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The use of gamma-survey measurements to better understand radon potential in urban areas

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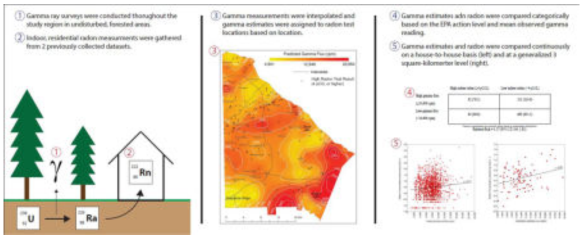
Graphical abstract



1. INTRODUCTION

Radon gas is one of the most common radioactive elements to which people are exposed (Kauppinen et al., 2000), with indoor air concentrations of radon typically ten times higher than average outdoor concentrations (Harley et al., 1988; UNSCEAR, 1994). As the radon decays the resulting radon products, called radon progeny, can be breathed in and lodged in lung tissue, delivering a dose of radiation when they decay further (Keith et al., 2012). Therefore, radon progeny account for as much as 37 percent of the average American's lifetime radiologic dose (Schauer, 2009). Increasing cumulative radon progeny exposure, either through increased duration or increased magnitude, is directly correlated with heightened lung cancer risk (NRC, 1999; WHO, 2009; Planchard and Besse, 2015; Kang et al., 2016). As a result, only smoking leads radon as a cause of lung cancer; radon is responsible for 3 to 14% of all lung cancer deaths worldwide, with most of these deaths occurring in smokers who are at increased risk of radon induced lung cancers (Darby et al., 2001; NRC, 1998; Gray et al., 2009; World Health Organization, 2009; Noh et al., 2016; Oh

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et al., 2016; Sheen et al., 2016). In the United States specifically, based on mid 1990's data (NRC 1999), radon accounted for an estimated 21,100 deaths annually (EPA, 2003 and 2009).

Radon emanates from materials containing the unstable radionuclides, thorium-232 (^{232}Th) and uranium-238 (^{238}U) (NRC, 1999; Peterson et al., 2007). The ^{238}U decay series specifically forms gaseous radon-222 (^{222}Rn) via the alpha decay of solid radium-226 (^{226}Ra) (Sakoda et al., 2011). This is important because ^{222}Rn is generally the most common radon isotope found in buildings, though buildings on thorium rich soil may have elevated concentrations of thoron (^{220}Rn) (WHO, 2009).

The decay of ^{238}U and its daughters in soil and bedrock forms radon. The amount of ^{238}U contained in an area's soil and underlying bedrock will directly impact the amount of geogenic ^{222}Rn released to the air in that area. However, the concentration of ^{238}U is not uniform across all geologies; for example, areas of granitic bedrock are expected to have relatively high ^{238}U (Quindos Poncela et al., 2004; Muikku et al., 2007). Increased permeability and porosity of bedrock and its overlying soil increases the rate of ^{222}Rn released into the surrounding groundwater and air (Bossew and Lettner, 2007). The presence of faults can also affect ^{222}Rn concentrations by providing pathways for radon to escape (Pereira et al. 2010).

Home-construction characteristics also affect indoor radon concentrations. Homes lacking structural defects may have low indoor radon concentrations even if the geogenic radon emissions are high (Vauptic et al., 2002). If there are foundation cracks or unsealed concrete joints, then radon will likely flow into the often lower pressure of the home via the defect (Appleton, 2007). Additionally, climate controls within the home will alter temperature and humidity, which can affect indoor air pressure (e.g., air conditioning can create a pressure gradient that draws air into the home) and thus rates of ^{222}Rn infiltration (Akbari et al. 2013). Finally, building materials, especially concrete and wallboard, can contain ^{238}U and its decay products such as ^{226}Ra; therefore, as these decay, the building materials that contain them can become sources of ^{222}Rn (Chen et al., 2010).

1.1 Radon potential

In response to the national and international health hazard posed by radon, some have attempted to predict indoor radon concentrations using geology. The process involves generalizing known radon concentrations, which are sparsely sampled, to the underlying geology, which is spatially continuous, and using the radon-geology relationship to extrapolate radon values across a region (Cinelli et al., 2011). However; the lack of indoor radon concentration data in homes and the at times inaccuracy of geologic data are major limitations of radon-geology studies (Chen 2009; Friedman and Groller, 2010). Often these studies only find correlations with some rocks (e.g. granite, shales, and U-enriched phosphate rocks) and radon concentrations (Buttafuoco et al., 2007), leaving the understanding of the relationship between other rock types and radon unexplained. In some cases, only a quarter of all variation in radon concentration can be explained by geology (Appleton and Miles, 2010). Further, this method necessitates that both indoor radon concentration and geologic data be available and reliable.

Using gamma radiation instead of, or in addition to, geology should improve radon potential mapping. Gamma radiation is produced naturally as a result of the decay of some radioactive elements, including potassium-40, uranium-235, ^{232}Th, ^{238}U, and others (Wilford, 2012). ^{238}U, which as noted earlier is the progenitor of ^{222}Rn, is so well linked to gamma radiation that gamma spectroscopy was used for uranium mining exploration (Wilford and Minty, 2007). It is worth noting that overall gamma emissions in an area are the result of the combined radioactive decay of a variety of radionuclides. Gamma emissions also have been shown in certain circumstances to have a direct relationship to soil ^{226}Ra (Garcia-Talvera et al., 2013), which is in turn correlated to indoor ^{222}Rn (Nason and Cohen, 1980; Jackson, 1992; Szegvary et al., 2007a). One study found that equivalent ^{238}U concentrations, derived from aerial gamma emission rate measurements, was the most important independent variable in predicting radon potential (Appleton et al., 2011a). Other studies report that gamma dose rate accounts for as much as 60% of radon flux variability (Szegvary et al., 2007b; Griffiths et al., 2010). Still more studies have found that the inclusion of gamma emission rates with other variables, such as bedrock and surficial geology can lead to greatly improved radon potential maps (Smethurst et al., 2008; Ielsch et al., 2010).

Despite the potential of using gamma emissions for radon mapping, the use of aerial gamma measurements has serious limitations. These measurements have relatively large spatial resolutions (e.g., 1 km plus) (Appleton et al., 2011b; Drolet et al., 2013) resulting in the inclusion of the built environment features in the sample pixels, which can artificially increase or decrease gamma readings. Further, legal restrictions require aircraft to fly higher over cities than rural areas (14 C.F.R. § 91.119) introducing additional error because the accuracy of gamma measurements decrease exponentially with distance from the ground (Appleton et al., 2008). Gamma surveys in urban environments also run the risk of introducing confounders directly from building materials. Previous work has shown that indoor gamma dose rate can be higher than outdoor dose rate as a result of gamma emitters found in building materials (Clouvas et al., 2001). While building materials can clearly have a large impact on gamma dose rate, they are understood to play a minimal role in indoor radon concentrations in the majority of cases (EPA, 2009). Thus aerial gamma surveys that cannot distinguish between natural and built environments run the risk of measuring gamma flux from sources that do not play an important role in determining radon.

1.2 Purpose

Therefore, the purpose of this study is to evaluate the effectiveness of *in situ* gamma instrument readings from nearby/interspersed undisturbed environments for assessing radon potential in urbanized environments. The two main objectives are as follows: (1) to create a spatially complete database of forest-soil gamma instrument readings for the entire study region, and (2) to examine the relationship between gamma value as interpolated from in situ gamma surveys (i.e. the natural gamma flux at each test location prior to building) and indoor radon concentrations.

2. DATA AND METHODS

2.1 Study Region

The study region, DeKalb County, Georgia, USA, covers approximately 700 square kilometers and has over 700,000 residents and more than 300,000 residential units (U.S. Census Bureau www.census.gov/quickfacts (accessed 26 Oct. 2016)) (Figure 1). This study area was selected for four reasons. First, the county is heavily urbanized, yet still has nearby/ interspersed undisturbed, non-flood plain forest soils. This enables a comprehensive sampling of gamma. Second, the county is geographically well sampled for radon with all parts of the county having at least some residential tests and these data being available, allowing for the completion of the second objective of this project. Third, the county acts as a good case study for the type of area where knowing radon potential is important. Not all of the county is developed, despite being in the rapidly growing Atlanta Metropolitan Statistical Area. In the future, new development may lead to people living in these previously undisturbed areas of the county. Knowing if those areas are at risk of radon exposure before development could help county officials make planning decisions (e.g., building codes) to protect people from radon, especially considering that DeKalb is considered a zone 1 radon risk county by the EPA (zone 1 is the highest level of risk).

2.2 gamma ray surveys

A total of 402 gamma surveys were taken throughout the county using the same Ludlum model 2221 scaler ratemeter (Ludlum Measurements Inc., Sweetwater, Texas, USA) attached to a Thermo Fisher Scientific SPA-3 high sensitivity gamma scintillator (Thermo Fisher Scientific Inc., Waltham, Massachusetts, USA), which has an energy detection range from roughly 60 keV to 2 MeV. The gamma scintillator, which contains a 2″ × 2″ NaI (TI doped) scintillation crystal, was held 0.5 m above the ground during measurements. All measurements took place on weekends between 8 A.M. and 8 P.M. from May-October 2015, and the mean temperatures during the sampling days ranged from 19.2 °C to 28.1 °C. To minimize the influence of transported soil and artificial objects on gamma readings, all survey sites were located in undisturbed areas within forest patches, outside of flood plains (i.e., floodplain soils are not authigenic), and away from artificial objects (e.g., concrete pipes).

