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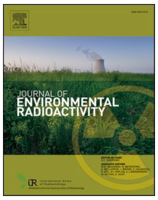

Patterns of indoor radon concentrations, radon-hazard potential, and radon testing on a small geographic scale in Utah

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ABSTRACT

Introduction.

Currently, there are no publicly-available estimates of indoor radon concentration at scales smaller than the county. Radon-hazard potential soil maps that reflect underlying geologic factors can be created at small geographic scale and linked to residential and census data. We determined the association between residential radon tests and high radon-hazard potential soil at the residential and block group levels using a large Utah-based dataset. We also identified characteristics of block groups with limited tests in the dataset.

Methods.

We geocoded a dataset of residential radon tests obtained from 2001 to 2017 by a statewide educational program. We linked each location to maps of radon-hazard potential soil, the Environmental Protection Agency's (EPA) county radon zones. We also calculated the number of tests conducted in each block group and linked block groups to demographic data from the 2020 United States census.

Log-linear and logistic models identified the association between residential home test results and 1) radon-hazard potential soil of each residence, 2) percent of residences on high radon-hazard potential soils in block groups, and 3) EPA's radon zones. We compared demographic characteristics among block groups with ≥5 or <5 residential tests in our dataset.

Results.

Approximately 42% of homes in the dataset tested ≥4 pCi/L. We found significant positive associations for residential radon test results with 1) residential location on high radon-hazard potential soil and 2) block groups with >0% of residences on high radon-hazard potential soil. EPA radon zones were not associated with residential test results. Block groups with <5 tests had higher than the statewide median percentage of Hispanic residents (OR = 2.46, 95% CI = 1.89–3.21) and were located in rural counties.

Discussion.

Radon-hazard potential soil has a significant association with residential home radon tests. More efforts are needed to improve radon testing in block groups that are rural and have greater percentages of racial minorities.

1. Introduction

Radon is a widespread environmental hazard requiring monitoring and management (Chahine et al., 2011). The carcinogenic gas is the second-leading cause of lung cancer in the United States (US) and is linked to lung cancer incidence (Krewski et al., 2005, 2006; Lantz et al., 2013). Radon gas is estimated to contribute to 21,000 lung cancer deaths per year, which accounts for 16% of all lung cancer deaths

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(Environmental Protection Agency, 2021; Surveillance and End Results Program, 2021). Radon-attributable lung cancer deaths are more common than the approximately 8,700 annual deaths from melanoma, another common adult cancer (Environmental Protection Agency, 2021; Surveillance and End Results Program, 2021). County level estimates of indoor radon concentrations are publicly available from national public health agencies. The Environmental Protection Agency (EPA) classifies counties by the predicted average screening concentration (radon zones) (Environmental Protection Agency, 2022). The Centers for Disease Control's (CDC) National Environmental Public Health Tracking Network (NEPHTN) provides county level summary statistics of pre-mitigation concentrations obtained from laboratory tests (Radon Task Force, 2014; Eggers, 2015). While these data have been used in epidemiologic studies of radon and cancer (Environmental Protection Agency, 2019; Teras et al., 2016; Ou et al., 2018), variation in indoor radon tests within counties would lead to errors in exposure estimates and potentially bias epidemiologic study results (The Policy Surveillance Program, 2016; Khoury et al., 2016; Kearney et al., 2015). Creating estimates of indoor radon concentrations at smaller geographic scales can assist in overcoming these challenges by capturing more of the spatial variability of indoor radon concentrations, which would reduce error in exposure estimates.

Efforts to predict radon concentrations at a smaller geographic scale include a spatiotemporal model that predicted outdoor particulate radioactivity across the United States (US) on a 32 km resolution (Li et al., 2021). But, the concordance of this data with indoor radon concentrations has not yet been validated (Li et al., 2021). Currently, the only publicly available, nationwide data sources for indoor radon concentrations are laboratory data obtained from home tests that have been aggregated by county (The Policy Surveillance Program, 2016; Khoury et al., 2016; Kearney et al., 2015). In lieu of indoor radon testing data that is publicly available at a scale smaller than counties, the soil composition may provide an avenue to approximate indoor radon tests. Soil composition is correlated with the results of indoor radon tests in a single state assessment (Haneberg et al., 2020). Data about soil composition are available at small spatial scale and may help bridge the current data gaps by acting as a proxy measure for indoor radon concentrations from laboratory tests (Environmental Protection Agency, 2022; Haneberg et al., 2020).

A limitation of the laboratory data for indoor radon tests aggregated by NEPHTN is that the tests were all conducted voluntarily; the US has no nationwide legislation requiring radon tests in public or private spaces (Gordon et al., 2018). In surveys, radon testing is more likely to be completed by persons who are Non-Hispanic White, college-educated, high income, homeowners, and who speak English as their primary language (Ou et al., 2019; Zahnd et al., 2018; Denu et al., 2019). The laboratory tests reported by NEPHTN likely reflect the indoor radon concentrations of people with these demographic characteristics. This leaves gaps in our knowledge about indoor radon concentrations among low-income people, racial and ethnic minorities, and renters.

