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Confluent impact of housing and geology on indoor radon concentrations in Atlanta, Georgia, United States

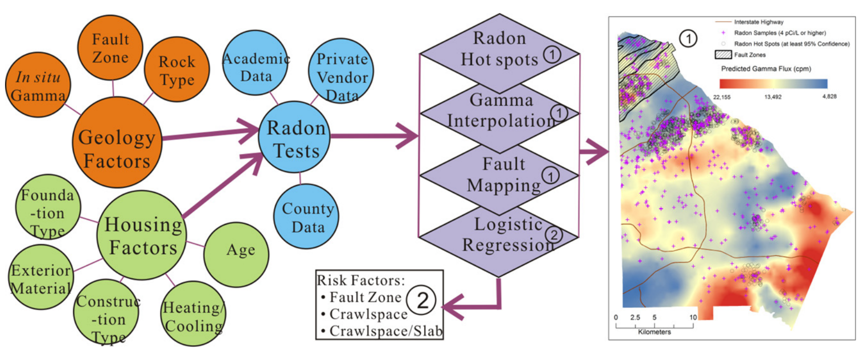
Dajun Dai [a,*], Fredrick B. Neal [a,b], Jeremy Diem [a], Daniel M. Deocampo [a], Christine Stauber [c], Timothy Dignam [d]

[a] Department of Geosciences, Georgia State University, 38 Peachtree Center Avenue, Atlanta, GA 30303, United States of America
[b] Critigen LLC, 7555 East Hampden Avenue, Suite 415, Denver, CO 80231, United States of America
[c] School of Public Health, Georgia State University, 140 Decatur Street, Atlanta, GA 30303, United States of America
[d] Division of Environmental Health Science and Practice, National Center for Environmental Health, Centers for Disease Control and Prevention, Atlanta, GA, 30341, United States of America

HIGHLIGHTS

- Using housing, fault mapping, in situ gamma, and rock types to determine radon risk.
- Fault zone is a significant risk factor for indoor radon above the action level.
- Foundations of crawlspace or a combination of crawlspace and slab have lower risks.

GRAPHICAL ABSTRACT



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ABSTRACT

Radon is a naturally released radioactive carcinogenic gas. To estimate radon exposure, studies have examined various risk factors, but limited information exists pertaining to the confluent impact of housing characteristics and geology. This study evaluated the efficacy of housing and geological characteristics to predict radon risk in DeKalb County, Georgia, USA. Four major types of data were used: (1) three databases of indoor radon concentrations ($n = 6757$); (2) geologic maps of rock types and fault zones; (3) a database of 402 in situ measurements of gamma emissions, and (4) two databases of housing characteristics. The Getis-Ord method was used to delineate hot spots of radon concentrations. Empirical Bayesian Kriging was used to predict gamma radiation at each radon test site. Chi-square tests, bivariate correlation coefficients, and logistic regression were used to examine the impact of geological and housing factors on radon. The results showed that indoor radon levels were more likely to exceed the action level—4 pCi/L (148 Bq/m^3) designated by the U.S. Environmental Protection Agency—in fault zones, were significantly positively correlated to gamma readings, but significantly negatively related to the presence of a crawlspace foundation and its combination with a slab. The findings suggest that fault mapping and in situ gamma ray measurements, coupled with analysis of foundation types and delineation of hot spots, may be used to prioritize areas for radon screening.

1. Introduction

Radon (^{222}Rn) is a radiative carcinogenic gas naturally released from rocks and soils (U.S. Environmental Protection Agency, 2016; World

* Corresponding author at: 38 Peachtree Center Avenue, Atlanta, GA 30303, United States of America.
E-mail address: ddai@gsu.edu (D. Dai).

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Health Organization, 2016). Radon exposure is estimated to cause approximately 21,000 lung cancer deaths per year in the United States (U.S. Environmental Protection Agency, 2003) and 3 to 14% of all lung cancer deaths worldwide (World Health Organization, 2016). Residential exposure to radon is the second greatest cause of lung cancer after smoking and the leading cause of lung cancer among non-smokers (Darby et al., 2005; Lantz et al., 2013; McCarthy et al., 2012; Torres-Duran et al., 2016). Despite the prevalence of inexpensive radon testing methods, testing rates among dwellings remain low (Stauber et al., 2017; Zahnd et al., 2018). Therefore, it is necessary to identify high-risk households to prioritize outreach campaigns and testing.

^{222}Rn, as the product of the decay of radium-226 (^{226}Ra), is one of three natural radon isotopes and the only one that poses a health risk (Drolet et al., 2013). Both ^{222}Rn and ^{226}Ra are daughter elements of uranium-238 (^{238}U). Indoor radon comes primarily from three sources: underlying bedrock (Ielsch et al., 2010; U.S. Environmental Protection Agency, 2016), well water (Martins et al., 2013; Ravikumar et al., 2014), and building materials (Cosma et al., 2013; Kim and Yu, 2014). In particular, underlying bedrock is the major source of indoor radon (U.S. Environmental Protection Agency, 2016). Atmospheric radon levels are expressed in picocuries per liter (pCi/L) in the United States and in SI units of becquerel per cubic meter (Bq/m^3) in other countries. There is no safe level of radon. World Health Organization recommends a reference level of 100 Bq/m^3 to minimize health hazards from indoor radon exposure, and this reference level should not exceed 300 Bq/m^3 (World Health Organization, 2009). The U.S. Environmental Protect Agency (EPA) suggests 4 pCi/L (148 Bq/m^3) as the action level for remediation (National Research Council, 1999).

The bedrock and soil containing ^{238}U underneath a structure impacts the amount of geogenic ^{222}Rn, which in turn influences indoor radon levels. Underlying geologic formations of granite, gneiss, or some sediments have high ^{238}U levels, with granite being the most potent (Farah et al., 2012; Minda et al., 2009; Park et al., 2001). Additionally some sedimentary rocks (e.g., carbonate rocks) or soil with high permeability may increase migration of radon (Buttafuoco et al., 2010; Kitto and Green, 2008; Kropat et al., 2014). Fissures, crevice and cracks in rocks may provide focused gas transport conduits to the surface. Therefore, fracture density and degree of openness are positively associated with radon potential (Rafique et al., 2012; Wu et al., 2003). Gamma radiation results from the decay of some radioactive elements and has been shown to have a direct relationship to soil ^{226}Ra (Wilford, 2012; Wilford and Minty, 2006). Therefore, mapping fault, fractures, and gamma radiation have potential to estimate radon concentrations.

There are many housing factors that have large impacts on indoor radon levels. Many studies demonstrate that foundations have an effect on indoor radon particularly at the lowest levels of a residence (Barros-Dios et al., 2007; Geiger and Barnes, 1994; Kropat et al., 2014), but the findings are inconsistent. Having a basement or semi-basement foundation are reported to have increased levels of radon, compared to homes with only concrete slab foundations where dwellings are in direct contact with the ground (Alghamdi and Aleissa, 2014; Kitto and Green, 2008). Other studies reported higher radon levels in dwellings with slabs rather than those with a basement or crawlspace (Andersen et al., 2007; Borgoni et al., 2013; Demoury et al., 2013). Building materials including radium content and material porosity may also contribute to indoor radon accumulation (Borgoni et al., 2014; Franco-Marina et al., 2003). Studies suggest single-story or freestanding houses have elevated indoor radon concentrations compared to upstairs rooms in multi-story homes or apartment buildings (Brauner et al., 2013; Lorenzo-Gonzalez et al., 2017; Zhang et al., 2007). But this elevation may result from the tests at lower levels in houses (basements, kitchens, and dens) close to the ground before radon decays and migrates upward (Borgoni et al., 2013; Demoury et al., 2013). Some studies suggested that older homes tend to have higher radon concentrations due to cracks and holes in flooring and the foundations (Barros-Dios et al., 2007; Borgoni et al., 2014), but housing age alone is not a predictor of radon (U.S. Environmental Protection Agency, 2016). Heating and ventilation systems may influence radon accumulation as well due to the vagaries of air exchange with outside environment (Lugg and Probert, 1997).

Although the role of housing and geological factors in radon levels has been widely documented in many countries, their confluent impact on indoor radon remains unclear, and thus warrant further investigation. Several studies that included lithology, fault, or gamma radiation in their research (Berens et al., 2017; Drolet et al., 2014; Ielsch et al., 2010; Minda et al., 2009) did not consider the contribution of housing factors. Others (e.g., Barros-Dios et al., 2007; Kitto and Green, 2008) explored the relationship between housing characteristics and indoor radon, but did not examine geological factors. Some studies (e.g., Demoury et al., 2013; Hauri et al., 2012; Hunter et al., 2009; Smith and Field, 2007) considered both factors; yet geological units in these analyses were aggregated at national or regional levels and may not have shown details relevant to analysis at the county or even finer scale. Of the studies in the United States, majority focused on the northern states (e.g., Breysse et al., 2011; Farah et al., 2012; Harley et al., 2011; Kitto and Green, 2008; Mitchell et al., 2016; Shendell and Carr, 2013; Smith and Field, 2007; Steck, 2009; Vinson et al., 2008; Zahnd et al., 2018). There is dearth of information hitherto pertaining to the impact of housing and geology on indoor radon in the southern states where warmer climates prevail. As important as these factors may be, methods used to investigate their impacts have been challenging. The primary objective has been to gain insight into the risk factors associated with indoor radon. As in the present work, various statistical approaches, such as linear regression and log-linear regression models (e.g., Fojtikova et al., 2011; Hauri et al., 2012) or mixed-effect regression and Bayesian methods (e.g., Borgoni et al., 2014; Kitto and Green, 2008), have been used to identify these risk factors. Spatial techniques using Geographic information systems (GIS) have been mostly used to map radon distributions (e.g., Cinelli et al., 2011; Harnapp et al., 1997). Cluster detection approaches, rather than heat maps, are effective in identifying hot spots of soil contaminants (Lee et al., 2006; McClintock, 2012), diseases (Bautista et al., 2006; Lai et al., 2004), crimes (Grubesic, 2006; Nelson et al., 2001), among others. However, little attention has been paid to radon clustering. These hot spots will suggest locations of statistically significant high values of indoor radon as an evidence to inform program decisions and strategically target specific areas for intervention and prevention. Inspired by the importance of both factors and current methodological need, this present study is proposed to examine the spatial variation in indoor radon and its association with both housing and geological factors in a densely populated region in the southeastern United States.