Each geologic unit within a forest patch was surveyed. Using the digital scaler, the sum of counts for one minute was recorded at three or four locations within 10 m of each other. The mean value (measured in counts per minute or cpm) of the multiple measurements was used as the gamma reading at a location. The bedrock units were identified using a U.S. Geologic Survey (USGS) geologic map (Dicken et al. 2007) with a scale of 1:100,000, while soil units (i.e. floodplain or non-floodplain soil) were identified using a U.S. Department of Agriculture (USDA) soils map with a scale of 1:12,000. The bedrock layer used was cross checked against a USGS-produced geologic map specific to the Atlanta region (Higgins et al. 2003) to determine if any areas of the GIS layer contained anomalies. The latitude, longitude, soil type, bedrock type, and mean of each reading were recorded at each survey site. Information on the depth to bedrock was not available. It should be noted that no process for assessing instrument accuracy day to day was used, though the device was within its manufacturer calibration period for the duration of sampling.

2.3 Radon sampling and analysis

A total of 2,254 indoor radon test results were acquired from multiple sources (2,054 from Air Chek, Inc. and 200 from Stauber et al., 2017). All tests were short term residential tests (2–7 days) with recommendation to used closed house conditions. The Air Chek data were collected in residences where the owners independently chose to test. Stauber et al. data were collected via an effort that attempted to get residents of previously under tested areas to agree to test their homes, though residents still allowed testing on a voluntary basis. Test were collected from 1990 to 2015 (all data from before 2015 came from Air Chek). All home radon tests come with instructions that explain the EPA testing protocols intended to produce accurate test results. Additionally, Stauber et al. (2017) specifically informed residents of these protocols and followed EPA quality assurance and control standards. Test results lacking latitude and/or longitude coordinates were not included in the analysis. Additionally, only the first test result from a location was included. Multiple readings after the first at any location were removed to ensure that steps taken as the result of a high initial reading did not distort the analysis. Finally, all zero test results were removed. A value of zero is not indicative of the true radon value at that test site (i.e., radon is essentially omnipresent). The zero value could be the result of testing or data entry errors, or zeros may result from radon values lower than the test’s detection limit. After the removal of invalid data, 1,351 points remained for further analyses with the gamma data.

2.4 Gamma and radon variations by bedrock type

Variations in both mean gamma reading and indoor radon concentration by bedrock type were explored with one-way analysis of variance (ANOVA) tests, where both gamma and radon were grouped by primary and secondary bedrock type. A Tukey post-hoc analysis was then done for both variables to determine if any rock type had a consistently distinct mean. Any rock type with an n of 1 was excluded as ANOVA requires a variance value to properly analyze a mean. The two-tailed significance of the ANOVA and the Tukey post-hoc test were based on $\alpha = 0.05$. The radon values were log transformed prior to testing to account for the highly positively skewed nature of radon data, which is often log-normally distributed (Kitto and Green, 2008; Borgoni et al., 2011; Bossew et al., 2014; Kropat et al., 2014). Where log-transformed radon data was used the geometric mean is reported if appropriate.

2.5 Spatial dependence and interpolation

The spatial dependence of the radon and gamma measurements was examined using semivariograms. Semivariograms show spatial autocorrelation by comparing the variance and distance between all the unique pairs of points of a given sample. A mathematical model can then be fitted to the plotted pairs and used to make determinations about the spatial dependence of the phenomenon. The range was analyzed to ensure that the sampling scale was appropriate relative to the operational scale of the data. The range, as a break point in the semivariogram, can be used as the operational scale (Lam and Quattrochi, 1992; Diem, 2003). The nugget was also analyzed to ensure that any micro-scale variations did not degrade interpolation accuracy.

The gamma readings were used to create a continuous surface of predicted gamma flux for DeKalb County via empirical Bayesian kriging (EBK). Kriging, which requires strong positive spatial autocorrelation, was chosen because it provides a method of not only estimating gamma emission rates between sampling sites, but also the standard errors of those estimates, which is unique relative to other interpolation methods (Cressie, 1993). Also unique to kriging, clustering of input points does not appreciably decrease output accuracy (assuming the sampling interval was sufficiently small across the whole study region). EBK was chosen because, through an iterative sub-setting and simulation process, the standard errors can be estimated more accurately (Esri, 2012). Additionally, EBK does not make many of the assumptions that classical kriging does, most importantly that the data is known to be stationary. While gamma emission rates may be stationary, this cannot readily be confirmed without an onerous amount of sampling, making EBK the more conservative choice (Krivoruchko, 2012). Prior to analysis, the raster resulting from the EBK modeling was resized to have cells with sides equal to the average nearest neighbor of the gamma sample locations. This was done to acknowledge the inherent uncertainty introduced by modeling. The values from the resulting raster were extracted back to the input points and predicted values were compared with those observed. In addition to a basic comparison of means and standard deviations of the predicted and observed values, the index of agreement, which runs from zero to one with one being a perfectly predictive model, was calculated to insure the model was predicting well in accordance with suggested validation practices for geographic models (Wilmott, 1981).

2.6 Joint analysis of radon and gamma emissions

At each of the 1,351 valid radon reading sites gamma flux rate was estimated based on the kriging. A Pearson product-moment correlation test ($\alpha = 0.05$; two-tailed) was used to determine if a significant positive correlation existed between predicted gamma flux and indoor radon. Indoor radon values were log-transformed prior to correlation testing, as they were for the ANOVA test, to account for radon's log normal distribution. The points were also grouped by radon value into below and at or above the EPA radon action level (4.0 pCi/L) to test for categorical relationships. Predicted gamma flux means of the two groups were compared using a Student's t-test ($\alpha = 0.05$; two-tailed). A chi-squared test ($\alpha = 0.05$) was used to compare radon, grouped by EPA action level, and gamma, grouped by observed mean reading (i.e. above or below the mean).

While several studies mentioned above show an important association between aerial gamma data and indoor radon, a previous study found that indoor *in situ* gamma emission measurements and indoor radon were not correlated (Clouvas et al., 2003). Additionally the EPA notes that adjacent buildings may have very different indoor radon levels (EPA, 2009). So in addition to testing for the kriging surface's predictive ability on a house by house scale, the kriging surface's ability to predict on a more general, but still sub-county scale was also tested. The predicted gamma flux raster was resized to 3 km square in order to determine the efficacy of predicted gamma flux rate in predicting indoor radon in a more generalized way. After resizing the raster log-transformed indoor radon values were aggregated to each grid square using the mean of all the log-transformed points in each grid cell. A Pearson's product moment correlation test ($\alpha = 0.05$; two-tailed) was used to determine if an association between the 9 km^2 predicted gamma flux cell and aggregated log-transformed radon concentration existed.

3. RESULTS

3.1 Gamma emission rates

The gamma sampling produced 402 valid mean gamma readings (from 1,283 individual measurements that were averaged by survey site) at locations throughout the county, with three falling just outside the county (Figure 2). Gamma readings ranged from 2,798 to 25,575 cpm, with a mean reading of 10,606 cpm (95% CI: 10,206 to 10,961 cpm) and a median of 10,340 cpm (approximate 95% CI: 10,032 to 10,741). The distribution of the gamma readings was essentially normal, with a slight positive skew of less than one and a mean and median that are essentially equivalent. It should be noted that two areas sampled north of Stone Mountain and two areas south of Stone Mountain that were labelled ultramafic were determined to be incorrect when analyzing the geology GIS layer for inaccuracies. All four of these areas were reassigned to the appropriate rock type, with two being reclassified as mica schist/gneiss and two being reclassified as granitic gneiss in the GIS layer for analysis purposes.

3.2 Gamma emission rate variation by bedrock type

Gamma readings varied between bedrock types (Figure 3-A), with granitic gneiss having the highest mean reading and ultramafic rock having the lowest. Granitic gneiss had a higher mean gamma reading than the others (14,800 cpm), with a mean higher than all included rock types and statistically significantly higher than all included rock types except gneiss. It is also worth noting that ultramafic had a generally lower mean gamma reading (5,085 cpm), with the lowest mean and a significantly lower mean than eight of 12 included rock types. While the ANOVA confirms that there is significant variability among the whole of bedrock ($F(13/288) = 13.41$, $p < .0001$), the Tukey test indicates that, aside from ultramafic and granitic gneiss, most rock types have fairly similar mean gamma readings. Thus, the overall predictive ability of bedrock was limited, especially in the middle ranges of readings, with an r^2 of only 0.31.

3.3 Radon spatial variability

The average indoor radon concentrations of the data in this study is below the EPA action level. The 1,351 readings had a mean concentration of 2.30 pCi/L (95% CI: 2.16 to 2.44 pCi/L), a geometric mean of 1.62 (95% CI: 1.58 to 1.66), and a median of 1.6 pCi/L (approximate 95% CI: 1.5 to 1.7 pCi/L), with values ranging from 0.3 to 43.1 pCi/L. The radon readings are log-normally distributed, with a positive skew of over six. When log-transformed the distribution of the log-transformed radon readings is normal, with a positive skew well below one. While there is minimal spatial autocorrelation there were clearly some areas with consistently low radon. Most notably the far southwestern part of the county, in the area of Soapstone Ridge, contained none of the 175 results at or above the EPA action level.

3.4 Indoor radon variation by bedrock type

Geometric means of radon concentration varied significantly between rock types according to ANOVA (F (12/1337) = 18.33, $p < .0001$), again with granitic gneiss having the highest concentrations and ultramafic having the lowest (Figure 3-B). Despite the significant difference among bedrock as a whole, no rock type was found to have a consistently distinct geometric mean according to the Tukey analysis. Again the predictive power of bedrock was poor with an r^2 value of only 0.14. It is worth noting, ultramafic rock had a reliably low geometric mean (0.61 pCi/L), with a geometric mean significantly lower than all but one included rock type: biotite gneiss/felsic gneiss.

