12-14-2016

Geographic Variation of Radon Gas Concentrations in Relationship to Housing Characteristics in Dekalb County, Georgia

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GEOGRAPHIC VARIATION OF RADON GAS CONCENTRATIONS IN RELATIONSHIP TO HOUSING CHARACTERISTICS IN DEKALB COUNTY, GEORGIA

by

FREDRICK B. NEAL

Under the Direction of Dajun Dai, PhD

ABSTRACT

Radon (RN-222), naturally released from underground, is the second leading cause of lung cancer for at-risk groups after smoking, and the leading cause of lung cancer. This research aims to investigate the relationship between housing characteristics and indoor radon levels. Indoor radon data (1993 – 2013) were obtained from the DeKalb County Board of Health alongside housing characteristics sourced from the DeKalb County Tax Assessor. Chi-square tests, logistic regression, and bivariate analysis were used to examine the housing risk factors. The results indicate a correlation between high radon concentrations, and homes constructed of brick, with a basement foundation and centralized heating and air systems. Analysis of geological data revealed no significant connection to elevated radon levels.

INDEX WORDS: Radon, GIS, Indoor air pollution, Lung cancer, Environmental health, Spatial autocorrelation

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A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of

Master of Science

in the College of Arts and Sciences

Georgia State University

2016

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December 2016

DEDICATION

I want to first thank the members of my committee Dr. Dajun Dai, Dr. Jeremy Diem, and Dr. Daniel Deocampo. I would like to thank Dr. Dajun Dai for his help and guidance throughout the development of this study and my time at Georgia State as a whole. He has always shown an interest in my academic progress and I will always be grateful. I also want to thank Dr. Diem who greatly influenced me to enter the graduate program at Georgia State. I dedicate this thesis to my wife Xanthe. She has always been my biggest supporter throughout my entire time in graduate school. Without her support, I would not have been able to complete this work. She has picked up the slack many a late night and long day while I worked on my course work and this thesis. My two children Ottmah and Camille provided me with the motivation to begin school again and to continue my studies further once my undergraduate degree was obtained. Lastly, I dedicate this work to my mother and sister, who set the example to achieve higher education and for all of their love and patience. I am truly surrounded by a strong and loving support group. Thank you.

ACKNOWLEDGEMENTS

I wish to thank my committee members for all the time and assistance they have afforded me during this process. I would like to formally thank Ryan Cira for giving me the opportunity to work on the dataset at the DeKalb County Board of Health (DCBOH) and the permission to use that dataset for this study. Ryan was always willing to answer any question, no matter how small. I also want to thank Mandy Seaman for aiding me while I was at the DCBOH. Additionally, I would like to thank The DeKalb County Tax Assessor and GIS Department for their data contributions. I would also like to acknowledge Timothy Dignam (CDC, Environmental Health) for his input and insight.

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1 INTRODUCTION

High indoor concentrations of radon gas represent a substantial health hazard to residents in geographic regions where uranium-rich geologic formations are prevalent. Literature suggested that an upwards of 90 percent of lung cancer cases are a result of cigarette smoking (Khan, et al., 2011; IARC, 2004). However, radon gas within the indoor air environment is believed to be the second leading cause of lung cancer (Gray, et al., 2009) after smoking and the leading cause among non-smokers. Some studies have concluded that heavy exposure to the gas over time increases the odds of developing lung cancer (Field & Withers, 2012; Krewski, *et al.*, 2006). The World Health Organization estimates that lung cancer rates are attributable to radon ranges from 3 to 14%; based on the average radon concentration in each country measured and the calculation methods involved. Radon gas occurs naturally; emanating from bedrock, soil, and from common household building materials (Abd El-Zaher, 2013; Miles, 1998). Radon is tasteless, odorless, and colorless, therefore making it undetectable other than through surveillance devices (Drolet, et al., 2013). The EPA recommends that radon concentrations are dangerous when above 4 pCi/L, however, literature has concluded that there are possible health risks associated with mid to lower levels of radon at or above 2.7 pCi/L (Brauner, et al., 2012). The annual United States death toll attributed to radon is estimated to be nearly 21,000 people per year (EPA, 2016). However, awareness of the risks are low and since the connection has been made between radon exposure and negative health outcomes during the 1980's, the national radon program has seen a gradual reduction of funding and, as a result, there has been little headway made in new-home construction mitigation systems, public building monitoring, and a general decrease in awareness (Angell, 2008).

1.1 Risk Factors

1.1.1 Geology of Radon Prone Areas

Bedrock formations account for a varying percentage of high radon concentrations across terrain and groundwater (Appleton & Miles, 2010; Ravikumar, et al., 2014). Radon – 222 (^{222}Rn) is one of three natural radon isotopes (the only one that poses a health risk) that is the product of the decay of radium-226 (^{226}Ra). Both of the aforementioned are daughter elements of uranium – 238 (^{238}U) (Drolet, et al., 2013). Numerous studies have included underlying geology as a predictor for hazardous indoor radon concentrations (Andersen, et al., 2007; Drolet, et al., 2013; Kitto & Green, 2008). One of the ways for a structure to have a high concentration of radon is that there is a source of uranium in the underlying geologic formations of granite, gneiss, sedimentary, or sedimentary fault; with granite being the most potent (Farah, et al., 2012; Minda, et al., 2009; Park, et al., 2011). Additionally, carbonate rocks (a class of sedimentary rocks), are formations that are prone to weathering known as karstification, resulting in extensive cave systems that hold and transport high quantities of radon (Buttafuoco, et al., 2010; Kropat, et al., 2014). Studies have concluded that a significant portion of indoor radon variation can be attributed to underlying bedrock although other factors are shown to contribute as well (Gundersen & Schumann, 1996; Ielsch, et al., 2010).

1.1.2 Soil Permeability

Soil permeability or texture is considered a predictive factor for high radon concentrations. Soils that are sandy or gravely, are more permeable than finer soils, which have been found to effectively block radon from rising into dwellings (Barnet, 2012; Borgoni, et al., 2011). Dry or cracked soils have been linked to higher radon variability because it increases soil porosity and the influence of atmospheric conditions (Szabo, et al., 2013). Another aspect of soil permeability is when basement and foundation types come into direct contact with aforementioned soil types, affecting the likelihood of high radon concentrations (Johner & Surbeck, 2001). Regions with underlying bedrock of crystalline rocks and karst formations are shown to have higher concentrations of radon, however, soil permeability is considered the primary surficial deposit responsible for the migration of radon from bedrock into the basements and substructures of houses and commercial buildings alike (Chen, et al., 2013; Hauri, et al., 2012). Additionally, fractures in the underlying deposits, water table level, and saturation are variables that contribute to the mobility of radon (Thomas, et al., 2011; Drolet, et al., 2013). Sandy or gravely soils are more permeable, allowing radon to easily flow through to the surface where finer organic soil types such as silt or clay, form near-impermeable barriers to radon migration in structures where the foundation has not penetrated through the soil layer (Cosma, et al., 2013; Szabo, et al., 2013).

1.1.3 Foundation Type

Radon comes from beneath the surface and therefore foundation type has an effect on the level of radon concentration within a home, particularly the lowest levels (Barros-Dios, et al., 2007). One vein of thought is that a different foundation type (basement, crawl space, and concrete slab) has a meaningful impact on variations of high residential radon concentrations (Brauner, et al., 2013). Basements are subterranean whereas concrete slabs are built flush to the surface and crawlspaces are above ground enclosures with dirt floors. Other studies suggest that homes with a basement or semi basement foundation are likely to have greatly increased levels of radon when compared to levels found in homes with only slab foundations (Arvela, et al., 2012; Alghamdi and Aleissa, 2014; Kitto & Green, 2008). Lower levels of structures are often poorly ventilated which allows the gas to build up to harmful levels (Alghamdi & Aleissa, 2014, Harnapp, et al., 1997). In contrast, other studies have concluded that radon levels were higher in dwellings that were in direct contact with the ground (concrete slab) than those with a basement or crawl space (Borgoni et al., 2011, Andersen, C.E. *et al.*., 2007). Similarly, other research also found that direct contact with the ground was a determining factor in higher radon concentrations (Demoury et al., 2013). Basement water mitigation features such as sump pumps and perimeter drains have been linked with high radon levels (Shendell et al., 2013, Smith, B. J. and Field, R. W., 2007).