The objectives of this study are to (1) evaluate spatial variation in indoor radon concentration in DeKalb County in Metropolitan Atlanta of Georgia, USA using GIS and clustering detection techniques; and (2) assess the relationship of indoor radon concentrations with housing characteristics and geology using logistical regression modeling. The contribution of this research is twofold. First, it helps to understand the extent and severity of elevated indoor radon in the study area. Areas where high levels of radon are clustered may be prioritized as the targets of a surveillance campaign. Second, it identifies risk factors related to housing characteristics and geology. These factors may provide information to community residents when they consider their homes for screening tests.

2. Data and methods

2.1. Study area

The study area is DeKalb County (Fig. 1) of Georgia, United States. DeKalb County is the third most populous county in the State of Georgia, with an estimated population of 740,321 according to the

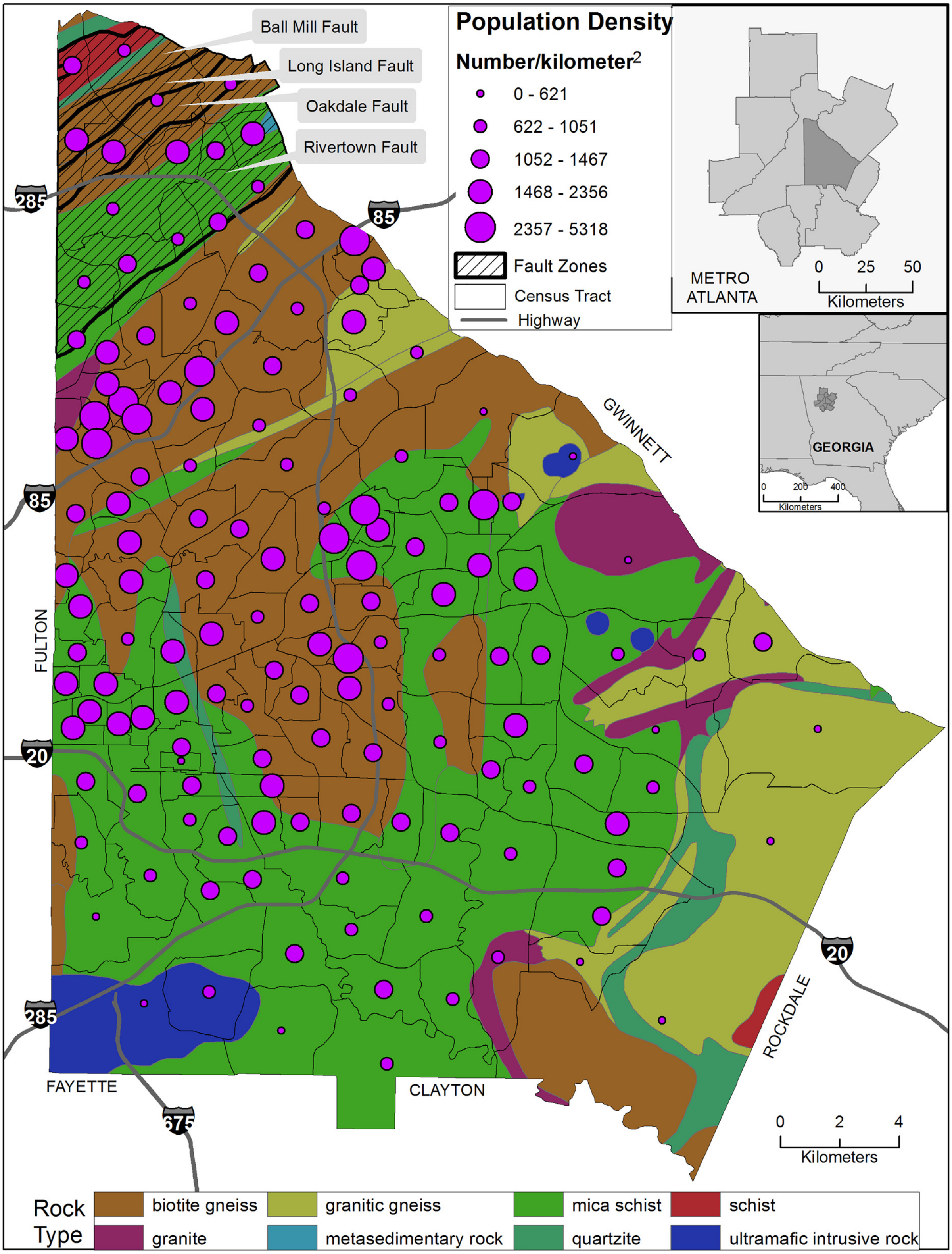

Fig. 1. Study area (DeKalb County, Georgia, USA) with population density by dot size.

2016 Census Statistics (U.S. Census Bureau). It spans over 694 km^2 as one of the core counties in the Atlanta metropolitan statistical area. DeKalb County has high geogenic radon potential and is classified as Zone 1 by the U.S. Environmental Protection Agency with predicted average indoor radon screening levels >148 Bq/m^3 (https://geopub.epa.gov/Radon/).

2.2. Radon data

This study obtained 6757 indoor radon records from three databases: 4302 from the DeKalb County Board of Health (DCBOH) radon surveillance system (1993–2015), 2254 from a private vendor, Air Chek, Inc. (1990–2015), and 201 test results from a radon study conducted by Georgia State University (GSU) in 2015 funded by the National Institutes of Health (NIH). This study follows a protocol approved by the GSU Institutional Review Board (IRB No. H14542). All three sources were based on short-term tests (2–7 days) and are detailed below.

The first data source was from the Environmental Health Division at the DeKalb County Board of Health (DCBOH). DCBOH manages a radon surveillance program that has been in operation since 1993 (https://www.dekalbhealth.net/envhealth/radon2/). The program is voluntary to any home owner in the county, providing free tests if the owner makes the request. Two tests were administered in each residence: one test was placed in the lowest level of the home, and the other in a higher level of the dwelling. The tests used cylindrical canisters containing activated charcoal, which absorbed radon over the course of approximately 48 h. The second data source (1990–2015) was from Air Chek, a private vendor. Residents voluntarily chose Air Chek test kits, which are available at home supplies stores, to test their dwellings. Air Chek test kit is an envelope containing activated charcoal, hanging on interior walls for 3 to 7 days. The third data set was collected in 2015 by GSU radon research team to assess homes in under tested areas on a voluntary yet randomly selected basis. The data were collected primarily using Air Chek test kits. Four homes were tested using both Air Chek envelopes and canisters used by DCBOH and the average differences between the two types of test kits were 27 Bq/m^3. Both canisters and Air Check test kits were shipped to manufacturers' lab for analysis and results. All measurements included in this study were obtained via voluntary sampling. Therefore, it is unknown if volunteers for radon measurements or those paying for radon measurements were more aware of radon because they live in risk areas. Therefore it is acknowledged that the radon measurements might be overestimated in some portions of the study area.

The raw data sets from DCBOH and Air Chek were reviewed for discrepancies, duplicate entries and data omissions. If multiple tests were placed simultaneously, only the readings at the lowest level of a home were retained. Additionally, only the initial test result from a home was included if multiple tests were conducted. Follow-up tests at times were conducted either for confirmation or for re-testing after remediation. All tests with zero readings were excluded to be consistent with a previous study (Berens et al., 2017). Because radon is present everywhere given the naturally radioactive breakdown of uranium in soil, rock, and water (U.S. Environmental Protection Agency, 2016), a value of zero may result from the radon values lower than the sampler's detection limit which may be as low as 7.4 Bq/m^3 on the dry condition (Alvarez, 1990). It may also result from sampling or data recording errors. Finally, test results lacking precise location data were excluded from the analysis. In total, we retained 5518 records for our analysis.

2.3. Housing data

The housing characteristics of a tested residence were compiled based on the original test forms except heating/cooling information, which was obtained from the DeKalb County Tax Assessor database. Because the Air Chek data lacks information on housing conditions, the subsequent housing related analysis was only based on the DCBOH and the GSU data sets. The housing data (Table 1) includes the age of a home, foundation type, external building material type, construction type, and heating/cooling system.

2.4. Geological data

The impact of geology on radon levels was assessed from three perspectives. First, we obtained underlying bedrock types in the study area (Fig. 1) from the United States Geological Survey (https://mrdata.usgs.gov/geology/state/). No radon samples were collected on metasedimentary rock, so this type was removed from analysis. Second, we digitized the four fault zones located in the study area (Fig. 1)—Ball mill fault zone, Long island fault zone, Oakdale fault zone, and Rivertown fault zone—from the National Geologic Map Database (Higgins et al., 2003) because the degree of fracture openness is highly associated with radon gas (Wu et al., 2003). Therefore, faults and fractures are a conduit for radon to migrate to the soil and then the surface. By overlaying the test sites to the fault map, we dichotomized the radon results using a binary code (1/0) to determine if a test site was located in the fault zones. The third data source was based on gamma radiation data. We used gamma data to estimate background radon potential because inclusion of gamma emission rates with bedrocks improved radon potential estimation (Berens et al., 2017). Gamma emission samples ($n = 402$) were collected in undisturbed areas in 2015. Detailed information about the gamma data is available in Berens et al. (2017).