3.5 Spatial Dependence

As indicated by the semivariogram model, there was a strong positive spatial autocorrelation among the gamma readings. The average nearest neighbor distance of gamma survey sites was 445 m, with the most isolated point having a nearest neighbor distance of 4,075 m. Both distances were much smaller than the operational scale (defined as the range of the semivariogram in this study) of gamma in DeKalb County, which was roughly 6,400 m (Figure 4). The nugget (i.e., variance at no spatial lag) was less than six percent of the variance at the range distance and less than seven percent of the semivariogram model’s averaged variance. Given that the sampling interval of the gamma measurements was sufficiently small (i.e. less than the range), these sample measurements should be highly useful for the spatial modeling of gamma readings. The small nugget confirms that minimal micro-scale variations occurred and thus that spatial interdependence can be relied upon for interpolation.

In contrast to the gamma readings, indoor radon concentrations lack strong spatial dependence (Figure 4). The variance at the nugget of the indoor radon semivariogram model is more than 57 percent of the variance at the range distance and more than 60 percent of the model’s average variance. This indicates that a majority of variance in indoor radon concentrations cannot readily be explained by spatial interdependence.

3.6 Gamma Interpolation

A kriged surface of gamma readings was examined to determine the spatial variation in emissions across the county (Figure 5). After completing the resizing and extraction procedure explained in the data and methods section above, the observed and predicted means were determined to be statistically indistinct with a mean gamma readings of 10,582 and 10,454 cpm for observed and predicted values, respectively. The observed and predicted standard deviations were also similar at 3,634 and 3,292 cpm, respectively. The root-mean-square error (RMSE) of the predicted values as extracted to the observed values was very similar to the EBK predicted overall RMSE, at 2,125 and 2,289 cpm, respectively. The index of agreement was 0.90, very close to the ideal value of 1.0. The similarity of the means and standard deviations, in conjunction with the index of agreement value near one indicate the EBK model can be treated as accurate (Wilmott, 1981; Diem, 2003).

The results of the EBK model indicate several areas of extreme values. High gamma emissions exist in the southeastern part of the county (e.g., Arabia Mountain) and an area just northwest of Clarkston. Low values dominated the area of Soapstone Ridge, the area north of Dunwoody, and the area east of Chamblee.

3.7 Radon/gamma comparison and analysis

The correlation coefficient between log-transformed radon and predicted gamma flux was 0.11 ($n = 1351$, $p < .001$), indicating a weak positive correlation (Figure 6) which only accounted for about one percent of radon variability. The mean predicted gamma flux of 10,220 cpm ($n = 1176$) for dwellings with indoor radon concentrations below 4.0 pCi/L was significantly lower than the mean predicted gamma flux of 10,664 cpm ($n = 175$) in dwellings with indoor radon concentrations of 4.0 pCi/L (the EPA action level) or higher ($t(238) = -2.6$, $p < .01$). Further, homes with actionable radon were disproportionally located on areas with above predicted gamma flux above the observed mean gamma reading ($\chi^2(1) = 4.8$, $p < .05$) with dwellings located on areas with gamma measurements above the mean having a 37% increased risk of having an indoor radon concentration at or above 4.0 pCi/L (RR=1.37, 95% CI 1.04, 1.81) (Table 1). The correlation between the resized predicted gamma flux raster and the aggregated log-transformed radon showed a stronger positive correlation with a coefficient of 0.29 ($n = 90$, $p < .005$) (Figure 7), which accounted for about nine percent of aggregated radon variability.

4. DISCUSSION

4.1 Gamma and radon by bedrock

Gamma readings varied by rock type in an expected way. Granitic gneiss had the highest mean gamma reading of any rock type included in the ANOVA test, which corroborates findings in other studies, as granitic rocks generally have a higher concentration of gamma-emitting material (Quindos Poncela et al., 2004; Muikku et al., 2007). On the other end of the spectrum, ultramafic rock had the lowest mean gamma reading with a mean reading rate less than 35% the mean for granitic gneiss, which is also generally expected (Murata and Richter, 1966). Additionally, it is worth noting the amount of variation in gamma emissions explained by bedrock type, 31% based on the ANOVA, is similar to the amount of variation of radon explained by rock type in previous studies (Appleton and Miles, 2010). Past studies of rock outcroppings have also found that only a few ^{238}U rich rock types such as granitic rocks may be predictive of radon flux (Buttafuoco et al., 2007). Our findings are similar with the most predictive value by rock type were on the extremes, with granitic gneiss functioning as a reasonably reliable predictor of high gamma readings and ultramafic rock doing the same for low gamma readings.

As with gamma readings, granitic gneiss had the highest geometric mean radon value, though this value was significantly different from only a few other rock types and ultramafic rock had the lowest geometric mean. Ultramafic rock functioned as the best indoor radon predictor having a statistically lower geometric mean than all but biotite gneiss/felsic gneiss. In fact, of the 34 tested homes underlain with ultramafic bedrock, none had indoor radon levels above the EPA recommended action level.

4.2 Spatial dependence of gamma emissions

The results of the gamma readings semivariogram and interpolation model indicate that this project succeeded in completing its first objective of creating a spatially complete database of forest soil gamma readings for the study region. Two parts of the semivariogram would indicate that this project sampled enough locations. The first is the range, which as a break in the semivariogram provides the operational scale for gamma emissions (Lam and Quattrochi, 1992; Diem, 2003). The range provides the absolute farthest distance sample points should be from one another. Based on Figure 4 the range of gamma in DeKalb is about 6.4 km. Therefore, all of DeKalb is sufficiently covered because the most isolated gamma survey site is less than 4.1 km from its nearest neighbor. The nugget in Figure 4 also indicates that enough sampling of gamma readings was done. The nugget can be understood to show some systemic error or a variation in the phenomenon occurring at distances well below the sampling interval (Burrough and McDonnell, 1998). The small nugget in Figure 4 would indicate that most of the variation in gamma readings in DeKalb has been captured by the sampling interval. This likely means that, while additional sample sites may make the predictions of the interpolation model more robust, further sampling is unlikely to change the outcome.

4.3 Confounding effects on the radon/gamma relationship

Housing characteristics can confound relationships between indoor radon and its environmental sources. Factors including construction materials (although these rarely produce radon problems according to the EPA [2009]), construction quality and home features (e.g., ventilation systems) can influence indoor radon levels (Vauptic et al., 2002; Appleton, 2007; Chen et al., 2010; Akbari et al., 2013). In fact, building characteristics may influence indoor radon more than natural controls of radon (Borgoni et al., 2014). These confounding variables likely contributed to poor predictive abilities of the predicted gamma values by adding a large degree of micro-scale variation in radon readings. This micro-scale and house to house variability is likely part of the reason the EPA recommends testing your home regardless of location, emphasizing that a low radon concentration in your neighbor’s home does not indicate that your home will also have low radon (EPA, 2009).

Though a weak positive correlation between radon and predicted gamma flux existed in the finer scale analysis, some environmental factors not considered by this study may have confounded this relationship. Depth to bedrock, a variable not considered in the gamma surveying, may impact the results of the gamma surveys in this study. Soil characteristics such as moisture content can alter gamma flux in an area (Grasty, 1997). Temporal variability of radon may also have contributed to the weak correlation. Though the time integrating testing methods used in the data of this study would attenuate diurnal effects (EPA guidance provided with tests recommends starting and stopping test at the same time of day to avoid over/under estimating radon based on diurnal variations), seasonal effects were not accounted for and may have added an additional confounder.

The lack of a daily accuracy check of the gamma scintillator may have allowed measurement error of time to further occlude the radon/gamma relationship, though the use of strict data collection protocols (outlined in section 2.2) and the use of a single gamma detector all within one year (i.e. a single calibration period) may have helped attenuate some measurement error. That said, the weak but positive relationship between predicted gamma flux and indoor radon concentrations found in this study is in keeping with previous findings (Jackson, 1992; Szegvary et al., 2007a; Szegvary et al., 2007b). This is also conceptually sensible as ^{238}U is an important geologic driver of both radon and gamma flux (Garcia-Talvera et al., 2007; Peterson et al., 2007; Sakoda et al., 2011; Wilford 2012).

4.4 Radon potential

The weakness of the correlation between indoor radon and predicted gamma flux, when calculated on a case by case basis (i.e. comparing data of all valid radon test points) would seem to indicate that neighborhood scale prediction of radon risk is unlikely to be successful. The multitude of housing, environmental, and even meteorological factors that affect indoor radon make testing the only way to truly determine in home radon levels (EPA, 2009). However, the stronger correlation between predicted gamma flux and indoor radon when aggregated to 9 km^2 cells indicates some sub-county level predictions could be possible. This improvement is probably the result of a reduction in noise in the data, especially in the radon data. This affect, known as the modifiable areal unit problem or the scale problem, is characterized by an increase in correlation as fewer, larger areal units are used for comparison (Openshaw, 1984). However, in so far as the noise reduction is primarily a function of averaging out perturbations in radon caused by housing characteristics, these aggregated predictions could still be useful for determining areas that might be environmentally predisposed to radon issues. It is sensible that a large portion of the noise in the radon data is a function of housing, rather than environment, as housing characteristics are more likely to vary randomly throughout space. While these predictions would be general they could help inform the distribution of finite county health department resources or show where potential problem areas may exist.