1.1.4 Housing Type

Residential architecture or number of stories may have a relationship with elevated radon levels. Literature suggests that there is a relationship between variations of radon concentrations and the architectural style of a home (Brauner, et al., 2013; Zhang, et al., 2007). Upstairs rooms in a multi-story home and apartment buildings are shown to have a lesser amount of radon than do single story homes (Sundal, et al., 2004). Freestanding houses typically have higher concentrations of radon than do apartment buildings, in part, because of the lower levels in houses (basements, kitchens, and dens) and their proximity to the ground (Borgoni, et al., 2011; Demoury, et al., 2013). Studies have concluded that models that include house specific factors along with other variables (Demoury, et al., 2013) can explain variation in radon levels.

1.1.5 Construction Type

The materials, from which homes are constructed such as porous concretes, are a source of radon gas that, when combined with other sources, can pose a risk to inhabitants (Chauhan & Kumar, 2013; Rafique, et al., 2011). Homes that are constructed from materials that contain decaying radioactive uranium such as stones used for masonry walls are often found in regions with that type of underlying geology (Lamonaca, et al., 2014; Demoury, et al., 2013). Studies have concluded that there is a relationship between tiles and countertops made from granite and high levels of radon (Aykamis, et al., 2013; Rafique & Rathore, 2013; Sahoo, et al., 2011) In addition to natural building materials, some artificially fashioned building materials such as concrete release radon into the air of dwellings (Keller, et al., 2001). In one study, over 40 types of human made building materials derived from natural substances were evaluated; coal slag (abrasives and sealants) and coal slag concrete were found to be risky to use due their radon exhalation, depending on the origin of the coal (Szabo, et al., 2013).

1.1.6 Year of Construction

Older homes are going to have higher concentrations of radon because they typically have more cracks in flooring and the foundation and thus have higher risk of contamination (Barros-Dios, et al., 2007; Borgoni, et al., 2011). One study was conducted on two hundred new homes built in Denmark were monitored for radon and only 14% was found to have levels above 100 Bq/m3 (2.7 pCi/L) (Brauner, et al., 2013). Features synonymous with older housing such as smaller rooms and poor ventilation have been found to be a precursor to high radon levels (>100 Bq/m3); older homes are often occupied by people that live a lifestyle of shutting the doors and windows while working long days (Alghamdi & Aleissa, 2014; Smith & Field, 2007). Indeed, older structures provide many pathways for gasses to seep in, but new buildings can be found to have high concentrations regardless of geology. Some studies have concluded that if high radon in new buildings is not primarily caused by underlying bedrock, then construction materials are the likely cause (Park, et al., 2011)

1.1.7 Seasonality and Heating Systems

Variability in radon measurements can also be linked to seasonal changes and meteorological factors (Kropat, et al., 2014; Alghamdi & Aleissa, 2014). Highly permeable soils have higher radon gas concentrations in the winter than in summer due to winter freezing which effectively locks radon in the soil; the atmospheric conditions of the summer work to release stored radon in loose soils (Szabo, et al., 2013). Fluctuating soil exhalation rates caused by differences in temperature, humidity, and air masses are all possible reasons to explain variability of radon readings on a temporal scale (Zimnoch, et al., 2014). In contrast, some studies have concluded that elevated concentrations have been found to be higher during winter months due to a combination of a lack of air circulation and shut windows and doors (Badhan, et al., 2012; Denman, et al., 2007; Fujiyoshi, et al., 2013). Additionally, literature concludes that there is a positive correlation between outdoor barometric pressure, low indoor humidity, and outdoor temperature and indoor radon levels during winter months when pressure is typically higher and temperature is lower. (Xie, et al., 2015). Heating and ventilation systems have been included as determining factors for elevated radon concentrations for the possibility of spreading radon containing dust in a home (Alghamdi & Aleissa, 2014; Steck, 2009). Highly energy efficient homes may ultimately lead to less air exchange with the outside environment, trapping radon inside (Lugg & Probert, 1997).

1.2 Research Question

The materials presented in this paper will attempt to determine what housing factors are correlated to indoor residential radon levels greater than 4 picocuries per liter (pCi/L). The focus of the analysis will be on housing characteristics and to the geogenic radon potential of underlying bedrock prevalent in DeKalb County. It is important to gain a better understanding of the conditions that are most likely to result in levels that are detrimental to human health. The study will seek to answer the following questions*: What housing characteristics and geologic factors are associated with elevated concentrations of indoor radon gas?*

1.3 Significance of the Research

Health problems that arise from radon gas are insidious in nature and are hard to trace. Furthermore, the hazard severity of radon is not apparent to the general public and is not a prominently discussed danger or risk. There are two main points of significance that can be attributed to this research: Identifying what housing factors that result in higher radon concentrations can be utilized to predict residences that are more likely to contain the gas. Accurate predictions would prove useful for public awareness campaigns that target at-risk households. Another significance use for this research could be to shape state and local building codes so that mitigation efforts can be installed during the construction process. The combination of targeted awareness campaigns, pre-existing structure testing, and pre-emptive mitigation efforts will decrease the radon exposure risk to the public and lead to a reduction in negative health outcomes.

2 DATA AND METHODS

2.1 Study Area

DeKalb County is the third most populous county in the state of Georgia, with an estimated population of 713, 340 according to the 2010 U.S. Bureau. It is also one of the primary counties that make up the greater Atlanta area, spanning over 267.58 square miles. DeKalb County is a site worth studying due to its status as a region with high geogenic radon potential, with underlying geologic formations of granite and gneiss granite which are known to contain and emit the gas (Borgoni *et al.*, 2013, Lamonaca *et al.*, 2014). The county is home to a large exposed granite formation named Stone Mountain which could be considered indicative of a region of high radon concentration. Unique compared with much of the United States, is the availability of the free radon surveillance system the DeKalb County Board of Environmental Health has been maintaining since 1993. The system is voluntary to any home owner in the county and for the purposes of this study 4,302 data points ranging from 1993 to 2014 were extrapolated. This large data source will provide the basis for GIS and statistical analysis of radon concentrations and its possible correlations to housing characteristics.