Table 1
Chi-square test of radon levels in relationship to housing and geology.

	Pearson chi-square		Pearson chi-square
Foundation type		Exterior materials	
Basement	62.51**	*Brick*	11.92**
Crawlspace[a]	64.11**	*Block*	1.87
Slab[b]	4.5*	*Frame*	10.25**
Basement/Crawlspace	0.67	*Brick/Frame*	1.12
Basement/Slab	10.21**	*Brick/Block*	2.77
Crawlspace/Slab	3.43	*Frame/Block*	0.91
Heating/cooling		Rock type	
No heating	4.28*	*Biotite Gneiss*	0.02
Non central heat	0.08	*Granite*	0.39
Central heat	0.39	*Granite Gneiss*	0.19
Central heat/AC	0.29	*Mica Schist*	0.18
Construction type		*Quartzite*	0.05
Multi-story	0.86	*Schist*	0.08
Ranch	0. 2	*Ultramafic Intrusive*	1.16
Split-level	3.11	Fault zone	8.7**
Multi-story/split-level	0.68	Age[c]	0.05**
Ranch/multi-story	0.59	Gamma[c]	0.03
Ranch/split-level	0.29		

[a] Crawlspace - a hollow area between the ground and the first floor, up to several meters high.
[b] Slab - a thick concrete layer with direct contact to the ground, a common foundation in southern states with warm climates.
[c] Pearson Correlation coefficient and significance after natural log transformation.
* Significance at a = 0.05 level.
** Significance at a = 0.01 level.

2.5. Spatial variation in radon

Spatial variation in indoor radon concentrations was evaluated using local Getis-Ord Gi* statistic (Getis and Ord, 2010; Ord and Getis, 1995) in ArcGIS 10.6 (ESRI, Redlands, CA, USA). This method examined whether houses with either high or low radon levels clustered spatially. The Gi* statistic returned a z-score for each house to evaluate the statistical significance of the clustering. Statistically significant positive z-scores suggest intense clustering of high radon levels, thus indicating hot spots. Ord and Getis (1995) demonstrated the statistic's flexibility and distributional properties using a series of simulations. Its reliability was discussed previously (Anselin, 1995; Anselin et al., 2006) and further elaborated in Anselin (2018). This method has been widely used in various disciplines such as public health (e.g., Cartabia et al., 2012; Maciel et al., 2010) or environmental science (e.g., de la Torre et al., 2012; Garrah et al., 2015; Kelly-Hope et al., 2009) to identify hot spots of interest. This test requires an input of a distance matrix to conceptualize the spatial relationship between sampling sites. To evaluate the clustering consistency, we first used a fixed distance band (1.74 km optimized by ArcGIS) when computing the distance matrix. We then alternated the band (i.e., 0.87 and 3.48 km) to compare the results. Last, we tested the other two distance-matrix methods, inverse distance and inverse distance squared, respectively.

2.6. Spatial variation in gamma

A continuous surface of interpolated gamma flux for the study area was generated using Empirical Bayesian Kriging (EBK) method. Radon tests were then associated with predicted gamma values. Kriging is one of several methods that use samples to interpolate values of a variable over a continuous space. Unlike deterministic interpolation methods such as Inverse Distance Weighted Interpolation, Kriging preserves spatial variability that would be lost using deterministic methods. Besides, it provides standard errors of the prediction which is unique to many other interpolation methods (Krivoruchko, 2011). Compared to other kriging methods, EBK automatically calculates parameters through subsetting and simulations to obtain accurate results and accounts for the error introduced by estimating the underlying semivariogram (Krivoruchko, 2012). To account for the uncertainty inherent in modeling, we resized the EBK result using the cell size equal to the average nearest neighbor of the gamma sampling locations, which is consistent with the previous study (Berens et al., 2017). Predicted gamma values at dwellings tested for radon were then extracted.

2.7. Joint analysis of radon in relationship to housing and geology

To prepare for the analysis of radon in relationship to housing and geology, natural log transformation was taken to normalize the raw readings of radon, housing age, and gamma readings because of the aberrant distributions in the raw data (Fig. 2). Box and whisker plots were graphed to assess difference in radon levels when each of the housing and geological characteristics was considered, which included foundation type, external material type, construction type, heating system, rock types, and fault zones.

The analysis included chi-square tests, bivariate correlation coefficient analysis, and logistic regression. A binary category (1/0) was used to indicate if radon in a house was above 148 Bq/m^3. Variables describing housing and geological characteristics were converted into binary (1/0) determined by the presence/absence of a particular factor. A two sided test at the 0.05 significance level was used to determine the statistical significance. Chi-square tests were used to examine the association between each variable (except home age and gamma measure) and radon outcome. Bivariate correlation analysis was conducted on home age and gamma measure to test the significance of their relationships with radon concentrations.

In the logistic regression model, the dependent variable was dichotomized based on the action level, which is ≥148 Bq/m^3 (coded as 1) or <148 Bq/m^3 (coded as 0). Independent variables with two responses were binary coded (1/0) and independent variables with more than two responses have absence of a factor as the reference group except that gamma and housing age were continuous variables. For example, when basement type was evaluated, all homes without a basement served as the reference category. Although radon levels were continuous, dichotomizing them using the action level (148 Bq/m^3) suggested if dwellings needed corrective measures to reduce radon exposure. This study, therefore, modeled the risk of having elevated levels of radon when a particular type of factors was present. The Homer & Lemeshow goodness of fit test was used to evaluate the fitness of the model and the Nagelkerke R Square was used to measure the percentage of the radon variation explained by the model (Long, 1997). A P value >0.05 suggests that the model fits well. All statistical tests were conducted using IBM SPSS Statistics version 25 (IBM Corp, Armonk, NY, USA). The logistic regression test initially used the enter method, a procedure to enter all independent variables in the model in a single step. To verify how sensitive the results are due to the method selection, the test was repeated using the method of backward elimination (likelihood ratio), which relies on the probability of the likelihood-ratio statistic using the maximum partial likelihood estimates (IBM Corporation, 2017).

3. Results

3.1. Spatial variability of indoor radon

The radon tests spatially varied across the county and were concentrated in the central and northern areas (Fig. 3). There was a noticeable decrease in testing in the southwestern and southeastern portions of the county. These two areas were more sparsely populated than the rest of the county (Fig. 1). The radon concentrations in this study ranged from 3.7 to 1594.7 Bq/m^3 with an average level of 69.6 Bq/m^3 and a standard deviation of 75.4.

Mapping spatial variation in radon levels (Figs. 3 and 4) depicted a swath of elevated readings (≥148 Bq/m^3) formulating radon hot spots in the north and in the middle of the county (circles in Fig. 4). Elevated readings were also present sparsely in the southern portion of the study area and formulated two hot spots on the southeast area. The clustering did not change significantly when we alternated the distance matrix calculations in Getis-Ord Gi* tests.

3.2. Radon and geology

A visual comparison of the rock type map (Fig. 1) with radon map (Fig. 3) and radon hot spots (Fig. 4) did not reveal a clear relationship between radon and rock types. The chi-square tests results, which ranged from 0.03 to 1.14 in Table 1, suggested that the correlation between each rock type and indoor radon concentrations was statistically insignificant. The box plot (Fig. 5a) did not visually indicate higher radon concentrations in a particular rock type either.

The EBK prediction revealed that high gamma values existed in the north, the central, and the southeastern portions of the county (Fig. 4),

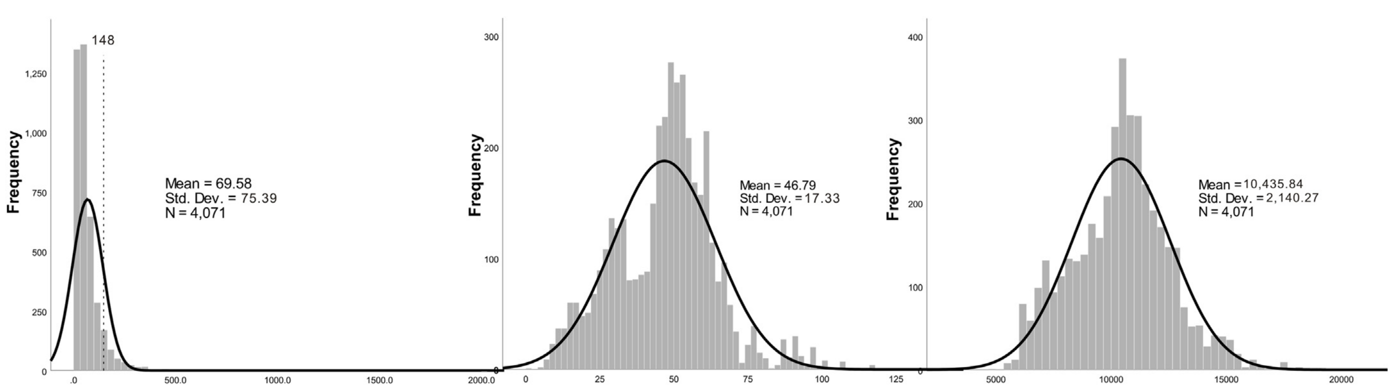

Fig. 2. Histograms of radon (a), housing age (b), and gamma ray (c). Note the dash line in (a) is the EPA's action level of 148 Bq/m^3.

