Assessing Indoor Radon Exposure on the Navajo Nation

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A dissertation
submitted in partial fulfillment of the
requirements for the degree of

Doctor of Philosophy

University of Washington

2017

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Abstract

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This study was done to provide an assessment of indoor radon exposure on the Navajo Nation, a geographic region in the Southwest U.S. with naturally elevated levels of uranium in the soil and rocks. Radon is a decay product of uranium and is a known lung carcinogen. Radon has no odor, color, and can pass from the soil into homes. The Navajo Nation also has a legacy of uranium mining with over 500 abandoned uranium mines exposing nearby communities to uranium waste tailings, which were sometimes used to build homes. As a result, communities living in a geographic region with elevated levels of uranium impacted by uranium mining could potentially be exposed to higher levels of radon.

To measure indoor radon levels on the Navajo Nation, we recruited a sample of volunteers from the Community Uranium Exposure Journey To Healing (CUEJTH) Program. The CUEJTH program provides education on the health effects associated with uranium to communities across the Navajo Nation. To increase the number of homes with indoor radon measurements, we combined the CUEJTH indoor radon measurements with indoor radon measurements collected through the Navajo Birth Cohort Study (NBCS), which is an on-going epidemiologic study on the Navajo Nation. Using the two datasets of indoor radon measurements, we developed an indoor radon prediction model for homes on the Navajo Nation.

To develop our indoor radon prediction model, we used a combination of data collected through both the CUEJTH program and NBCS in combination with existing geographic land predictors identified in

the literature as known predictors of indoor radon levels. We used a land use regression model in combination with spatial mapping to develop our model. Key findings in our study show that indoor radon levels depend on both the house type and the sediment soil uranium concentration. We also observed a spatial pattern informing us that in addition to the type of home and sediment soil uranium concentration, that where the home is located matters as well. By location, we are referring to where the home is located which is a combination of geospatial factors. In addition to the soil uranium concentration at each home location, where the home is built along with the microclimate around the home, i.e., the temperature during radon testing and the elevation of the home are associated with indoor radon concentration levels. The findings from this study could be used the Navajo Nation to encourage indoor radon testing for homeowners on the Navajo Nation, but also to raise radon awareness in areas predicted to potentially have elevated levels of indoor radon.

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Chapter 1
BACKGROUND

1.1 Introduction

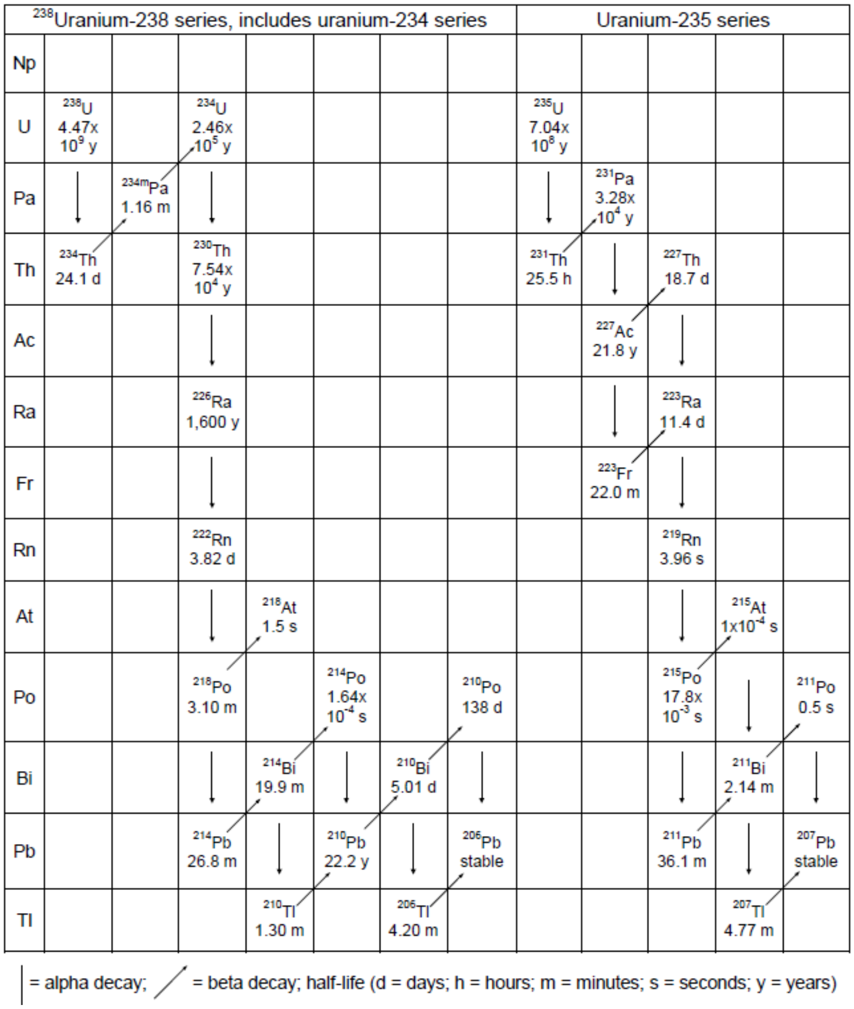
This project was undertaken to provide analytic support to the Community Uranium Exposure Journey To Healing Program (CUEJTH) which is sponsored by the Navajo Area Indian Health Service located in Shiprock, New Mexico.[1] The Navajo Nation is located on the Colorado Plateau, a region which contains high levels of natural uranium in the soil and rocks.[2, 3] A decay product of uranium is radon, a lung carcinogen, which has no color or odor and is able to diffuse from the soil into homes.