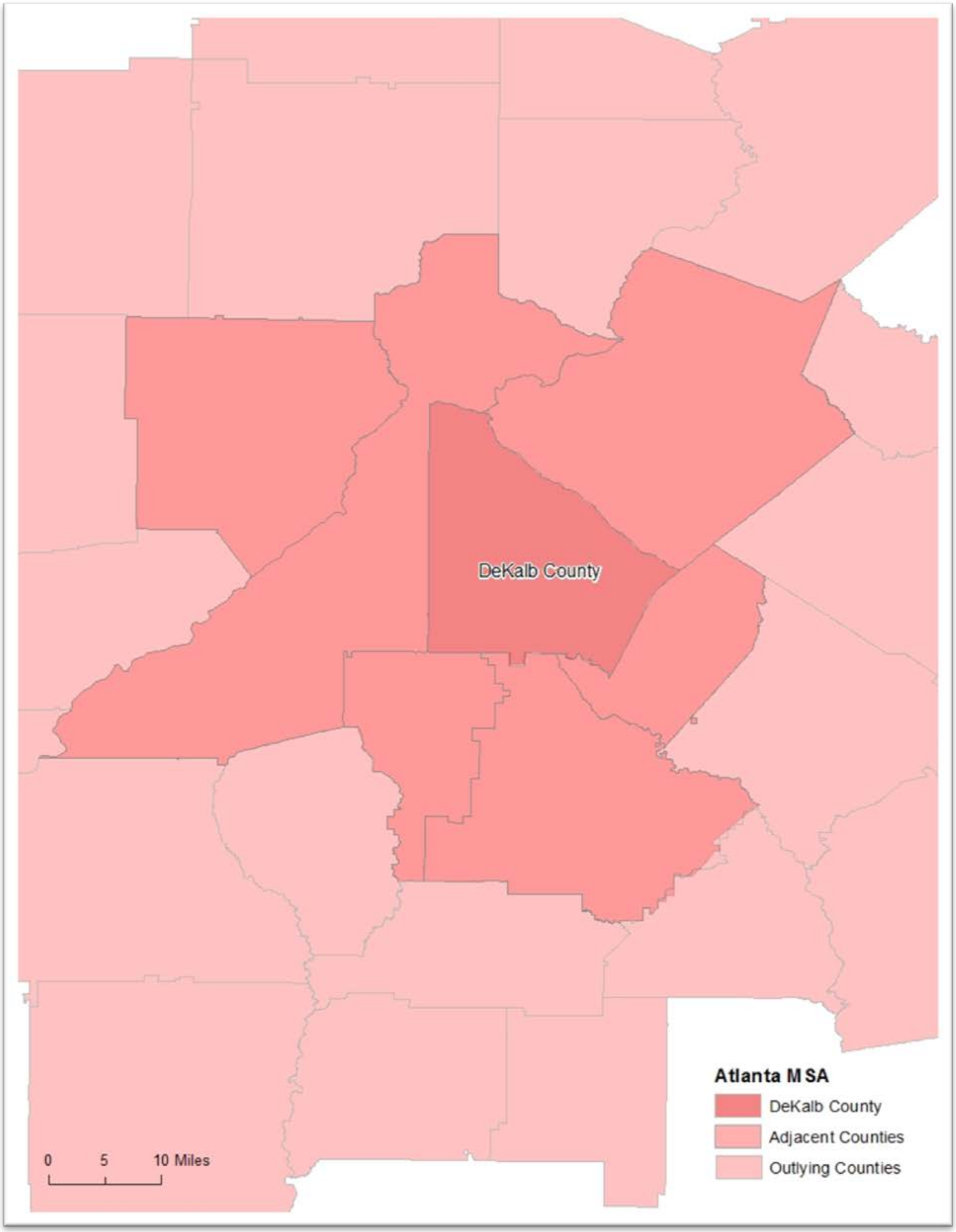

Figure 1 Map of Atlanta MSA
Map of the area of interest shows DeKalb County and surrounding counties that are part of the Atlanta Metropolitan Statistical Area (MSA).

2.2 Data

The data set used in this study was obtained from the DeKalb County Board of Health's (DCBH) radon surveillance system. The DCBH system began conducting radon tests in residential structures in 1993. The test is free so long as the home is owned by the person that makes the request. Two tests are administered in each residence: one test is placed in the lowest lived in room of the home (usually the basement), and the other in another first level room of the dwelling. The tests are cylindrical or hockey puck-like canisters containing activated charcoal, which absorbs radon over the course of approximately 48 hours. The canisters are collected and then sent off to the test manufacturer's lab for analysis and results.

Figure 2 Radon Testing Kit
Accustar (PicoCan 400) activated carbon, short-term radon test kit used for sampling by the DeKalb County Board of Health.

Figure 3 Radon Testing Kit
Accustar (PicoCan 275) activated carbon, short-term radon test kit used for sampling by the DeKalb County Board of Health.

The raw data set was reviewed for discrepancies, duplicates entries and data omissions. Using 2014 as the cut-off date, there were 4,302 total records of which 3,905 were suitable for analysis. Each address was geo-coded in ArcGIS 10.3 (ESRI, Redlands, CA) so that coordinates for each test site could be ascertained for mapping purposes. The age of a home and what type of heating system were taken from the DeKalb County Tax Assessor database. A county-wide map of underlying bedrock was generated using data obtained from the United States Geological Survey. A histogram was generated to determine how the radon concentrations are distributed. A natural log transformation was applied to the variable in an attempt to normalize distribution. Every value was added one in order to avoid zeros in the log transformation. A natural log transformation of the EPA criterion plus one is 1.61, which can be used as the reference value for the interpretation of the box plots. Box and whisker plots were plotted to identify difference in radon levels among the different factors. A scatter plot was constructed to examine the relationship between the age of a home and elevated radon levels. Optimized hot-spot analysis (Getis-Ord Gi* hotspot analysis) was employed to identify areas of the county where clusters of high and low radon concentrations are present. Getis-Ord Gi* calculates Z-scores and P values to measure statistical significance where higher Z-scores indicate more intense clustering.

Three subsets of housing characteristics were chosen from the data available: foundation type, housing type, construction type, and heating and cooling. For foundation type, there are six variables: basement, crawlspace, and slab. In the dataset, there are combinations of the aforementioned foundation types such as basement-crawlspace, basement-slab, and crawlspace-slab. Construction type is divided into brick, fame, and concrete block and a combination of the three. Building type consists of: ranch, multi-story and split-level homes and combinations of the three. Heating and cooling systems are broken into four: no heat, non-central heat, centralized heat, and central heat and air. The age of a home was chosen as a factor to examine. The geology of study area was divided into the following subtypes: biotite gneiss, granite, granite gneiss, mica schist, quartzite, schist, and ultramafic intrusive rock.

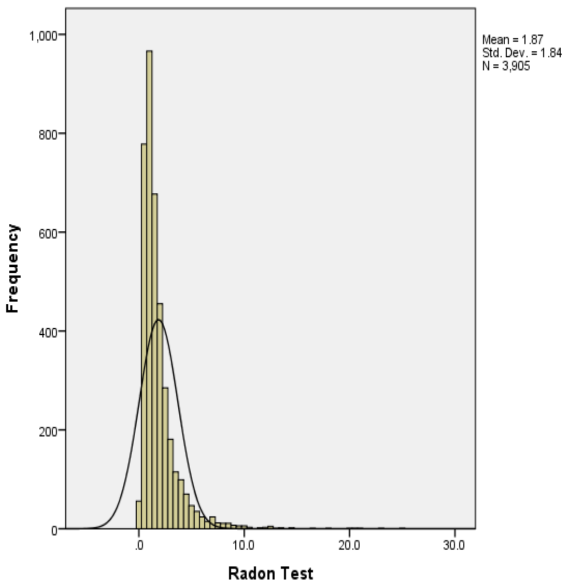

Figure 4a Radon Level Histogram: Distribution of radon concentration test results.

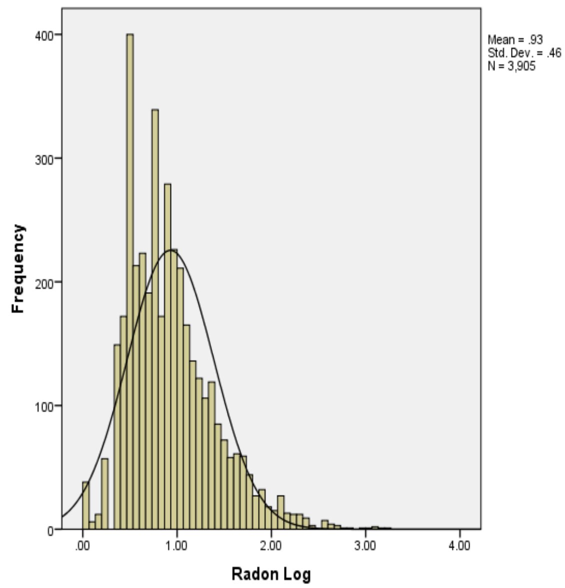

Figure 4b Radon Natural Log Levels Histogram Distribution of radon Log transformed concentration test results.

Figure 4 Radon Level Histogram and Radon Natural Log Levels Histogram

Table 1 Summary of Variables
Table displaying the different categories of dichotomized predictive factors analyzed by a Chi-square test. The age of a home was non-dichotomized and was analyzed using bivariate analysis.

CATEGORY						
FOUNDATION	BASEMENT	CRAWL SPACE	SLAB	BASEMENT/ CRAWLSPACE	CRAWLSPACE/ SLAB	BASEMENT/ SLAB
CONSTRUCTION TYPE	BRICK	FRAME	BLOCK	BRICK/ FRAME	BRICK/ BLOCK	FRAME/ BLOCK
HOUSE TYPE	RANCH	MULTI	SPLIT	RANCH/ MULTI	RANCH/ SPLIT	MULTI/ SPLIT
HEATING & COOLING	NO HEAT	NON-CENTRAL HEAT	CENTRAL HEAT	CENTRAL HEAT & AIR		
GEOLOGY	BIOTITE GNEISS	GRANITE	GRANITE GNEISS	MICA SCHIST	QUARTZITE	SCHIST
	ULTRAMAFIC INTRUSIVE ROCK					
HOUSE AGE	AGE					
PRESENT = 1, NOT-PRESENT = 0						