The observed relationship between indoor radon and predicted gamma flux, especially when such data are aggregated to coarser scales, indicates that gamma readings are one component to consider when predicting potential for elevated indoor radon levels, though the inclusion of other variables is likely be needed to generate a prediction of risk and such a prediction would likely have to be only very general. While the predictive value of aerial gamma readings has been inconsistent (Ball et al., 1992), the use of aerial gamma in concert with other environmental variables has been shown to improve predictions of radon potential (Szegvary et al., 2007b; Smethurst et al., 2008; Griffiths et al., 2010; Appleton et al., 2011a). Further, at least one study that aimed to produce a comprehensive regression model of geogenic radon risk does not include gamma activity of the soil, likely due to lack of data (Pasztor et al., 2016). This would indicate the methods of in situ gamma surveys of this study could be useful for studies facing similar data gaps in the future. The fact that this study’s kriged gamma values show a positive relationship with indoor radon, indicates that continuous gamma surfaces produced using EBK based on gamma reading data collected *in situ* may be informative in understanding radon potential, even if not at a neighborhood level, thereby fulfilling this study’s second objective, which aimed to establish the relationship between gamma emissions and indoor radon.

4.5 Implications of findings

The direct relationship established between exposure to radon and increased risk for lung cancer highlights the potential applications of *in situ* gamma data for informing the public of areas of potentially elevated radon levels so that they can take action to test and remediate as appropriate. *In situ* gamma instrument reading data coupled with EBK interpolation is a feasible methodology for identifying particular areas of concern in DeKalb County, and could potentially be applied in other counties. With such information public health officials within local and county health departments, for example, could be better equipped to make decisions to allocate resources for targeted outreach and testing activities. This project's method of gamma surveying could allow researchers attempting to map radon potential in an area with unreliable or unavailable gamma data to include gamma readings as a variable at low cost both in terms of man power and money. Despite limitations in the project, the findings' agreement with prior radon potential mapping literature would indicate this method could be worthwhile. These additional resources could lead to greater awareness of personal exposure, ideally leading to a decreased exposure. Additionally, such activities could have a direct impact on the number of lung cancer cases. For instance, each year there are approximately 216 lung cancer deaths in DeKalb County (State Cancer Profiles statecancerprofiles.cancer.gov (accessed 20 Oct. 2016)). It is possible that close to 26 of these deaths could be attributable to radon exposure (estimate based on the average of the preferred models from NRC, 1999).

Awareness of areas of high gamma emissions may be useful to professionals in the private sector as well. City planners equipped with knowledge about an area's geology and gamma emissions could consider instituting standard practices of radon-resistant construction for new developments in areas with the potential for elevated radon. For example, this study indicates the southeastern portion of DeKalb County along the DeKalb/Rockdale border may be at increased risk of indoor radon problems in the future. This region, which is largely undeveloped as is clear in Figure 1, has some of the highest predicted gamma flux as seen in Figure 5. As the Atlanta region continues to grow, it is possible that this region will become urbanized. With population increases in this area, more people could be exposed to high radon levels if preventative action incorporating radon resistant features in new construction. It should be noted that, while areas of certain geology or lower gamma readings may be less likely to have homes with elevated radon levels, the potential for high indoor radon concentrations still exists regardless of location. As such all homes should be tested.

4.6 Limitations

This study has four main limitations. First, the comparison of indoor radon and gamma readings is overly simplified. Data and time constrains meant that additional relevant variables and controls could not be considered (e.g. depth to bedrock, soil permeability and porosity, seasonal effects, housing characteristics, thorium confounding, etc.). This may have contributed to the lack of a robust radon potential prediction. The second limitation compounds the problem of the first. The area with the highest predicted gamma flux, southeastern DeKalb County, is the most poorly sampled region in the county when it comes to indoor radon, due to a lower density of housing units in that area. The underrepresentation of this high gamma region in the radon data may contribute to the weak correlation evident in Figure 6. Third, with the whole project taking place in only one county, it is difficult to assess the applicability of this study's findings to locations beyond the study region. While the findings likely provide a good springboard for future studies within the Piedmont physiographic province, in which all of DeKalb County exists, it is difficult to know if other physiographic provinces will show similar trends regarding gamma readings. Fourth, a lack of metadata associated with the radon tests and the homes in which the tests occurred made controlling for test and housing conditions impossible.

4.7 Future work

More work is needed to understand and predict indoor radon risk. However, focusing on urban area gamma surveys is a possible way to improve any model's predictive power. Additional variables that may be considered in future research might include topography, fault location and activity, depth to bedrock, and housing characteristics. Future work could test *in situ* gamma reading ability to predict geogenic radon flux by measuring for radon directly in the soil rather than indoors. Future work could also focus on incorporating soil variables such as permeability and porosity into the model. The addition of more stringent gamma measurement protocols could allow for more accurate and ensure there is minimal measurement bias. The use of gamma spectroscopy could help eliminate gamma emissions that are not radon related from the data, also. Adding controls for factors related to the radon tests may help further isolate the gamma/radon relationship. Focusing on test metadata such as the type of test used, the duration of test, and the season of the test could be especially helpful in removing radon confounders. Replications of this study in other physiographic provinces could help assess the applicability of these findings in various geographic regions. Finally, work to produce a more comprehensive model of radon potential, one that compares residential radon tests to multiple variables including gamma readings, could help in determining the value of *in situ* gamma measurements as a component for predicting indoor radon.

5. CONCLUSIONS

This study analyzed the efficacy of using *in situ* gamma measurements as a proxy for indoor radon potential. Using a scintillation device, 402 locations throughout the study region were surveyed to obtain gamma readings. From those a continuous surface of predicted gamma readings was created via EBK (empirical Bayesian kriging). This surface was then used to pair 1,351 indoor radon test results with predicted gamma values based on radon test location. Various statistical comparisons between indoor radon and geogenic gamma readings showed a weakly positive association between the two variables, in keeping with the literature. Despite this positive association, gamma readings alone proved a weak quantitative predictor, instead indicating risk in a more general way. This study also found that two rock types clearly give an upper and lower bound in terms gamma readings for the county, with granitic gneiss having a higher mean gamma reading and ultramafic rock having lower. This trend held true for indoor radon as well, with granitic gneiss having some of the highest indoor radon concentrations and ultramafic having some of the lowest.

For DeKalb County specifically, this study determined that the southeast of the county is potentially at elevated risk for radon exposure if development increases in that area. The high gamma readings in the region, coupled with the relative lack of development currently, would make that area a good place to begin taking steps to limit radon in homes. This could mean encouraging radon resistant new construction or increased retrofitting of old homes with radon mitigation systems. These steps might be the most important since the advent of radon resistant construction materials and techniques, as well as ventilation systems that reduce indoor dust concentration (which reduces the attached fraction of radon daughters) can significantly reduce radiation dose from radon progeny and therefore reduce lung cancer risk. In spite of the weak positive association between gamma instrument readings and indoor radon, it is worth noting that even some areas of low gamma readings had homes with high radon. This would indicate that all homes, regardless of location or environmental factors, should be tested for radon, and homes with elevated radon levels should be remediated.

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The findings and conclusions in this study are those of the authors and do not necessarily represent the official position of the Centers for Disease Control and Prevention or the Agency for Toxic Substances and Disease Registry.

References

Akbari K, Mahmoudi J, Ghanbari M. Influence of Indoor Air Conditions on Radon Concentration in a Detached House. Journal of Environmental Radioactivity. 2013; 116:166–73. DOI: 10.1016/j.jenvrad.2012.08.013 [PubMed: 23159846]

Appleton JD, Doyle E, Fenton D, Organo C. Radon Potential Mapping of the Tralee–Castleisland and Cavan Areas (Ireland) Based on Airborne Gamma-Ray Spectrometry and Geology. Journal of Radiological Protection. 2011; 31(2):221. [PubMed: 21617292]

Appleton JD. Radon: Sources, Health Risks, and Hazard Mapping. Ambio. 2007; 36:85–89. [PubMed: 17408197]

Appleton JD, Miles JCH. A Statistical Evaluation of the Geogenic Controls on Indoor Radon Concentrations and Radon Risk. Journal of Evironmental Radioactivity. 2010; 101(10):799–803.

Appleton JD, Miles JCH, Green BMR, Larmour R. Pilot Study of the Application of Tellus Airborne Radiometric and Soil Geochemical Data for Radon Mapping. Journal of Environmental Radioactivity. Oct; 2008 99(10):1687–97. DOI: 10.1016/j.jenvrad.2008.03.011 [PubMed: 18562054]

Appleton JD, Miles JCH, Young M. 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. Science of the Total Environment. 2011; 409:1572–83. DOI: 10.1016/j.scitotenv.2011.01.023 [PubMed: 21310464]

Ball TK, Cameron DG, Colman TB. Aspects of Radon Potential Mapping in Britain. Radiation Protection Dosimetry. 1992; 45(1–4):211–14.

Borgoni R, de Francesco D, de Bartolo D, Tzavidis N. Hierarchical Modeling of Indoor Radon Concentration: How Much Do Geology and Building Factors Matter? Journal of Environmental Radioactivity. 2014; 138:227–37. [PubMed: 25261869]

Borgoni R, Tritto V, Bigliotto C, de Bartolo D. A Geostatistical Approach to Assess the Spatial Association between Indoor Radon Concentration, Geological Features and Building Characteristics: The Case of Lombardy, Northern Italy. International Journal of Environmental

Research and Public Health. May 6; 2011 8(12):1420–40. DOI: 10.3390/ijerph8051420 [PubMed: 21655128]

Bossew P, Lettner H. Investigations on Indoor Radon in Austria, Part 1: Seasonality of Indoor Radon Concentration. Journal of Environmental Radioactivity. 2007; 8:329–45.