The state of Utah can be used as a case study to determine if alternate data sources are correlated with indoor radon test results better than county-level estimates provided by EPA and the CDC tracking network. The Utah Geological Survey published maps showing the location of uranium-enriched soils in the state and categorized them according to their potential to raise indoor radon concentrations (radon-hazard potential) (Bill, 2022). This study explores the use of radon-hazard potential soil classifications at the block group level as a proxy measure for indoor radon exposure in Utah, and examines patterns in testing according to sociodemographic characteristics. Census block groups are standardized aerial units that can be used to measure environmental exposures at small spatial scale (Liu et al., 2021). We assess the ability of block group estimates of radon-hazard potential soil to predict indoor radon concentrations. Our goals were to determine the association between residential indoor radon tests and 1) radon-hazard potential soil of the home, 2) Census block group (BG) radon-hazard potential soil, and 3) EPA's county-level radon zones. Last, we identify demographic characteristics of block groups with low numbers of residential tests in our dataset and block groups with median radon greater than the health standard of 4 pCi/L (picocuries per liter; 148 Bq/m^3).

2. Materials and methods

2.1. Test based measures of residential radon

2.1.1 Testing Data: We obtained results for 64,061 short-term radon tests conducted in Utah from 2001 to 2017 through the Utah Radon Program, a statewide program that aims to educate the public about radon and provide testing resources (Utah Department of Environmental Quality, 2022). Radon tests distributed by the program were commercially available radon tests that were analyzed at certified labs. We excluded tests that did not meet quality testing standards so results should be comparable across test and years. Radon tests in the database included 1) short-term tests provided directly to the public at no cost, 2) short-term tests conducted by the agency's staff at the request of schools, individual home owners, or managers of public buildings, and 3) short-term test results shared by one of the analysis labs for tests conducted by individuals or commercial radon testers in Utah. Since all radon testing is done voluntarily in Utah, these 72-h tests were conducted based on the testers' convenience. Information from the radon tests included the mailing address where results were sent, a test start and end date, the date the test was received by the lab, and the radon test result. Some of the observations also contained self-reported text fields with information about the building tested, the location of the test within the building, descriptions of room that the test was placed in, and reasons why the test was being conducted including mitigation or real estate transactions. No demographic data about the persons conducting the tests or information about the home were available.

2.1.2 Geocoding and residential characteristics: The mailing addresses of the radon tests were geocoded and spatially joined to the neighborhood and county level attributes. Only tests with geographic coordinates and had residential addresses were included (Fig. 1). There were a number of cases where a large number of test results were associated with the same location and/or date. We assumed that the location provided was the mailing address of a radon mitigator or real estate agent rather than the address where the test was conducted and excluded them from the analysis. Coordinates in the upper 95th percentile for the number of testing days (>4) or tests (>6) were excluded from the analysis. According to test manufacturers' instructions, we removed tests that were mailed to the lab <2 days or >8 days after the test start date, tests whose reported end date occurred before start date, test whose analysis date occurred before the end date, or if test was analyzed by the lab >15 days from the test end date. We identified homes with post-mitigation tests using text strings and patterns of home testing; homes where first test was ≥ 4 pCi/L and all subsequent tests were <4 pCi/L were considered as having subsequent post-mitigation tests. We removed one outlier with a maximum residential radon test of 481 μg/m^3. The final dataset had 20,368 unique residences and 23,963 radon tests. Of these, 242 residences only had post-mitigation tests.

We identified the maximum radon test result from any of the pre-mitigation tests conducted at each residential location. If a location only had one test, that test was used as the maximum. We classified each residence as having a test with a maximum radon test result of <4 pCi/L or ≥ 4 pCi/L. We categorized the first year of testing for each residence as 2001 to 2006, 2007 to 2011, and 2012 to 2017. Using the geocodes, we determined if each home was located on low, moderate, or high radon-hazard potential soil.