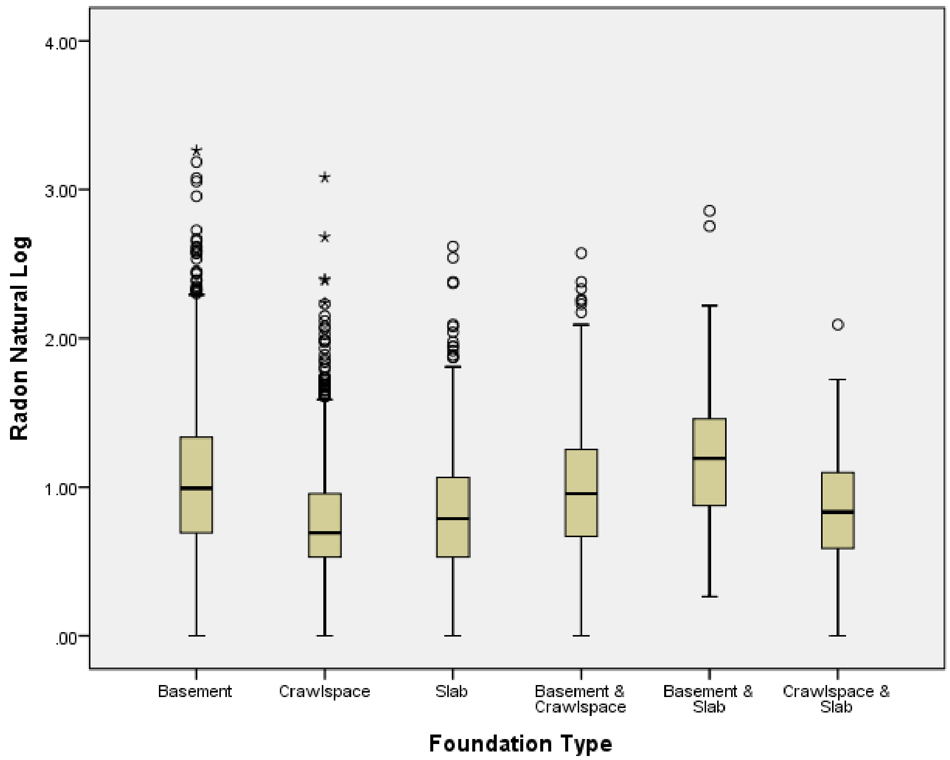

Figure 5 Box Plot for Foundation Type
Box plots of radon levels (natural log) by foundation type.

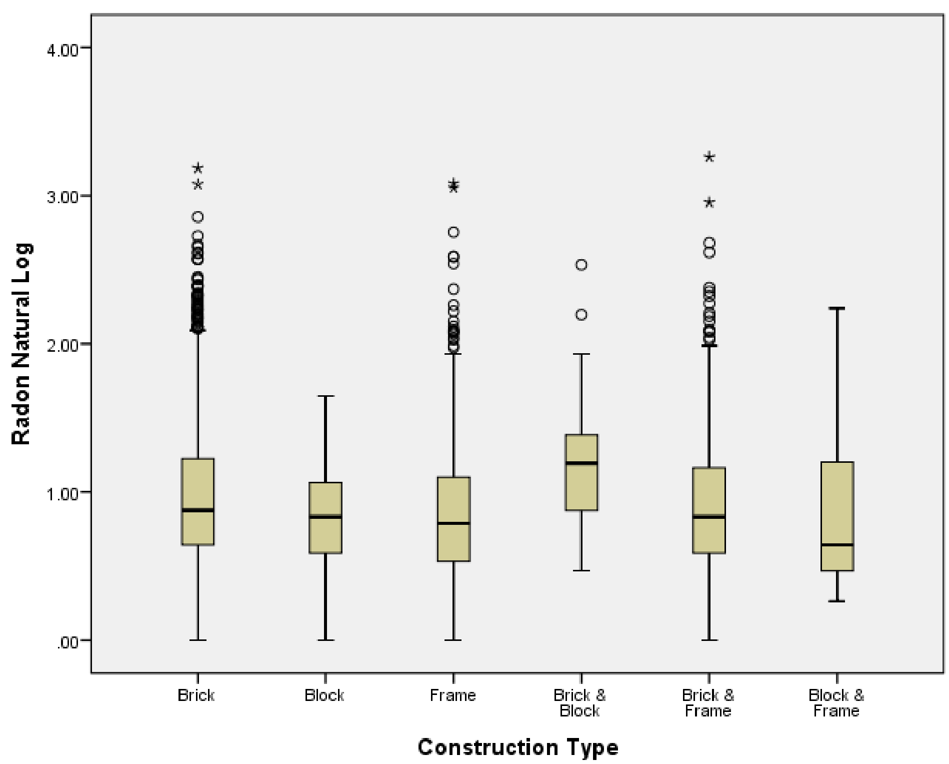

Figure 6 Box Plot for Construction Type
Box plots of radon levels (natural log) by construction type.

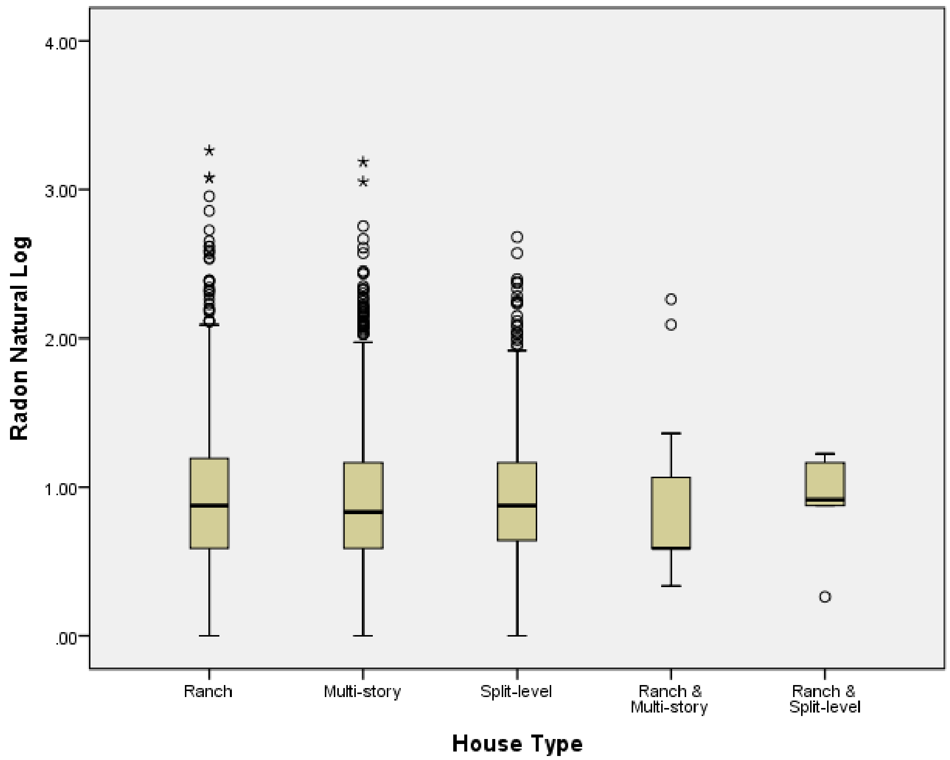

Figure 7 Box Plot for House Type
Box plots of radon levels (natural log) by house type.

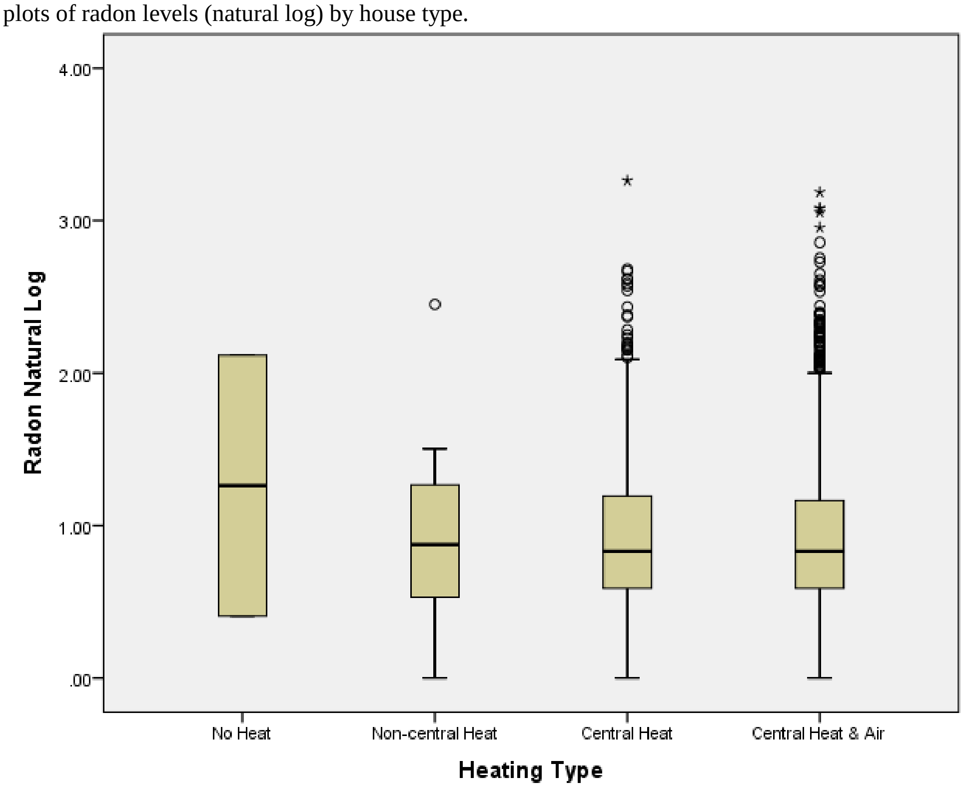

Figure 8 Box Plot for Heat System Type
Box plots of radon levels (natural log) by heating type.

