Abstract

The scope for using Tellus Project airborne gamma-ray spectrometer and soil geochemical data to predict the probability of houses in Northern Ireland having high indoor radon concentrations is evaluated, in a pilot study in the southeast of the province, by comparing these data statistically with in-house radon measurements. There is generally good agreement between radon maps modelled from the airborne radiometric and soil geochemical data using multivariate linear regression analysis and conventional radon maps which depend solely on geological and indoor radon data. The radon maps based on the Tellus Project data identify some additional areas where the radon risk appears to be relatively high compared with the conventional radon maps. One of the ways of validating radon maps modelled on the Tellus Project data will be to carry out additional indoor measurements in these areas.

1. Introduction

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 in-house radon measurements, grouped by 5-km grid squares (Green et al., 1999). Methods have been developed to use indoor radon results in conjunction with geological boundaries to map indoor radon with greater accuracy and detail than currently available for Northern Ireland (Miles and Appleton, 2005). However, the improved mapping method can have significant uncertainties where radon data are sparse. The Tellus Project has produced new geochemical and geophysical maps of Northern Ireland which will support the exploration for and development of mineral and hydrocarbon resources, inform land-use planning and provide environmental baseline data. The main purpose of the pilot study reported here was to examine the scope for using new Tellus Project airborne gamma-ray spectrometer and soil geochemical data (Young and Earls, 2007) to provide supplementary data for the method described by Miles and Appleton, and hence improve the accuracy of maps of indoor radon. In this study, the Tellus Project data are compared statistically with in-house radon measurements to determine which is the most appropriate combination of Tellus Project variables to use. The pilot project was carried out in the southeast sector of the province, where there is a high density of indoor radon measurements and a wide range of radon concentrations.

Uranium and radium concentrations in surface rocks and soils are a useful indicator of the potential for radon emissions from the ground. Uranium can be estimated by airborne gamma spectrometry surveys of gamma rays from ^{214}Bi, referred to as eU (equivalent uranium). The close correlation between airborne radiometric measurements and indoor radon concentrations has been demonstrated in Virginia and New Jersey in the USA, Nova Scotia in Canada and also in parts of England (Appleton & Ball, 2001; Ford et al., 2001; Scheib et al., 2006). Airborne gamma-ray spectrometry has been used in Sweden (Åkerblom, 1987), the Czech Republic (Mikšová and Barnet, 2002), and the USA to inform the production of radon potential maps.

After uranium and radium concentrations, the permeability and moisture content of rocks and soils are probably the next most significant factors influencing the concentration of radon in soil gas and buildings. Enhanced radon in near-surface soil gas is associated with high permeability features such as fractures, faults and joints in the underlying rock strata and/or sub-soil. The fracturing of clays, resulting in enhanced permeability, combined with their relatively high radium content and their emanation efficiency may also result in higher radon concentrations in dwellings. Duval and Otton (1990) identified a linear relationship between average indoor radon levels and surface radium content for soils of low to moderate permeability. However, areas with high permeability (>50 cm hr^{-1}) had significantly higher indoor radon levels than would otherwise be expected from ^{226}Ra concentrations, reflecting an enhanced radon flux from permeable ground. Grasty (1997) demonstrated that any estimate of natural gamma-ray flux from the uranium decay series (i.e. radium) in the ground must take into consideration the radon emanation coefficient of the soil as well as its radon diffusion coefficient, which depends largely on soil moisture. Clay soils tend to have higher eU when wet whereas sandy soils have lower eU (Grasty, 1997).

2. Materials and methods

The Northern Ireland Tellus Project at the Geological Survey of Northern Ireland (GSNI) has collected geochemical data (50 elements in soil samples at a density of 1 per 2 km^2 in rural areas and 4 per km^2 in urban areas) and airborne geophysical data (magnetic, electrical and gamma ray spectrometry). The geophysical data include airborne 256-channel gamma spectrometry covering 0.3-3 MeV at 200-m line spacing, 55-m height, except over towns where a height of 250 m is used. The spectrometric data are integrated over flying distances of about 70 m. A range of corrections is applied to the data including removing aircraft, cosmic and radon background; application of stripping corrections derived from calibration data and application of height attenuation corrections.

Potassium (^{40}K), equivalent uranium (eU) and equivalent thorium (eTh, estimated from ^{208}Tl) data were acquired and processed to produce equivalent ground concentrations in % K, mg kg^{-1} eU and mg kg^{-1} eTh. The eU and eTh data do not imply that uranium and thorium are actually present, since uranium and thorium can be leached away while radium remains. The ^{214}Bi gamma ray dose rate results effectively report short-lived radon decay product concentrations in the top 30 cm or so of the ground. The area of view of the detector for each measurement is more than 10,000 m^2 (Beamish et al., 2006a, b).

Varying levels of soil moisture affect the airborne radiometric measurement results, and the effects of radon decay products washed-out of the air by rain. The airborne survey was not normally carried out during rain or for a few hours afterwards, so washout should not cause a problem. Rain was too frequent in Northern Ireland during the summer of 2005 and 2006 to wait until ground was dry before making measurements, so ground moisture levels will have varied from day to day during the airborne survey. Radiometric data are commonly affected by atmospheric radon, which is not fully removed by the processing procedure. This problem is usually seen as a raised “level” of a complete line. There are a number of processing procedures designed to level data, some of which are specific to radiometrics and others that are general for geophysical data. Full details of the seasonal correction and levelling procedures are given in Beamish et al. (2006c).

Another possible source of uncertainty in the Tellus airborne radiometric data for Northern Ireland is in limestone regions, where there may be significant flow of air carrying radon within the ground, the direction of flow depending on outdoor air temperature, local topography and wind speed and direction. However, limestone does not occur in the pilot study area. In urban areas, where a significant proportion of ground area is covered in buildings and/or asphalt paving, the airborne radiometric data may be less reliable.

Soil samples were systematically collected from alternate kilometre grid squares. Each sample comprised five sub samples taken from the corners and centre of a 20- x 20-m square where material was recovered from 5-20 cm depth using a hand auger. Samples were oven-dried at 30ºC, disaggregated and sieved to minus 2 mm using nylon mesh. A sub-sample of this material was pulverised and homogenised in an agate ball-mill for 30 minutes prior to preparation of a 12-g pressed powder pellet. Analysis by X-ray fluorescence spectroscopy (XRF) provided data for 58 elements; soil pH and loss-on-ignition (LOI) at 450^{o}C were also determined. Full details of all sampling, analytical, quality control and map-production methods are given in Smyth (2007).

The work reported here relies on correlating Tellus data with the results of indoor radon measurements in dwellings. The Radiation Protection Division of the UK Health Protection Agency (HPA) maintains the UK national radon database, which contains the results of nearly 29,000 measurements in Northern Ireland; the large majority funded by the Environment and Heritage Service. Because of the generally rural nature of the area mapped, less than 0.4% of the homes measured had both living room and bedroom above first floor level, with less than 0.1% having both living room and bedroom above second floor level. Despite being elevated above the source of radon in the ground, homes above first floor level had a mean radon concentration only 33% lower than that found in the full data set, and included two homes with radon concentrations above the UK Action Level. This pattern is likely to be because the apartments are not purpose-built, but converted from three- or four-storey houses, with movement of air between the storeys. Accurate coordinates for house measurement results are required for the study reported here. Of the 24,000 radon results for domestic dwellings, 23,000 have precise coordinates obtained from Ordnance Survey of Northern Ireland Pointer® location data. These results were used for the data analysis and for preparing radon potential maps.

A provisional method for evaluating the use of Tellus airborne and soil geochemical data for radon mapping was developed:

(1) Allocate house radon results to 1-km/bedrock-superficial geology (parent material; PM) polygons derived from 1:250,000 scale data (GSNI 1991, 1997) using a simplified geological classification.

(2) Calculate mean eU for each 1-km/PM polygon using original measurement positions (Figure 1).

(3) For each PM separately, use the procedures described in Miles and Appleton (2005) to calculate Geometric Mean indoor radon (GMRn) for data grouped by 1-km/PM combinations for those PMs with >80 indoor radon results. For PMs with <80 results available, determine the geometric mean from all measurements located on that PM in the pilot area.

(4) For each PM separately, plot mean eU against GMRn to derive a relationship between the two quantities, specific to that PM.

(5) Evaluate whether these relationships are statistically significant and if they are, (a) apply the derived relationship to 1-km/PM polygons with no or few radon results, to estimate GMRn for these polygons; (b) use lognormal modelling, based on the estimated GMRn with Geometric Standard Deviation (GSD) radon derived from polygons with sufficient results, to estimate the proportion of dwellings above the AL (referred to as D200) for all polygons.

(6) Combine the estimates for all different PMs into a digital radon potential data set for Northern Ireland.

Miles and Appleton (2005) mapped intra-geological unit variation for bedrock/superficial combinations with more than 100 radon measurements. A slightly lower threshold for intra-unit interpolation was used for Northern Ireland because fewer radon measurements are available. The selection of 80 for the Northern Ireland study is considered by the authors to be an adequate number for intra-geological unit interpolation.

This provisional method was extended to include the linear regression analysis approach developed in Central England (Scheib et al., 2006). Average soil K_2O, U, Th, Zr, Y, LOI (% loss of weight on ignition at 450^oC), CaO, SiO_2, Al_2O_3, MgO, and Fe_2O_3 were calculated for each 1km/PM polygon from the three soil samples on the same PM located nearest to the centroid of each polygon (Figure 1).