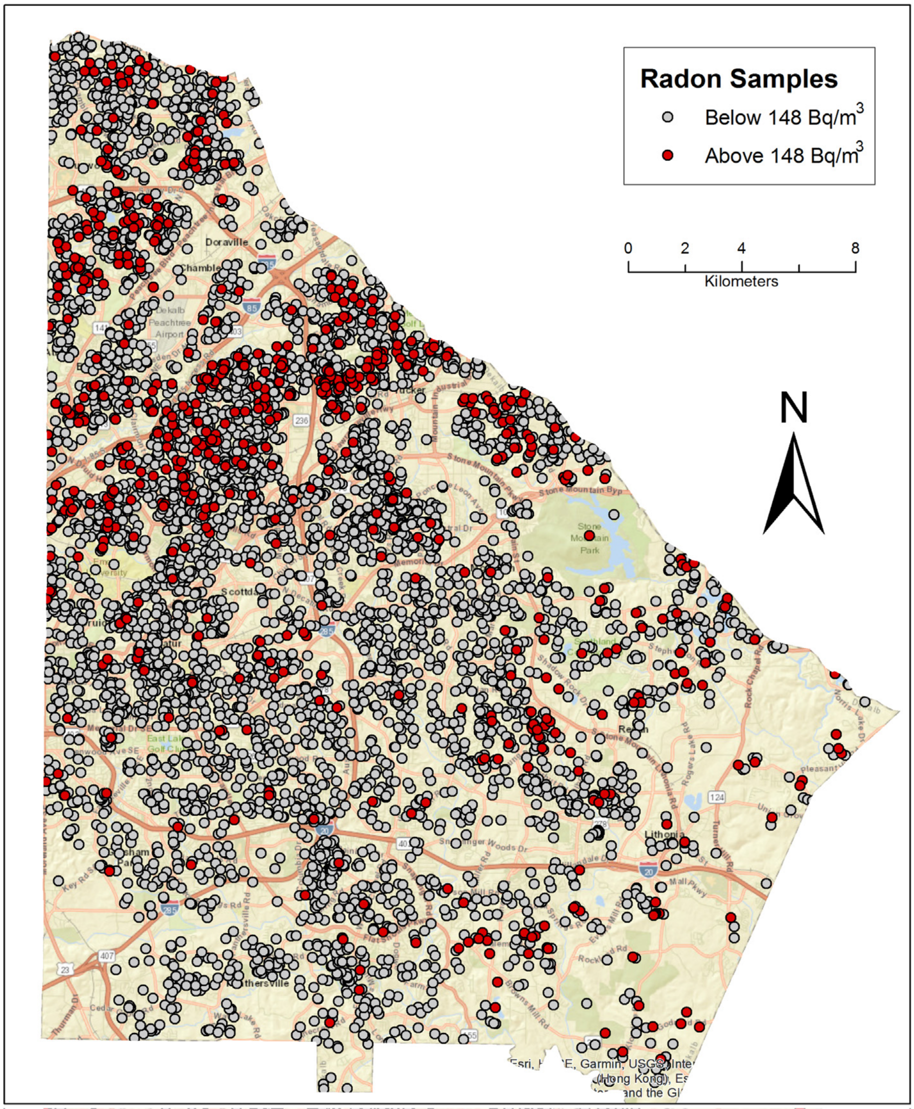

Fig. 3. Sample locations and corresponding radon levels in the study area.

where high radon concentrations were found. The southeastern area presented extremely high gamma emissions yet were less populated (Fig. 1) compared to the rest of the county. There were very low gamma levels in the southwestern part of the county, where no high radon concentrations were present. The Pearson correlation coefficient (Table 1), however, did not suggest a statistically significant linear relationship between gamma and radon.

Overlaying the fault zone map with radon (Fig. 4) suggested that elevated radon levels and radon hot spots were present in the fault zones. The box plot (Fig. 5b) suggested that dwellings in the fault zones had higher radon concentrations than these outside the fault zones, which is supported by the chi-square test result (8.7 in Table 1) reporting a statistically significant correlation between elevated radon levels and the fault zones.

3.3. Radon and housing characteristics

Descriptive statistics using box plots (Figs. 6–7) suggested that indoor radon levels varied across different housing characteristics, which is in line with the Pearson chi-square results (Table 1) ranging from 0.08 to 64.11. Results from Table 1 suggest that elevated radon levels (≥ 148 Bq/m^3) were statistically significantly correlated ($P <$ 0.05) with houses with basements (62.51), crawlspace (64.11), slab (4.5), basements mixed with slab (10.21), absence of heating systems (4.28), brick (11.92), and frame (10.25). Older homes were statistically significantly more likely to have higher levels of radon, as indicated by the Pearson correlation coefficient of 0.05 in Table 1.

3.4. Confluent impact of housing and geology

When the logistic regression was used to model the confluent impact of all housing and geological variables, the Homer & Lemeshow test of the goodness of fit suggested the model was a good fit to the data as $P = 0.37$ (>0.05). A Nagelkerke R Square value of 0.076 revealed that the model explained roughly 7.6% of the variation in the action level of radon. Consistent with the chi-square tests, the logistic regression model (Table 2) suggested that elevated radon risks existed in houses built in the fault zones and without crawlspace foundation. In particular, after controlling for the other variables, houses in the fault zones had statistically significant higher risks (by 41%) of having radon levels above 148 Bq/m^3 compared to those outside the fault zones (odds ratio of 1.41 and $P < 0.05$). Crawlspace foundation or combination of crawlspace and slab appeared to be protective (odds ratios of 0.15 and 0.17, respectively in Table 2 and P < 0.05). Their odds ratios suggested that the risk of having radon levels above 148 Bq/m^3 decreased approximately 85% or 83% if a house had a foundation of crawlspace or a

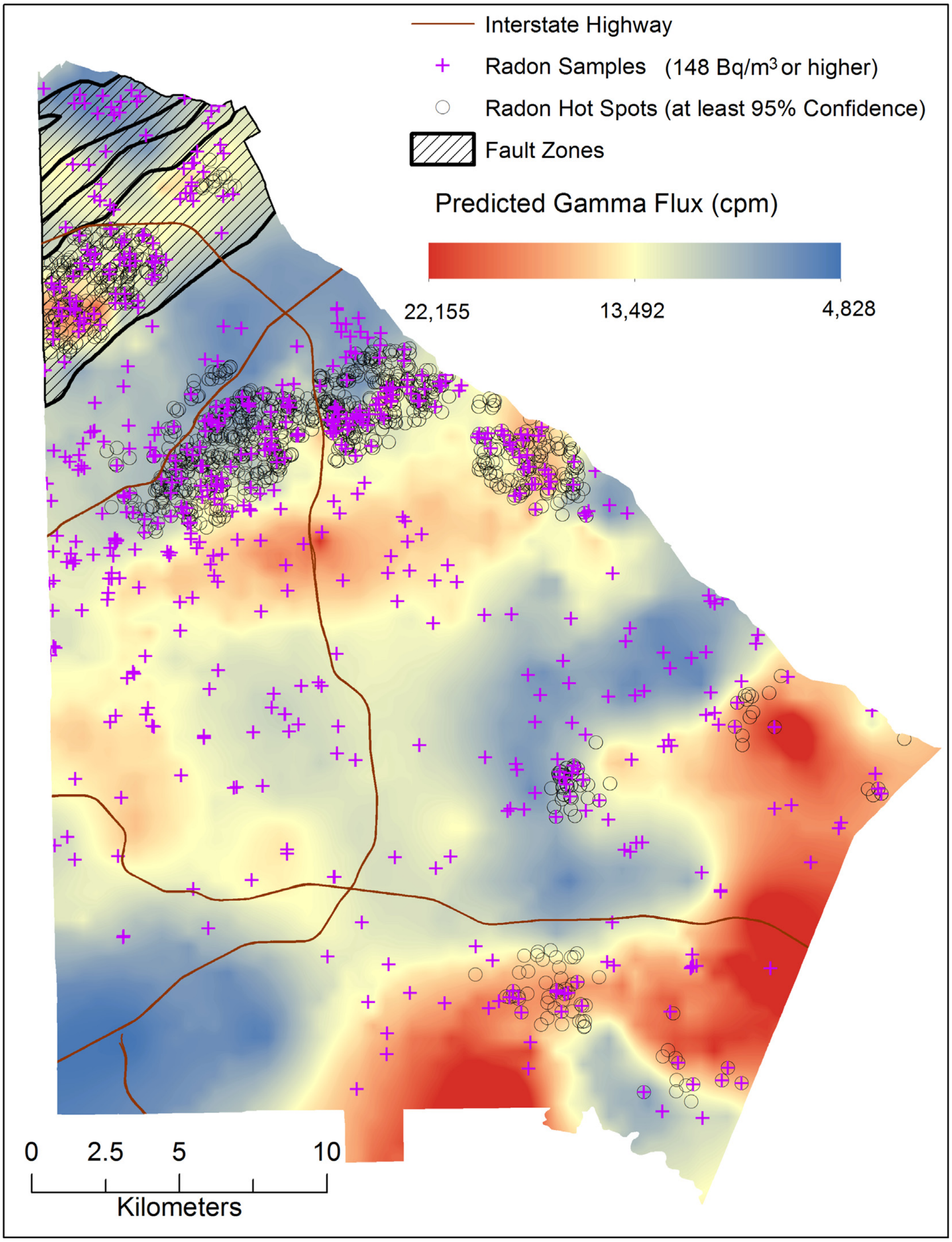

Fig. 4. Gamma prediction and radon variation.

combination of slab and crawlspace, respectively. Conversely compared to the bivariate correlation coefficient analysis, houses with higher background gamma radiation presented significantly higher risks of having radon levels above 148 Bq/m^3. The change in correlation may result from dichotomizing radon levels in the logistical regression model. Influence of basement foundation became statistically insignificant when the rest of variables were controlled. Odds ratios cannot be interpreted in isolation from the sample size. A closer examination of the data suggests that houses in the study area commonly have crawlspace ($n = 1248$ or 30.7%) but not a combination of crawlspace and slab ($n = 89$ or 2.2%). Therefore interpreting the impact of the combination of crawlspace and slab on indoor radon takes caution. The variables of brick, frame, no heating, or age, identified as statistically significant variables in bivariate analysis (Table 1), were not statistically significant in relationship to the action level of radon when all variables were considered in the logistical regression model (Table 2). When the backward elimination method was chosen, the results were consistent except that the presence of the two variables, slab and brick, became significantly associated with the action level of radon.

