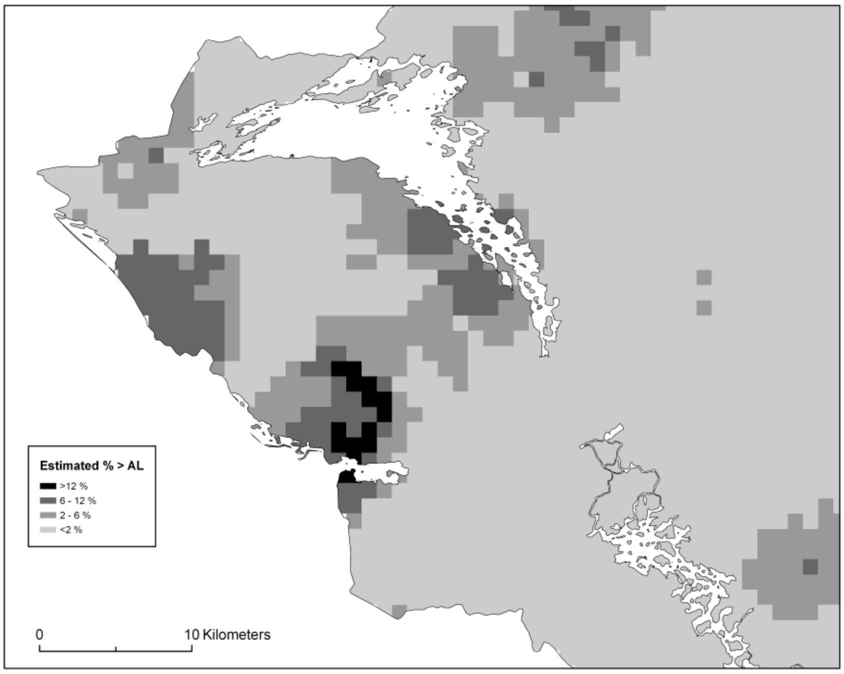

Figure 6. HPA 1-km grid radon map of part of County Fermanagh (extract from Figure 3)

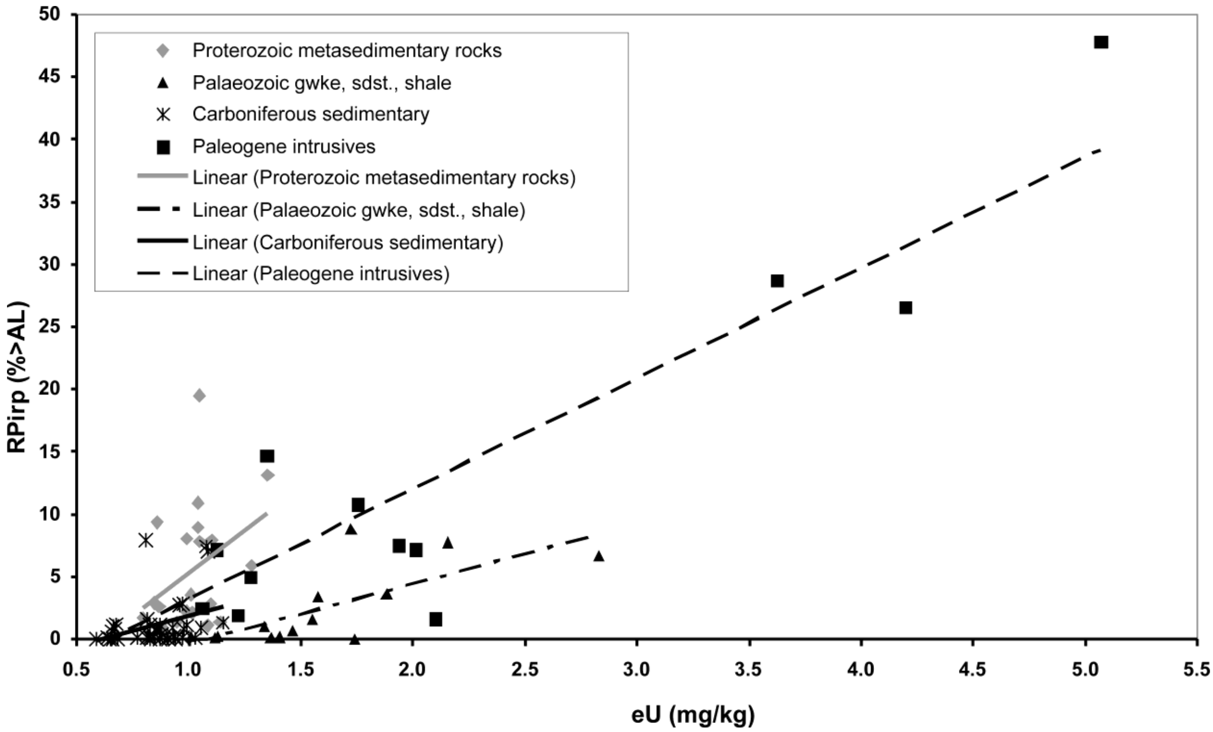

Figure 7. Relationship between eU and RP_{irg} for BS data grouped by bedrock or geological terrain