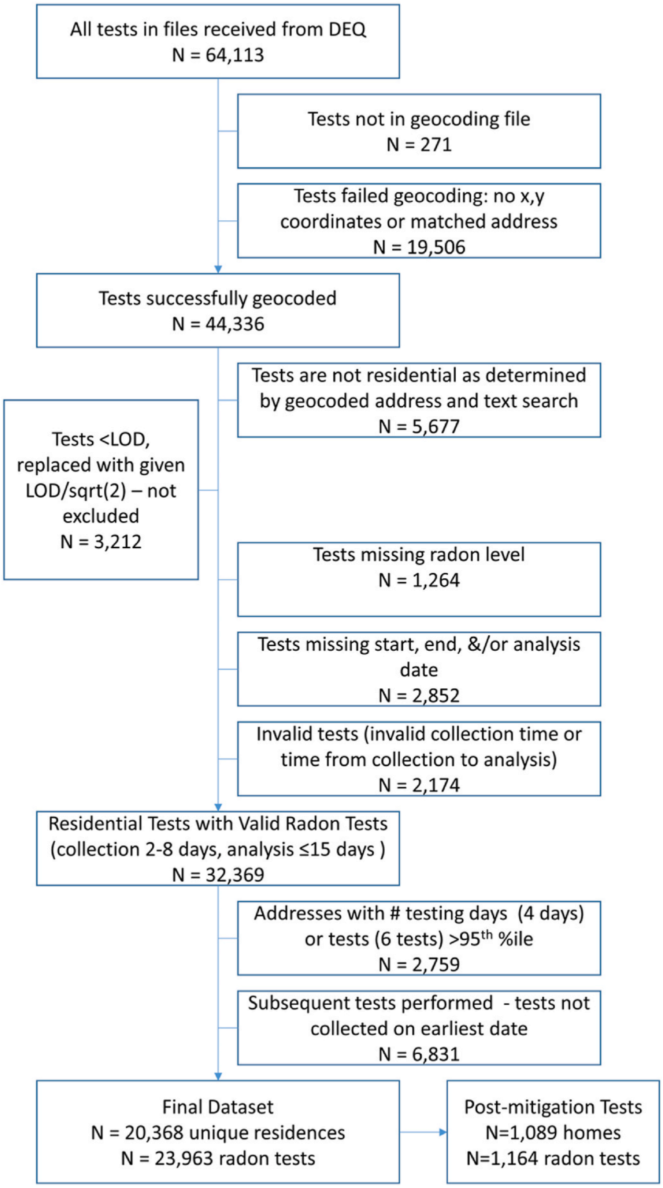

Fig. 1. Identification of residential radon tests.

2.2. Developing block group measures of radon risk characterization

2.2.1 Block Group (BG) Level Radon-Hazard Potential Soil and Population Characteristics: The Utah Geological Survey (UGS) created and mapped a hazard-potential ranking system of soils in Utah using soil uranium concentration, soil permeability to water and air, and groundwater depth (Bill, 2022). The radon-hazard potential soil categories shown in the map were high areas, meaning geologic factors were favorable for elevated indoor radon concentrations >4 pCi/L; moderate, meaning areas with factors favorable for elevated indoor radon concentrations, but are limited by one or more unfavorable factors; and low, areas with geologic factors unfavorable for elevated indoor radon concentrations (Fig. 1).

Census blocks from the 2010 US Census were spatially joined to the radon-hazard potential soil map. We first determined the feasibility of using Census blocks as the main unit of analysis. After a review of the linkage to radon-hazard potential soil maps, the number of homes with radon tests in each block, and availability of data on demographic characteristics from the US Census, we aggregated census blocks into block groups. We calculated the percent of the block group's total landmass on high radon-hazard potential soil (Bill, 2022). We used this same approach to calculate the number of housing units in each block group on high radon-hazard potential soil. We categorized the percent landmass and percent housing units on high radon-hazard potential soil into 0%, 1–24%, 25–75%, and 75–100%. We assigned block groups the radon-hazard level reflective of the soil composition of the largest area.

EPA county-level radon zones were obtained from the EPA website and assigned to each residence and block group (Environmental Protection Agency, 2019).

2.2.2 Block Group Median Radon Testing Levels: We linked each geocoded residence to their block group. We calculated the block group median of each residence's maximum radon test result and categorized the median as ≥4 pCi/L or <4 pCi/L. We identified block groups with ≥5 and <5 residential radon tests in our dataset to identify block groups that we consider as having low testing participation. Block groups with <5 homes tested were excluded from summary statistics of radon concentrations due to uncertainty of the radon measurement.

2.3. Sociodemographic and testing measures

2.3.1 Block Group Characteristics: We used 2013 American Community Survey (ACS) data to extract the following housing characteristics at the block group level; (a) median year of home construction, (b) percent of detached single-family homes, and (c) median income. If the median year of home construction was missing, data from the ACS in the nearest subsequent year was used (n = 530). Demographic characteristics from the 2010 United States Census were available by block group. We calculated the percent Hispanic ethnicity, American Indian/Alaska Native, and Hawaiian or Pacific Islander populations. We focused on Hispanics because they are the fastest growing minority in Utah and Utah is also home to a large Pacific Islander population (Hollingshaus et al., 2019). Native Americans have also lived in areas with potential for high radon emissions. We also classified block groups as urban (Salt Lake, Davis, Weber, and Utah County) or rurally located (any other county).

3. Statistical analysis

We first described the radon test results in individual residences by year of their first test, radon-hazard potential of the residence's soil, the median year of construction of the residence's block group, and the residence's EPA radon zone. We compared the distribution of having a maximum pre-mitigation residential test <4 pCi/L and ≥4 pCi/L by these characteristics using the Chi-square test.

Next, we wanted to understand the correlation between the residential radon test results and 1) the radon-hazard potential soils of the home itself, 2) block group measures of radon hazard risk, and 3) the EPA radon zones. To conduct this analysis, we log-transformed the individual residential test results to create a normal distribution. We used linear regression models to estimate the association between the log-transformed residential radon test result with a) the radon-hazard potential of soil at residence, b) block group percent of landmass on high radon-hazard potential soil, c) block group percent of residences on high radon-hazard potential soil, d) EPA radon zone, and e) median year of home construction in each block group. We controlled for year of first radon test to account for potential differences in testing or laboratory methods and block group median year of home construction with robust standard errors to account for clustering by block group. We identified significant trends in the median residential radon test results across the block group and EPA county categories.

Since the radon health standard of ≥4 pCi/L has public health implications, we wanted to know if the methods of designating radon exposure potential by block group and EPA radon zone were correlated with having a residential radon test ≥4 pCi/L. We used logistic regression to estimate the association between having a residential radon test ≥4 pCi/L and a) the radon-hazard potential of soil at residence, b) block group percent of landmass on high radon-hazard potential soil, c) block group percent of residences on high radon-hazard potential soil, d) EPA radon zone, and e) median year of home construction with a logistic regression model. These models also controlled for year of test and block group median year of home construction. Test for trends in the odds ratios were conducted using Wilcoxon rank sum and Cochran-Armitage Trend Test.