4. Discussion

The motivation for this study—that housing characteristics and geology influence indoor radon—is based on the idea that housing factors added a large degree of variation in radon concentrations in homes with varying geological contexts. Our study in part supports this

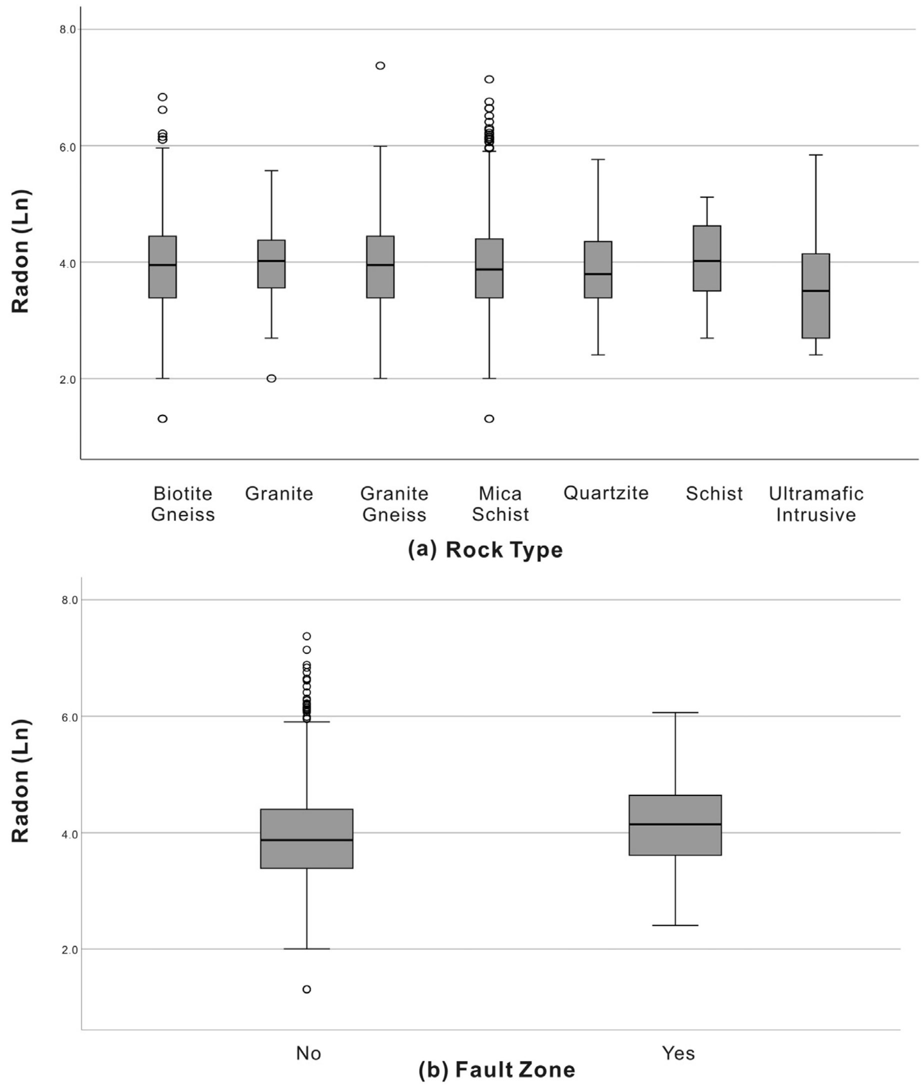

Fig. 5. Box plots of radon with rock type (a) and fault zone (b).

hypothesis. We postulated that various housing and geological features would be influential in explaining elevated levels of radon. In relating radon to housing and geological characteristics, we demonstrated that the indoor radon level was more likely to exceed the action level when a house was built in the fault zone (1.41 times increased risk). Presence of a crawlspace foundation or a combination of crawlspace and slab was associated with a decreased likelihood of having radon concentrations above 148 Bq/m^3. Background gamma radiation had a significant association on indoor radon when the other covariates were controlled, but this association was not statistically significant when gamma radiation was considered alone. On the contrary, association of housing basement, brick, frame, and without heating was found to be significant in the chi-square test but became insignificant when the other factors were controlled. Neither rock types underneath nor building types were significant predictors of elevated indoor radon levels.

4.1. Housing impact on radon

These findings provide an alternative view of residential radon risks with detailed housing data after accounting for geology using radon records spanning over two decades. The results of this study suggest that housing characteristics, when geology is considered, can explain some, albeit small variations of indoor ^{222}Rn. The importance of a basement on indoor radon is well documented (Alghamdi and Aleissa, 2014; Barros-Dios et al., 2007). Consistent with previous studies, a house with a basement was more likely to have radon above the action level when other factors were not controlled. Yet this association became insignificant after the rest of the variables were controlled and the direction of the association was changed. Our data does not describe basement conditions and thus this study was unable to determine if a basement is ventilated or remodeled to reduce radon entry. Therefore, the association between basement and the action level of radon when geological and other housing covariates are controlled requires additional research in other areas. For empirical studies of dwelling impact on radon, crawlspace foundation has received less attention. This study gives unique insight into the protective role of crawlspace. A crawlspace provides a space beneath the building to protect the house from moisture coming up from the soil (Tunno et al., 2017). Such protection may reduce radon moving into dwellings.

4.2. Geological influence on radon

This study found being in fault zones rather than rock types underneath dwellings was a strong predictor to determine if indoor radon concentrations exceeded the action level. Faults and fractures affect transportation of radon to the surface of earth's crust, which may explain this study's finding. This is in line with previous research reporting

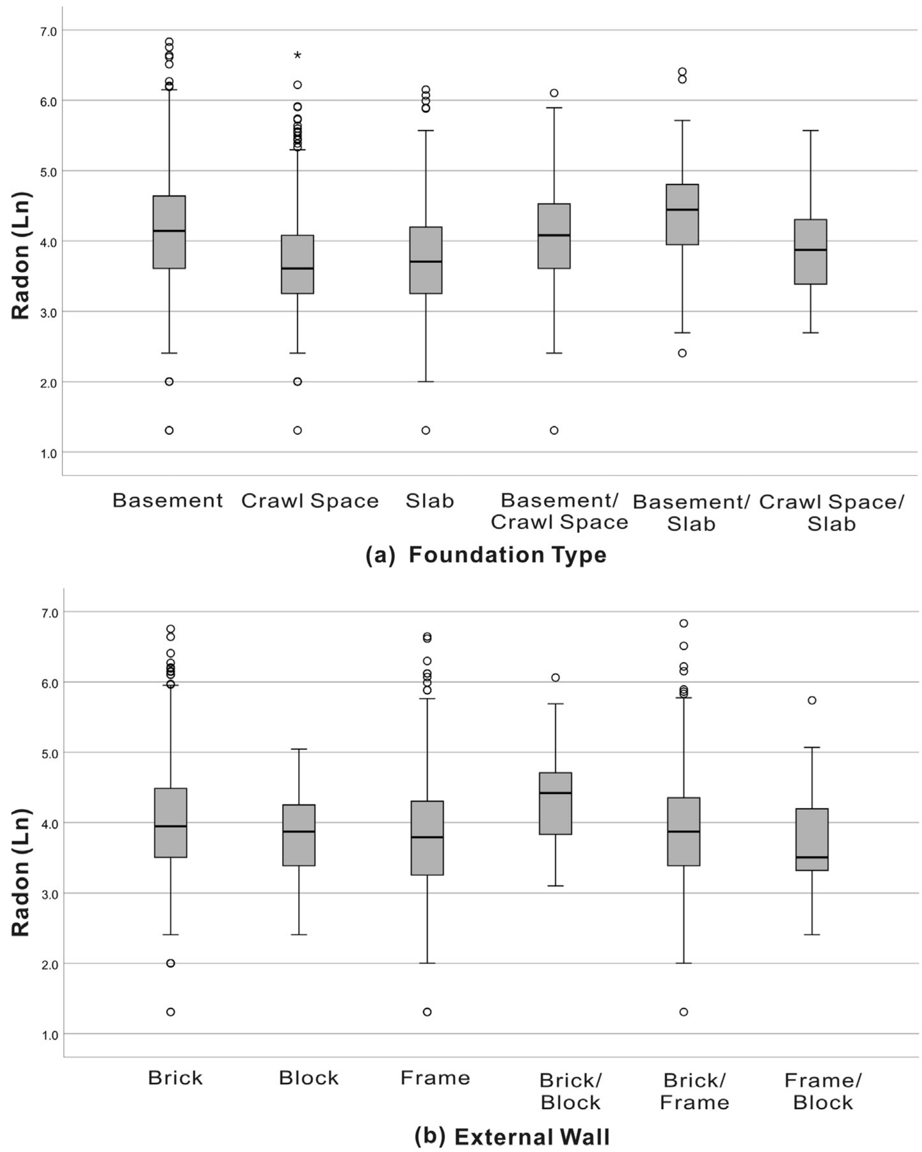

Fig. 6. Box plots of radon with foundation type (a) and external wall type (b).

that the density and openness of fractures may be correlated to radon emission (Rafique et al., 2012; Wu et al., 2003). The insignificant correlation between rock types and indoor radon was possibly attributed to the fact that although there is some lithologic across the study area, nearly all the underlying rocks are felsic igneous or metamorphic rocks, all potentially uranium-bearing, with the exception of the small area of ultramafic igneous rocks. In situ gamma measures in this study serve as a proxy for geogenic radon potential, but the weak correlation between predicted gamma flux and indoor radon indicates that predication using gamma measures alone is unlikely to be successful. Despite that a previous study (Berens et al., 2017) reported a significant correlation between gamma and indoor radon when the gamma data was aggregated to 9 km^2 resolution, this finding was subject to the scale problem, which is a typical modifiable areal unit problem (Gehlke and Biehl, 1934; Opensh-aw, 1984).