It was necessary to group some similar mapped geological units to ensure that there were a sufficient number of indoor radon measurements for intra-geological unit grid square mapping to be carried out over a greater proportion of the study area. Grouping was based on age, lithology and permeability. There are 30 mapped bedrock geological units and these were grouped using a simplified bedrock classification comprising only 20 units. For example, five mapped subunits of the Mourne Mountains Granite were grouped together.

All bedrock and superficial geological units were assigned numeric permeability values so that the influence of permeability on indoor radon could be evaluated using stepwise regression analysis. No results from direct field tests were available so the classifications for superficial geology units were derived from Ball et al. (2005). Values of 1, 2 and 3 respectively were assigned to Low, Medium and High permeability units. Approximately 80% of the study area is underlain by superficial deposits. The permeability classification of bedrock units is based largely on aquifer category (Ball et al., 2005; McConvey, 2005) although a few bedrock units were assigned slightly different numeric values based on other bedrock permeability information (Lewis et al., 2006). Digital soil data for Northern Ireland is for surface soils which are normally removed prior to construction and building foundations normally penetrate through to subsoils. In addition, the urban areas where most of the indoor radon data is located are mapped as “urban” soil, which does not provide a guide to ground permeability. Consequently, estimates of the relative permeability of superficial and bedrock geological units provide the best available indication of ground permeability.

3. Results and discussion

3.1 Preliminary data analysis

There is a close correlation between the broad distributions on the radiometric and surface soil geochemical maps for K, Th and U, although these do differ in detail, as would be expected due to different data density and the impacts of other geochemical and physical factors. Comparison of airborne and soil data show that airborne estimates of K_2O are about 20% less than soil K_2O concentrations, airborne eTh is about 30% less than soil Th and airborne eU is only about a third of the soil U. Radiometric data could be depressed (a) due to dilution caused by high organic content of the top 5 cm of the profile and (b) more water in peaty soils, which will adsorb the ^{40}K, ^{214}Bi and ^{208}Tl. The discrepancy observed for U may be caused in part by a calibration problem with the airborne data or other factors (Jones et al., 2007).

Geometric means for eU could not be calculated readily for all 1-km/PM polygons due the presence of negative values in the data set. This occurs where values are near the detection limit; the removal of background can result in negative values and is observed especially over urban areas. As the highest density of indoor radon measurements is in urban centres, there was concern that these negative eU values may impact on studies of the relationship between indoor radon and eU. A statistical analysis of eU data within the urban centres and 1500-m wide buffer zones around the urban centres, with data grouped by PM, shows that eU is, on average 8% higher in the urban areas, although the range is from 36% higher in the urban area to 25% higher in the buffer zone.

The most likely explanation for the large number of negative eU values over urban areas is not a depression of the overall eU caused by buildings, roads and artificially covered ground, but the higher variability/uncertainty in the results when the detector height is about 250 m instead of about 50 m over rural areas. Whereas the quality of the gamma-ray spectrometric data decreases as the aircraft height increases because the fall-off of intensity of radiation with height is roughly exponential (Minty, 1997),, the algorithm commonly used for height correction is adequate for survey heights in the range 50 – 250 m (IAEA, 2003). Spectra for a calibration line flown at 244 m demonstrate that it is possible to discriminate effectively between radioelements at the survey flying height for major urban areas. In addition, a significant positive correlation (r = 0.85, p= 0.05) between airborne eU and the proportion of dwellings with indoor radon above 200 Bq m^{-3} for urban centres in the Republic of Ireland (unpublished data) confirms that airborne eU data from 250m flight heights can be used for estimating radon risk in urban areas.

On average the standard deviation (SD) is 51% higher for measurements in the urban zones compared with the surrounding rural areas, although the SD difference varies from 0.2 to 97%. Consequently, there will be greater uncertainty attached to average eU data for urban areas. In order to reduce uncertainty, airborne data are included in the statistical analyses reported in this pilot study only if there are 10 or more airborne eU measurements over a particular 1-km grid square/PM polygon. The average eU data used in this study should not be systematically reduced over urban areas compared with the surrounding rural areas.

In Northern Ireland, moderate and high indoor radon levels are associated with (1) Lower Carboniferous (Dinantian) limestone, (2) Late Caledonian Newry Granodiorite Complex, Palaeogene Slieve Gullion felsic intrusives and granites of the Mourne Mountains Complex of County Down and County Armagh, (3) Silurian Hawick Group greywackes and shales and (4) the Neoproterozoic Argyll and Southern Highland Group psammites, semipelites and metalimestones (Table 1 and Figure 2). Most of these geological units are also characterised by relatively high airborne eU (Figures 2 and 3) and shallow soil U data (Table 1), although notable exceptions include the Dinantian limestone, which has an average eU of only 0.9 mg kg^{-1}. Consistently low radon, eU and soil U are associated with the Palaeogene basic volcanic rocks of the Antrim Lava Group. Correlation coefficients (Table 2) reflect the strong geochemical contrasts between the major geological units and their associated superficial deposits (Figures 2 and 3).

The southeast sector of Northern Ireland includes a relatively large number (74) of 1-km/PM polygons with the 30 or more indoor radon measurements and 10 or more airborne gamma spectrometry data points required to test the relationship between indoor radon (Figure 4), radiometric eU (Figure 5), eTh, K and the shallow soil geochemical variables for a range of PMs. The area also has (1) a relatively wide range of rock types, principally Late Caledonian and Palaeogene acid intrusive rocks and Ordovician/Silurian greywackes and shales, and (2) a significant lateral variation of GMRn within PMs. The south west sector of the province, characterised principally by Lower Carboniferous (Dinantian) rocks and a wide range of indoor radon concentrations would have been an alternative area for a pilot project, but this area does not have as many indoor radon measurements as the south east sector.

3.2 Linear regression analysis of indoor radon and eU

The only significant ($p<0.05$) correlation of indoor radon data and Tellus airborne eU for an individual PM is for Hawick Group greywackes overlain by glacial sand and gravel (HWK/glacial SAGR). All other regression coefficients are not statistically significant. For this reason, it is not statistically valid or practical to follow the provisional methodology detailed in the materials and methods section above. It would not be appropriate to apply a statistically insignificant relationship between eU and GMRn for a geological combination to 1-km/PM polygons with no or few radon results in order to estimate either the GMRn or D200 for these polygons. It was concluded that the provisional method has insufficient power to significantly improve the radon map in the pilot area.

3.3 Multivariate linear regression analysis

In view of the general lack of statistical significance of the eU-GMRn regression coefficients for individual PMs, multivariate linear regression analysis was investigated as an alternative method for predicting GMRn and D200 for areas where few indoor radon measurements are currently available. Scheib et al. (2006) reported the results of a study on the application of linear regression modelling for predicting GMRn from airborne radiometric and soil geochemical data in the sedimentary terrain of Central England. Whereas K was shown to be a good indicator of the clay content and permeability in an area characterised by limestones, mudstones, siltstones and sandstones, this is not likely to be the case in the pilot area of south east Northern Ireland where acid igneous intrusive rocks and greywackes are the dominant bedrocks. In contrast to earlier results for Central England (Scheib et al., 2006), the data for the southeast part of Northern Ireland do not exhibit a relatively consistent increase in GMRn with permeability for a specific eU level.

Multiple linear regression analysis in S-Plus 6.2 and 7.0™ was used to model geometric mean indoor radon using (1) average eU, K, eTh and average permeability and (2) those airborne radiometric and soil variables identified as being significant by forward-backward stepwise linear regression analysis. These two models were compared with the simple model based solely on eU and a model based on all the airborne and soil parameters.

The significance of the correlation between modelled (fitted) GMRn and measured GMRn increases in the following order: (1) simple model (GMRn-eU) based on eU (R^2 = 0.21, Figure 6); (2) model (GMRn-3) based on airborne K, eTh, eU and permeability (R^2 = 0.34); (3) model (GMRn-2) based on the most significant airborne radiometric and soil variables selected by stepwise linear regression (eU, K, eTh, permeability, soil yttrium, soil LOI, and soil MgO; R^2 = 0.50) to (4) the model (GMRn-4) based on all the radiometric and soil variables (not including soil K, Th, U as these duplicate the radiometric data; R^2 = 0.5307, Figure 7). The proportion of the total variation explained by eU was approximately 21% in all models with airborne K, eTh and permeability accounting for 4, 3 and 7% respectively (Table 3). Each of Y, LOI and MgO accounted for 4 to 6% of the total variation in the GMRn-2 model, whilst the other parameters accounted for 1% or less in the GMRn-4 model. There is relatively good agreement between maps of measured GMRn and GMRn modelled on eU, K, eTh, permeability, soil Y, soil MgO and soil LOI, although, as expected, these maps do differ in detail. The distribution of GMRn modelled from radiometric data (eU, eTh, K) and permeability fits less well with the GMRn map derived solely from statistical interpretation of the indoor radon data.

The fit between the estimated proportion above the Action Level (D200) by modelling and by direct measurement increased from (1) R^2 = 0.3286 for a model (D200-eU) based on eU; (2) R^2 = 0.434 for the model (D200-2) based on airborne K, eTh, eU and permeability and (3) R^2 = 0.5413 for a model (D200-1) based on eU, eTh, K, permeability, soil Zr, Y and SiO_2 which are the most significant variables selected by stepwise linear regression analysis; Figure 8). While eU explains 33-36% of the total variation, K, permeability and eTh explain 3, 7 and <1% respectively (Table 3). Soil Y explained 5% of the total variation in the D200-1 model. There is relatively good agreement between maps of the measured proportion above the Action Level (D200; Figure 9) and D200 modelled on eU, K, eTh, permeability, soil Y, soil LOI and soil MgO (Figure 10), although these do differ in detail. The distribution of D200 modelled from radiometric data (eU, eTh, K) and permeability fits less well with the D200 map derived solely from statistical interpretation of the indoor radon data.