Exposure to radon in non-occupational settings could potentially occur from naturally enriched soil with uranium or from anthropogenic hazardous waste, such as abandoned uranium mines (AUMs), or wastes from uranium mine and mill tailings.[4] According to the United States Environmental Protection Agency (US EPA), during the period between 1944 and 1986 approximately four million tons of uranium from the Navajo Nation was extracted leaving behind over 500 abandoned uranium mines (AUMs). Thus, people who live near uranium mines may be exposed to greater levels of uranium and radon compared to communities who do not live near such sites.[5] Radon itself decays into radioactive progeny that are capable of binding to dust particles creating a potential for inhalation exposure. Health effects associated with occupational exposure to uranium and its decay progeny which includes radon have been well established in previous epidemiologic studies.[6-11] In one epidemiologic nested case-control study conducted among non-smoking uranium miners employed in the uranium industry during the time period 1956 to 1990 in the western U.S., the authors observed a relative risk of 29.2 [95% CI: 5.1, 167.2] for miners exposed to 1,450 working level months (WLM) compared to those with less than 80 WLM.[7] In contrast, there have been relatively few studies of the health effects associated with radon exposure in non-occupational settings. These studies in addition to animal studies suggest an association between inhalation exposure to radon and lung cancer. [5, 12]

1.2 Uranium

1.2.1 Properties of Uranium

Uranium is an actinide metal with radioactive properties; it is naturally found in the earth's crust, ores, and rocks. This radioactive element has 22 known isotopes, but only 3 occur naturally which include ^{238U} (99.274%), ^{235}U (0.72%), and ^{234}U (0.0057%).[3, 13] As a radioactive property, ^{238}U is considered a parent that decays into other progeny to reach a state of stability where it is non-radioactive. These naturally occurring isotopes and some of their progeny release alpha particles, beta particles, and x-and-gamma rays when transforming into other radioactive elements. There are two decay series through which ^{238}U reaches stability as depicted in Figure 1 below.



	^{238}Uranium-238 series, includes uranium-234 series							Uranium-235 series				
Np												
U	^{238}U 4.47x 10^9 y		^{234}U 2.46x 10^5 y					^{235}U 7.04x 10^8 y				
Pa	↓	^{234m}Pa 1.16 m	↓					↓	^{231}Pa 3.28x 10^4 y			
Th	^{234}Th 24.1 d		^{230}Th 7.54x 10^4 y					^{231}Th 25.5 h	↓	^{227}Th 18.7 d		
Ac			↓						^{227}Ac 21.8 y	↓		
Ra			^{226}Ra 1,600 y						↓	^{223}Ra 11.4 d		
Fr			↓						^{223}Fr 22.0 m	↓		
Rn			^{222}Rn 3.82 d							^{219}Rn 3.96 s		
At			↓	^{218}At 1.5 s						↓	^{215}At 1x10^{-4} s	
Po			^{218}Po 3.10 m		^{214}Po 1.64x 10^{-4} s		^{210}Po 138 d			^{215}Po 17.8x 10^{-3} s	↓	^{211}Po 0.5 s
Bi			↓	^{214}Bi 19.9 m	↓	^{210}Bi 5.01 d	↓			↓	^{211}Bi 2.14 m	↓
Pb			^{214}Pb 26.8 m	↓	^{210}Pb 22.2 y	↓	^{206}Pb stable			^{211}Pb 36.1 m	↓	^{207}Pb stable
Tl				^{210}Tl 1.30 m		^{206}Tl 4.20 m					^{207}Tl 4.77 m	

| = alpha decay; ⁄ = beta decay; half-life (d = days; h = hours; m = minutes; s = seconds; y = years)

Figure 1: Uranium Decay Chain (ATSDR, 1999)

In the first decay series, ^{238}U decays to ^{234}U which eventually decays to stable lead-206 (^{206}Pb).[3] In the second radioactive decay series, ^{238}U decays to ^{235}U through 13 radioactive progeny which produces stable lead-207 (^{207}Pb). The amount of time required for one-half of the parent radioactive element to decay is called the half-life. The decay half-lives for ^{238}U, ^{235}U, and ^{234}U are $4.5X10^9$, $7.0X10^8$, and $2.5X10^5$ years respectively.[14] It is perceivable uranium will remain in the environment for thousands of years and continue decaying to form other radioactive products.[15] During uranium radioactive decay, two radioactive progeny formed are ^{226}Radium (^{226}Ra) and ^{222}Radon (^{222}Rn) which have the potential to lodge onto dust particles (often called 'Radon Daughters'). As explained in more detail further in this chapter, the half-life of the uranium decay product ^{222}Rn is 3.82 days. Based on their states and decay half-lives in the natural environment, exposure to uranium is more of a heavy metal risk exposure often via ingestion; and in comparison, radon exposure with a short decay half-life poses more of an inhalation risk as an airborne gas. Inhalation or ingestion of these radioactive particles causes cellular damage through the release of alpha particles, which cause cellular tissue damage.[13] As a consequence, damage to cellular contents affects the mitochondria, enzyme, and DNA.

1.2.2 Uranium Mining and Regulation on the Navajo Nation

Uranium is naturally found in the environment as a radioactive metal element with high concentrations in the Southwest region of the US. In this region is the Navajo Reservation which spans approximately 27,000 square miles in New Mexico, Arizona, and Utah, and is the largest Indian reservation in the United States. Beginning in the late 1940s through the 1960s, the US Government was the sole purchaser of uranium ore in this region.[16] During this period on the Navajo Reservation there was an estimated 1,200 mines and four mills producing uranium.[17] Furthermore, approximately 4,000 Navajo miners were employed during this time in addition to 500-600 mill workers.[17] Although the mines are closed today, communities on the Navajo Reservation continue to be affected by AUMs which are deserted and unmaintained. These AUMs along with uranium contamination detected in homes and drinking water sources continue to adversely impacts Navajo Nation residents and are potential sources of indoor radon exposure.[2]

1.2.3 Abandoned Uranium Mines

In November 1993, the Navajo Nation expressed its health concerns to a US Congressional Subcommittee regarding AUMs on the Navajo Nation.[18] The US EPA also exercised their federal authority under the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) to assist the Navajo Tribe.[18] The EPA Superfund program, created by CERCLA, develops short-and-long term actions to address actual or threatened releases of hazardous substances, which included man-made wastes from uranium mining and waste piles.[19] In response to a hearing with the Tribe, the US EPA Region 9 initiated the Navajo Abandoned Uranium Mines (NAUM) Project in 1994. A product of this NAUM project is a Geographical Information System (GIS) database which identified additional abandoned AUMs. In 2007 the U.S. House of Representatives Committee on Oversight and Government Reform tasked key federal agencies to address and clean up uranium on the Navajo Reservation.[2] In a recent report prepared by these key agencies for the time period 2008-2012, 521 mine sites were surveyed in addition to 45 high priority mine sites.[1] The US EPA was one of the agencies which reported there were 226 mines sites found to have radiation levels ten times above background.