A major weakness of this dataset is that the testing results are affected by public engagement. To better understand which populations for which we did not have testing data, we compared demographic differences between block groups with ≥5 residences and <5 residences that had a radon test in our dataset. We examined differences in the means of: 1) block group % landmass on high radon-hazard potential soil, 2) rural/urban county status, 3) mean percent of racial and ethnic minorities in each block group, and 4) the block group median year of home construction. Chi-square tests and Wilcoxon rank sum tests provided the p-values for differences in comparison.

To further explore these gaps in radon testing, we used logistic regression to determine the association between having <5 homes tested (low radon testing) and the block group percent of homes on high radon-hazard potential soil, the block group median year of home construction, and the percent of racial and ethnic minorities in each block group (% any racial or ethnic minority; % Hispanic; % Native American, Hawaiian, and Pacific Islander). The first univariate model included the block group median year of home construction. The second included the block group percent of homes on high radon-hazard potential soil controlling for block group median year of home construction as a proxy for changing radon testing practices over time. The last set of models examined the association between the block group percent of racial/ethnic populations and odds of having <5 homes tested in each block group. Each racial/ethnic group was included in a separate model that controlled for the block group median year of home construction.

We were concerned that racial/ethnic minorities may live in block groups with high radon testing, but may have low levels of engagement in radon testing in general. To explore this question, we calculated the odds for the association of the block group percent of residencies on high radon-hazard potential soil and having <5 test in the dataset, stratified by the percent of any racial/ethnic minorities and Hispanics in each block group, separately. We divided block groups by the statewide median percent of any racial/ethnic minority and Hispanics, which is the largest ethnic minority group in Utah (Hollingshaus et al., 2019). We used an interaction term to determine if there was effect modification of the association.

4. Results

The Utah Geological Survey map of high radon-hazard potential soil shows a high degree of variation within counties throughout the entire state (Fig. 2). EPA's county-based classification system only shows evidence of high radon in Eastern Utah counties, and the county-aggregated radon laboratory test data provided by NEPHTN classifies nearly all Utah counties as having indoor radon test results greater than the health standard (Utah Geologic Survey, 2022). Table 1 shows the descriptive statistics for all residences as well as stratified by the EPA's recommended level for remediation, ≥4 pCi/L. We identified 20,126 residences with residential radon tests in our dataset. Approximately 41.6% ($N_{\text{test max} \geq 4\text{ pCi/L}} = 8{,}375$; $N_{\text{total tests}} = 20{,}126$) residences had at least one test ≥4 pCi/L. The highest home radon test value was 170.3 pCi/L (Table 1). The majority of the residential radon test results were completed after 2012 (75.5%). We found significant differences in the percent of homes with test maximums <4 or ≥4 pCi/L by residential radon-hazard potential and block group median year of home construction. Homes built between 1976 and 1998 had higher than expected proportions of residential radon tests ≥4 pCi/L. We found no association between residential radon measures and EPA county risk classification.

Linear and threshold models were used to quantify the association between residential radon levels and radon-hazard potential (Table 2). Residences on high radon-hazard potential soil had significantly higher geometric means of residential radon test levels and higher odds of having a test ≥4 pCi/L (OR = 1.71, 95% CI = 1.38–2.13), relative to residences on low radon-hazard potential soil. The block group percent of landmass and block group percent of homes on high radon-hazard potential soil followed similar patterns. For both measures, the association of residential radon test results increased as the percentages of landmass or residences on high radon-hazard potential soil increased. In both the linear and logistic models, the relative increases were very similar. While the increases were small, we found significant trends across the increases in the linear and logistic model by categories of percent landmass or percent residences on high radon-hazard potential soil. Relative to residences in moderate EPA radon zones, residences in EPA high radon zones had a lower estimated residential radon tests and

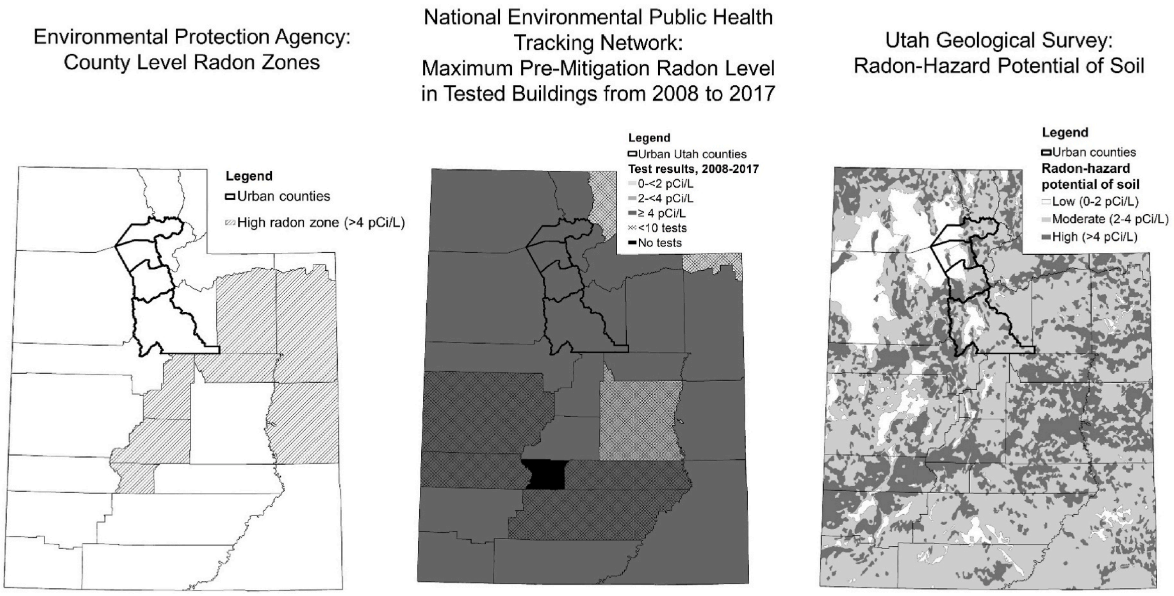

Fig. 2. Methods of estimating risk for indoor radon exposure in Utah counties according to three public health agencies.