3.4 Data smoothing

It is possible that random variation in the measured variables obscures genuine correlations between them, and that smoothing some variables might improve the correlation. It is also possible that genuine spatial variations in the variables could obscure correlations, if different parameters are averaged over different areas. For instance, in an area where geometric mean radon is estimated by averaging over results within 5 km of the centre of each target square (in order to obtain the required 30 house radon results), but eU is estimated from results located within each target 1-km/PM polygon, genuine spatial variations from square to square would lead to worse correlations being measured than if both parameters were averaged over the same area.

It was not possible, within the scope of this pilot project, to investigate these possibilities in detail, but some preliminary investigation was carried out to determine the validity of these ideas. To investigate whether applying some smoothing to 1-km eU values in an area where geometric mean radon is estimated using data over more than a single grid square, we used the data for the Hawick Group greywackes overlain by glacial sand and gravel (HWK/Glacial-SAGR) which is the only PM combination with a significant correlation between indoor radon and eU. Smoothing the data increases the R^2 value and increases the slope of the regression line (Figures 11 and 12). The initial conclusion from this exercise is therefore that smoothing may well improve correlations between parameters.

4. Conclusions

There is generally good agreement between radon maps modelled from the Tellus airborne radiometric and soil geochemical data using multivariate linear regression analysis and radon maps produced by conventional radon mapping, based solely on geological and indoor radon data. The radon maps based on the Tellus data identify some additional areas where the radon risk appears to be relatively high compared with the conventional radon maps. One of the ways of validating radon maps modelled on the Tellus data will be to carry out additional indoor measurements in these areas.
The methodology developed in this pilot project is being applied to the whole of Northern Ireland and also to sectors of the Republic of Ireland. Preliminary results indicate that the methodology is widely applicable. The methodology can be used for assessing radon risk in both uninhabited and urban areas.

The results of the pilot project open up possibilities for further investigation for improving radon maps, including:

(i) Evaluate whether the greater spatial accuracy of the 1: 50 000 geological data increases the confidence level of the data analysis.

(ii) Evaluate whether variations in the housing mix may impact on the conventional radon maps and radon maps modelled from Tellus data.

(iii) Examine the results of the pilot study to identify factors that affect radon potential.

(iv) Extend the pilot study investigations to the remainder of Northern Ireland.

(v) Make more radon measurements to test the hypotheses generated.

(vi) Validate, test, and revise the models.

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FIGURE CAPTIONS

Figure 1 Attribution of airborne data (●) and soil data (■) to 1-km grid square parent material (PM; bedrock/superficial geology) polygons. The large filled circles (⬤) are the centroids of the 1-km/PM polygons.

Figure 2 Simplified bedrock geology of Northern Ireland

NC – Newry Igneous Complex; SG = Slieve Gullion Complex; MM = Mourne Mountains Complex

Figure 3 Distribution of average eU (mg kg^{-1}) for airborne data grouped by 1-km/PM polygons.

Figure 4 Geometric mean indoor radon (Bq m^{-3}) (gridded GMs for PMs with >80 radon measurements; GM of all data in pilot area for PMs with <80 radon measurements).

Figure 5. Average eU (mg kg^{-1}) based on average of airborne points located within 1-km/PM polygons.

Figure 6 Relationship between estimated (fitted) and measured GMRn. Model based on airborne eU (Model GMRn-eU, R^2 = 0.21)

Figure 7 Relationship between estimated (fitted) and measured GMRn; Model based on airborne K, eU, eTh, ground permeability, and soil Y, LOI, MgO, Zr, CaO, SiO_2, Al_2O_3, Fe_2O_3 (Model GMRn-4, $R^2 = 0.53$)

Figure 8 Relationship between estimated (fitted) and measured probability of exceeding the radon Action Level (D200). Model based on airborne K, eU, eTh, ground permeability, and soil Zr, Y, and SiO_2 (Model D200-1, $R^2 = 0.54$)

Figure 9 Provisional estimated probability of exceeding the radon Action Level of 200 Bq m^{-3}. (Gridded estimates for PMs with >80 radon measurements; estimate based on all radon data in pilot area for those PMs with <80 radon measurements. This is a provisional radon map which should not be used in its present form for legislative (e.g. Building Regulations) purposes).

Figure 10 Modelled probability of exceeding the radon Action Level (D200; Model D200-1)

Figure 11 Logarithm of geometric mean radon plotted against smoothed Tellus airborne eU for HWK/glacial sagr.

Figure 12 Logarithm of geometric mean radon plotted against smoothed Tellus airborne eU for HWK/glacial sagr.

Table 1 Summary indoor radon, soil and airborne statistics for bedrock-superficial combinations with more than 80 indoor radon measurements

Geology		Indoor radon		Soil data			Airborne data		
Bedrock	Superficial	GMRn[1]	%>AL	K_2O[2]	U[3]	Th[3]	K[2]	eTh[3]	eU[3]
Oligocene Clays	Till	21	0.0	1.2	2.2	4.1	0.9	2.7	0.6
Palaeogene mafic intrusions	Till	47	1.7	1.8	2.9	6.8	1.2	4.5	1.0
Antrim Lava Group		20	0.0	0.6	1.3	2.0	0.3	0.9	0.2
Antrim Lava Group	Till	19	0.0	0.8	1.4	2.7	0.5	1.5	0.4
Mourne Mountains Complex granite	Till	85	15.1	1.9	7.1	9.8	1.7	9.1	2.2
Slieve Gullion Felsic Intrusion	Till	76	11.2	2.3	7.4	10.0	2.2	8.0	1.8
Sherwood Sandstone Group	Till	28	0.2	1.8	2.3	4.7	1.3	3.5	0.8
Dinantian lmst., sltst., & mdst.	Till	40	1.2	1.4	3.0	5.9	0.9	3.5	0.9
Dinantian limestone		54	7.1	1.3	3.2	5.6	0.6	2.8	0.9
Dinantian limestone	Till	40	3.6	1.2	3.2	5.3	0.7	3.1	0.9
Dinantian mdst., slts., & sdst.	Till	31	0.9	1.5	3.1	6.0	0.9	3.4	0.9
Dinantian mudstone	Till	27	0.3	1.0	3.2	6.0	0.5	3.3	0.9
Dinantian sdst., sltst. & mdst.	Till	31	0.4	1.6	2.5	5.4	0.9	3.3	0.8
Dinantian sandstone	Till	32	0.0	1.8	2.4	5.4	1.1	3.5	0.7
Upper Devonian sdst., sltst., & mdst.	Till	31	0.4	1.8	2.7	7.0	1.2	4.3	1.0
Middle Devonian congl. & sdst.	Till	40	2.7	1.6	2.5	5.7	1.0	3.8	0.8
Newry Granodiorite Complex 3	Till	58	2.9	2.4	4.3	8.6	2.0	7.2	1.5
Newry Granodiorite Complex 2		52	4.9	2.4	3.1	6.7	1.9	5.7	1.2
Newry Granodiorite Complex 2	Till	50	1.9	2.3	3.4	6.5	1.9	5.7	1.2
Newry Granodiorite Complex 1	Till	39	0.3	2.3	3.3	6.7	1.8	6.0	1.3
Silurian Gala Gp. gwck. & shale		39	0.7	2.0	2.9	7.1	1.6	5.8	1.3
Silurian Gala Gp. gwck. & shale	Till	33	0.3	2.0	2.8	6.9	1.5	5.5	1.2
Silurian Hawick Gp. gwck. & shale		55	5.3	1.7	3.4	7.8	1.5	7.0	1.6
Silurian Hawick Gp. gwck. & shale	Till	58	4.3	2.0	3.8	8.7	1.7	7.8	1.8
Ordovician Gilnahirk Gp. sandstone	Till	27	0.3	1.8	2.4	5.6	1.3	4.5	1.0
S. Highland Gp. psam. & pelite		48	1.7	1.8	2.5	6.6	1.1	4.1	0.9
S. Highland Gp. psam. & pelite	Till	36	1.1	1.8	2.5	6.1	0.9	3.5	0.8
Argyll Group metalimestone	Till	53	3.9	1.7	2.6	6.2	1.0	4.0	0.9
Argyll Group psam. & semipelite		47	5.4	1.5	2.2	5.4	0.8	3.0	0.7
Argyll Group psam. & semipelite	Till	44	2.8	1.8	2.4	6.3	1.0	3.6	0.8

Units: [1] = Bq m^{-3}; [2] = %; [3] = mg kg^{-1}

Abbreviations: lmst. = limestone; sltst. = siltstone; mdst. = mudstone; sdst. = sandstone; congl. = conglomerate; gwck. = greywacke; psam. = psammite; Gp. = Group.