1.2.4 Sources and Routes of Uranium Exposure

Non-occupational exposure to uranium most commonly occurs through ingestion of food or water that is contaminated with uranium.[20,3] Typically, uranium ingested in food contributes an exposure of approximately 0.6-1.0 pCi/day (0.9-1.5 ug/day).[3] Because uranium can be incorporated into plant roots, uranium can also be found in foods such as potatoes and other root vegetables.[3] As a result, communities living near AUMs may have their highest exposure to uranium from locally grown foods. The average amount of uranium ingested in water is approximately 0.8 pCi/L. In comparison, inhalation intake is much smaller ranging between 0.0007 to 0.007 pCi/day (0.001-0.01 ug/day).[3] Dermal exposure most often is a concern in the occupational setting such as those involved with processing uranium.

1.2.5 Health Effects of Uranium

Uranium exposure can affect multiple organ systems. Respiratory damage and lung cancer are well established in persons exposed to radon progeny, a decay product of uranium.[21] Inhaling uranium airborne particles or decay products depends on two main factors: 1) the deposition site in the respiratory tract and 2) the endpoint for these particles.[3] The deposition site mainly depends on the particle size while the fate of these particles depends on both the physiochemical properties of the particles and also the physiological condition of the lungs. Smaller particles will travel deeper into the lungs reaching the alveoli where gas exchange occurs.

Uranium is also capable of entering the blood and damaging the kidneys through any route of exposure: inhalation, oral, or dermal exposure.[3, 21, 22] Previous studies have observed kidney disease and kidney stones among residents living near a uranium processing plant where uranium was released into the air and surface water.[21] Further, animal studies show that the toxicological effects of uranium are primarily to the kidney tubular cells when exposed to soluble uranium compounds.[3]

Developmental and reproductive effects have been observed in animal studies. Birth defects were observed in litters whereby pregnant mice were exposed to uranyl acetate dehydrate through injection or ingestion.[21] Effects on DNA related to chromosomal aberration have been observed. In one of these studies, there was suggestive evidence that residents who were non-smokers and resided near uranium mining or milling sites had a higher frequency of aberrant cells and chromosome deletions compared to non-exposed populations.[21] Effects on the skeletal system have been observed in rats exposed to insoluble uranium. Exposed rats showed less weight gain, had shorter and thinner trabeculae, and had lower bone length and height.[21] Over half of uranium absorbed in the body is deposited and found in the bones. Gastrointestinal effects were observed in an experiment conducted on humans which showed that ingestion of 1 gram of uranyl nitrate resulted in acute nausea, vomiting, and diarrhea.[21] Finally, the few studies that have examined the association of uranium exposure and cardiovascular health observed no increase in cardiovascular mortality.[21]

1.3 Radon

1.3.1 Chemical and Physical Properties of Radon

Radon is a radioactive noble gas that is inert, colorless, odorless, denser than air, and soluble in water.[23] Radon forms from both the decay of uranium and thorium into radium first and then into radon.[4] Rn is the chemical symbol for radon which as an atomic number of 26 and has an atomic weight of 222 grams/mol.[5] As noted above in the two uranium decay chains in Figure 1, [Uranium Decay Chain] ^{238}U decays into radium-226 (^{226}Ra) and then into radon-222 (^{222}Rn) while the decay chain for ^{235}U decays into radium-222 (^{222}Ra) and then into radon-220 (^{220}Rn, Thoron). ^{222}Rn has a physical half-life of 3.82 days compared to ^{220}Rn which has a much shorter half-life of 56 seconds.[24] Taking into account the short half-life of ^{220}Rn compared to ^{222}Rn, the contribution of ^{220}Rn to the general population exposure is less (20%).[23-25] Thus, most often the literature generally refers to radon as ^{222}Rn. Radon also decays to other radioactive progeny (daughters) which includes polonium-218 (^{218}Po), polonium-214 (^{214}Po), and bismuth-214 (^{214}Bi) which emit alpha particles during their decay. Unlike radon which is a gas, the radon decay progeny are electrically charged and thus are capable of attaching to particles and surfaces. Inhalation of these charged dust particles may result in particle deposition in the nose, pharynx, and tracheobronchial tree.[6]

1.3.2 Quantities and Units

Activity is defined as “the number of radioactive transformations of a radionuclide over time in a specified material”.[23(p.175)] The International System of Units (SI) quantifies this activity using the Becquerel (Bq) which is equivalent to one disintegration per second. The curie (Ci) is also used to classify this and one curie is equivalent to $3.7X10^{10}$Bq. Further, the activity concentration for measuring indoor radon is provided in units of Bq/m^3 or pCi/L (1 pCi/l=37 Bq/m^3). Concentration of radon is used to define the “total alpha potential energy concentration of the radon decay product mixture present, being the sum of the alpha energies of all the short-lived radon decay product atoms present per unit volume of air.”[23(p. 175)] In the radon decay chain the potential alpha energy occurs when the atom decays to lead-210. In SI units, the potential alpha energy concentration in air is defined in joules (J)/m^3 which is equivalent to $6.24X10^9$ million electron volts (MeV)/L of air.[23] The working level (WL) is also used which is equivalent to $1.3X10^5$ MeV of alpha energy emission per liter of air. In the occupational setting as was done in underground mining studies, the working level month (WLM) is used to estimate exposure to radon decay products. In this instance, “1 WLM corresponds to exposure to a concentration of 1 WL for a reference period of 170 hours: 1 WLM=170WLh=$3.5X10^{-3}$ Jh/m^3.”[23](p. 176) Given this information, radon concentration and radon progeny concentration can be distinguished as follows. Radon concentration in the air is measured in units of radioactivity per volume of air, pCi/L.[26] In comparison, radon progeny concentrations are expressed in WL as described above.[27] In the US as reported by the USEPA, the average outdoor concentration of radon is 0.4 pCi/L while the average indoor radon concentration is 1.3 pCi/L.[28] Furthermore, indoor radon levels in the US can range anywhere between 0-80 pCi/L.[4]