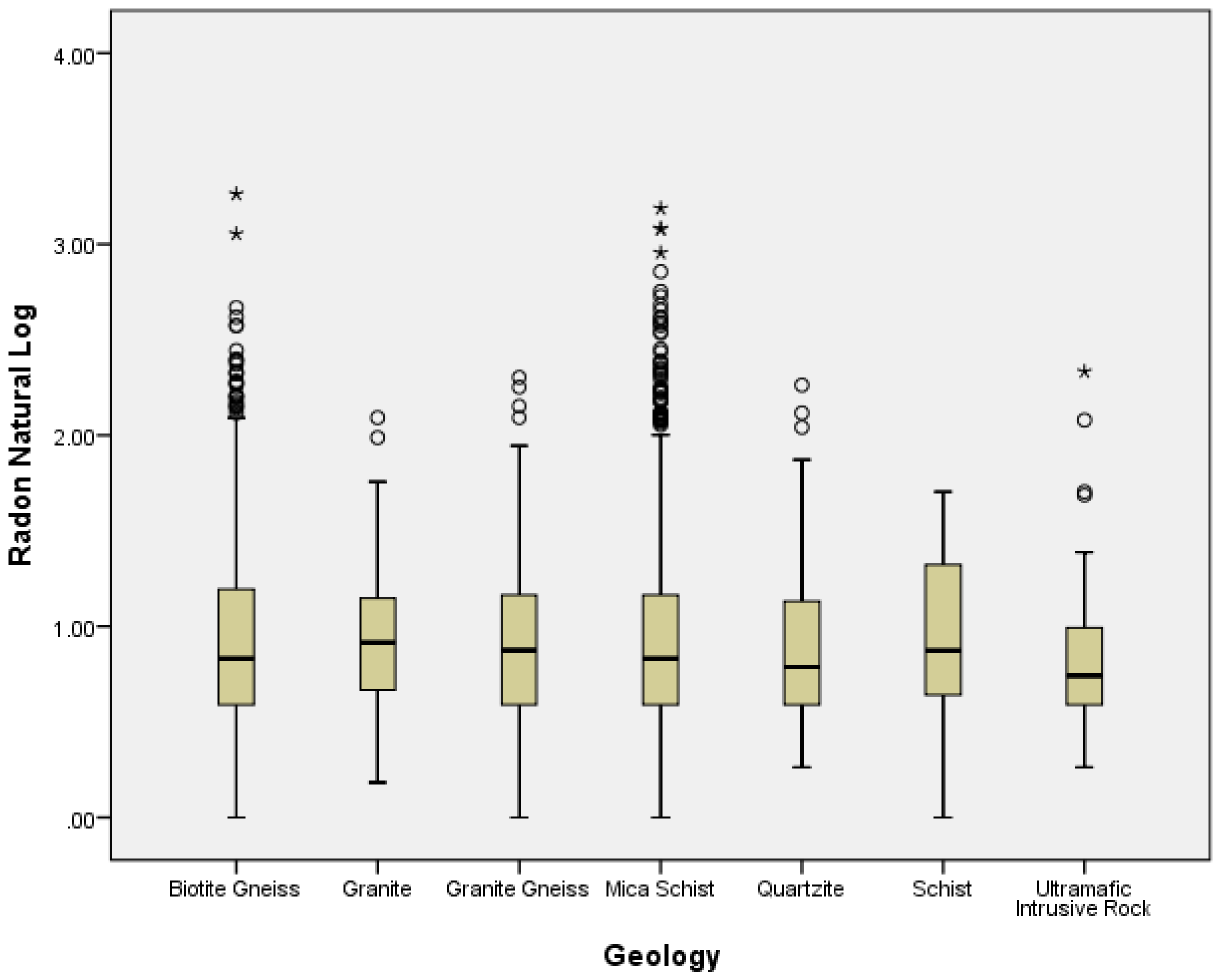

Figure 9 Box Plot for Geologic Formation
Box plots of radon levels (natural log) by foundation type.

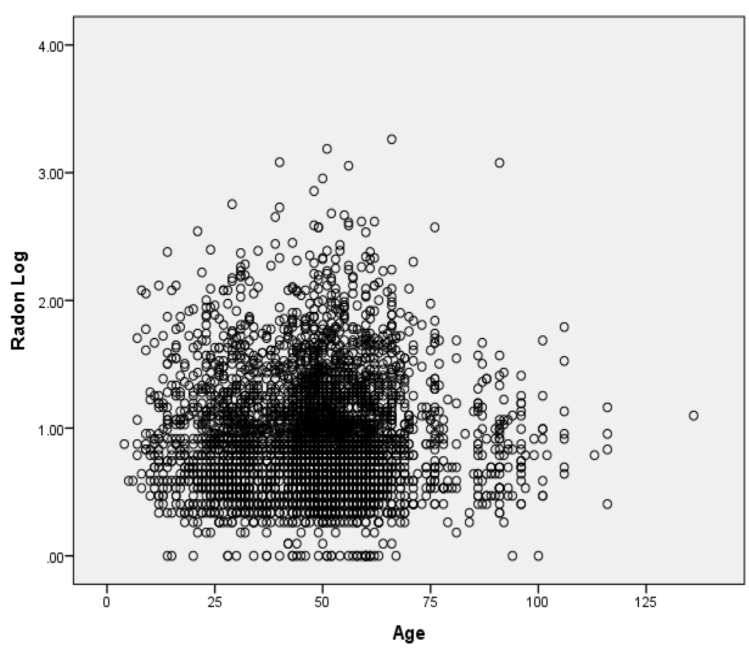

Figure 10 Scatter Plot for Age of Home
Scatter plot of radon levels by age of home.

2.3 Chi-square Testing

Chi-square tests were performed on each housing characteristic and geologic type to determine if there was a statistical significance with radon levels above 4 pCi/L. A two sided asymptotic figure below.05 is indicative of a statistical significance among the variables and radon. Additionally, a Phi Cramer V symmetric measure was calculated to determine the strength of the statistical relationship. The Phi measure was utilized because the Chi-square test resulted in a two-by-two cross table. Bivariate analysis was run on the scaled value of age of home to test for significance.

2.4 Logistic Regression Analysis

A logistic regression model was applied to ascertain the effects of housing characteristics on indoor radon concentrations. As mentioned above, the categorical, non-linear nature of the dataset necessitates the use of the model Housing characteristics were converted into binary and divided into housing type, foundation type, construction type, and heating system. The dependent variable is a binary value based on radon concentration measured in picocuries per liter (pCi/L) as either 1 or 0. For the purpose of this study, any radon measure of 4 pCi/L or higher was assigned a 1, while any test below was assigned a 0.

3 RESULTS

3.1 Sampling Sites

The map (Figure 11) produced from radon test results provides an overview of the spatial distribution of the sampling. Visually examining the map, the sampling is concentrated in the central and northern areas of the county. There is a noticeable drop off in screening in the southwest and southeastern areas of the county. These two areas are more sparsely populated then the rest of DeKalb County. Additionally, the households in these areas are generally lower income compare with the northern part of the county. The map (Figure 12) produced form USGS geological data shows large swaths of Biotite Gneiss along the northern and middle portion of the county and there is a large deposit of Schist along the southern portion of DeKalb. The hot spot map (Figure 13) shows clustering along the mid-northern part and in some areas of the county. Hot-spots with a confidence interval of 99% reside in the northern and in small pockets in the southeastern part of the county. Significant cold-spot clusters are located in a band across the central part of the county and a small pocket in the south-central section of DeKalb County.