Table 1
A description of residential radon test results in individual homes in a large Utah-based database (N = 20,126).

Maximum test result at a location	Total N = 20,126		Test maximum ≥4 pCi/L N = 8375		Test maximum <4 pCi/L N = 11,750		Chi-square p-value
	Median	Min-Max	Median	Min-Max	Median	Min-Max	
	3.2	0.0–170.3	7.3	4.0–170.3	1.9	0.0–3.9	
	n	%	n	%	N	%	
Year of first residential radon test							
2001 to 2006	166	0.8	NA	NA	NA		
2007 to 2011	4760	23.7					
2012 to 2017	15,199	75.5					
Radon-hazard potential of soil at residence							
Low (0-<2 pCi/L)	2395	11.9	834	10.0	1561	13.3	<.0001
Moderate (2-<4 pCi/L)	10,056	50.0	3878	46.3	6178	52.6	
High (≥4 pCi/L)	7674	38.1	3663	43.7	4011	34.1	
Median year of construction of residence’s block group							
1939 to 1950	1111	5.5	387	4.6	724	6.2	<.0001
1951 to 1975	4202	20.9	1581	18.9	2621	22.3	
1976 to 1987	4503	22.4	1958	23.4	2545	21.7	
1988 to 1998	5188	25.8	2391	28.6	2797	23.8	
1999 to 2007	5110	25.4	2055	24.5	3055	26.0	
EPA radon zone							
Moderate risk county (2-<4 pCi/L)	19,798	98.4	8247	98.5	11,551	98.3	0.36
High risk county (≥4 pCi/L)	327	1.6	128	1.5	199	1.7	

Table 2
The association of block group measures of radon exposure, Environmental Protection Agency radon zones, and maximum pre-mitigation radon test result from individual residences.

	Linear model for residential radon test				Logistic model for residential radon test ≥4 pCi/L			
	β	95% CI	p-value trend	R^2	OR	95% CI	p-value trend	Pseudo R^2
Radon-hazard potential of soil at residence								
Low (0-<2 pCi/L)	Ref		<.0001	0.014	Ref			0.0103
Moderate (2-<4 pCi/L)	0.07[a]	0.03–0.12			1.18	0.96–1.45	<.0001	
High (≥4 pCi/L)	0.28[a]	0.24–0.33			1.71[a]	1.38–2.13		
Block group % landmass on high radon-hazard potential soil								
0%	Ref		<.0001	0.018	Ref		<.0001	0.0129
1–24%	0.24[a]	0.19–0.29			1.57[a]	1.27–1.93		
25–74%	0.26[a]	0.22–0.30			1.55[a]	1.31–1.82		
75–100%	0.26[a]	0.23–0.29			1.62[a]	1.41–1.86		
Block group % of residences on high radon-hazard potential soil								
0%	Ref			0.018	Ref		<.0001	0.0132
1–24%	0.27[a]	0.22–0.32	<.0001		1.60[a]	1.28–2.00		
25–74%	0.25[a]	0.20–0.29			1.54[a]	1.28–1.85		
75–100%	0.26[a]	0.23–0.29			1.61[a]	1.41–1.83		
EPA radon zone								
Moderate risk county (2-<4 pCi/L)	Ref			0.0006	Ref		0.36	0.0004
High risk county (≥4 pCi/L)	−0.002	−0.11–0.11	0.93		0.90	0.65–1.26		
Block group median year of home construction								
1939 to 1950	Ref		<.0001	0.01	Ref		<.0001	0.0054
1951 to 1975	0.06[a]	0–0.13			1.13	0.09–1.43		
1976 to 1987	0.21[a]	0.15–0.27			1.45[a]	1.14–1.84		
1988 to 1998	0.25[a]	0.19–0.32			1.60[a]	1.26–2.03		
1999 to 2007	0.15[a]	0.09–0.22			1.26	0.98–1.61		

Models were run separately; All models control for year of first radon test and block group median year of home construction.
Log-linear model used median one-way analysis of trend; logistic model used two-way Cochran-Armitage trend test.

[a] Indicates statistical significance.

lower odds of having a radon test ≥4 pCi/L.

Of the 1,683 block groups in Utah, 527 block groups (31%) had <5 residences tested for radon in our dataset (Table 3). The median age of homes in block groups with <5 residences tested were generally older than block groups with ≥5 residences tested. A larger percent of block groups with <5 residences tested had 0% (68.5% vs 58.7%) or 1–24% (12.3% vs 8.0%) of homes on high radon-hazard potential soil or were located in rural counties (37.2% vs 20.4%). Block groups with <5 residences tested had as significantly higher percentage of Hispanics (18.4% vs 10.3%) and American Indian/Native Americans (2.5% vs 0.7%) in their populations.