1.3.3 Sources of Radon Exposure

The primary source of radon inside homes is from soil gas that enters beneath the home through cracks in the infrastructure, floors, and other openings such as around pipes.[4, 12, 25, 27, 29] Radon from natural geologic concentrations of uranium mostly remains in the rocks and soil; however, it has been estimated that 10-50% of the radon gas escapes to the surface.[29] A potential second source of exposure may occur when radon dissolves water in the soil and if transported into the home may contribute to indoor concentration by volatilization.[4, 25] Similarly, the National Research Council (NRC) on the Biological Effects of Ionizing Radiation (BEIR) also stated that contaminated water with radon may contribute to radon in the home when the radon evaporates or is aerosolized. [12, 30] A third source of indoor radon exposure is construction materials originating from uranium mill tailing pile waste.[30]

1.3.4 Routes of Radon Exposure

The primary route of radon exposure indoors is through inhalation.[31] Comparing uranium and radon exposures, radon exposure is mainly through inhalation while uranium exposure mostly occurs through ingestion as previously described.[3, 20] Even though radon itself is inert, its progeny are charged particles and are able to bind onto dust particles increasing the likelihood of inhalation exposure and deposition. A secondary route of exposure to radon is through oral ingestion. Radon and its progeny in the soil and rocks may come into contact with water and as a result dissolve into the water. If swallowed in drinking water, the radon and radon progeny may reach the stomach and intestine. Also, because radon is an inert gas, most of it is breathed out when it reaches the alveoli in the lungs.[31] While radon does not stay resident in the lungs it is thought that the cumulative exposure to ionizing radiation by radon-contaminated air results in genetic damage and eventual cancer.[4] A potential third route of exposure is dermal exposure through the skin. Because of its noble gas characteristics, radon would have to be absorbed through diffusion. However, the skin generally protects deeper tissues from the alpha emitting properties of radon and radon progeny because alpha particles do not penetrate the dead cell layers in the superficial skin.[31] Therefore dermal exposures are considered negligible.

1.3.5 Predictors of Indoor Radon Exposure

Predictors of indoor radon exposure capture the local soil concentration of uranium, direct presence of uranium byproducts in the home, and the ability of radiation to penetrate into the home. They include the pressure difference between the subsurface air and indoor air, building construction characteristics, geologic characteristics of the soil, the weather, groundwater, season, and residence proximity to AUMs.[26, 30, 32, 28]

First, factors such as pressure differences may contribute to lower pressures inside the home compared to the outside. For example, warmer temperatures inside the home compared to the outside of the home causes air to rise and exit out of the home. This creates a pressure vacuum in which air from the soil, which may contain radon gas, to replace this air inside the home known as the stack effect.[33] The movement of radon gas from the soil into the house may occur through cracks and other openings in the underlying structure leading to increased levels of indoor radon concentration.[32]

Second, homes built with contaminated uranium materials may also contribute to elevated levels of indoor radon concentrations; as reported by the International Agency for Research on Cancer (IARC), sand tailings from uranium processes were often used in concrete as part of home foundations in the western US during the 1960s.[13, 34]

Third, another main source of indoor radon concentrations is from soil enriched with radium, a decay product of uranium. Soil enriched with uranium and thus radium would provide a source of radon gas that may enter the indoor air from cracks in the floor or walls. Further, soil characteristics such as a higher permeability and moderate moisture content both favor diffusion of radon from the soil into the air.[34]

A fourth source of indoor radon exposure is radon gas dissolved in groundwater which is a consequence of surrounding rock enriched with radium-226 such as near uranium ore bodies often containing 238-U and radium-226.[12, 28, 34] Groundwater compared to surface water has the potential to accumulate more radon gas, especially in geographic areas enriched with uranium.[35, 36] When this enriched groundwater enters the home and is used increasing the agitation and mixing of water through use such as bathing and laundering, radon gas can be released via evaporation from the water into the air potentially increasing inhalation exposure.

Fifth, seasons in which windows and doors are closed could contribute to increased levels of indoor radon concentrations as a result of lower ventilation in the home potentially elevating health risks. The ventilation rate at which outside air enter and leaves the home can be affected by domestic behaviors inside the home. In colder weather condition, mechanical ventilation systems are often used to warm air inside the home creating the stack effect.[35] Further, in colder seasons domestic behaviors such as closing windows and doors decreases the overall natural ventilations of air into and out of the home. As a result, there is the potential for radon gas to accumulate inside the home during colder seasons.

In addition, humidity and temperature affect the exhalation rate of radon from the soil surrounding the home, usually in the reverse direction. For instance, increased atmospheric pressure, rain, and snow reduce the exit of radon gas from the soil thereby increasing the accumulation of radon gas in the soil. This may then result in the movement of radon gas from the soil inside the home.[34] As a consequence, this would potentially increase radon concentration in the home during the winter season. Combined with a closed housed system and increased soil radon concentrations in the winter would provide optimal conditions for elevated indoor radon concentrations.

Last, individuals who live near uranium mines also may be potentially exposed to higher levels of radon compared to the general population.[26, 37]

1.3.6 Geologic Factors

The Navajo Reservation lies on the Colorado Plateau which geologically contains higher concentrations of soil uranium.[2, 3, 29] Because natural soil uranium undergoes radioactive decay as described in section 1.2.1, the decay product radium is continuously produced. This natural decay product was measured in a process called aerial radiometric survey, which was done by placing an instrument on a plane that measures radioactivity from the ground surface called a gamma ray spectrometer. [29] As the plane flies over an area, the measurements are referred to as equivalent uranium which provides an approximation of the total uranium in the top layer (about 30cm) of soil.[29] These aerial radiometric data then provide an estimate of the regional uranium concentration with correlates with the radon concentration in the soil. Two regions noted to have elevated levels of uranium concentration are near Grants and Gallup, New Mexico which are two communities associated with uranium mining.

1.4 Dissertation Intent

The goal of this project is to conduct an indoor radon survey of CUETH participants, to build an exposure assessment model of indoor radon exposure, and to validate the exposure assessment model. First, we will conduct an indoor radon survey from a group of CUEJTH volunteers. Second, we will utilize existing exposure information to build a geospatial prediction model and map. Third, we will compare indoor radon measurements observed against predicted indoor radon concentrations from our exposure assessment model for validation. We propose the following specific aims:

Aim 1: To conduct an indoor radon survey among a sample of CUEJTH participants.

Aim 2: To create a geospatial exposure assessment model characterizing potential exposure to indoor radon for residents of the Navajo Nation.