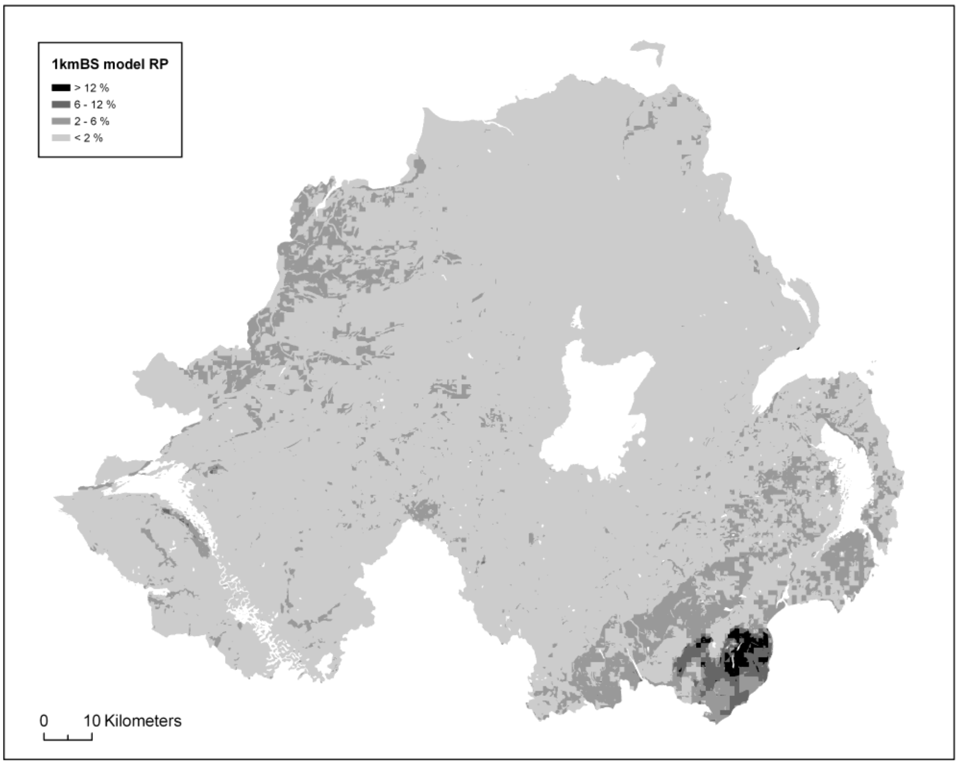

Figure 8 Radon potential (RP_{mod}; estimated % >AL) map produced using the 1kmBS linear regression model

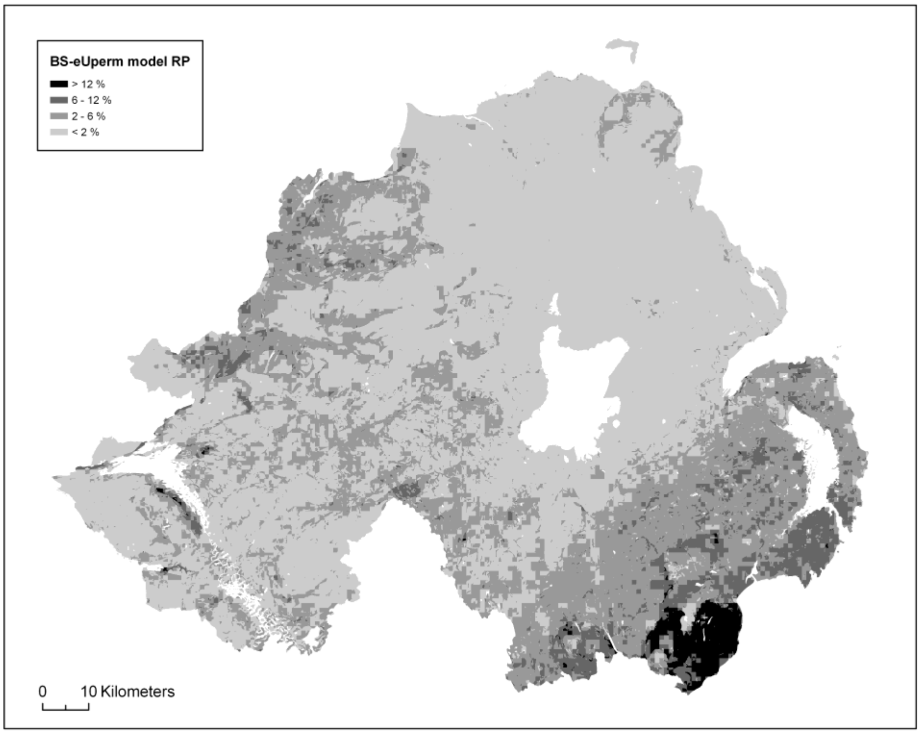

Figure 9Radon potential (RP_{mod}; estimated %> AL) map produced using the BS-eUperm linear regression model