We found significant demographic differences among block groups with <5 residences with tests in our dataset (Table 4). Block groups whose median year of home construction was between 1988 and 1998 (OR = 0.40, 95% CI = 0.26–0.63), or 1999 and 2007 (OR = 0.15, 95% CI = 0.08–0.26) had lower odds of having <5 residences with tests in the dataset. After controlling for block group median year of home construction, the high radon-hazard potential soil showed significant but inconsistent associations with odds of having <5 residences with tests in the dataset. Block groups with 1–24% of residences on high radon-hazard potential soil had higher odds of having <5 residences in the dataset (OR = 1.40, 95% CI = 0.98–1.99). Block groups with 25–74% (OR = 0.63, 95%CI = 0.42–0.95) and 75–100% (OR = 0.51, 95% CI = 0.38–0.70) of homes on high radon-hazard potential soil had significant

Table 3
Characteristics of block groups tested in a large Utah-based dataset by number of homes.

	All	Number of residences tested in each block group					
		≥5 homes tested	<5 homes tested	p-value			
	N	%	N	%	N	%	
All	1683		1156		527		
Block group % landmass on high radon-hazard potential soil							
0%	1040	61.8	679	58.7	361	68.5	<.0001
1–24%	158	9.4	93	8.0	65	12.3	
25–74%	152	9.0	117	10.1	35	6.6	
75–100%	333	19.8	267	23.1	66	12.5	
Rural county status							
Urban	1251	74.3	920	79.6	331	62.8	<.0001
Rural	432	25.7	236	20.4	196	37.2	
Population characteristics	Mean	Min-Max	Mean	Min-Max	Mean	Min-Max	
% Hispanic	12.8	0–74.4	10.3	0.4–60	18.4	0–74.4	<.0001
% American Indian/Native American	1.3	0–97.6	0.7	0–27	2.5	0–97.6	<.0001
% Hawaiian or Pacific Islander	0.9	0–17.2	0.8	0–10.5	1.1	0–17.2	0.92
Block group median year of home construction							
1939 to 1950	114	6.8	66	5.7	48	9.1	<.0001
1951 to 1975	523	31.1	318	27.5	205	38.9	
1976 to 1987	474	28.2	304	26.3	170	32.3	
1988 to 1998	371	22.0	287	24.8	84	15.9	
1999 to 2007	199	11.8	180	15.6	19	3.6	

Table 4
Multivariable models showing the association between characteristics and block groups with <5 residential with radon tests a large Utah-based dataset.

	Univariate model for median year home construction		% of residences on high radon-hazard potential soil controlling for median year of home construction		Individual models for racial/ethnic group, each controlling for median year of home construction	
	OR	95% CI	OR	95% CI	OR	95% CI
Block group median year home construction						
1939 to 1950	Ref		Ref			
1951 to 1975	0.89	0.59–1.34	0.88	0.58–1.33		
1976 to 1987	0.77	0.51–1.17	0.79	0.52–1.20		
1988 to 1998	0.40*	0.26–0.63	0.42*	0.27–0.66		
1999 to 2007	0.15*	0.08–0.26	0.15*	0.08–0.28		
Block group % of residences on high radon-hazard potential soil						
0%			Ref			
1–24%			1.40	0.98–1.99		
25–74%			0.63*	0.42–0.95		
75–100%			0.51*	0.38–0.70		
Any racial or ethnic minority						
<15%					Ref	
>=Median 15%					2.72*	2.18–3.40
Hispanic						
<8.3%					Ref	
≥Median 8.3%					3.07*	2.45–3.84
Native American						
<0.6%					Ref	
≥Median 0.6%					3.77*	2.99–4.75
Hawaiian or Pacific Islander						
<0.4%					Ref	
≥Median 0.4%					0.97	0.79–1.20

inverse odds of having <5 homes in the dataset. Block groups with greater than median percentages of the population who were any racial/ethnic minority (OR = 2.72, 95% CI = 2.18–3.40), Hispanic (OR = 3.07, 95% CI = 2.45–3.84), and Native Americans (OR = 3.77, 95% CI = 2.99–4.75) had higher odds of having <5 residences with tests in our dataset.

We determined if racial and ethnic composition of the block group modified the association of block group percent of residences on high radon-hazard potential soil and having <5 residences with tests in the dataset (Table 5). We found significant effect modification of this association by block group median percent of any racial/ethnic minority and Hispanic populations. Block groups with <15% of any racial/ethnic minority population and had 1–24% of homes on high radon-hazard potential soil had higher odds of having <5 tests in the dataset (OR = 2.41, 95% CI = 1.55–3.74), while block groups with 75–100% of homes on high radon-hazard potential soil had significant inverse odds of having <5 test in the data (OR = 0.27, 95% CI = 0.15–0.47). Block groups with <8.3% of Hispanics and 1–24% of residences on high radon-hazard potential soil had a significantly higher odds of having <5 residences tested in the dataset (OR = 2.70, 95% CI = 1.73–4.22) relative to block groups with 0% of residences on high radon-hazard potential soils. Block groups with ≥8.3% Hispanic population and 25–74% of homes on high radon-hazard potential soils had inverse odds of having <5 residences with test in the dataset (OR = 0.47, 95% CI = 0.26–0.85).