Bossew P, Žunić ZS, Stojanovska Z, Tollefsen T, Carpentieri C, Veselinović N, Komatina S, et al. Geographical Distribution of the Annual Mean Radon Concentrations in Primary Schools of Southern Serbia – Application of Geostatistical Methods. Journal of Environmental Radioactivity. Jan.2014 127:141–48. DOI: 10.1016/j.jenvrad.2013.09.015 [PubMed: 24231373]

Burrough, PA., McDonnell, RA. Principles of Geographic Information Systems. New York, NY: Oxford University Press; 1998.

Buttafuoco G, Tallarico A, Falcone G. Mapping Soil Gas Radon Concentration: A Comparative Study of Geostatistical Methods. Environmental Monitoring and Assesment. 2007; (131):135–51. DOI: 10.1007/s10661-006-9463-7

Chen J. A Preliminary Design of a Radon Potential Map for Canada: A Multi-Tier Approach. Environmental Earth Science. 2009; 59:775–82. DOI: 10.1007/s12665-009-0073-x

Chen J, Rahman NM, Atiya IA. Radon Exhalation from Building Materials for Decorative Use. Journal of Environmental Radioactivity. 2010; 101:317–22. DOI: 10.1016/j.jenvrad.2010.01.005 [PubMed: 20167403]

Cinelli G, Tondeur F, Dehandschutter B. Development of an Indoor Radon Risk Map of the Walloon Region of Belgium, Integrating Geological Information. Environmental Earth Science. 2011; 62:809–19. DOI: 10.1007/s12665-010-0568-5

Clouvas A, Xanthos S, Antonopoulos-Domis M. Extended survey of indoor and outdoor terrestrial gamma radiation in Greek urban areas by in situ gamma spectrometry with a portable Ge detector. Radiation Protection Dosimetry. 2001; 94(3):233–246. [PubMed: 11487806]

Clouvas A, Xanthos S, Antonopoulos-Domis M. A combination study of indoor radon and in situ gamma spectronmetry measurements in Greek dwellings. Radiation Protection Dosimetry. 2003; 103(4):363–366. [PubMed: 12797560]

Cressie, N. Statistics for Spatial Data. New York, NY: Wiley; 1993.

Darby S, Hill D, Doll R. Radon: A Likely Carcinogen at All Exposures. Annals of Oncology. 2001; 12(10):1341–51. [PubMed: 11762803]

Dicken, CL., Nicholson, SW., Horton, JD., Foose, MP., Mueller, JAL. Preliminary Integrated Geologic Map Databases for the United States. US Geological Survey. 2007. pubs.usgs.gov

Diem JE. A critical examination of ozone mapping from a spatial scale perspective. Environmental Pollution. 2003; 125(3):369–383. [PubMed: 12826415]

Drolet JP, Martel R, Poulin P, Dessau JC, Lavoie D, Parent M, Lévesque B. An Approach to Define Potential Radon Emission Level Maps Using Indoor Radon Concentration Measurements and Radiogeochemical Data Positive Proportion Relationships. Journal of Environmental Radioactivity. Oct.2013 124:57–67. DOI: 10.1016/j.jenvrad.2013.04.006 [PubMed: 23660346]

Environmental Protection Agency. EPA Assessments of Risks from Radon in Homes. Washington,DC: Office of Radiation and Indoor Air; Jun. 2003

Environmental Protection Agency. A Citizen's Guide to Radon: The Guide to Protecting Yourself and Your Family from Radon. Environmental Protection Agency. 2009. epa.gov/radon

Esri. What Is Empirical Bayesian Kriging?. ArcGIS Resources. 2012. resources.arcgis.com

Friedmann H, Groller J. An Approach to Improve the Austrian Radon Potential Map by Bayesian Statistics. Journal of Environmental Radioactivity. 2010; 101:804–8. DOI: 10.1016/j.jenvrad.2009.11.008 [PubMed: 20022149]

García-Talavera M, García-Pérez A, Rey C, Ramos L. Mapping Radon-Prone Areas Using γ-Radiation Dose Rate and Geological Information. Journal of Radiological Protection. 2013; 33(3):605–20. DOI: 10.1088/0952-4746/33/3/605 [PubMed: 23803560]

Garcia-Talavera M, Matarranz JL, Martinez M, Salas R, Ramos L. Natural Ionizing Radiation Exposure of the Spanish Population. Radiation Protection Dosimetry. May 25; 2007 124(4):353–59. DOI: 10.1093/rpd/ncm213 [PubMed: 17906301]

Grasty R. Radon Emanation and Soil Moisture Effects on Airborne Gamma-Ray Measurements. Geophysics. 1997; 62(5):1379–85.

Gray A, Read S, McGale P, Darby S. Lung cancer from indoor radon and the cost effectiveness and potential of policies to reduce them. BMJ. Feb.2009 338doi: 10.1136/bmj.a3110

Griffiths AD, Zahorowski W, Element A, Werczynski S. A Map of Radon Flux at the Australian Land Surface. Atmospheric Chemistry and Physics. Sep 27; 2010 10(18):8969–82. DOI: 10.5194/acp-10-8969-2010

Harley NH, Fisenne LM, Harley JH, McGregor RG, Nero AV, Wilkening MH. Measurement of Radon and Radon Daughters in Air. NRCP. 1988

Higgins, MW., Crawford, TJ., Atkins, RL., Crawford, RF. Geologic Map of Atlanta 30′ × 60′ Quadrangle. Geologic Investigation Series US Geological Survey. 2003. ngmdb.usgs.gov

Homer CG, Dewitz JA, Yang L, Jin S, Danielson P, Xian G, Coulston J, Herold ND, Wickham JD, Megown K. Completion of the 2011 National Land Cover Database for the Conterminous United States-Representing a Decade of Land Cover Change Information. Photogrammetric Engineering and Remote Sensing. 2015; 81(5):345–54.

Ielsch G, Cushing ME, Combes P, Cuney M. Mapping of the Geogenic Radon Potential in France to Improve Radon Risk Management: Methodology and First Application to Region Bourgogne. Journal of Environmental Radioactivity. Oct; 2010 101(10):813–20. DOI: 10.1016/j.jenvrad.2010.04.006 [PubMed: 20471142]

Jackson SA. Estimating Radon Potential from an Aerial Radiometric Survey. Health Physics. 1992; 62(5):450–452. [PubMed: 1559817]

Kang DR, Kang D, Min KB, Kim C, Oh SS, Koh SB. Trends in Research on Indoor Radon Exposure and Lung Cancer in South Korea. Annals of Occupational and Environmental Medicine. 2016; 28(3)

Kauppinen T, Toikkanen J, Pedersen D, Young R, Ahrens W, Boffetta P, Hansen J, et al. Occupational Exposure to Carcinogens in the European Union. Occupational and Environmental Medicine. 2000; 57(1):10–18. [PubMed: 10711264]

Keith S, Doyle JR, Harper C, et al. Toxicological Profile for Radon. Agency for Toxic Substances and Disease Registry. 2012

Kitto ME, Green JG. Mapping the Indoor Radon Potential in New York at the Township Level. Atmospheric Environment. Nov; 2008 42(34):8007–14. DOI: 10.1016/j.atmosenv.2008.06.039

Krivoruchko, K. Empirical Bayesian Kriging. Esri: Redlands, CA, USA. 2012. http://www.esri.com/NEWS/ARCUSER/1012/files/ebk.pdf

Kropat G, Bochud F, Jaboyedoff M, Laedermann JP, Murith C, Palacios (Gruson) M, Baechler S. Predictive Analysis and Mapping of Indoor Radon Concentrations in a Complex Environment Using Kernel Estimation: An Application to Switzerland. Science of The Total Environment. Feb. 2015 505:137–48. DOI: 10.1016/j.scitotenv.2014.09.064 [PubMed: 25314691]

Lam NS, Quattrochi DA. On the Issues of Scale, Resolution, and Fractal Analysis in the Mapping Sciences. The Professional Geographer. 1992; 44(1):88–98.

Muikku M, Heikkinen T, Puhakainen M, Rahola T, Salonen L. Assessment of Occupational Exposure to Uranium by Indirect Methods Needs Information on Natural Background Variations. Radiation Protection Dosimetry. 2007; 125:492–95. [PubMed: 17309870]

Murata, KJ., Richter, DH. The 1959–60 Eruption of Kilauea Volcano, Hawaii. Vol. 537 A. Washington, D.C.: United State Government Printing Office; 1966. Chemistry of the Lavas of the 1959–60 Eruption of Kilauea Volcano, Hawaii.

Nason R, Cohen BL. Correlation between 226Ra in Soil, 222Rn in Soil Gas, and 222Rn inside Adjacent Houses. Health Physics. 1980; 52:73–74.

National Research Council. Health Effects of Exposure to Radon BEIR (Biological Effects of Ionizing Radiation) VI. Washington, D.C.: National Academy Press; 1999.

Noh J, Sohn J, Cho J, Kang DR, Joo S, Kim C, Shin DC. Residential Radon and Environmental Burden of Disease among Non-Smokers. Annals of Occupational and Environmental Medicine. 2016; 28(8)

Oh SS, Koh S, Kang H, Lee J. Radon Exposure and Lung Cancer: Risk in Nonsmokers among Cohort Studies. Annals of Occupational and Environmental Medicine. 2016; 28(6)

Openshaw, S. Concepts and Techniques in Modern Geography Number 38: The Modifiable Areal Unit Problem. Norwich: Geo Books; 1984.