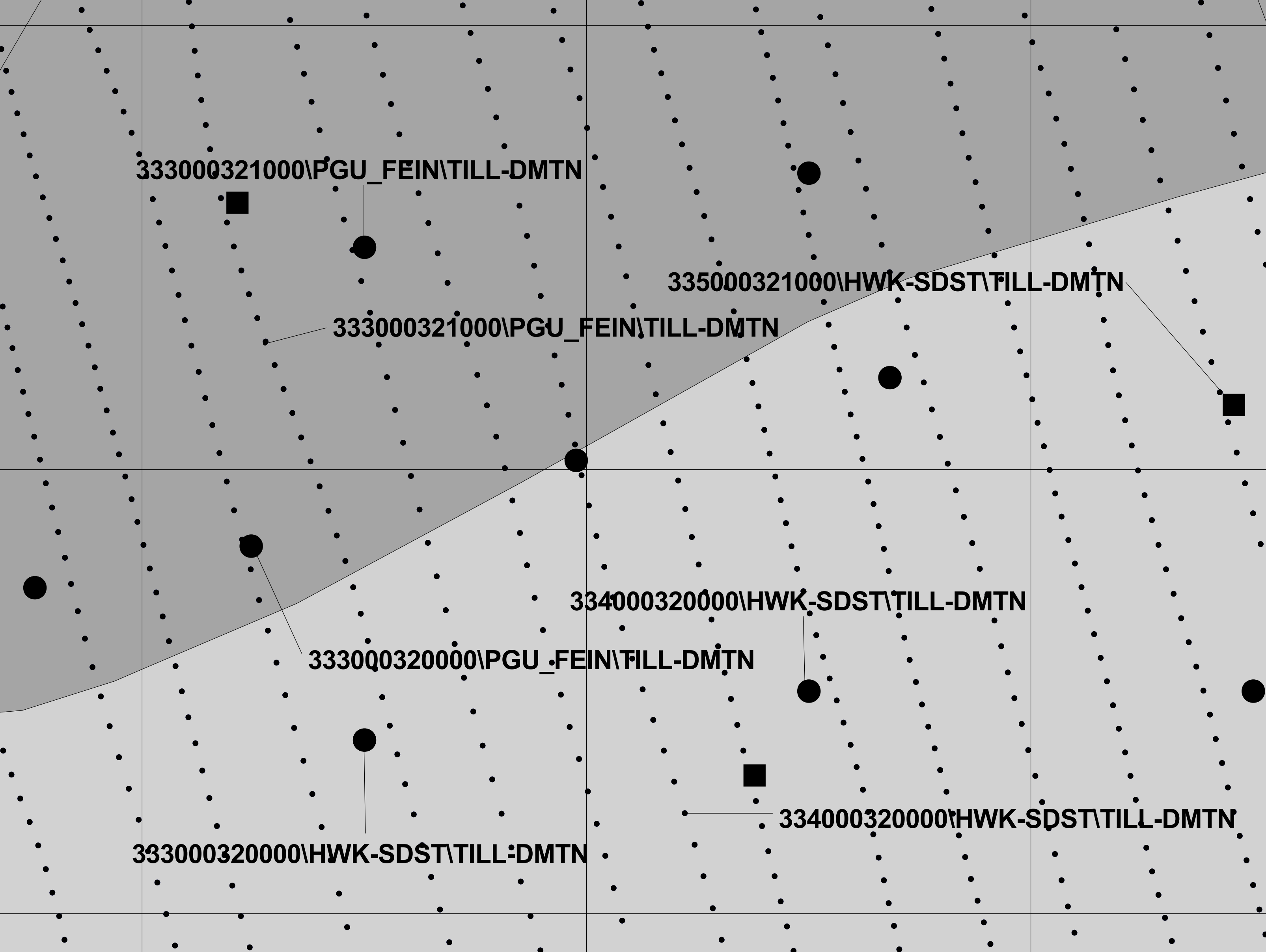
Table 2 Pearson correlation matrix of radon potential (%>AL), soil geochemistry, and airborne radiometric data in Northern Ireland for data grouped by 1-km grid square, bedrock and superficial geology where bedrock-superficial combination has more than 80 radon measurements (n = 21, 813; p 0.05 = <0.05; correlation coefficients >0.50 indicated in bold).

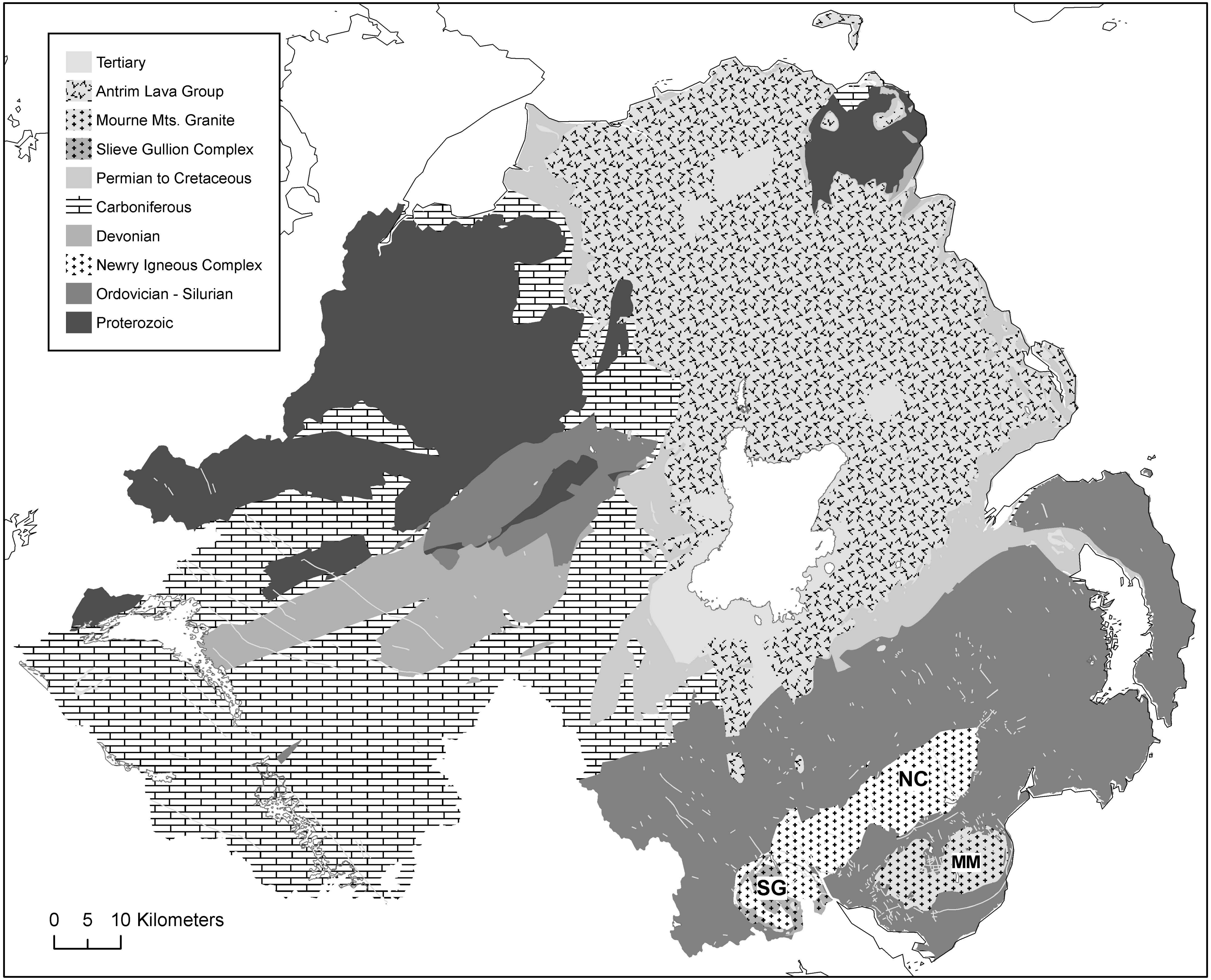
%>AL	**0.82**														
K_2O	0.48	0.21													
U	**0.53**	0.36	0.46												
Th	**0.65**	0.40	**0.81**	**0.71**											
Zr	0.34	0.16	**0.67**	0.29	**0.62**										
Y	0.19	0.18	0.30	0.37	0.46	0.17									
LOI	-0.08	0.00	**-0.52**	-0.18	-0.43	**-0.66**	-0.46								
CaO	-0.35	-0.16	-0.48	-0.30	-0.49	**-0.51**	0.26	0.00							
SiO_2	0.25	0.09	**0.62**	0.34	**0.57**	**0.79**	0.22	**-0.87**	-0.35						
Al_2O_3	-0.20	-0.18	0.21	-0.12	0.12	0.08	**0.64**	**-0.63**	0.41	0.25					
MgO	-0.34	-0.22	-0.22	-0.34	-0.32	-0.42	0.41	-0.18	**0.65**	-0.21	**0.73**				
Fe_2O_3	-0.46	-0.25	-0.45	-0.46	-0.49	-0.48	0.39	-0.08	**0.74**	-0.35	**0.67**	**0.85**			
K-air	0.46	0.21	**0.80**	**0.51**	**0.73**	0.46	0.33	-0.43	-0.34	**0.52**	0.21	-0.07	-0.36		
eU	**0.56**	0.37	**0.61**	**0.62**	**0.75**	0.38	0.37	-0.33	-0.31	0.45	0.07	-0.18	-0.37	**0.79**	
eTh	**0.58**	0.35	**0.69**	**0.62**	**0.80**	0.40	0.40	-0.34	-0.34	0.46	0.12	-0.14	-0.37	**0.89**	**0.90**
	GMRn	*%>Al*	*K2O*	*U*	*Th*	*Zr*	*Y*	*LOI*	*CaO*	*Si2O3*	*Al2O3*	*MgO*	*Fe2O3*	*K-Air*	*eU*