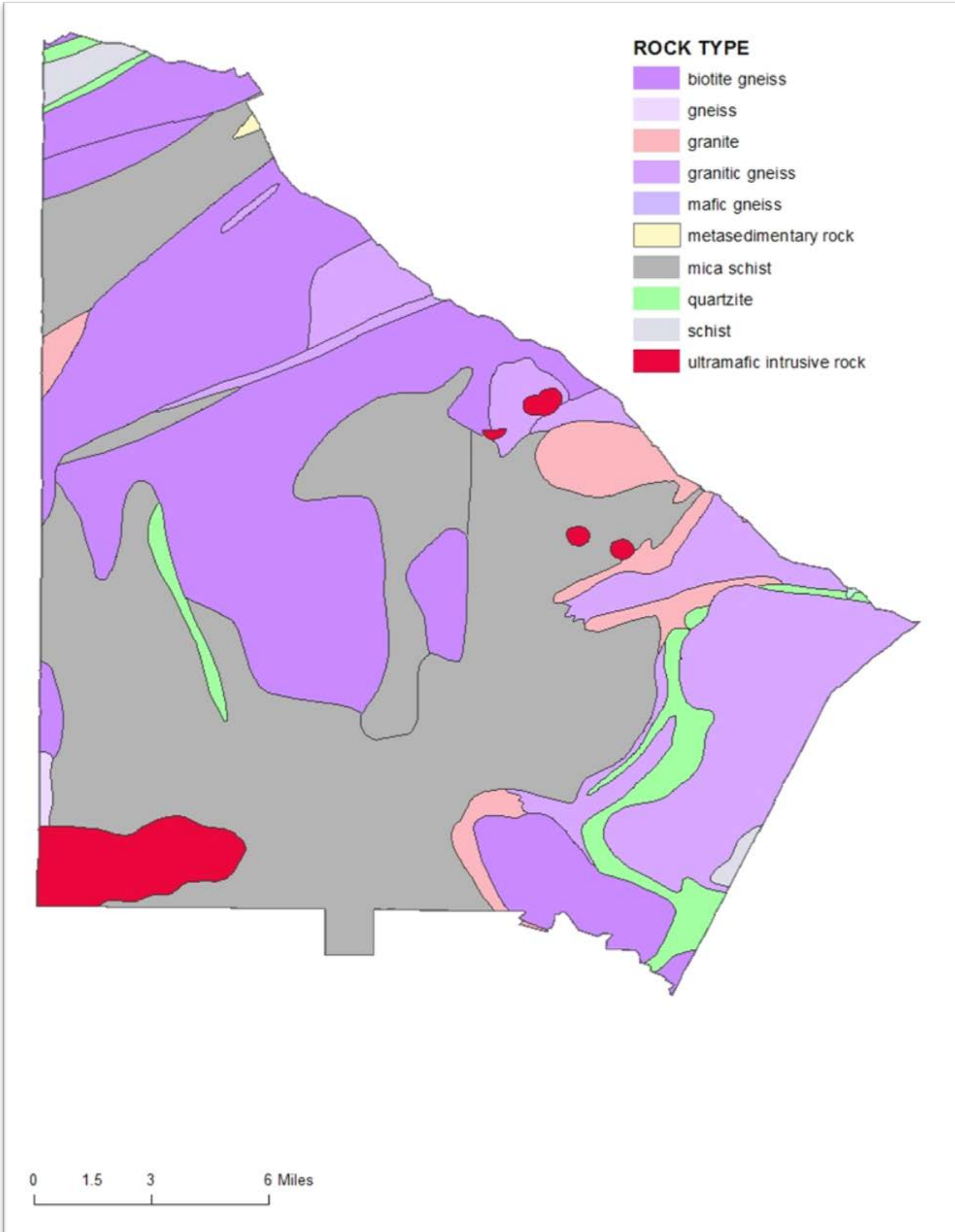

Figure 11
Bedrock formations of DeKalb County.

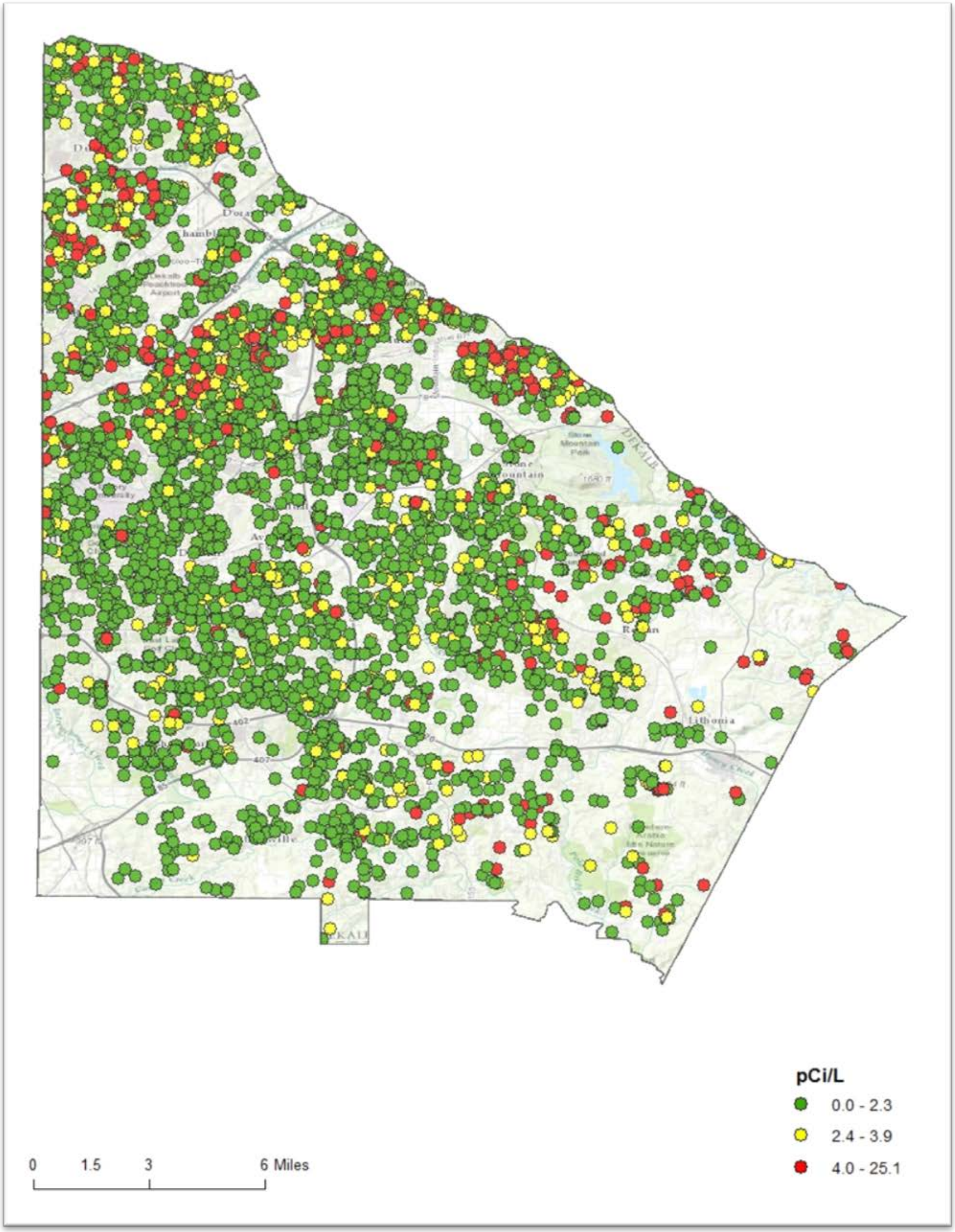

Figure 12
Radon sampling sites in DeKalb County.