Pasztor L, Szabo KZ, Szatmari G, Laborczi A, Horvath A. Mapping geogenic radon potential by regression kriging. Science of the Total Environment. 2016; 544:883–891. DOI: 10.1016/j.scitotenv.2015.11.175 [PubMed: 26706761]

Pereira AJSC, Godinho MM, Neves LJPF. On the Influence of Faulting on Small-Scale Soil-Gas Radon Variability: A Case Study in the Iberian Uranium Province. Journal of Environmental Radioactivity. Oct; 2010 101(10):875–82. DOI: 10.1016/j.jenvrad.2010.05.014 [PubMed: 20554356]

Peterson J, MacDonell M, Haroun L, Monettee F, Hildebrand RD, Toboas A. Radiological and Chemical Fact Sheets to Support Health Risk Analysis for Contaminated Areas. Argon National Laboratory (ANL) Environmental Science Division and US Department of Energy. 2007

Planchard D, Besse B. Lung Cancer in Never-Smokers. European Respiratory Journal. 2015; 45(5): 1214–17. [PubMed: 25931484]

Quindós LS, Fernández PL, Sainz C, Fuente I, Nicolás J, Quindós L, Arteche J. Indoor Radon in a Spanish Region with Different Gamma Exposure Levels. Journal of Environmental Radioactivity. Oct; 2008 99(10):1544–47. DOI: 10.1016/j.jenvrad.2007.12.011 [PubMed: 18255206]

Quindós Poncela LS, Fernández PL, Gómez Arozamena J, Sainz C, Fernández JA, Suarez Mahou E, Martin Matarranz JL, Cascón MC. Natural Gamma Radiation Map (MARNA) and Indoor Radon Levels in Spain. Environment International. Feb; 2004 29(8):1091–96. DOI: 10.1016/S0160-4120(03)00102-8 [PubMed: 14680892]

Sakoda A, Ishimori Y, Yamaoka K. A Comprehensive Review of Radon Emanation Measurements for Mineral, Rock, Soil, Mill Tailing and Fly Ash. Applied Radiation and Isotopes. 2011; 69:1422–35. DOI: 10.1016/j.apradiso.2011.06.009 [PubMed: 21742509]

Schauer DA. Ionizing Radiation Exposure of the Population of the United States. National Council of Radiation Protection and Measurements. 2009

Sheen S, Lee KS, Chung WY, Nam S, Kang DR. An Updated Review of Case-Control Studies of Lung Cancer and Indoor Radon-Is Indoor Radon the Risk Factor for Lung Cancer? Annals of Occupational and Environmental Medicine. 2016; 28(9)

Smethurst M, Strand T, Sundal A, Rudjord A. Large-Scale Radon Hazard Evaluation in the Oslofjord Region of Norway Utilizing Indoor Radon Concentrations, Airborne Gamma Ray Spectrometry and Geological Mapping. Science of The Total Environment. Dec 15; 2008 407(1):379–93. DOI: 10.1016/j.scitotenv.2008.09.024 [PubMed: 18962827]

Stauber C, Dai D, Chan S, Diem J, Weaver S, Rothenberg R. A Pilot Study to Examine Exposure to Residential Radon in Under Sampled Census Tracts of DeKalb County, Georgia in 2015. International Journal of Environmental Research and Public Health. Mar 22.2017 14(332)doi: 10.3390/ijerph14030332

Szegvary T, Conen F, Stöhlker U, Dubois G, Bossew P, de Vries G. Mapping Terrestrial-Dose Rate in Europe Based on Routine Monitoring Data. Radiation Measurements. Oct; 2007 42(9):1561–72. DOI: 10.1016/j.radmeas.2007.09.002

Szegvary T, Leuenberger MC, Conen F. Predicting Terrestrial 222 Rn Flux Using Gamma Dose Rate as a Proxy. Atmospheric Chemistry and Physics. 2007; 7(11):2789–2795.

UNSCEAR. Unscear 1993. Nuclear Energy-Journal of the British Nuclear Energy Society. 1994; 33(3):132–33.

Vaupotic J, Andjelov M, Kobal I. Relationship between Radon Concentrations in Indoor Air and in Soil Gas. Environmental Geology. 2002; 42:583–87. DOI: 10.1007/s00254-002-0573-4

Wilford J. A Weathering Intensity Index for the Australian Continent Using Airborne Gamma-Ray Spectrometry and Digital Terrain Analysis. Geoderma. 2012; 183(184):124–42. DOI: 10.1016/j.geoderma.2010.12.022

Wilford J, Minty B. The Use of Airborne Gamma-Ray Imagery for Mapping Soils and Understanding Landscape Processes. Developments in Soil Science. 2007; 31doi: 10.1016/S0166-24810631016-1

Willmott CJ. On the Validation of Models. Physical Geography. 1981; 2(2):184–194.

World Health Organization. WHO Handbook on Indoor Radon: A Public Health Perspective Edited by Hajo Zeeb and Ferid Shannoun. Geneva, Switzerland: WHO Press; 2009.

Highlights

- Efficacy of the use of in situ gamma reading in place of unavailable areal data to determine 2 radon exposure potential is analyzed.
- In situ gamma readings show weak but positive relationships with indoor radon on a house by 4 house basis.
- At courser spatial resolutions the positive association between in situ gamma readings and 6 generalized indoor radon is stronger.
- In situ gamma reading may function as a predictor variable of generalized radon potential when 8 combined with other variables.

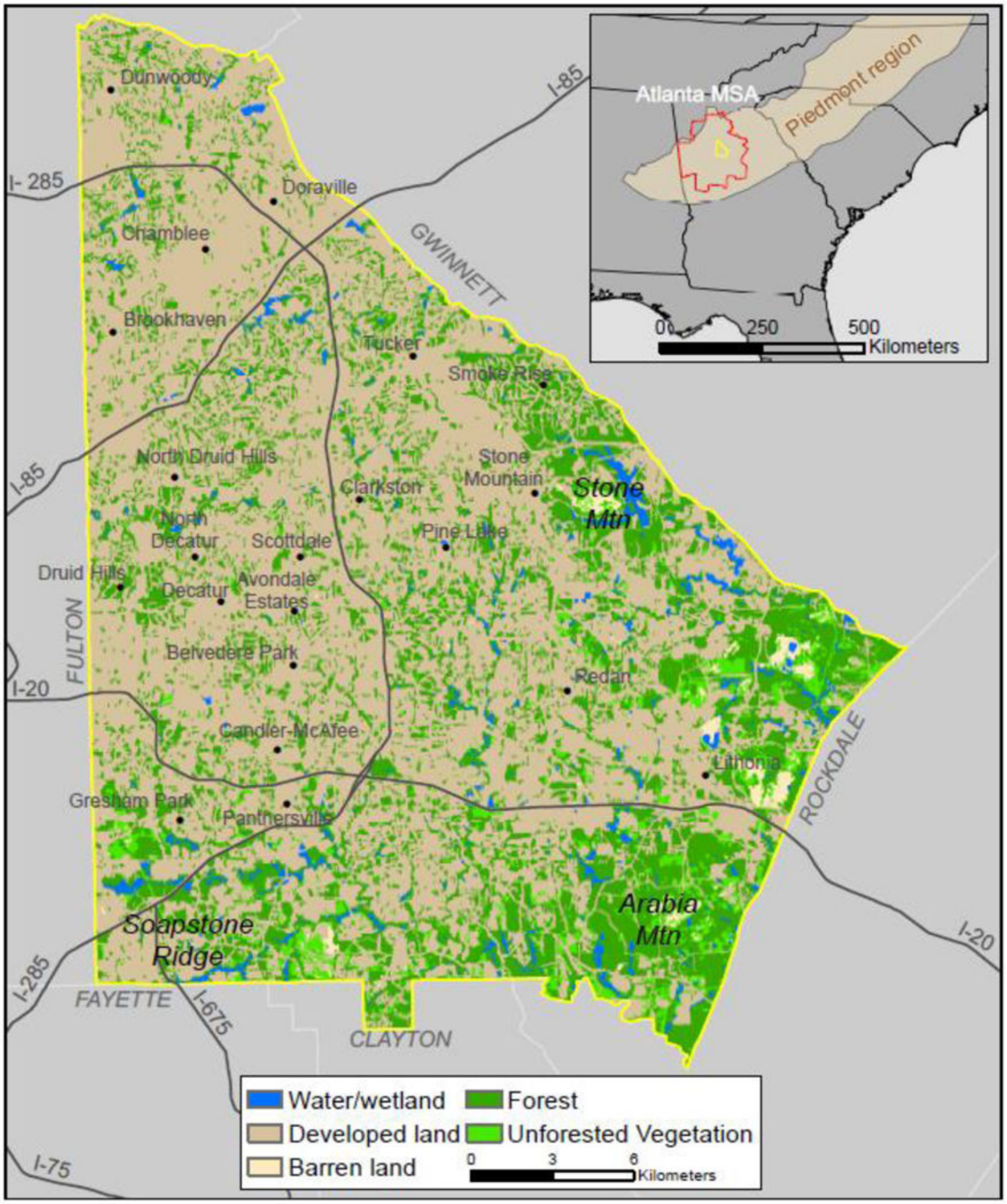

Figure 1.