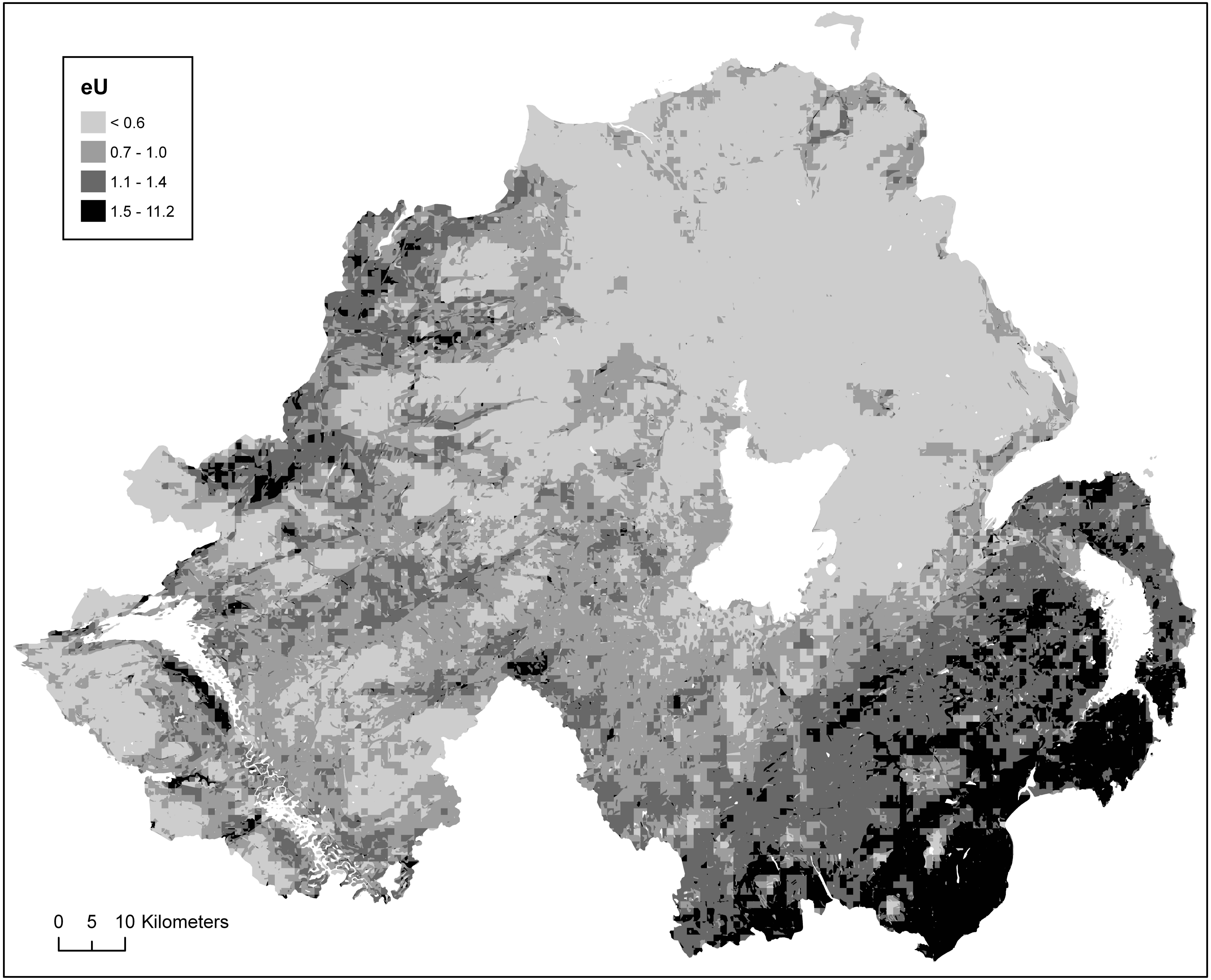
Table 3 Percentage variance accounted for by variables in linear regression models.

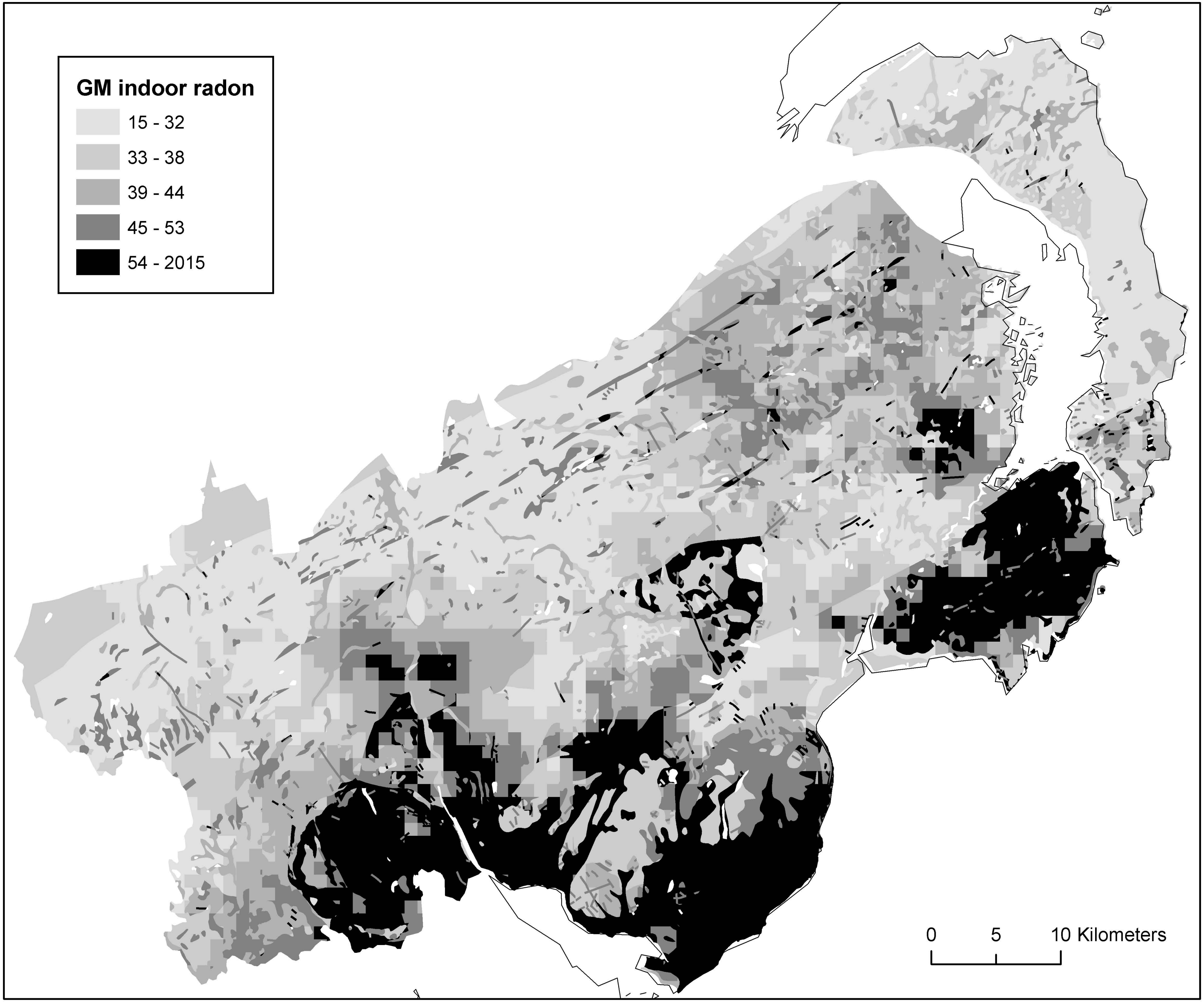
Model variables	Abbreviation used in Figures 6-8	Model Name[1]						
		GMRn-eU	GMRn-2	GMRn-3	GMRn-4	D200-eU	D200-1	D200-2
eU-airborne	UAIR	21.00	21.19	20.97	21.19	32.86	36.33	32.86
K-airborne	KAIR		4.32	6.51	4.32		3.20	2.83
eTh-airborne	THAIR		2.60	0.00	2.60		0.78	0.37
Permeability	PERM		6.87	6.61	6.87		7.12	7.35
Y-soil	Y3		6.20		6.20		5.11	
LOI-soil	LOI3		5.68		5.68			
MgO-soil	MG3		3.61		3.61			
Zr-soil	ZR3				0.05		0.01	
CaO-soil	CA3				0.36			
SiO_2-soil	SI3				0.07			
Al_2O_3-soil	AL3				0.96			
Fe_2O_3-soil	FE3				1.16			
Residuals		79.00	49.54	65.90	46.93	67.14	47.46	56.60
Multiple R Squared		0.21	0.50	0.34	0.53	0.32	0.54	0.43