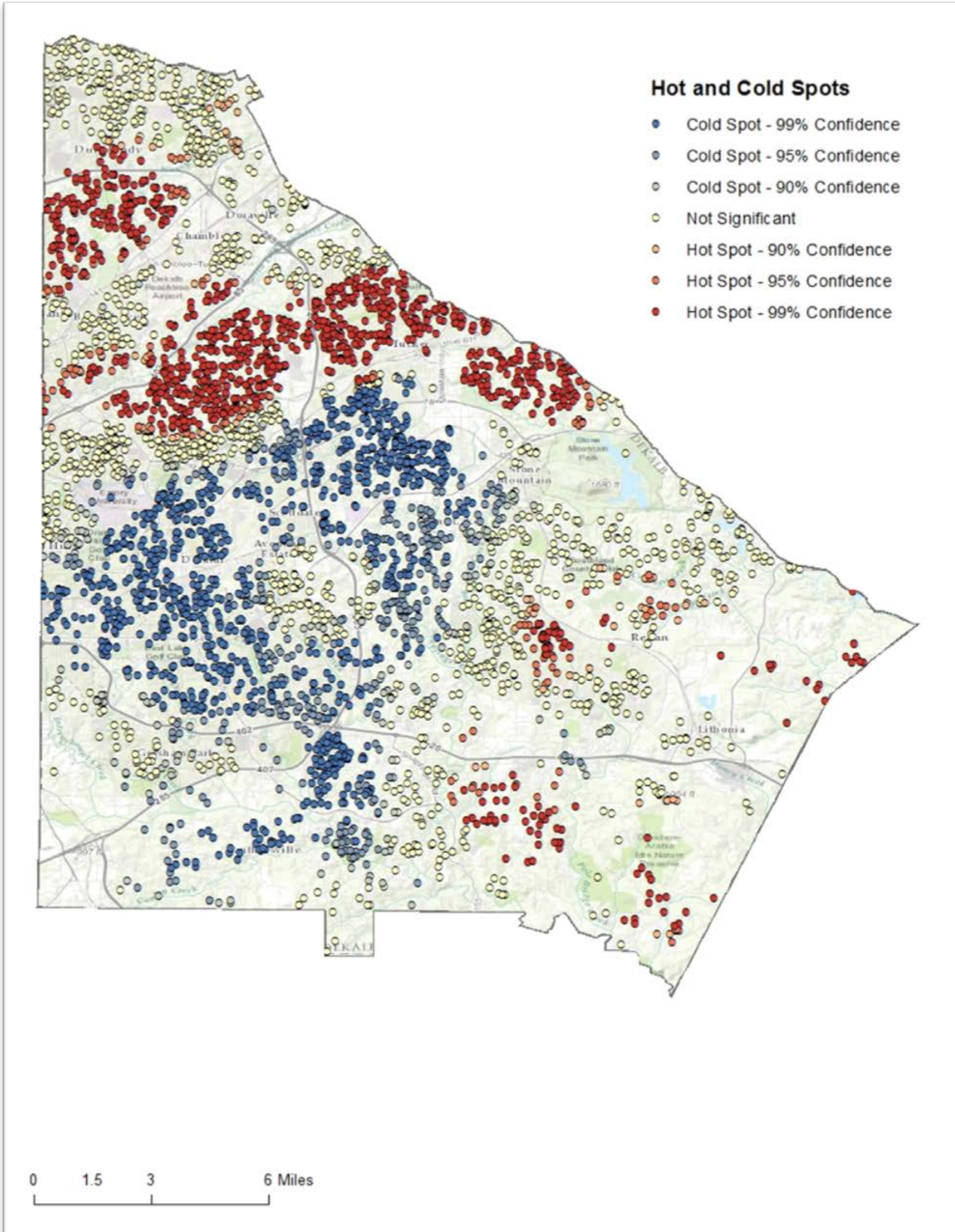

Figure 13
Getis-Ord Gi* hotspot analysis showing areas of clustering of high and low indoor radon concentrations.

3.2 Chi-square Tests

The results of Chi-square testing for foundation type found that basement, crawlspace, and basement mixed with concrete slab were all statistically significant with values of .000, .000, and .002 respectively. The strengths of the significances (Phi) were .131, -.135, and .05 which are not strong measures. Brick (sig .002) and frame (.006) were shown to be significant to elevated radon concentrations. The associations were weak with Phi scores of .05 and -.044. Homes that have no heating system were found to be significant (.004) but had a very weak Phi value of .034. None of the characteristics in the housing type group or geology were found to be statistically significant. Bivariate analysis results of age of home were not significant with a value of .416.

Table 2 Foundation Chi-square Test Results
Chi-square test results for foundation factors relating to radon concentrations (Log transformed) above 4 pCi/L.

	Basement	Crawlspace	Slab	Basement & Crawlspace	Basement & Slab	Crawlspace & Slab
Asymp. Sig. (2-sided)	.000	.000	.120	.505	.002	.055
Pearson Chi-Square	67.195	71.37	2.412	0.445	9.707	3.672
Phi	0.131	-.135	-0.025	0.011	0.05	-0.031

Table 3 Construction Type Chi-square Test Results
Chi-square test results for construction materials relating to radon concentrations (Log transformed) above 4 pCi/L.

	Brick	Block	Frame	Brick & Block	Brick & Frame	Frame & Block
Asymp. Sig. (2-sided)	.002	.165	.006	.086	.302	.632
Pearson Chi-Square	9.64	1.927	7.653	2.947	1.067	0.23
Phi	0.05	-.022	-0.044	0.027	-0.017	0.008

Table 4 Heating Chi-square Test Results
Chi-square test results for heating and cooling systems relating to radon concentrations (Log transformed) above 4 pCi/L.

	No Heat	Heat Non-Central	Central Heat	Central Heat & AC
Asymp. Sig. (2-sided)	0.04	0.715	0.634	0.707
Pearson Chi-Square	4.207	0.134	0.227	0.141
Phi	0.034	-0.006	0.008	-0.006

Table 5 House Type Chi-square Test Results
Chi-square test results for house type relating to radon concentrations (Log transformed) above 4 pCi/L.

	Multi-story	Ranch	Split-level	Multi-story & Split-level	Ranch & Multi-story	Ranch & Split-level
Asymp. Sig. (2-sided)	.271	.895	.112	.427	.480	.480
Pearson Chi-Square	1.211	0.017	2.526	0.632	0.499	0.499
Phi	0.018	.002	-0.025	0.013	-0.011	-0.011

Table 6 Geologic Formations Chi-square Test Results
Chi-square test results for underlying bedrock formations and their relationship to radon concentrations (Log transformed) above 4 pCi/L.

	Biotite Gneiss	Granite	Granite Gneiss	Mica Schist	Quartzite	Schist	Ultramafic Intrusive
Asymp. Sig. (2-sided)	.618	.514	.834	.488	.800	.722	0.967
Pearson Chi-Square	0.248	0.425	0.044	0.48	0.064	0.126	0.002
Phi	-0.008	-.100	0.003	0.011	-0.004	-0.006	-0.001

Table 7 Age of Home Bivariate Analysis Results
Bivariate analysis results for the age of a home and any relationship to radon concentrations above 4pCi/L.

		AGE
Radon	Pearson Correlation	-.013
N = 4079	Sig. (2-tailed)	.416

*****. Correlation is significant at the 0.01 level (2-tailed).***

3.3 Logistic Regression Analysis

Logistic regression was run on the housing characteristics that were found to be statistically significant to hazardous levels of radon in residences that were identified by Chi-square testing. The Homer and Lemeshow test value of .972 shows that the model is a good fit. A Nagelkerke R value of .063 reveals that the model explained 6.3 percent of radon concentrations above 4 pCi/L. Homes that only have a basement foundation are statistically significant (.001) at a .01 level and had an odds ratio of 1.595. Homes with basement foundations are 1.6 times (rounded) more likely to have dangerous radon levels than those without. The characteristic of crawlspace was significant (.000) with an odds ratio of .342. The variable of the combination of basement and slab are statistically significant (.008) at the .01 level and had an odds ratio of 2.299. This can be interpreted that homes with a combination of basement and slab foundations are 2.3 times more likely to have hazardous radon concentrations than those without. The variable of brick, frame, and no heat we not found to be statistically significant.

Table 8 Logistic Regression Results
Logistic regression analysis results on factors with statistical significance. Homer & Lemeshow test is indicative of goodness of fit and Nagelkerke R tells how much the model explains radon variance for levels above 4pCi/L.

	B	***S.E.***	***Wald***	***df***	***Sig.***	***Exp(B)***
Basement	.467	.146	10.271	1	.001	1.595
Crawlspace	-1.073	.210	26.226	1	.000	.342
Basement & Slab	.833	.312	7.134	1	.008	2.299
Brick	.211	.160	1.733	1	.188	1.235
Frame	-.094	.196	.232	1	.630	.910
No Heat	1.812	1.417	1.636	1	.201	6.123

Homer & lemeshow Test Sig. - .972 **Nagelkerke R** - .063

4 DISCUSSION

4.1 Research Question

What housing characteristics and geologic factors are associated with elevated concentrations of indoor radon gas?