5. Discussion

Environmental public health tracking systems are critical tools to understanding complex relationships between human health and environmental exposures, and identifying population-level disparities in exposure to hazardous environmental contaminants. Our study showed that residential location on high radon-hazard potential soil had a significant positive correlation with a radon test result above the health standard. We also that radon test results from individual residences were

Table 5
An examination of patterns in block group high radon-hazard soil and low residential radon testing by the statewide median percent of racial and ethnic minorities per block group in Utah.

		<5 residential tests in dataset		
	% residences on high radon-hazard potential soil	OR	95% CI	p-value effect modification
Strata 1:				
Block group % any racial/ethnic minority <15	0%	Ref		<.0001
	1–24%	2.41*	1.55–3.74	
	25–74%	0.83	0.48–1.47	
	75–100%	0.27*	0.15–0.47	
Block group % any racial/ethnic minority ≥15	0%			
	1–24%	1.07	0.57–2.01	
	25–74%	0.58	0.32–1.05	
	75–100%	1.10	0.74–1.65	
Strata 2:				
Block group % Hispanic <8.3	0%	Ref		<.0001
	1–24%	2.70*	1.73–4.22	
	25–74%	1.03	0.59–1.81	
	75–100%	0.27	0.15–0.50	
Block group % Hispanic ≥8.3	0%	Ref		
	1–24%	0.98	0.53–1.80	
	25–74%	0.47*	0.26–0.85	
	75–100%	0.91	0.62–1.35	

correlated with the block group percent of residences on high radon-hazard potential soil, which reflects the underlying geology. While soil composition is an important factor in determining indoor radon exposure, it is not the only determining factor. The house's construction and its isolation measures from soil play a crucial role in the level of radon contamination inside the residence (Stanley et al., 2019). Differences in construction and vapor intrusion between homes in close spatial proximity will lead to variability in radon intrusion. Members of the public should note that because of these differences, their neighbors' test results may not reflect their own radon concentrations.

In lieu of consistent surveillance for indoor radon exposure, assessments of high radon-hazard potential soil on a small geographic scale appear may aid in the identification of residences at-risk for radon exposure. In contrast, EPA's method of classifying counties at risk for radon exposure is not correlated with indoor residential radon test results. This finding is particularly relevant for epidemiologic studies or precision interventions that may need, but not have, laboratory testing or other radon data at geographic resolution below the county level.

In our database, 42% of homes tested had radon ≥4 pCi/L. This is higher than previous reports that 1 in 3 Utah homes is at risk for radon exposure ≥4 pCi/L and self-reported percentages from the Utah Behavioral Risk Factor Surveillance System (BRFSS) of nearly 18% of Utah homes testing ≥4 pCi/L (Ou et al., 2019) As the maximum home result of 170.3 pCi/L is forty-times greater than the federal health standard, it appears that homes in Utah may be at risk for extremely high radon levels. Our findings support that individuals living in homes located on high radon-hazard potential soil and block groups with any percentage of residences on high radon-hazard potential soil are at risk for radon exposure above the health standard. After summing the population within each block group containing any high radon-hazard potential soil, up to 1.3 million or 42% of Utah residents (1,334,890/3,148,500 persons in the 2010 census) may be exposed to indoor radon concentrations above the health standard.

In the multivariable and stratified analysis, block groups with 1–24% of residences on high radon-hazard potential soil had higher odds of low engagement with radon testing (<5 residential tests in our dataset). Residences in these block groups are still at risk for having a radon test ≥4 pCi/L. Interventions to improve radon testing should not overlook these areas.

Effective interventions to increase radon testing in other states have utilized a multi-pronged approach and typically consist of internet, print, and televised media materials combined with in-person education. Successful implementation of these interventions can be costly if done on a statewide scale, especially in a state like Utah with sprawling counties and a rapidly diversifying population that speaks multiple languages. In 2014, legislation required Utah public health agencies to develop a statewide electronic campaign to educate the public about radon gas, including health risks and testing options. These online educational videos are available at no cost through public health agencies. But, these materials must be actively sought out through online query or found on social media pages of agencies related to public health. The active searching required to find these videos may lead to a gap in connecting populations with relevant, culturally appropriate educational materials. Additional follow-up of radon testing habits on a new BRFSS can help identify statewide longitudinal patterns in radon testing throughout the state.

The BRFSS survey also found that racial and ethnic minorities were significantly less likely to test their homes for radon than Non-Hispanic Whites (Ou et al., 2019). Our findings agree with this prior study as block groups with greater than median percentages of Hispanics and persons of any racial/ethnic minority had a higher odds of having <5 residential tests in the dataset. Our analysis supports the need for culturally appropriate, tailored interventions that can reach ethnic and racial minorities in the state of Utah. Currently, electronic educational materials on the topic of radon are provided in English and Spanish, but the low prevalence of radon testing among Hispanics suggests that Spanish-speaking persons may not access these materials or free resources to test their home for radon. Health educators that directly engage the Hispanic community in radon testing may have positive impacts in future interventions.

Because rural counties had greater percent of block groups with <5 residential tests in the data, we suspect that radon levels in rural counties may be underrepresented in this dataset. Because the statewide radon education program and other public health agencies are based in urban counties, public engagement in educational radon programs may be influenced by geographic location in the state. The current statewide program has one health educator that provides in-person education, but the rural counties in Utah cover large sprawling areas and it may be difficult to reach rural populations as their distance from the urban areas increases. As stable internet connections may not be available in rural locations, accessing online materials provided by public health agencies may also be difficult for rural populations.