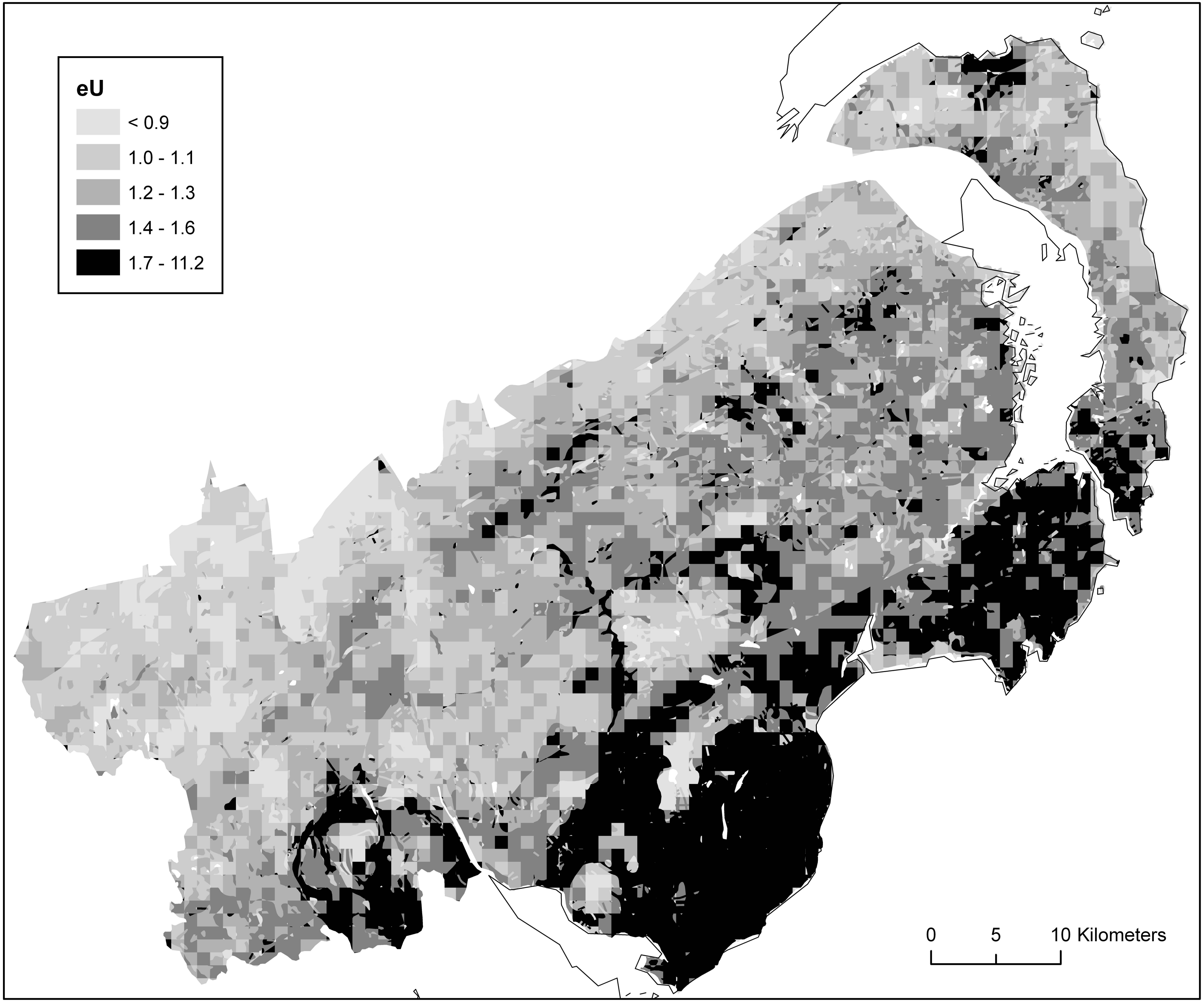
[1] see text for explanation of models

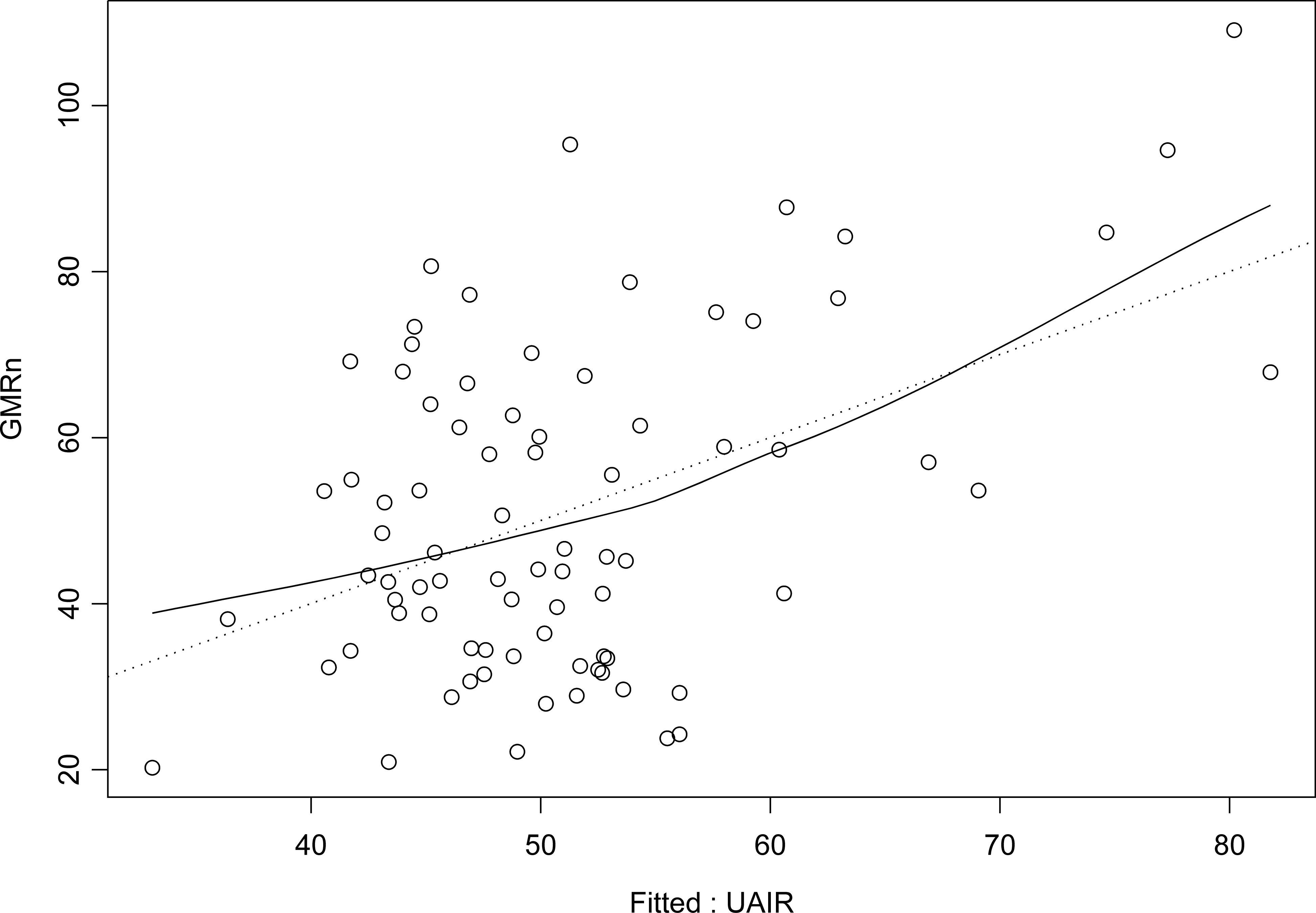

333000321000\PGU_FEIN\TILL-DMTN
335000321000\HWK-SDST\TILL-DMTN
333000321000\PGU_FEIN\TILL-DMTN
334000320000\HWK-SDST\TILL-DMTN
333000320000\PGU_FEIN\TILL-DMTN
334000320000\HWK-SDST\TILL-DMTN
333000320000\HWK-SDST\TILL-DMTN


Tertiary
Antrim Lava Group
Mourne Mts. Granite
Slieve Gullion Complex
Permian to Cretaceous
Carboniferous
Devonian
Newry Igneous Complex
Ordovician - Silurian
Proterozoic
NC
MM
SG
0 5 10 Kilometers