Aim 3: To conduct a validation study comparing indoor radon concentrations as estimated from our exposure assessment model against current indoor radon concentrations.

Chapter 2

INDOOR RADON SURVEY AMONG A SAMPLE OF COMMUNITY URANIUM EXPOSURE JOURNEY TO HEALING PARTICIPANTS

2.1 ABSTRACT

Uranium is naturally found in the environment and in higher concentrations in the Southwest. A decay product of uranium is radon gas, a lung carcinogen that has no color, odor, taste, and is able to pass from soil into homes. Radon gas is known to accumulate in some homes as a result of the location of their home in certain geographical regions, season during radon testing period, home construction materials, and home ventilation usage. Radon is the second leading cause of lung cancer in the U.S. behind smoking. Health effects associated with radon exposure have been well examined in underground uranium mining studies. There have been few studies of indoor radon levels and risk factors in areas with naturally higher exposures to uranium and radon, such as the Navajo Nation. Therefore, we aimed to conduct an indoor radon survey in three agencies on the Navajo Nation: Shiprock/Northern, Chinle, and Crownpoint/Eastern with a sample of participants from the Community Uranium Journey To Healing Program (CUEJTH).

As of 2013, the CUEJTH program consisted of 969 participants and a total of 329 indicated a willingness to be contacted. A total of 51 homes were measured for indoor radon with an arithmetic mean concentration of 1.6 picocurie/Liter (pCi/L) (SD=1.2). Mean indoor radon concentrations (pCi/L) by house type were as follows: mobile, 0.8 (SD=0.6); wood, 1.6 (SD=1.0); hogan, 2.0 (SD=0.0); homes constructed primarily of cement and wood, 2.2 (SD=0.1); and homes constructed primarily of concrete and cement, 2.9 (SD=1.5). A key observation in our indoor radon survey is that house construction type appears to be associated with the mean home indoor radon concentration. This observation has been published in that the basic structural make-up of the home may potentially affect the ventilation of a home and therefore indoor radon concentration levels.

Aim of Indoor Radon Survey

Assessing indoor radon exposure outside the work environment and inside homes is an important public health concern. As shown in previous studies, indoor radon levels vary according to soil, geologic, and housing characteristics including domestic behaviors.[32] By identifying homes with potentially higher levels of indoor radon concentrations, this survey will aid Navajo Nation homeowners and environmental professionals to identify homes that may have elevated radon levels, and take appropriate measures in reducing indoor radon to acceptable levels. The aim of the study was to collect indoor radon measurements from a sample of participants from the CUEJTH program. Participants in this indoor radon survey lived in three of the five agencies on the Navajo Nation: Shiprock/Northern, Chinle, and Crownpoint/Eastern.

2.2 INTRODUCTION

2.2.1 Background

As previously described in Chapter 1 section 1.3 on Radon, radon is a radioactive noble gas that is inert, colorless, odorless, denser than air, and soluble in water.[23] Radon forms from both the decay of uranium and thorium into radium first and then into radon.[4] Radon also decays to other radioactive progeny which includes polonium-218 (^{218}Po), polonium-214 (^{214}Po), and bismuth-214 (^{214}Bi) which emit alpha particles during their decay. Unlike radon gas, the radon decay progeny are electrically charged particles and thus are capable of attaching to airborne dust and surfaces. The attachment of the radon decay progeny to airborne dust particles is a source of potential inhalation exposure .[6]

2.2.2 Indoor Radon Exposure Pathways

As previously described in Chapter 1 section 1.3.5 on predictors of indoor radon exposure, naturally elevated levels of soil uranium concentration will continuously produce ^{226}Ra and radon gas. In addition to the the quantity of uranium in the soil, the substrate characteristics of the soil affect the movement of radon gas in the soil.[38] Radium atoms in the rock emit radon atoms that are transported by two main processes, diffusion or advective transport to the surface.[38] The major transport system is diffusion which is affected by moisture in the soil. Higher moisture levels fill the pores between soil particles, reducing the amount of space between grains thereby limiting the amount of air space for the radon gas to diffuse through the soil and potentially into homes. This also illustrates how the porosity of the soil can affect the movement of radon gas in the soil. Larger grains in the soil provide more pore space between grains creating the opportunity for radon gas to move more freely through the soil, with the exception of a high moisture environment. The second transport system, advective transport, takes into account the permeability of the soil, the fluid viscosity, and the pressure gradient that aids in the movement of radon gas from soil into the home.[39] Advective transport is also affected by the moisture of the soil as well as by a gradient favoring movement of radon gas from high to low concentrations.[38]

Also previously described in Chapter 1 section 1.3.5 predictors of indoor radon exposure include home ventilation and construction materials, natural soil uranium concentration levels, and radon gas dissolved in groundwater. Homes made of materials containing high radium content, as was done on the Navajo Nation with abandoned uranium waste materials, may produce higher levels of radon gas inside the home. Outside the workplace, such as in underground uranium mines, members of the general population may be exposed to radon gas in homes, schools, or other public buildings.[26] Residential homes without adequate ventilation may have higher levels of radon gas accumulating to levels found in underground uranium mines; potentially exceeding standards in the occupational setting. Residential locations located near uranium mines may also be exposed to higher levels of radon compared to the general population.[26] Well water located near sources of high radium concentrations may have higher levels of radon. Radon exposure from water ingestion is minimal compared to radon gas emitted from radon dissolved in water and inhaled.[26]

2.2.3 Health Effects Associated with Radon Exposure

Health effects of Radon inhalation have been extensively studied. Much of this work is summarized in the sixth in a series of reports of National Academy of Sciences entitled The Biological Effects of Ionizing Radiation (BEIR). One focus of this research has been the examination of respiratory cellular injury because these cells are assumed to receive the highest radiation dose. Compared to x-rays and gamma-rays, alpha particles are heavier and thus travel shorter distances, which is a characteristic of high Linear Energy Transfer (LET) radiation. High LET radiation can interact directly with cells and result in the ionization of DNA. According to evidence summarized in the BEIR VI report, alpha particle emission by polonium-218 and polonium-214 can deliver energy to the respiratory epithelium causing radon-associated lung cancer.[12]