4.3. Confounding impact of housing and geology on radon

Housing characteristics and underlying geology are important factors of indoor radon, however, each house has a unique condition for radon transportation and accumulation because of the micro-level difference in construction quality, pressure difference, interior materials and ventilation of buildings (Derbez et al., 2018; Giri and Pant, 2018; Sas et al., 2017), among others. Therefore, the model in this study was able to predict only a small portion of radon variability. Given the complexity of these confounding factors, home testing using readily available radon kits is a straightforward option which is recommended by the U.S. Environmental Protection Agency (2016). Fault zone delineation in this study, in this regard, could help inform the county health professionals and the public where potential radon hazardous areas may exist for promoting home testing.

4.4. Implications of findings

The implications of our findings are twofold. First, the fault zones with the hot spots delineated from the analysis may provide geographic targets for the local and county health departments to inform the public of areas of potentially elevated radon levels. Radon awareness and risk perception of residential exposure have been exasperating (Hazar et al., 2014; Zahnd et al., 2018). Home radon test kits are approximately 10–20 US dollars in home supplies stores, and are free in the surveillance program in our study area. However, even though this area is designated as Zone 1, fewer than 7% of homes have been screened (Stauber et al., 2017). A state-wide study in Illinois reported <3% of homes

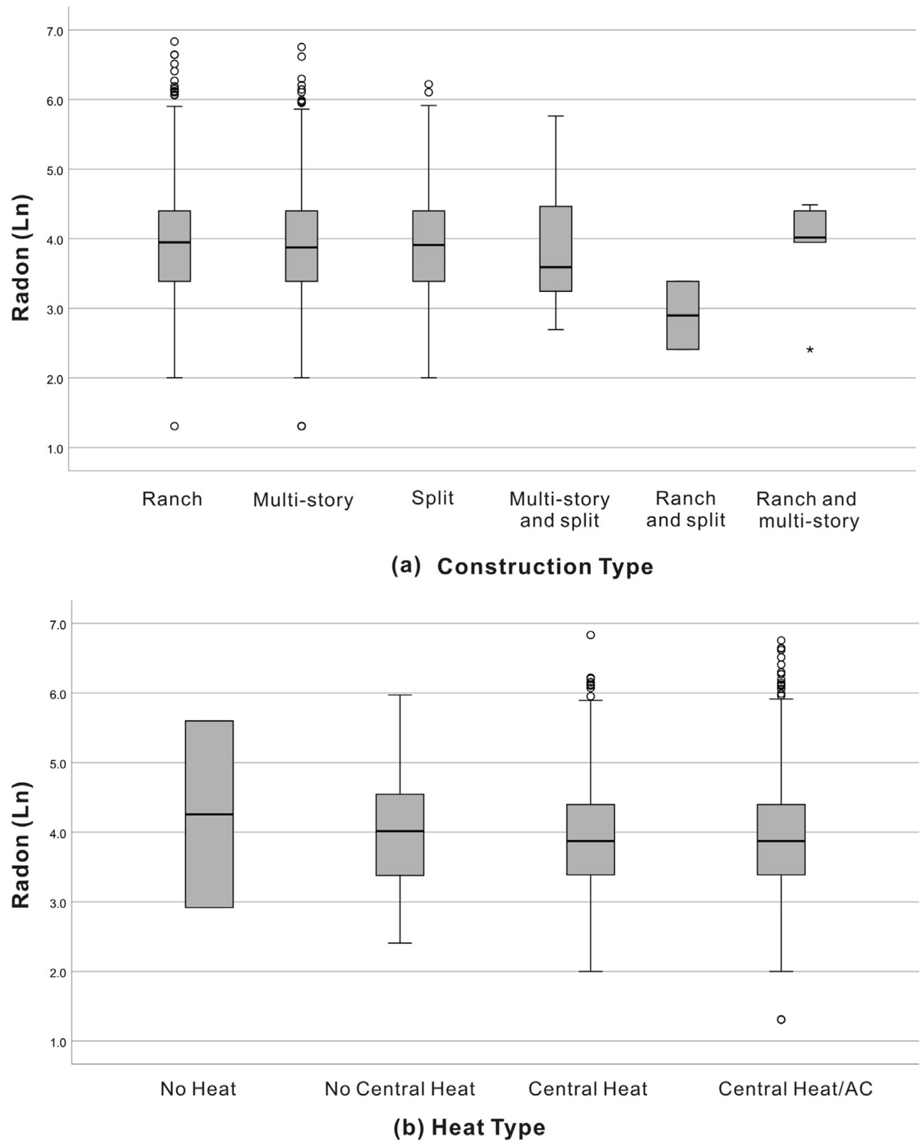

Fig. 7. Box plots of radon with construction type (a) and heating type (b).

screened in the same zone type (Zahnd et al., 2018). The fault zones and hot spot detection therefore may aid the development of geographically targeted interventions that promote radon awareness and testing.

The second implication is that housing characteristics interacting with geological factors, despite the small radon variation explained by the model, are influential in developing an indoor hazard. Existing houses in the fault zones, especially those without crawlspace foundations, suggest a strong need of radon screening there. New constructions, regardless of fault zones, would benefit from using radon resistant materials or radon screening given the high in situ gamma radiation in under-developed areas (Berens et al., 2017). The weak predictability of the model in this study suggests that other confounding factors may be mingled with the housing and geological features. Under these circumstances, increasing radon awareness and screening test rates may be a valuable way to reduce potential exposure.

Our study has several important limitations. First, the majority of the samples were self-selected because of opting for the test either through free service or paying for it. It is unclear if the owners were more aware of radon. Some areas may be under-sampled because of this self-selection nature and situations may vary. The tests thus may not accurately represent the situation across the region. Second, all of our measurements were based on short term activated charcoal adsorption detectors. These tests may serve as initial screening but are not as reliable as long-term alpha-track detectors (Ruano-Ravina et al., 2008; World Health Organization, 2009). The charcoal-based method only provides a good estimate of the average radon concentration over the testing period if changes in radon are small (World Health Organization, 2009). Besides, this method is affected by specific placement conditions. For example, Air Chek samplers shall be hung away from exterior walls, and canisters shall be placed away from granite countertops. These conditions in the DCBOH data and the Air Chek data could not be retrospectively verified. Third, seasonal and weather factors were not considered. Indoor radon concentrations fluctuate in different seasons (Faheem and Matiullah, 2007; Rafique et al., 2011). Difference in air circulation, indoor and outdoor air pressure, and ventilation will have subsequent impact on radon accumulation (Demoury et al., 2013; Smith and Field, 2007). Accounting for weather and seasonal factors requires the analysis of weather condition data during sampling periods. There are four weather monitoring sites in DeKalb County (https://www.weather.gov/ffc/obsitemap). Assigning weather conditions from these four sites and associating results to thousands of home radon measurements is possible. However, we did not conduct because of anticipated high uncertainty and large error values. Lastly, high-quality data pertaining to fractures, soil permeability, and soil

Table 2
Association between action level of radon, geology, and housing using logistic regression.

	B	S.E.	Exp(B)	C.I.
Foundation type				
Basement	−0.40	0.67	0.67	(0.18, 2,47)
Crawlspace	−1.92**	0.68	0.15	(0.038, 0.56)
Slab	−0.89	0.68	0.41	(0.11, 1.56)
Basement/crawlspace	−0.71	0.69	0.5	(0.13, 1.91)
Basement/slab	0.03	0.72	1.03	(0.25, 4.21)
Crawlspace/slab	−1.77*	0.88	0.17	(0.03, 0.96)
Exterior wall				
Brick	0.51	1.06	1.66	(0.21, 13.3)
Block	−0.75	1.47	0.47	(0.03, 8.42)
Frame	0.25	1.07	1.28	(0.16, 10.36)
Brick/frame	0.30	1.07	1.35	(1.66, 10.94)
Brick/block	0.77	1.19	2.16	(0.21, 22.41)
Frame/block	1.25	1.24	3.49	(0.31, 39.63)
Heating/cooling				
No heating	20.72	1.13E4	9.99E8	Not Available
Non central heat	18.34	1.13E4	9.26E7	Not Available
Central heat	18.88	1.13E4	1.59E8	Not Available
Central heat/AC	18.82	1.13E4	1.49E8	Not Available
Construction type				
Multi-story	−1.17	0.80	0.31	(0.06, 1.50)
Ranch	−0.92	0.80	0.40	(0.08, 1.93)
Split-level	−1.17	0.81	0.31	(0.06, 1.53)
Ranch/multi-story	−19.73	1.77E4	0	Not Available
Ranch/split-level	−19.45	2.82E4	0	Not Available
Rock type				
Biotite gneiss	−0.13	0.39	0.88	(0.41, 1.89)
Granite	−0.74	0.71	0.48	(0.12, 1.91)
Granite gneiss	−0.18	0.43	0.83	(0.36, 1.92)
Mica Schist	−0.10	0.39	0.91	(0.42, 1.95)
Schist	−1.11	1.10	0.33	(0.04, 2.82)
Ultramafic intrusive	−0.42	0.65	0.65	(0.18, 2.32)
Fault zone	0.34*	0.17	1.41	(1.02, 1.95)
Age (natural log)	0.012	0.13	1.012	(0.78, 1.31)
Gamma (natural log)	0.61*	0.29	1.84	(1.05, 3.21)

* Significance at a = 0.05 level; **Significance at a = 0.01 level; C. I.= Confidence Interval.

moisture may help to produce a comprehensive model. For example, our fault zones serve as a proxy of the fracture openness. But mapping fractures directly may be useful to understand the radon risks of each individual house. In addition, soil characteristics such as soil moisture can affect gamma flux (Grasty, 1997).