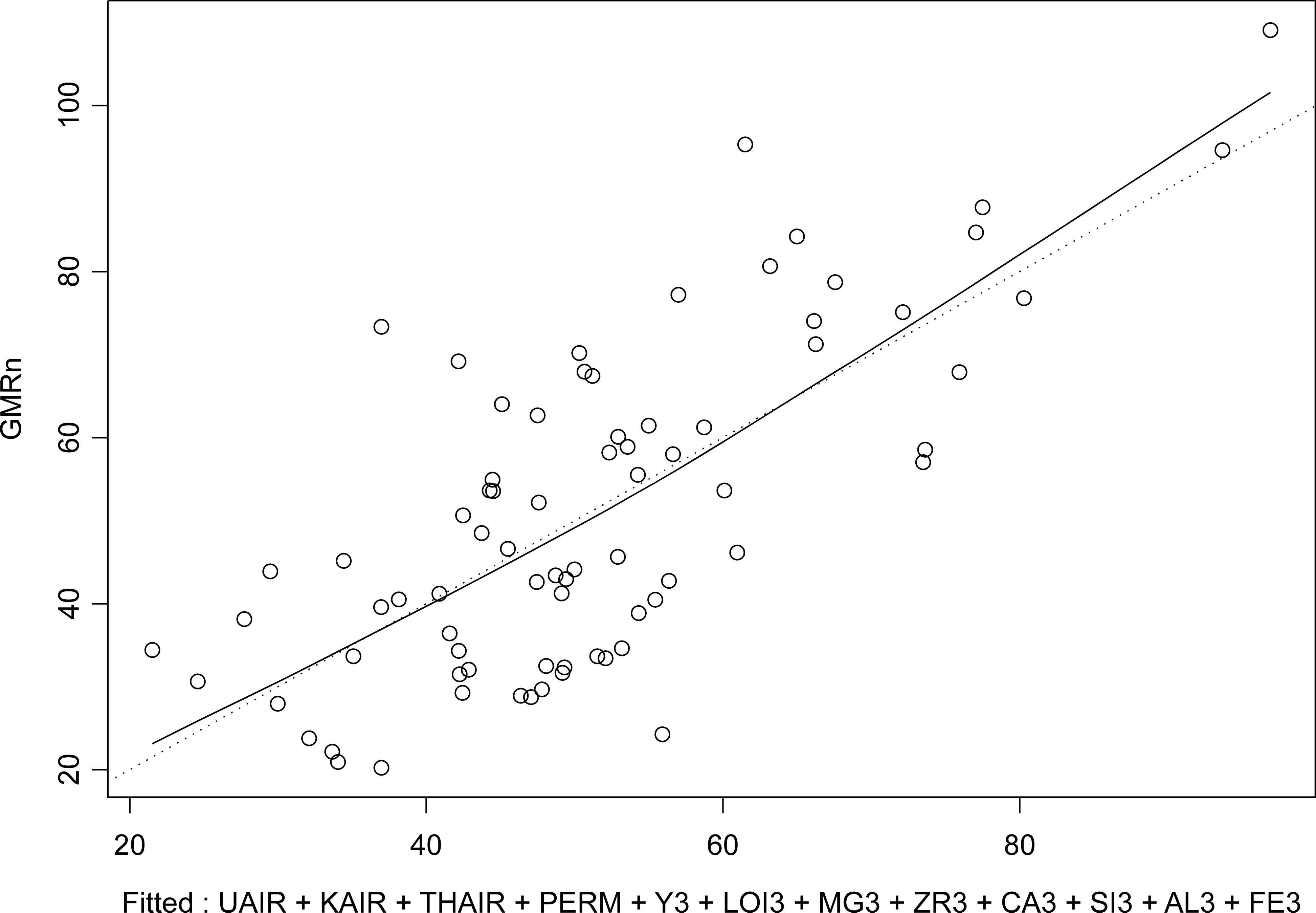

eU
< 0.6
0.7 - 1.0
1.1 - 1.4
1.5 - 11.2
0 5 10 Kilometers

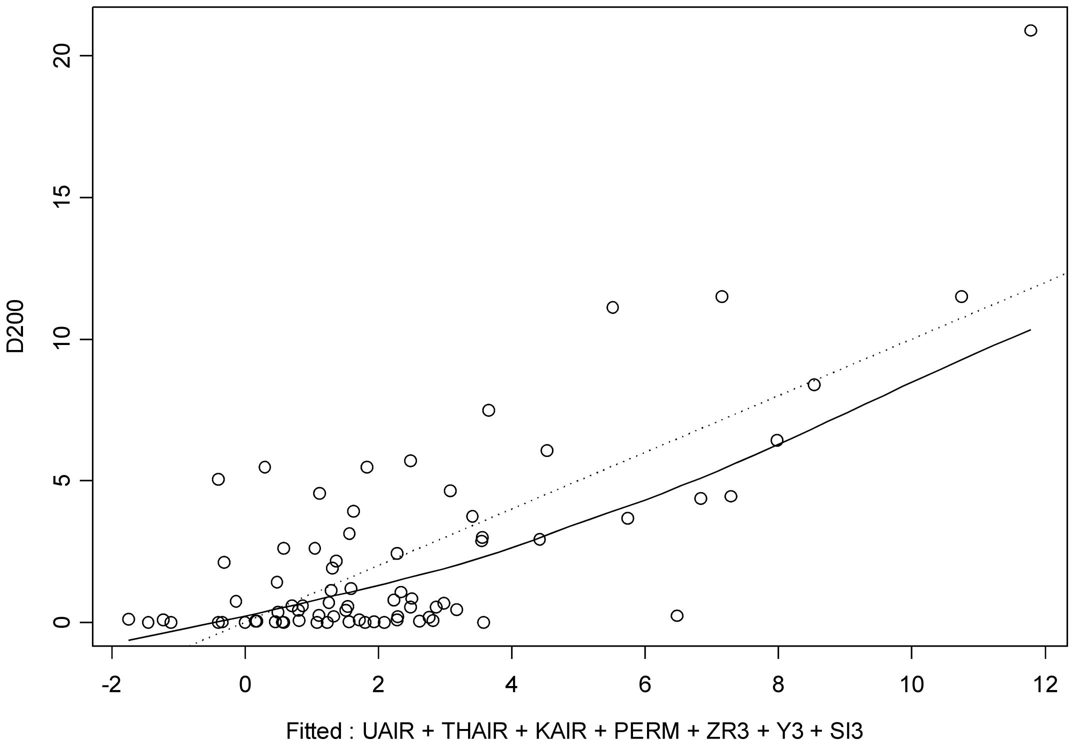

GM indoor radon
15 - 32
33 - 38
39 - 44
45 - 53
54 - 2015
0
5
10 Kilometers


eU
< 0.9
1.0 - 1.1
1.2 - 1.3
1.4 - 1.6
1.7 - 11.2
0
5
10 Kilometers

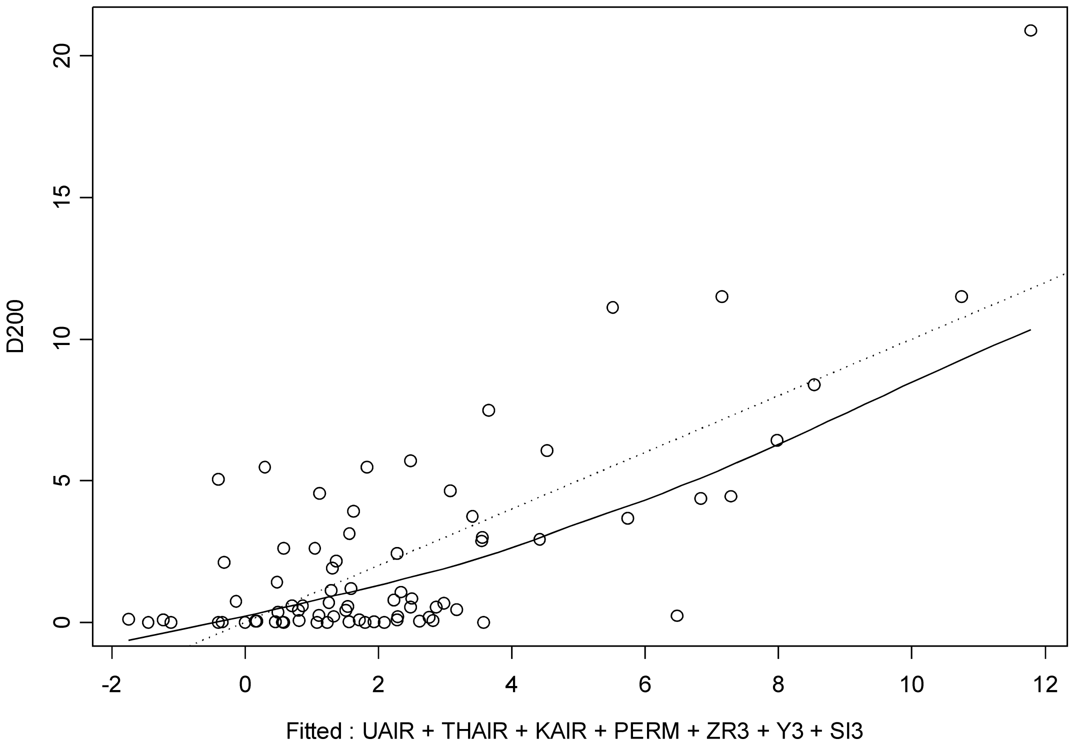


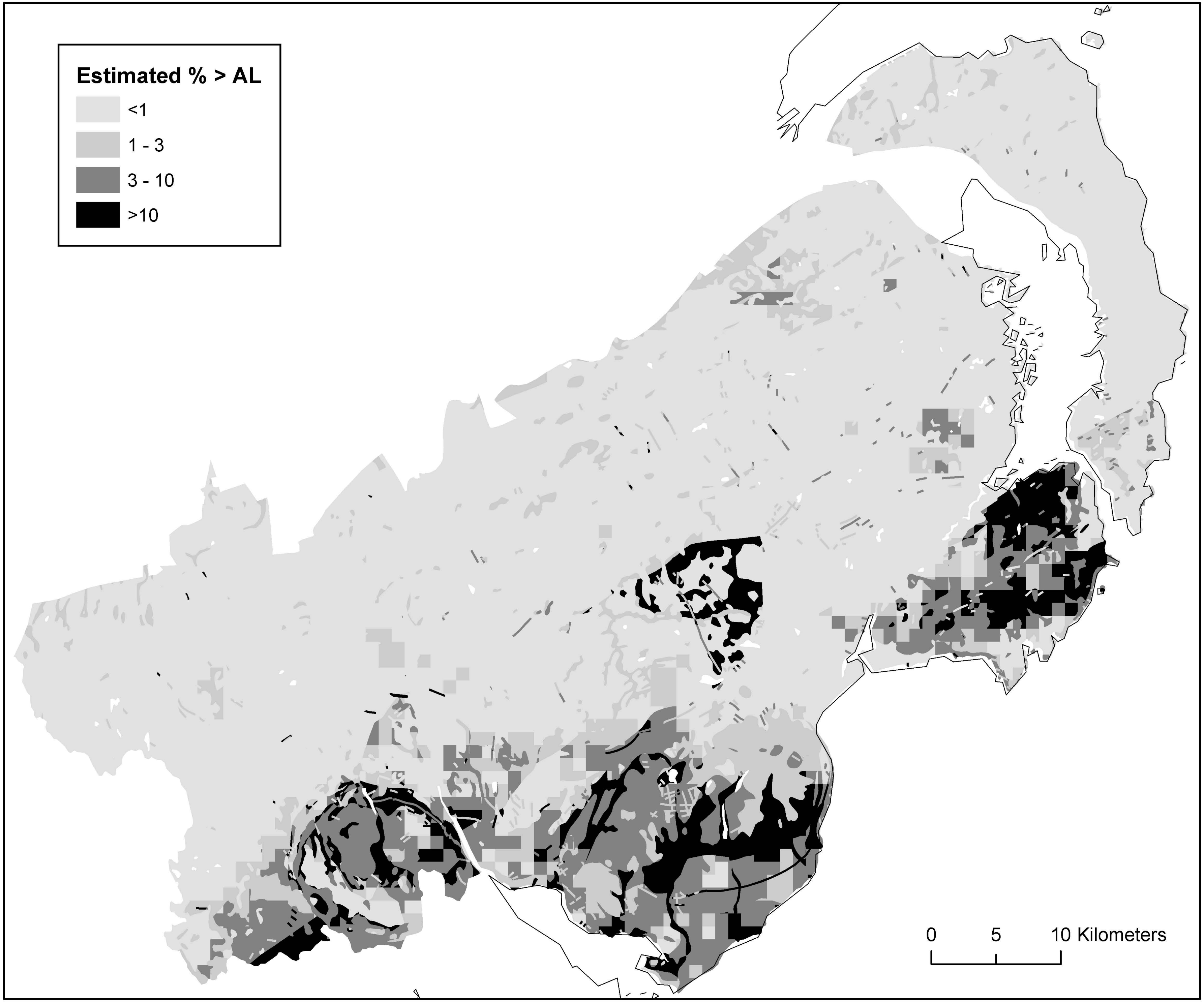
20
40
60
80
100
GMRn
40
50
60
70
80
Fitted : UAIR