The BEIR VI report also compares radon exposure levels between the occupational and residential setting, based on data from an indoor radon survey conducted by the Environmental Protection Agency. The BEIR VI committee estimated that residential indoor radon concentrations typically range from one-tenth to one-hundredth of the radon concentration observed in underground mines. As previously described in section 1.3.2, in the occupational setting as was done in underground mining studies, "1 WLM corresponds to exposure to a concentration of 1 WL for a reference period of 170 hours: 1 WLM=170WLh=$3.5X10^{-3}$ Jh/m^3."[23(p. 176)] Given this information, radon progeny concentrations are expressed in WL as described above, and in comparison radon concentration in the air is measured in units of radioactivity per volume of air, (pCi/L).[27], [26] Based on the BEIR report, the average annual mean radon exposure in the residential setting is 0.2 WLM and average lifetime radon exposure is 14 WLM. In comparison, the highest an exposed worker could be potentially exposed to 800 WLM over 5 years.[12] This is important to highlight because risk estimates from previous epidemiological studies used these higher exposure levels. Based on their report, the BEIR VI committee stated that data suggest indoor radon exposure in homes is associated with a small increase in lung cancer risk. Using indoor radon data from the National Residential Radon Survey conducted in the US, the BEIR VI committee estimated that among never smokers the number of lung cancer deaths due to radon was roughly 2,100-2,900 per year.[40]

Previous epidemiologic studies examining the association between uranium and their decay progeny which includes radon have been studied among mining populations. These epidemiologic study designs include cohort, case-control, and ecologic studies.[26] Adjusting for confounding factors, such as smoking (a well established risk factor for lung cancer), an increased risk of lung cancer was observed for underground uranium miners exposed to high levels of uranium and radon.[4, 30] The nested case-control study conducted by Gilliland et al. examining the association between radon progeny and lung cancer among non-smoking uranium miners illustrates this point.[7] Their cohort consisted of over 2,000 underground uranium miners who never smoked and were employed from 1956 to the early 1990's in the western US. Using conditional logistic regression, a 29.2 odds ratio was observed: the ratio of the odds that lung cancer cases were exposed to 1,450 WLM cumulative radon progeny exposure to the odds that controls were exposed to less than 80 WLM [RR=29.2; 95% CI: 5.1, 167.2]. These higher levels of radon observed in underground mines, while much higher than indoor residential radon levels, raised awareness as to the potential health effects associated with high indoor levels of radon in the non-occupational setting.

Previous epidemiologic case-control studies show positive associations when examining indoor radon residential concentration with lung cancer risk.[4, 30] Pooling the results of several case-control studies, investigators were able to estimate strong support for a positive association between residential radon and lung cancer risk, in both smokers and previous smokers.[4] In fact, the Agency for Toxic Substances and Disease Registry (ATSDR) reported that non-smokers living in homes with higher-concentrations of radon had a 25-fold higher risk of lung cancer.[4] Furthermore, a report from the American Cancer Society Cancer Prevention Study-II reported their findings on their prospective cohort study examining the association between residential radon and lung cancer mortality.[41] In their study using Cox proportional hazard models, they observed a hazard ratio of 1.15 (95% CI: 1.01, 1.31) for lung cancer mortality per 100 Bq/m^3 (1 pCi/l=37 Bq/m3) increase in residential radon. In addition, they observed 34% increase in lung cancer death comparing residential radon concentrations above the EPA guideline (148 Bq/m^3=4pCi/l) to those below the EPA guideline (<148 Bq/m^3) [adjusted hazard ratio=1.34; 95% CI: 1.07-1.68].[41] Radon-222 and its decay products have been classified as a Group 1 carcinogen by the International Agency for Research on Cancer (IARC).[42] Collectively, this information provides evidence that reducing both indoor radon and smoking cessation could potentially decrease the risk of lung cancer.

2.2.4 Environmental Protection Agency Home Indoor Radon Recommendation Levels

Concerns were raised about residential radon exposure during the 1980s when the Environmental Protection Agency (EPA) mandated a national residential radon survey (NRRS) of homes.[43] This concern was a result of previous studies demonstrating an association between radon exposure and lung cancer in occupational epidemiologic studies. In addition, the EPA became aware that some homes in the US, such as in New York and Pennsylvania, had elevated radon concentrations high enough to potentially cause 1 in 10 residents in these homes to get lung cancer.[43] In the NRRS, the EPA reported tin 1992 hat the average annual radon concentration for U.S. homes was 1.3 pCi/L, the average ambient annual radon level was 0.4 pCi/L, and that roughly 6% of U.S. homes (~6 million homes) had annual average radon levels above the EPA action level of 4.0 pCi/L.

Current indoor radon levels set by the Environmental Protection Agency (EPA) recommend remediation for home indoor radon levels at or above 4.0 pCi/L.[44] The EPA states that with proper intervention, home indoor radon levels in most cases can be reduced below 2.0 pCi/L.[44] This goal is intended to coincide with the goal set forth by the U.S. Congress in reducing indoor radon levels to be no more than outside radon levels, 0.4 pCi/L.[44] The EPA states among non-smokers 2 out of 1,000 people could get lung cancer in a home that has an average indoor radon concentration of 1.3 pCi/L, which is the current U.S. home indoor radon average concentration.[44] In contrast, this risk is highly elevated among smokers, where about 20 people could get lung cancer out of 1,000 people.

2.3 METHODS

As previously described in section 1.1, the Community Uranium Exposure Journey To Healing Program (CUEJTH) is sponsored by the Navajo Area Indian Health Service located in Shiprock, New Mexico.[1] The mission of this program is to provide health monitoring, health promotion and health education to communities who have been exposed to uranium across the Navajo Nation, which is the largest Indian reservation in the United States.[45] To help address community concerns regarding exposure to uranium including decay products such as radon, the CUEJTH program was established. The CUEJTH program is led by a medical director, nurse caseworker, staff, and volunteers who arrange community site visits throughout the Navajo Nation. At each community event, education presentation materials regarding uranium exposure are provided, in addition to on-site health screenings if desired by participating individuals.