Precision public health necessitates that environmental monitoring occurs consistently on a small geographic scale, but this degree of monitoring may be difficult to achieve for radon. No cohesive statewide system in Utah aggregates home radon tests conducted by public and private agencies on a consist basis. Unlike air or water pollutants that can be measured using instruments located on public land, indoor radon concentrations can only be detected within buildings that are owned by individuals or entities in the public and private sectors. This limitation has the potential to create legal barriers to creating a consistent, statewide radon monitoring plan. Testing for radon in private spaces may bring up questions of property rights, pit landlord obligations against renter's rights, and open the door for questions about responsibility for illness or injury that Utah's current policies do not address. Changing building codes, installation of new ventilation systems, and construction on buildings can also change the ways that radon can become trapped inside buildings in new construction, but will not resolve the issues that older buildings have. As radon data are already challenging to acquire, measuring public radon exposure will be challenging as Utah's population continues to expand and building codes change over time.

Modeling public exposure to radon is one approach that can aid in filling the gap in data collection, and the development of valid prediction models that estimate indoor exposure to radon would have immediate public health uses. Laboratory scientists and clinicians are actively seeking biomarkers that can identify radon-induced lung cancers, but these biomarkers will be difficult to validate in humans without a method to estimate prior radon exposure based on location. Building models to predict risk of indoor radon exposure can be accomplished through the creation of rich datasets that include radon-hazard potential of the soil and other geologic factors, age of the home, radon in water, and home construction among other relevant data. Yet without actual radon tests to validate the models, the predictive value of these models cannot be determined. Our current dataset will assist in building these models, but continued data collection is needed to validate model results and project how radon exposure will vary over time and geographic space.

The challenges to ongoing radon surveillance and risk estimation may be overcome through partnership and public engagement. Radon tests are conducted by realtors and mitigators on a regular basis. We identified a small percent of tests in our dataset as potentially having been collected by these entities, but we do not know exactly how many additional tests were conducted by realtors or mitigation companies. As we know that these persons are actively collecting radon data, we suspect that the actual number of homes tested for radon in Utah is larger than what is reflected by our dataset. There is no current avenue for mitigators or realtors to submit the results of the radon tests to public health agencies on a voluntary basis. Providing a means for voluntary reporting of laboratory-validated radon tests is a simple, low-cost way to collect this data. In addition, community engagement in air pollution monitoring has proven successful. If public health and researchers can engage and empower community groups to conduct and share radon test results, public engagement may help fill in gaps in data collection.

5.1. Limitations

Individual home age and foundation construction were not available in our data. While it is generally assumed that older homes may have higher radon levels than newer homes, a recent study of new homes suggests that radon exposure is rising across the North American West and that newer home designs are associated with increasing radon exposure (Stanley et al., 2019). We used data about the block group median year homes were built from the census to act as a proxy for these variables. We could not discern tests that were conducted in apartment buildings from those in single family homes, and these tests may have been removed based on the inclusion criteria for the tests themselves.

The collection of data for this study relied on public engagement and trust in the current educational program, their motivation to conduct the test, and their ability to complete the test without error. This leaves the collection of data vulnerable to bias due to public perceptions of the radon program, their personal motivation or resources (e.g. time, transportation, home ownership) to complete the tests, and the program's ability to reach certain populations. Because of this bias, our testing results may underrepresent the risk for indoor radon exposure in specific portions of the state or in certain populations. Since the focus of this study was to determine the capability of using a public dataset to identify radon exposure risk by block group, we chose to forgo averaging radon test results from block groups with <5 radon tests to ensure stability of results. The low sample size of measurements carried out in some of those areas may not allow definitive conclusions to be drawn in future studies.

All of the tests included in our dataset were short-term radon tests lasting around three days. As the statewide program's goal is to encourage radon testing, these short-term tests are the most cost-efficient and resource-efficient method to engage the public in radon testing. Long term radon monitoring is preferred as radon emissions can fluctuate over short periods of time. Due to the resource intensive nature of long-term radon testing, this method is not optimal for use in publicly-funded radon programs that have limited resources and personnel. However, comparisons between radon tests of varying duration found that the 5-day and 30-day tests reflected the 90-day tests over 85% of the time (Warkentin and Johnson, 2015). While we agree that the short-term radon tests should be evaluated with long-term radon monitoring systems, we suspect that the short-term tests used in this study may reflect long-term radon testing results.

Despite these limitations, to our knowledge, our database is the largest statewide dataset to date that contains geocoded information about the location of short-term radon tests distributed from statewide educational program and its laboratory partner. As such, it does provide valuable information about radon testing and radon levels in Utah residences at small geographic areas.

6. Conclusions

Small scale environmental data is key to identifying populations at risk for high levels of indoor radon exposure to facilitate interventions and understand disease risk. Block groups at risk for low radon testing and high radon exposure in Utah appear to have the highest percent of Hispanics, racial and ethnic minorities, and are located in rural areas. Consistent data collection is critical to continuing the work on characterizing population radon exposure, but there are several legal and logistic barriers to establishing a statewide system that routinely collects radon testing data. Engagement of radon mitigators, real estate agents, the public in radon testing may help bridge the gaps in the current radon data.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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