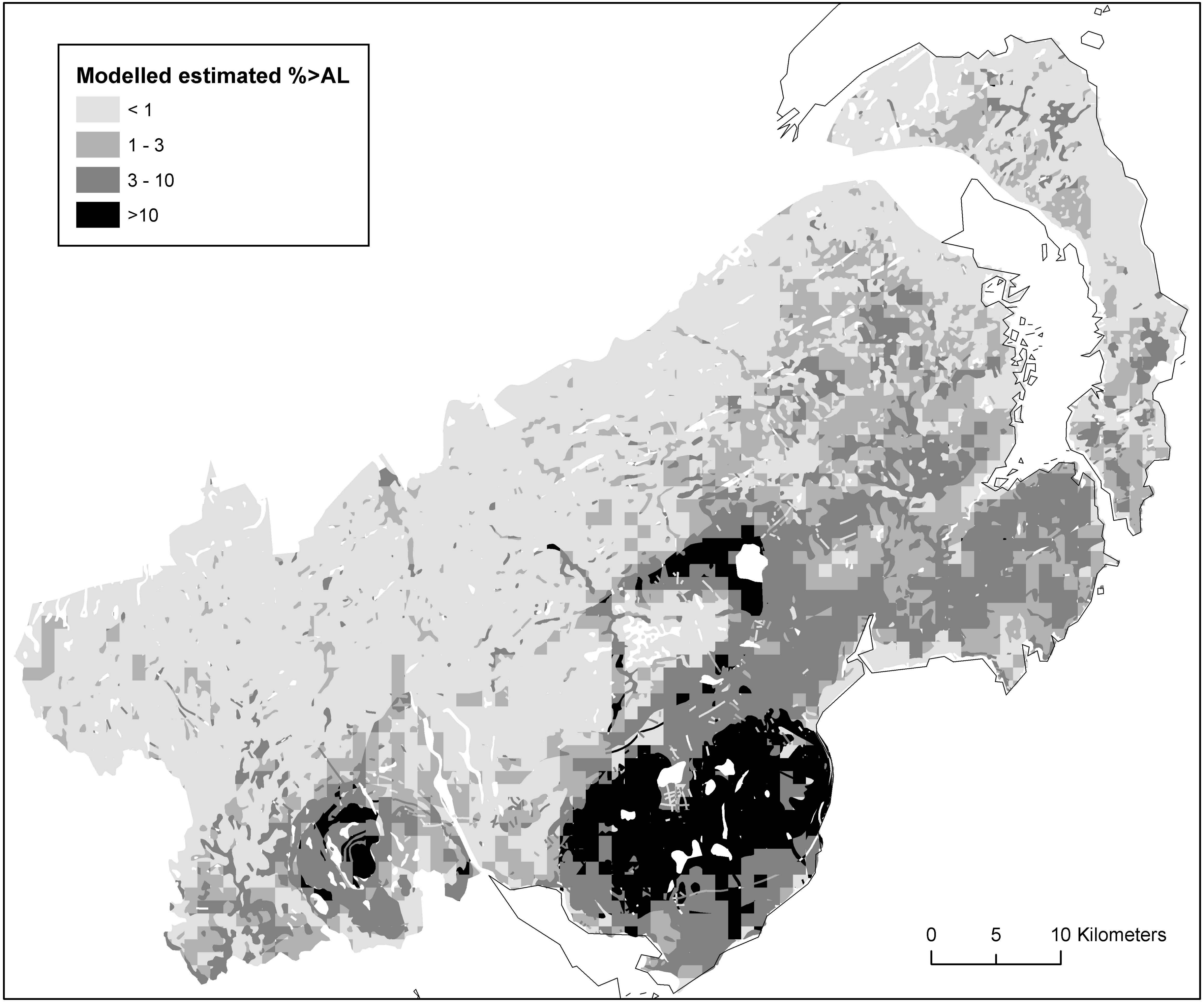

GMRn
20
40
60
80
100
20
40
60
80
Fitted : UAIR + KAIR + THAIR + PERM + Y3 + LOI3 + MG3 + ZR3 + CA3 + SI3 + AL3 + FE3



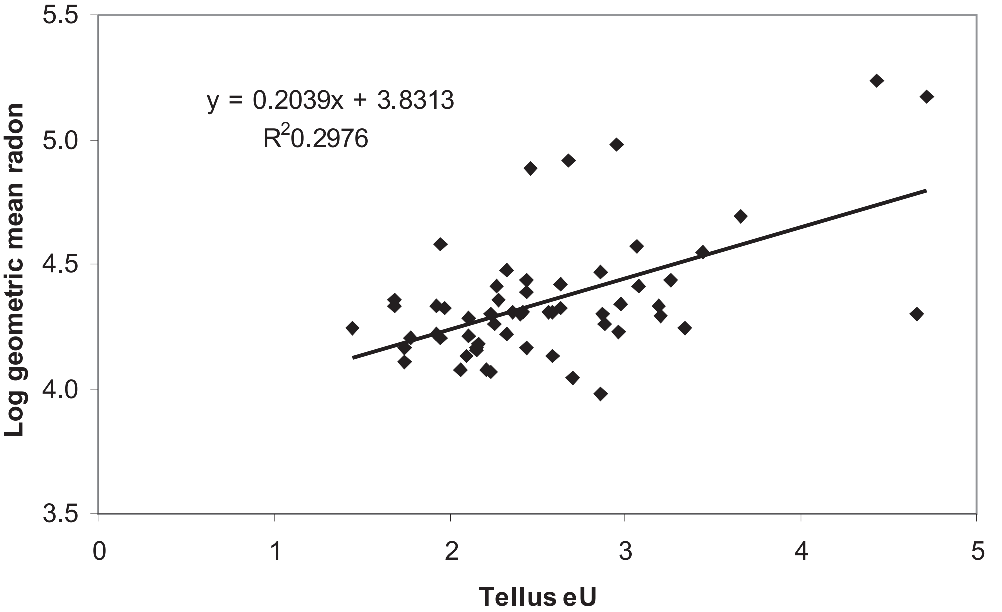
D200
0
5
10
15
20
-2
0
2
4
6
8
10
12
Fitted : UAIR + THAIR + KAIR + PERM + ZR3 + Y3 + SI3


D200
20
15
10
5
0
-2
0
2
4
6
8
10
12
Fitted : UAIR + THAIR + KAIR + PERM + ZR3 + Y3 + SI3

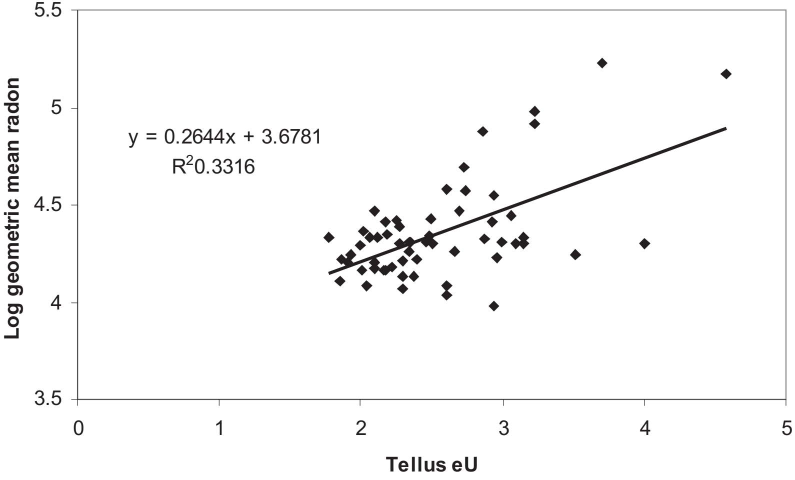

Estimated % > AL
<1
1 - 3
3 - 10
>10
0
5
10 Kilometers



Modelled estimated %>AL
< 1
1 - 3
3 - 10
>10
0
5
10 Kilometers



y = 0.2039x + 3.8313
R20.2976
Log geometric mean radon
Tellus eU
5.5
5.0
4.5
4.0
3.5
0
1
2
3
4
5



5.5
5
4.5
4
3.5
0
1
2
3
4
5
y = 0.2644x + 3.6781
R20.3316
Log geometric mean radon
Tellus eU