2.3.1 Identification and Recruitment of Study Participants

This study was an indoor radon survey conducted on a sample of participants from the Community Uranium Exposure Journey To Healing (CUEJTH) Program. The target population for this survey included: 1) a sample of participants from the CUEJTH program, 2) who previously indicated an interest to participate in future research, 3) who are residents of the Navajo Nation, and 4) were residents in either the Chinle, Shiprock/Northern, or the Crownpoint/Eastern agencies. As of December 2013, there were 964 participants registered with the CUEJTH program. An additional five participants later volunteered with the CUEJTH program bringing the total baseline recruitment sample to 969 participants.

Table 1: 2010-2013 CUEJTH Population Characteristics by State

		2010-2013 CUEJTH Total population n= 969 (%)
Age		59.1 (SD=14.9)
State	Arizona	31.3
	New Mexico	61.1
	Utah	6.9
	Missing	0.2

Based on the table above, 61% of CUEJTH participants were from New Mexico, 31% from Arizona, and 7% from Utah. The proportion of missing was 0.2% which was due to a lack of available data that could not be confirmed by looking up the patient's demographic information in their records. The average age of the CUEJTH population was 59.1 years (SD=14.9). In comparison, the median age of a Navajo resident living on the Navajo Nation according to a published profile of the Navajo Nation in 2010 was 28 years.[46] This corresponds with a published report prepared by the Navajo Division of Health Navajo Epidemiology Center which reported that over half (52%) of persons who identified as Navajo in combination with another race living on the Navajo Nation were in the age group 0-29 years.[47]

Table 2: CUEJTH Population and Navajo Residents Proportion by Agency

		2010-2013 CUEJTH Population Proportion n=969 (%)	*2010 Proportion of Navajo Residents n=173637 (%)
Agency	Chinle	3.3	16.0
	Crownpoint/Eastern	57.7	19.2
	Fort Defiance	3.3	25.3
	Shiprock	10.7	17.8
	Tuba City/Western	23.7	21.7
	Missing	1.3	
		100.0	100.0

*2010 US Census

Table 2 above illustrates the CUEJTH participant population by agency in comparison to the proportion of Navajo residents living in each agency based on the 2010 US Census.

Potential participants were included in the recruitment sample according to the following criteria: 1) filled out a research form, 2) listed their residence on the Navajo Nation, and 3) residence was within a target agency which included Shiprock/Northern, Crownpoint/Eastern, and Chinle. Those excluded from the recruitment sample were based on the following criteria: 1) deceased, 2) did not have any current contact information, 3) listed their current residence as off the Navajo Nation, 4) primary residence was not within the new target population agency which included Fort Defiance and Tuba City/Western, and 5) had their residence listed as the same as another CUEJTH participant.

2.3.2 Sample Size

A sample of indoor radon concentration levels previously measured across the Navajo Reservation during the time period 1997-2012 was provided by the Navajo Nation Air & Toxics Department Radon Program as shown below in Table 3.[48] The indoor radon measurements were obtained from residents of the Navajo Nation who requested a home indoor radon test. Indoor radon survey measurements represent homes that requested testing, as testing is only done at the request of homeowners. Routine indoor radon testing is only done at public facilities such as public offices and school buildings. Indoor radon testing was conducted using both charcoal canisters and EPERM test kits. Both devices are passive radon gas detectors used to measure indoor radon gas. The charcoal kit utilizes charcoal to absorb radon gas which is then measured using a sodium iodide detector at a selected laboratory. In contrast, the EPERM radon gas kit operates by using an ionization chamber where a voltage is generated in proportion to the radon concentration (pCi/L) in indoor air.[49] Both devices are used for short-term indoor radon testing, anywhere from 2-7 days.

Table 3: 1997-2012 Navajo Nation Residential Indoor Radon Survey

Agency	Obs no.	Mean (pCi/L)	SD	Min	Max
Chinle	24	5.8	3.5	1.0	13.7
Crownpoint/Eastern	99	2.4	2.2	0.0	8.8
Shiprock	74	0.8	0.8	0.0	3.7
Fort Defiance	10	2.4	1.6	0.6	6.0
Tuba City/Western	21	1.3	1.3	0.1	6.1

*Charcoal and EPERM Test Kits

£Available but not included are latitude/longitude coordinates and type of residential home

We observed that the mean indoor radon concentration was highest in the Chinle Agency at 5.8 pCi/L (SD=3.5). The next highest levels were observed in the Crownpoint/Eastern Agency at 2.4 pCi/L (SD=2.1).

As a note, two high indoor concentrations measurements were observed in the Crownpoint/Eastern agency collected on December 6, 2010, which were 95.7 and 90.0 pCi/L. The Crownpoint/Eastern agency mean indoor radon concentration was 4.4 pCi/L (SD=13.7) when averaged with these two high indoor radon concentrations. However, excluding these two extreme measures produced a lower mean indoor radon concentration of 2.4 pCi/L (SD=2.1) as seen above in Table 3. Compared to the Crownpoint/Eastern agency, the Fort Defiance agency had a similar mean indoor radon concentration of 2.4 pCi/L (SD=1.6). The Tuba City/Western agency had a mean indoor radon concentration of 1.3 pCi/l (SD=1.3) while the Shiprock agency had the lowest mean indoor radon concentration measured at 0.8 pCi/L (SD=0.8).

To determine our sample size estimate, we used two criteria. The first criterion was in regards to the approval of our study. Our research study was approved by the Navajo Nation Human Research Review Board to be conducted in only three of the five agencies; therefore, we did not consider sampling for indoor radon levels in homes located in both the Fort Defiance or Tuba City/Western agencies. Further, to date the CUEJTH program has very few participants from both the Fort Defiance and Western Agencies; mainly as a result of limited community activities in these agencies. Based on this information, we did not include either Fort Defiance or the Tuba City/Western agencies in our sample size estimates.

Second, using the mean indoor radon concentration levels given in Table 3, we estimated the number of samples needed to estimate the mean of a continuous variable by using the following formula:

$$\mathrm{n} = \frac{\mathrm{Z}^2\ \sigma^{\ 2}}{\mathrm{m}^2}$$

In the above formula, a Z value of 1.96 was used to reference a normal standard distribution at a 95% confidence interval; sigma represents the standard deviation calculated for each agency, and m represented the margin of error, in this case 1.4 was chosen. Using this formula for each agency, we estimated a sample size of approximately 24 indoor radon samples for the Chinle agency, 10 samples for the Crownpoint/Eastern agency, and 1 sample for the Shiprock/Northern agency (Table 4). By observation, the Chinle agency was observed to have the most exposure variability and was also estimated to require the most number of samples. Taking this into account, an alternative sample size of 25 home indoor radon samples was set as a goal to collect from each of the three agencies for a total of 75 indoor radon samples.