This effort’s study region, DeKalb County, Georgia (base map from Homer et al., 2015)

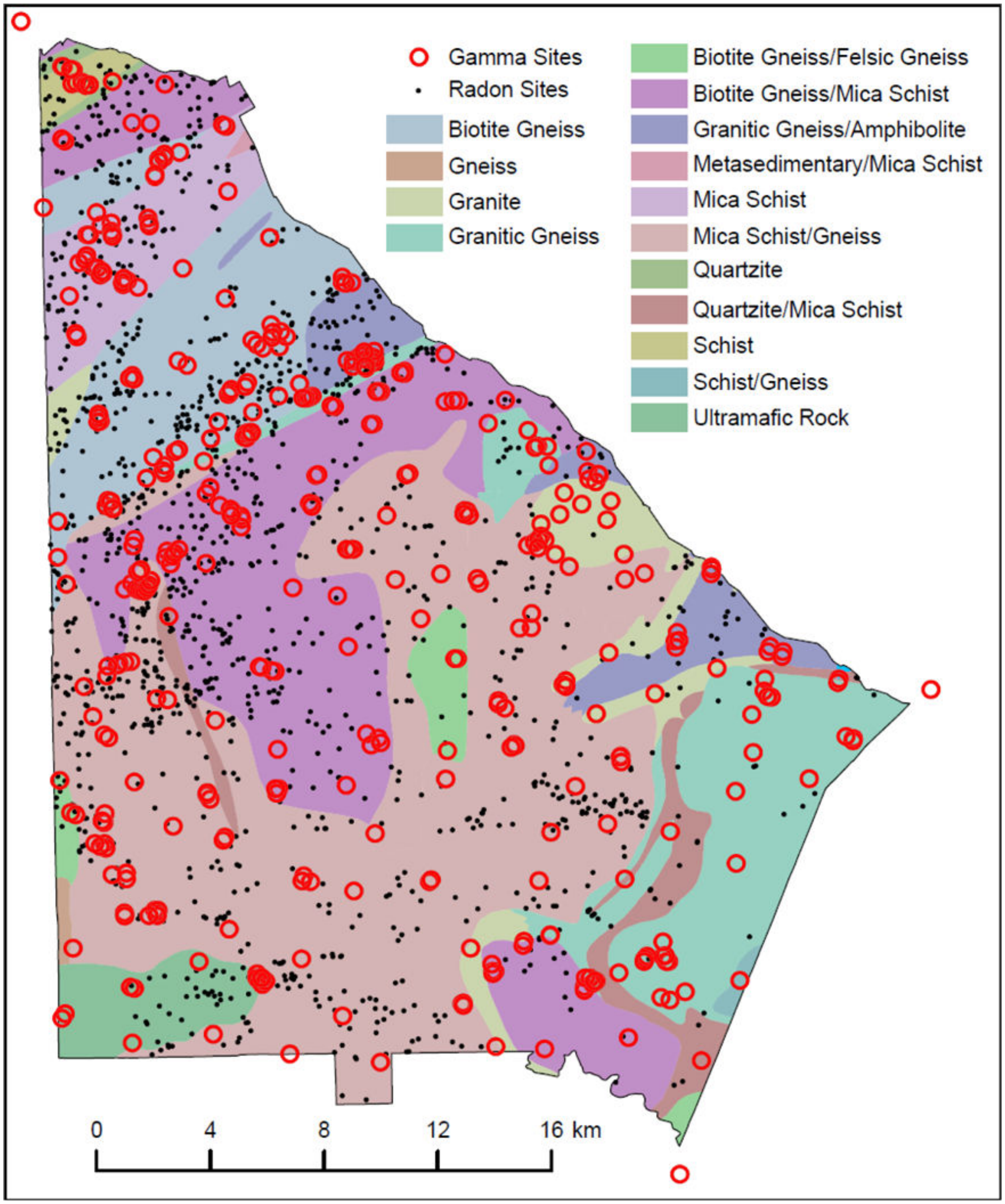

Figure 2.

DeKalb’s underlying geology with gamma and radon sample sites highlighted (base map from Dicken et al., 2007 with corrections based on Higgins et al., 2003)

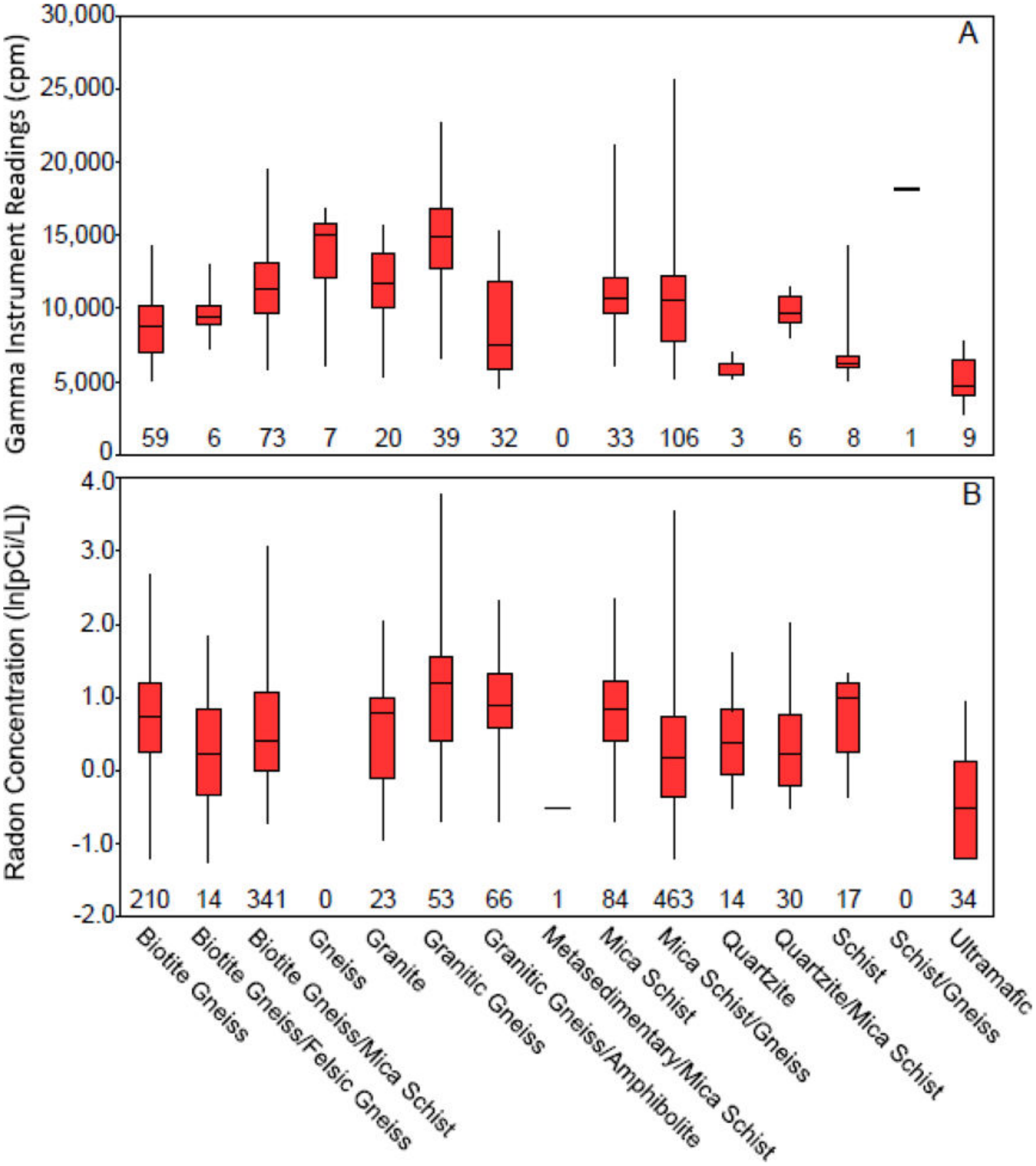

Figure 3.

Box and whisker plots of gamma readings and log-transformed indoor radon concentrations as grouped by bedrock type. The numbers are the sample sizes for each bedrock type.

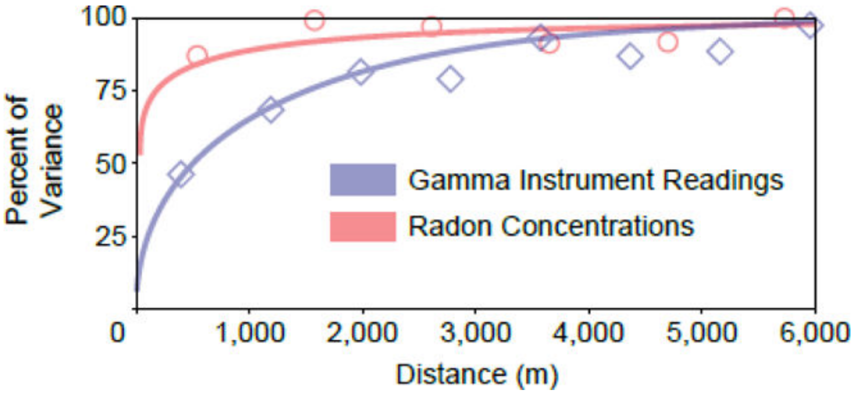

Figure 4.