Based on the results of the radon analysis in this study, housing characteristics can explain some, albeit small variations of indoor Rn-222. Air pressure and movement within a home must directly affect how much gas is allowed to build up (Harnapp, et al., 1997; Keller, et al., 2001). Each home will likely have variations in airflow, depending on a number and size of entry and exit points (or lack thereof) unique to each site. The geogenic potential of radon is undoubtedly a result of the presence of ^{226}Ra within the underlying bedrock, which explains indoor concentrations to some degree. In this study, the lack of reliable surficial deposit data rules out soil type as a predicting factor as well. There are many factors like pressure differential, seasonality, temperature, soil permeability and material exhalation that influence radon concentrations and, therefore, housing characteristics are not strong predictors of elevated indoor radon levels (Kitto & Green, 2008; Vasilyev & Zhukonsky, 2013; Xie, et al., 2015).

` For the presence of indoor radon gas, housing conditions and geogenic factors were expected to be determinants. This thesis examined the influence of housing characteristics and geological factors on radon levels. It raised the question: are housing characteristics and geologic data effective predictors of indoor residential radon concentrations? The results suggested that there is a relationship between homes with basements, and elevated radon levels. Additionally, homes constructed of brick and had no heating system were also associated with radon concentrations above 4 pCi/L. A home with a crawl space has a negative relationship with radon. There was no significant relationship found between geology and indoor radon.

The findings are consistent with results in literature where housing characteristics are found to be connected to radon levels above 4 pCi/L (Borgoni, et al., 2011; Demoury, et al., 2013; Hauri, et al., 2012). Consistent with other studies, proximity to soil is a primary factor for high radon concentrations (Louro, et al., 2013; Smith & Field, 2007). The results of the study did not match up to findings in studies that identified age of home as a determining factor for radon (Barros-Dios, et al., 2007; Kropat, et al., 2014).

4.2 Geology

From a geologic perspective, almost all of DeKalb County is considered a high geogenic risk for radon. The underlying geology of the county is consistent with other regions known to be high risk zones. Despite the fact that the region is a high-risk zone, not all homes that lie along formations associated with elevated levels of radon, such as granite, have dangerous levels of the gas. Furthermore, it is possible to have hazardous levels found in homes that are located in geographies that do not have bedrock formations expected to have high radon emissions. This could be caused by the gradual build-up of the gas from radon containing building materials. The lack of any significant correlation between the geology present in the region and residential radon points to a possible link with the conditions of the homes.

The results of both bivariate and logistic regression showed no correlation between the bedrock formations of DeKalb County, and high levels of the gas. The predominant theory is that radon concentrations are the result of many variables, and simply the presence of the gas's precursors is not an effective predictor of hazardous levels within the indoor environment. Another explanation is that soil permeability at the site of each home has an effect on radon concentrations, provided there is geogenic potential (Hauri, et al., 2012; Szabo, et al., 2013). Moist or impermeable soils may prevent gas from getting to foundations of homes and seeping into substructures through various entry points. For this study, accurate soil data was not procured and therefore soil distribution was not considered a reliable variable.

4.3 Foundation

The foundation of a home proved to be the most influential factor in a home having a hazardous radon concentration. Having a basement increases the likeliness that dangerous radon levels could be present. Since radon enters homes from the ground, the presence of a basement was expected to be a determinant of high concentrations (Alghamdi & Aleissa, 2014; Barros-Dios, et al., 2007; Harnapp, et al., 1997). Furthermore, the gas can enter through cracks in the foundation, floor drains, and sump drains, which are present in homes where water inundation in the substructure is an issue (Shendell, et al., 2013; Smith & Field, 2007). It would be possible that basements with cracked dirt floors and walls would be the most susceptible to gas entry. However, there is no way to determine this because the data set does not differentiate between basement conditions. The combination foundation of basement and slab explain a small amount of radon concentration variance. This could be attributed to the presence of some sort of a basement and very little to having a slab base structure.

In contrast to the positive relationship between having a basement and radon, the one between having a crawlspace and radon is negative, almost completely opposite. Crawlspaces are usually dirt floor and several feet high at best. Therefore, it was initially thought that would lend to radon permeating the floor and affecting the lower levels of those homes. However, the presence of a crawlspace and low levels of radon may be a result of indoor-outdoor pressure differences, when the indoor air pressure environment releases gas to lower pressure outdoor air (Harly, et al., 1986; Vasilyev & Zhukovsky, 2013; Xie, et al., 2015).

4.4 Building Materials

Building materials accounted for single-digit variability of indoor radon concentrations. Homes that were constructed of brick were more likely to have an elevated level than those constructed of either wood or concrete block based on bivariate analysis. Brick is more insulating than the other two mentioned materials and prevents more air exchange with the outdoor environment (Keller, et al., 2001; Rafique, et al., 2011). The brick itself could be a source of radon depending on the origin of the brick's primary composition. As expected, homes constructed of brick had a small positive relationship with high concentrations. Cracks and fissure form along joists and intersections, allowing radon to leak in and build up over time, but do not have an easy exit path (Brauner, et al., 2012; Vasilyev & Zhukovsky, 2013). Frame housing was significant in that it was negatively correlated to increased radon levels. The reasoning for this is likely due to the porous nature of wood and the less air-tight indoor air environment it fosters.

4.5 Housing Type

Housing type or architectural style was not expected to have much of an influence on indoor radon concentrations. Some studies have included building type as a factor for radon levels above 4 pCi/L (Friedman & Groller, 2010; Yarmoshenko, et al., 2013). It was thought that perhaps the construction materials or foundation types of certain architectural styles indicative of homes built in DeKalb County could help to explain a home's high radon level. The results did not support this idea as none of the architecture styles were statistically significant in bivariate or logistic regression analysis. In addition, a statistically significant relationship between age of a home and radon was not identified despite being included in other studies (Hauri, et al., 2012; Lamonaca, et al., 2014). One explanation may be that many of the homes in DeKalb County were constructed in waves and there is not a lot of difference in the average age of the homes, with the bulk of homes being constructed between 1955 and 1972.

4.6 Heating and Cooling Systems

Homes with no heating system at all had some association with radon levels above 4 pCi/L. The relationship is very small and cannot be considered to be of any real significance. A home with no heating system is likely to have very little air movement and the windows and doors are probably not left open.

4.7 Limitations

The conditions that lead to high radon concentrations are complex as they are varied. One of the major limitations of this study is a lack of certain types of data. The effects of air movement could have been better analyzed with indoor/outdoor pressure data. The condition of the basement would aid in assessing the difference presented by finished and unfinished sub-structures on radon levels. Additionally, an assessment of drains, sump pumps, and other basement features would prove as useful data points. The lack of accurate soil maps were limiting in that it is difficult to get a true idea of a test site's soil permeability. Lastly, a detailed map of test site footprints could be utilized to associate slope and other topographical features with each radon value.

5 CONCLUSIONS

Underlying bedrock can be used to determine the geogenic radon potential of a given area only by proximity. A higher resolution geology map should be employed to predict radon levels above 4 pCi/L. However, geological formations alone are not enough to predict high indoor concentrations. The same could be said for solely using housing characteristics as predictive factors as well. The conclusion drawn from the results of this study is that a home constructed of brick and has a basement foundation is more likely to have high radon concentrations in an area of high geogenic potential. That is to say that, for all areas homogeneous in radon exposure risk, homes with these characteristics singularly or in combination, presents an elevated risk worth administering a screening. Furthermore, homes with a basement foundation are particularly at risk, especially those that are finished and frequently used.

The primary aim of this study was to predict residential radon levels greater than 4pCi/L based on housing characteristics of homes previously tested and underlying geology. The housing data available for this study did not prove particularly strong for predicting hazardous dangerous gas concentrations. One take –away from this study is that in order to anticipate radon gas levels, more data needs to be collected in addition to housing characteristics and geological. Because the hazard presented by radon is due to the build-up of the gas in a contained space, the movement of air should play an integral role in a structure's indoor make-up. Therefore, collecting differential pressure data between the outdoor and indoor environment could be a determining factor in a predictive model. To build a more comprehensive soil map, soil samples should be collected at each radon testing site. Soil samples would be analyzed to determine permeability; accounting for seasonal differences that could affect exhalation. Another possible determinant could be the slope of the parcel on which a structure is built on. A high resolution digital elevation model (DEM) would provide the elevation data necessary to assess the slope of the land at a test site. Mapping the footprint of a home would be necessary to insure that slope calculated is representative of the land the structure rests on.

Due to its link to lung cancer and other respiratory illnesses, radon gas exposure poses a marked health risk to the general public. The insidious nature of RN-222 merits further research for determining factors. Future research for predictive factors in a logistic regression model should include geology, soil permeability, differential air pressure and movement, housing characteristics, and topographical features of sampling sites. Efficient prediction coupled with comprehensive policy would go far in protecting the public from the potentially fatal effects of prolonged radon exposure.

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