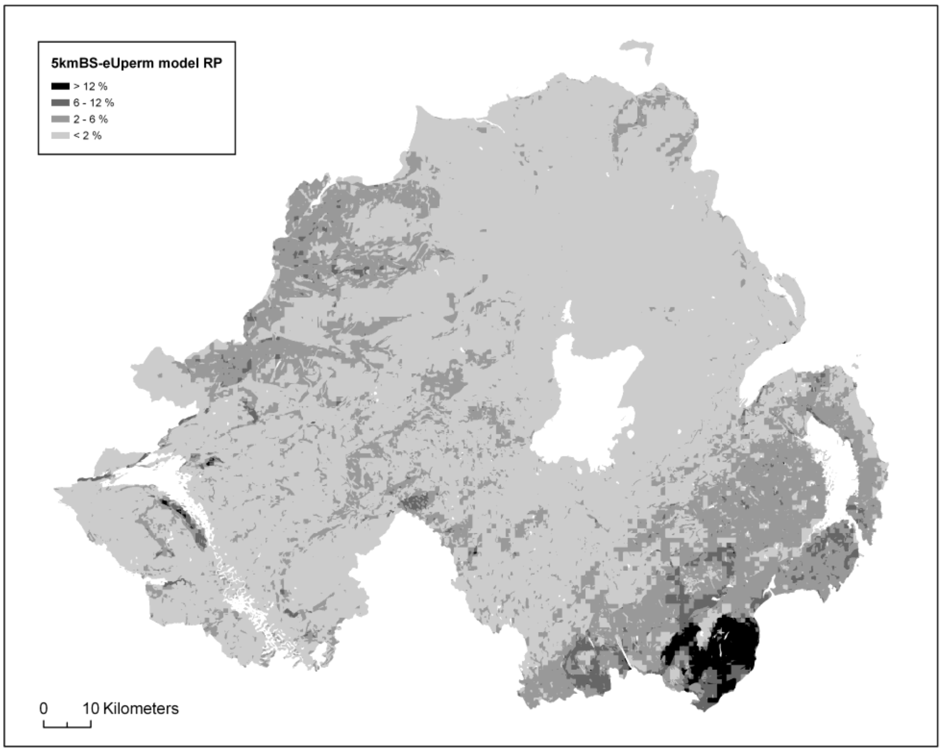

Figure 10 Radon potential (RP_{mod}; estimated % > AL) map produced using the 5kmBS-eUperm linear regression model

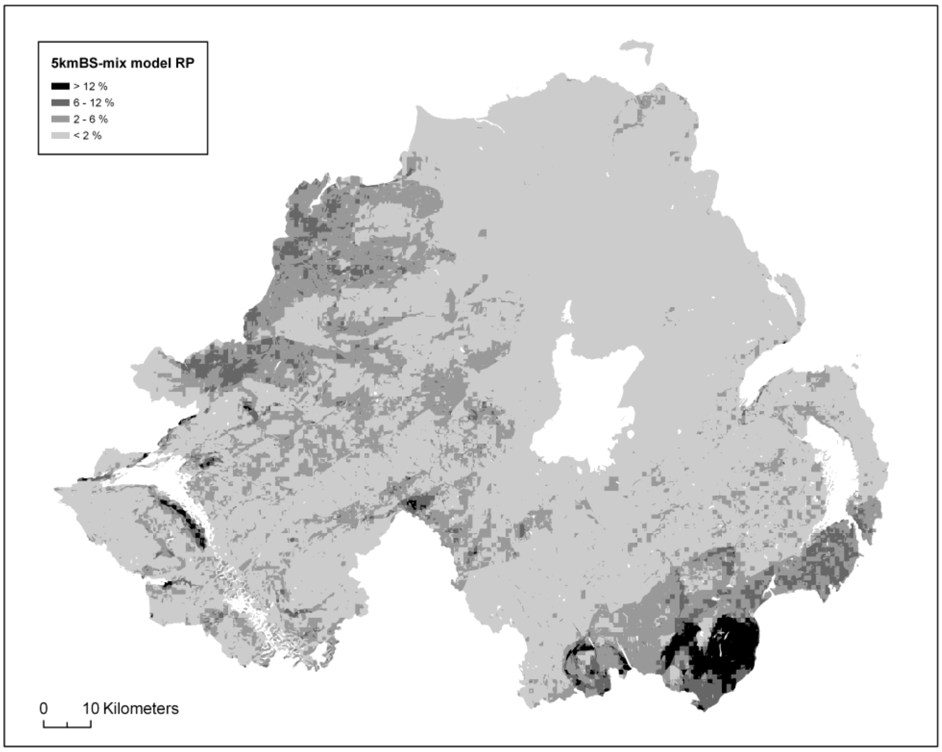

Figure 11 Radon potential (RP_{mod}; estimated % > AL) map produced using the 5kmBS-mix linear regression model