Semivariograms of gamma readings and indoor radon concentrations

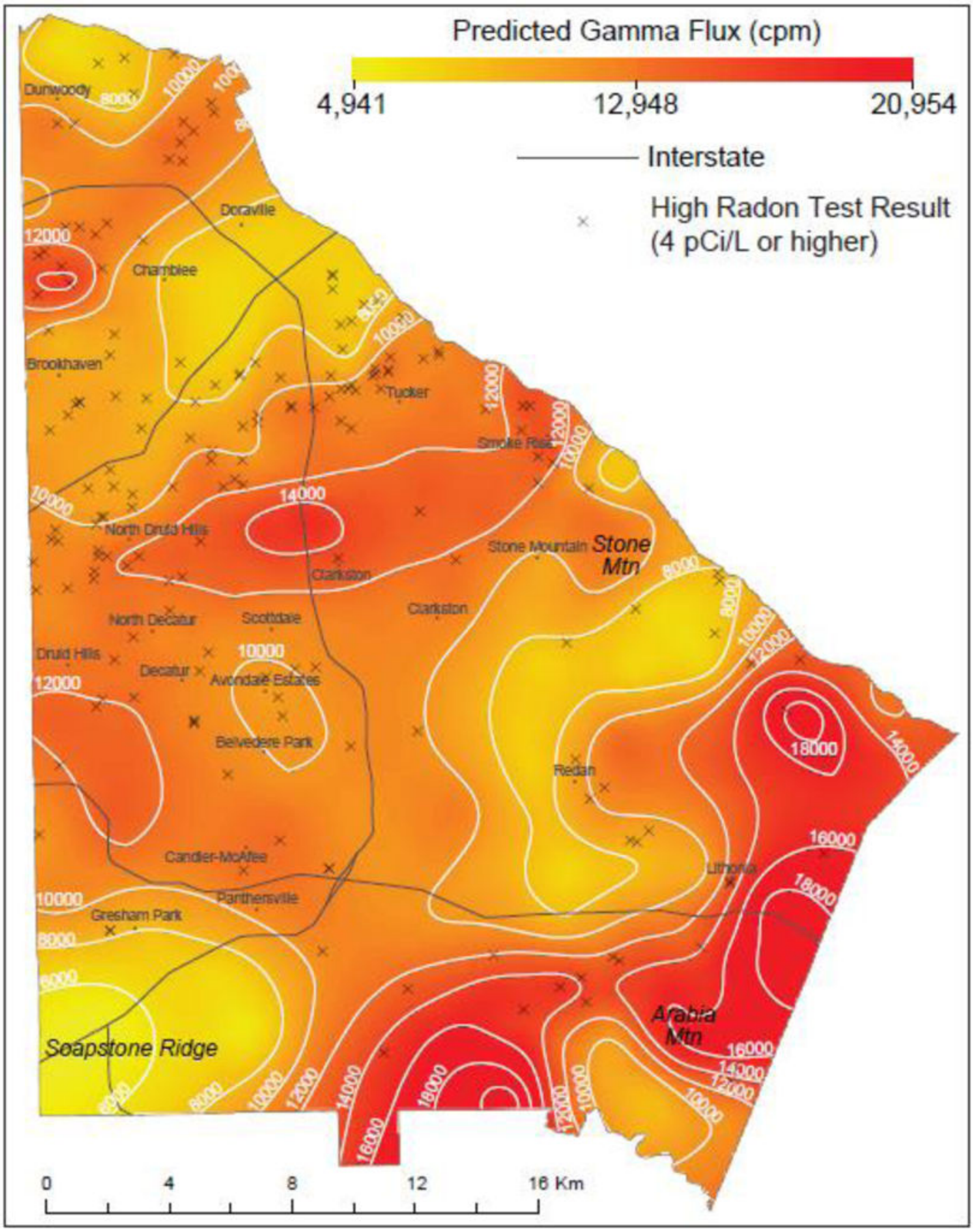

Figure 5.

A map of predicted gamma flux throughout DeKalb

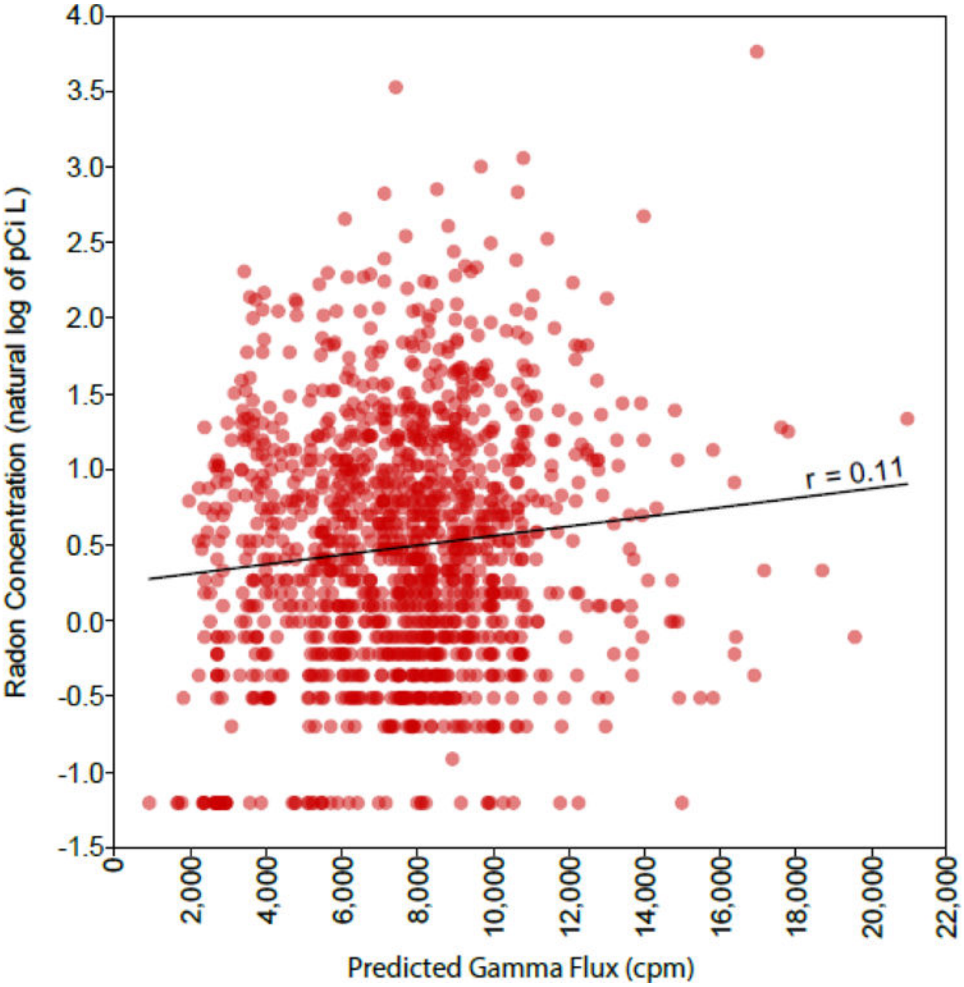

Figure 6.

Scatterplot of log-transformed indoor radon levels and predicted gamma flux

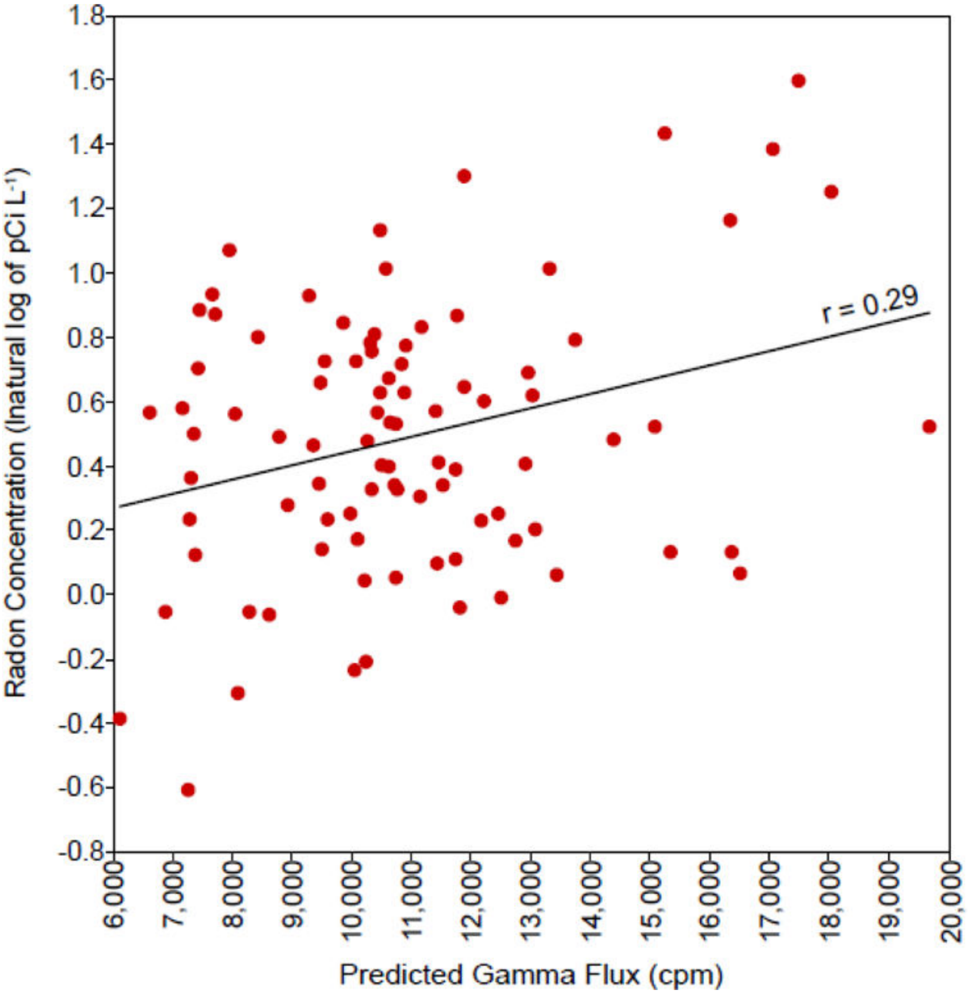

Figure 7.

Scatterplot of log-transformed indoor radon levels and predicted gamma flux with both aggregated to 3 km grid cells

Table 1

2×2 contingency table based on χ^2 test and relative risk calculation comparing gamma emission rates with indoor radon concentrations.

	High indoor radon (≥4 pCi/L)	Low indoor radon (<4 pCi/L)
High gamma flux (≥10,606 cpm)	92 (78.1)	511 (524.9)
Low gamma flux (<10,606 cpm)	83 (96.9)	665 (651.1)

Values in parentheses are expected values based on independent distribution