5. Conclusions

As a significant risk factor to lung cancer, radon exposure poses a marked health threat to the public. Understanding the confluent impact of housing characteristics with the context of underlying geology on indoor radon provides a proactive measure leading to potential action. This study analyzed the predictability of housing characteristics and geology to estimate indoor radon concentrations. Future studies may account for soil permeability and seasonality and examine their interactions with housing characteristics. This research is conducted in a single county where the entire county is considered as Zone 1. While the findings provide insights into the confluent impact of housing and geology on indoor radon within the Piedmont physiographic province, where the study area is located, future research may benefit from expanding the research to other physiographic provinces to examine if similar impact exists. Should a larger radon data set covering a broader region be available, a hierarchical model may provide more insight into the contribution of geology. Because of difference in building characteristics and geology, similar studies shall be conducted in other regions or countries to investigate the confluent impact of these factors. Efficient prediction coupled with comprehensive surveillance would protect the public from the potentially fatal effects of prolonged and silent radon exposure.

CRediT authorship contribution statement

Dajun Dai: Project administration, Conceptualization, Methodology, Formal analysis, Software, Data curation, Writing - original draft, Visualization, Supervision, Validation, Writing - review & editing, Funding acquisition. **Fredrick B. Neal:** Data curation, Formal analysis, Writing - review & editing. **Jeremy Diem:** Writing - review & editing. **Daniel M. Deocampo:** Writing - review & editing. **Christine Stauber:** Writing - review & editing. **Timothy Dignam:** Writing - review & editing.

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References

Alghamdi, A.S., Aleissa, K.A., 2014. Influences on indoor radon concentrations in Riyadh, Saudi Arabia. Radiat. Meas. 62, 35–40.

Alvarez, J.L., 1990. Analytical Procedures and Comparisons. Available at https://www.radon.com/radon_analysis/, Accessed date: 1 March 2019.

Andersen, C.E., Raaschou-Nielsen, O., Andersen, H.P., Linda, M., Gravesen, P., Thomsen, B.L., et al., 2007. Prediction of Rn-222 in Danish dwellings using geology and house construction information from central databases. Radiat. Prot. Dosim. 123, 83–94.

Anselin, L., 1995. Local indicators of spatial association - LISA. Geogr. Anal. 27, 93–115.

Anselin, L., 2018. A local indicator of multivariate spatial association: extending Geary's C. Geogr. Anal. https://doi.org/10.1111/gean.12164.

Anselin, L., Syabri, I., Kho, Y., 2006. GeoDa: an introduction to spatial data analysis. Geogr. Anal. 38, 5–22.

Barros-Dios, J.M., Ruano-Ravina, A., Gastelu-Iturri, J., Figueiras, A., 2007. Factors underlying residential radon concentration: results from Galicia, Spain. Environ. Res. 103, 185–190.

Bautista, C.T., Chan, A.S.T., Ryan, J.R., Calampa, C., Roper, M.H., Hightower, A.W., et al., 2006. Epidemiology and spatial analysis of malaria in the Northern Peruvian Amazon. Am. J. Trop. Med. Hyg. 75, 1216–1222.

Berens, A.S., Diem, J., Stauber, C., Dai, D.J., Foster, S., Rothenberg, R., 2017. The use of gamma-survey measurements to better understand radon potential in urban areas. Sci. Total Environ. 607, 888–899.

Borgoni, R., Tritto, V., de Bartolo, D., 2013. Identifying radon-prone building typologies by marginal modelling. J. Appl. Stat. 40, 2069–2086.

Borgoni, R., De Francesco, D., De Bartolo, D., Tzavidis, N., 2014. Hierarchical modeling of indoor radon concentration: how much do geology and building factors matter? J. Environ. Radioact. 138, 227–237.

Brauner, E.V., Rasmussen, T.V., Gunnarsen, L., 2013. Variation in residential radon levels in new Danish homes. Indoor Air 23, 311–317.

Breysse, J., Jacobs, D.E., Weber, W., Dixon, S., Kawecki, C., Aceti, S., et al., 2011. Health outcomes and Green renovation of affordable housing. Public Health Rep. 126, 64–75.

Buttafuoco, G., Tallarico, A., Falcone, G., Guagliardi, I., 2010. A geostatistical approach for mapping and uncertainty assessment of geogenic radon gas in soil in an area of southern Italy. Environmental Earth Sciences 61, 491–505.

Cartabia, M., Campi, R., Clavenna, A., Bortolotti, A., Fortino, I., Merlino, L., et al., 2012. Geographical epidemiology of antibacterials in the preschool age. Int. J. Health Geogr. 11, 10.

Cinelli, G., Tondeur, F., Dehandschutter, B., 2011. Development of an indoor radon risk map of the Walloon region of Belgium, integrating geological information. Environmental Earth Sciences 62, 809–819.

Cosma, C., Cucos-Dinu, A., Papp, B., Begy, R., Sainz, C., 2013. Soil and building material as main sources of indoor radon in Baita-Stei radon prone area (Romania). J. Environ. Radioact. 116, 174–179.

Darby, S., Hill, D., Auvinen, A., Barrios-Dios, J.M., Baysson, H., Bochicchio, F., et al., 2005. Radon in homes and risk of lung cancer: collaborative analysis of individual data from 13 European case-control studies. Br. Med. J. 330, 223–226.

Demoury, C., Ielsch, G., Hemon, D., Laurent, O., Laurier, D., Clavel, J., et al., 2013. A statistical evaluation of the influence of housing characteristics and geogenic radon potential on indoor radon concentrations in France. J. Environ. Radioact. 126, 216–225.

Derbez, M., Wyart, G., Le Ponner, E., Ramalho, O., Riberon, J., Mandin, C., 2018. Indoor air quality in energy-efficient dwellings: levels and sources of pollutants. Indoor Air 28, 318–338.

Drolet, J.P., Martel, R., Poulin, P., Dessau, J.C., Lavoie, D., Parent, M., et al., 2013. An approach to define potential radon emission level maps using indoor radon concentration measurements and radiogeochemical data positive proportion relationships. J. Environ. Radioact. 124, 57–67.

Drolet, J.P., Martel, R., Poulin, P., Dessau, J.C., 2014. Methodology developed to make the Quebec indoor radon potential map. Sci. Total Environ. 473, 372–380.

Faheem, M., Matiullah, N.M., 2007. Seasonal variation in indoor radon concentrations in dwellings in six districts of the Punjab Province, Pakistan. J. Radiol. Prot. 27, 493–500.

Farah, C., Beard, K., Hess, C.T., Hock, J.M., 2012. Analyzing spatial and temporal (RN)-R-222 trends in Maine. Health Phys. 102, 115–123.

Fojtikova, I., Barnet, I., Marusiakova, M., 2011. Radon index of a local administrative unit. Radiat. Prot. Dosim. 145, 107–109.

Franco-Marina, F., Villalba-Caloca, J., Segovia, N., Tavera, L., 2003. Spatial indoor radon distribution in Mexico City. Sci. Total Environ. 317, 91–103.

Garrah, E., Danby, R.K., Eberhardt, E., Cunnington, G.M., Mitchell, S., 2015. Hot spots and hot times: wildlife road mortality in a regional conservation corridor. Environ. Manag. 56, 874–889.

Gehlke, C.E., Biehl, K., 1934. Certain effects of grouping upon the size of the correlation coefficients in census tract material. J. Am. Stat. Assoc. 29, 169–170.

Geiger, C., Barnes, K.B., 1994. Indoor radon hazard - a geographical assessment and case-study. Appl. Geogr. 14, 350–371.

Getis, A., Ord, J.K., 2010. The analysis of spatial association by use of distance statistics. In: Anselin, L., Rey, S.J. (Eds.), Perspectives on Spatial Data Analysis. Springer-Verlag Berlin, Berlin, pp. 127–145.

Giri, A., Pant, D., 2018. Inhalation dose due to Rn-222, Rn-220 and their progeny in indoor environments. Appl. Radiat. Isot. 132, 116–121.

Grasty, R., 1997. Radon emanation and soil moisture effects on airborne gamma-ray measurements. Geophysics 62, 1379–1385.

Grubesic, T.H., 2006. On the application of fuzzy clustering for crime hot spot detection. J. Quant. Criminol. 22, 77–105.

Harley, N.H., Chittaporn, P., Marsicano, A., 2011. Residential radon remediation: performance over 17 years. Radiat. Prot. Dosim. 145, 194–197.

Harnapp, V.R., Dollwet, H.A., Rong, S.Y., 1997. Airborne radon in homes in Summit County, Ohio: a geographic analysis. Ohio J. Sci. 97, 17–23.

Hauri, D.D., Huss, A., Zimmermann, F., Kuehni, C.E., Roosli, M., 2012. A prediction model for assessing residential radon concentration in Switzerland. J. Environ. Radioact. 112, 83–89.

Hazar, N., Karbakhsh, M., Yunesian, M., Nedjat, S., Naddafi, K., 2014. Perceived risk of exposure to indoor residential radon and its relationship to willingness to test among health care providers in Tehran. J. Environ. Health Sci. Eng. 12, 8.

Higgins, M.W., Crawford, T.J., Atkins, R.L., Crawford, R.F., 2003. Geologic map of the Atlanta 30′ x 60′ quadrangle, Georgia. Available at https://pubs.er.usgs.gov/publication/i2602, Accessed date: 1 March 2019.

Hunter, N., Muirhead, C.R., Miles, J.C.H., Appleton, J.D., 2009. Uncertainties in radon related to house-specific factors and proximity to geological boundaries in England. Radiat. Prot. Dosim. 136, 17–22.

IBM Corporation, 2017. IBM SPSS Regression 25. Available at ftp://public.dhe.ibm.com/software/analytics/spss/documentation/statistics/25.0/en/client/Manuals/IBM_SPSS_Regression.pdf, Accessed date: 1 March 2019.

Ielsch, G., Cushing, M.E., Combes, P., Cuney, M., 2010. Mapping of the geogenic radon potential in France to improve radon risk management: methodology and first application to region Bourgogne. J. Environ. Radioact. 101, 813–820.

Kelly-Hope, L.A., Hemingway, J., McKenzie, F.E., 2009. Environmental factors associated with the malaria vectors Anopheles gambiae and Anopheles funestus in Kenya. Malar. J. 8, 8.

Kim, J.T., Yu, C.W.F., 2014. Hazardous materials in buildings. Indoor and Built Environment 23, 44–61.

Kitto, M.E., Green, J.G., 2008. Mapping the indoor radon potential in New York at the township level. Atmos. Environ. 42, 8007–8014.

Krivoruchko, K., 2011. Spatial Statistical Data Analysis for GIS Users. ESRI Press, Redlands, California.

Krivoruchko, K., 2012. Empirical Bayesian Kriging. ArcUser Fall. https://www.esri.com/news/arcuser/1012/files/ebk.pdf, Accessed date: 1 March 2019.

Kropat, G., Bochud, F., Jaboyedoff, M., Laedermann, J.P., Murith, C., Palacios, M., et al., 2014. Major influencing factors of indoor radon concentrations in Switzerland. J. Environ. Radioact. 129, 7–22.

de la Torre, A., Iglesias, I., Carballo, M., Ramirez, P., Munoz, M.J., 2012. An approach for mapping the vulnerability of European Union soils to antibiotic contamination. Sci. Total Environ. 414, 672–679.

Lai, P.C., Wong, C.M., Hedley, A.J., Lo, S.V., Leung, P.Y., Kong, J., et al., 2004. Understanding the spatial clustering of severe acute respiratory syndrome (SARS) in Hong Kong. Environ. Health Perspect. 112, 1550–1556.

Lantz, P.M., Mendez, D., Philbert, M.A., 2013. Radon, smoking, and lung Cancer: the need to refocus radon control policy. Am. J. Public Health 103, 443–447.

Lee, C.S., Li, X.D., Shi, W.Z., Cheung, S.C., Thornton, I., 2006. Metal contamination in urban, suburban, and country park soils of Hong Kong: a study based on GIS and multivariate statistics. Sci. Total Environ. 356, 45–61.

Long, J.S., 1997. Regression Models for Categorical and Limited Dependent Variables. Sage Publications, Thousand Oaks.

Lorenzo-Gonzalez, M., Ruano-Ravina, A., Peon, J., Pineiro, M., Barros-Dios, J.M., 2017. Residential radon in Galicia: a cross-sectional study in a radon-prone area. J. Radiol. Prot. 37, 728–741.

Lugg, A., Probert, D., 1997. Indoor radon gas: a potential health hazard resulting from implementing energy-efficiency measures. Appl. Energy 56, 93–196.

Maciel, E.L.N., Pan, W., Dietze, R., Peres, R.L., Vinhas, S.A., Ribeiro, F.K., et al., 2010. Spatial patterns of pulmonary tuberculosis incidence and their relationship to socio-economic status in Vitoria, Brazil. Int. J. Tuberc. Lung Dis. 14, 1395–1402.

Martins, L.M.O., Gomes, M.E.P., Neves, L., Pereira, A., 2013. The influence of geological factors on radon risk in groundwater and dwellings in the region of Amarante (Northern Portugal). Environmental Earth Sciences 68, 733–740.

McCarthy, W.J., Meza, R., Jeon, J., Moolgavkar, S.H., 2012. Lung Cancer in never smokers: epidemiology and risk prediction models. Risk Anal. 32, S69–S84.

McClintock, N., 2012. Assessing soil lead contamination at multiple scales in Oakland, California: implications for urban agriculture and environmental justice. Appl. Geogr. 35, 460–473.

Minda, M., Toth, G., Horvath, I., Barnet, I., Hamori, K., Toth, E., 2009. Indoor radon mapping and its relation to geology in Hungary. Environ. Geol. 57, 601–609.

Mitchell, A.L., Griffin, W.M., Casman, E.A., 2016. Lung cancer risk from radon in Marcellus shale gas in Northeast US homes. Risk Anal. 36, 2105–2119.

National Research Council, 1999. Health Effects of Exposure to Radon: BEIR VI. The National Academies Press, Washington, DC. https://www.nap.edu/catalog/5499/health-effects-of-exposure-to-radon-beir-vi, Accessed date: 1 March 2019.

Nelson, A.L., Bromley, R.D.F., Thomas, C.J., 2001. Identifying micro-spatial and temporal patterns of violent crime and disorder in the British city centre. Appl. Geogr. 21, 249–274.

Opensh-aw, S., 1984. The modifiable areal unit problem (Concepts and techniques in modern geography). Geo Books, Norwich, United Kingdom.

Ord, J.K., Getis, A., 1995. Local spatial autocorrelation statistics - distributional issue and an application. Geogr. Anal. 27, 286–306.

Park, E., Scherer, C.W., Glynn, C.J., 2001. Community involvement and risk perception at personal and societal levels. Health Risk Soc. 3, 281–292.

Rafique, M., Rahman, S.U., Mahmood, T., Rahman, S., Matiullah, 2011. Assessment of seasonal variation of indoor radon level in dwellings of some districts of Azad Kashmir, Pakistan. Indoor Built Environ. 20, 354–361.

Rafique, M., Qayyum, S., Rahman, S.U., Matiullah, 2012. The influence of geology on indoor radon concentrations in Neelum Valley Azad Kashmir, Pakistan. Indoor and Built Environment 21, 718–726.

Ravikumar, P., Davis, D., Mathew, S., Somashekar, R.K., Prakash, K.L., 2014. Spatio-temporal variation in radon concentration in groundwater with respect to rock types: a case study from Chitradurga district, Karnataka. J. Geol. Soc. India 83, 156–164.

Ruano-Ravina, A., Castro-Bernardez, M., Sande-Meijide, M., Vargas, A., Barros-Dios, J.M., 2008. Short- versus long-term radon detectors: a comparative study in Galicia, NW Spain. J. Environ. Radioact. 99, 1121–1126.

Sas, Z., Doherty, R., Kovacs, T., Soutsos, M., Sha, W., Schroeyers, W., 2017. Radiological evaluation of by-products used in construction and alternative applications; part I. Preparation of a natural radioactivity database. Constr. Build. Mater. 150, 227–237.

Shendell, D.G., Carr, M., 2013. Physical conditions of a house and their effects on measured radon levels: data from Hillsborough Township, New Jersey, 2010-2011. J. Environ. Health 76, 18–24.

Smith, B.J., Field, R.W., 2007. Effect of housing factors and surficial uranium on the spatial prediction of residential radon in Iowa. Environmetrics 18, 481–497.

Stauber, C.E., Dai, D.J., Chan, S.R., Diem, J.E., Weaver, S.R., Rothenberg, R.A., 2017. 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 14, 12. https://doi.org/10.3390/ijerph14030332.

Steck, D.J., 2009. Annual average indoor radon variations over two decades. Health Phys. 96, 37–47.

Torres-Duran, M., Ruano-Ravina, A., Kelsey, K.T., Parente-Lamelas, I., Provencio, M., Leiro-Fernandez, V., et al., 2016. Small cell lung cancer in never-smokers. Eur. Respir. J. 47, 947–953.

Tunno, T., Caricato, A.P., Fernandez, M., Leonardi, F., Tonnarini, S., Veschetti, M., et al., 2017. Critical aspects of radon remediation in karst limestone areas: some experiences in schools of South Italy. J. Radiol. Prot. 37, 160–175.

U.S. Environmental Protection Agency, 2003. EPA Assessment of Risks from Radon in Homes. Office of Air and Radiation. U.S. Environmental Protection Agency, Washington, DC. https://www.epa.gov/sites/production/files/2015-05/documents/402-r-03-003.pdf, Accessed date: 1 March 2019.

U.S. Environmental Protection Agency and USEP Agency, 2016. A Citizen's Guide to Radon: the Guide to Protecting Yourself and Your Family From Radon. U.S. Environmental Protection Agency, Washington, DC https://www.epa.gov/sites/production/files/2016-02/documents/2012_a_citizens_guide_to_radon.pdf, Accessed date: 1 March 2019.

Vinson, D.S., Campbell, T.R., Vengosh, A., 2008. Radon transfer from groundwater used in showers to indoor air. Appl. Geochem. 23, 2676–2685.

Wilford, J., 2012. A weathering intensity index for the Australian continent using airborne gamma-ray spectrometry and digital terrain analysis. Geoderma 183, 124–142.

Wilford, J., Minty, B., 2006. Chapter 16 the use of airborne gamma-ray imagery for mapping soils and understanding landscape processes. Dev. Soil Sci. 31, 207–218.

World Health Organization, 2009. WHO Handbook on Indoor Radon: A Public Health Perspective. World Health Organization, Geneva https://www.who.int/news-room/fact-sheets/detail/radon-and-health, Accessed date: 1 March 2019.

World Health Organization, 2016. Radon and Health: Fact Sheet. World Health Organization.

Wu, Y., Wang, W., Xu, Y., Liu, H., Zhou, X., Wang, L., et al., 2003. Radon concentration: a tool for assessing the fracture network at Guanyinyan study area, China. Water South Africa 29, 49–54.

Zahnd, W.E., Mueller-Luckey, G.S., Ratnapradipa, K., Smith, T., 2018. Predictors and spatial variation of radon testing in Illinois, 2005–2012. Journal of Public Health Management and Practice 24, E1–E9.

Zhang, Z.G., Smith, B., Steck, D.J., Guo, Q., Field, R.W., 2007. Variation in yearly residential radon concentrations in the upper midwest. Health Phys. 93, 288–297.