Table 4 Indoor Radon Sample Size Estimate for Three Agencies

Agency	Obs no.	Mean (pCi/L)	SD	Min	Max	Sample Size*	Alternative Sample Size
Shiprock/Northern	74	0.8	0.8	0.0	3.7	1.0	25.0
Crownpoint/Eastern	99	2.4	2.2	0.0	8.8	10.0	25.0
Chinle	24	5.8	3.5	1.0	13.7	23.0	25.0

$$\text{Sample size estimate (n)} = \frac{Z^2\ \sigma^{\ 2}}{m^2}$$

*Z=1.96; margin of error=1.4, $\sigma\ = \text{SD (standard deviation)}$

The sample size equation used to obtain the number of indoor radon samples, agency was a crude surrogate for location. These estimates were based on preliminary indoor radon data from the Navajo Nation Environmental Protection Agency Indoor Radon program, that didn't have detailed information on the home type or geolocation. The preliminary data suggested that home indoor radon concentration levels [pCi/L] varied in different agencies. This allowed us to structure a sampling strategy that was carried out in each agency to capture the variability of indoor radon concentration across the three agencies on the Navajo Nation. Considering the aim of this dissertation was to develop an indoor radon prediction model, we decided on the following sampling strategy approach.

2.3.3 Sampling Strategy

We utilized a multistage sampling approach in our survey. First, all potential volunteers were categorized into their respective agencies: Shiprock, Crownpoint/Eastern, and Chinle. Within each agency on the Navajo Nation, there a number of chapters where government activities take place for each local community. Second, chapters were then categorized into one of two categories: 1) chapters with known abandoned uranium mines and 2) chapters not documented to have abandoned uranium mines according to a report prepared by the U.S. Environmental Protection Agency.[18] As such, the approach was a simple random stratified sampling by agency and chapter group. This was done to potentially increase the exposure variability within each agency. An initial attempt to rotate sampling between each agency every other week to potentially adjust for temperature and weather changes did not work due to challenges related to traveling. For example, heavy rain and sometimes snow conditions limited traveling to some agencies due to road conditions, mostly unpaved, that were not suitable for most off road vehicles. Based on our sample size estimate, logistical considerations and potential non-response, we aimed to contact 25 participants within each of the three agencies for a total of 75 indoor radon measurements.

2.3.4 Data Collection

Phone

Using the randomized list, calls were made to potential participants using information provided on research forms previously filled out. On each form, participants provided the following information: 1) name, 2) address, 3) physical description of home, 4) phone numbers, 5) email address (not utilized in this study), and 6) and other contact information to reach participants, such as phone numbers of relatives. This contact information was then compared and confirmed with demographic information for each potential participant in their respective Indian Health Service electronic health record.

Phone calls were structured using two standardized scripts, a recruitment script which was followed by an informed oral consent script if the participant expressed interest to learn more about indoor radon exposure. The recruitment script was structured to introduce the name of the project and a brief introduction to the project. Participants were provided with opportunities to ask questions and if he/she expressed interest to learn more about the project, then the informed oral consent script was read which provided additional information on 1) the purpose of the project, 2) procedures, 3) risks/discomfort/ benefits, and 4) confidentiality of data. If the participant agreed to participate over the phone, then the first of two home visits was scheduled at their convenience.

Navajo Interpretation

Seldom, was a Navajo interpreter requested at the time of an initial phone call to the homeowner. In these situations, an English speaking individual (who was also a resident at the home) answered the phone on behalf of the potential participant. During the initial call, a potential participant may have expressed a preference for Navajo conversation and translation. Anticipating such circumstances, all research scripts were previously translated into the Navajo language by a skilled Navajo translator. The translated scripts were reviewed and approved by the Navajo Nation Human Research Review Board and later by the University of Washington Human Subjects Division. Approval of these translated scripts reflect that the content was culturally appropriate and provided suitable translations of the research project mission and activities. Two individuals fluent in the Navajo language, both with public health and research backgrounds were available via phone to arrange phone call interpretation for research introductions and home visit scheduled if participant expressed interest. If a participant agreed to volunteer and preferred to speak Navajo at the time of a home visit, then additional measures were made with residents of the home fluent in Navajo and English to aid in English-Navajo interpretation throughout the home visit. All research scripts translated into the Navajo language followed the same protocol as discussed below.

2.3.5 Home Indoor Radon Assessment

Data Collection: Home Characteristic Survey

The home characteristic survey took between 30-60 minutes to complete and consisted of a checklist of items used to obtain information about certain household characteristics thought to be associated with indoor radon levels. The first section of the survey included basic information about the home: 1) latitude and longitude coordinates which was recorded using a handheld GPS device, GARMIN eTrex 20, 2) the chapter and agency in which the participant resided, 3) and dates of home visits.[50] The second section of the survey pertained to the structure of the home. Observations were recorded about the description of the home, e.g., hogan, mobile, or rental unit, the approximate age of the home, and the home foundation. The second section of the survey recorded information about the structural components of the rooms in which the kits were placed, e.g., concrete, brick, wood, or other materials. The third section of the survey collected information on whether the home sat above a crawl space in addition to materials that made up the outside of the crawl space, such as vinyl skirting sometimes used to close the crawl space underneath mobile homes. The fourth section of the survey honed in on home ventilation, such as observing how tightly sealed doors and windows appeared along with any home exhaust systems installation. The fifth section focused on collecting information about the floor of the home; such as the type of floor material (concrete, dirt, wood) and a basic description about condition of the floor, i.e. visible cracks in the floor. The sixth section inquired about woodstoves or fireplaces in the home. In this section, basic information was also obtained on whether drinking water was stored in the home and also the source of the home water as water is a potential source of indoor radon exposure if collected from water wells with elevated levels of uranium. The last section of the survey pertained to ceiling surface conditions, such as opening and cracks, and if present, observing if these openings were open or closed.

Indoor Radon Exposure Data Collection

The target sample size estimated for this project was to collect a total of 75 indoor radon samples, 25 indoor radon samples from each of the three approved agency areas on the Navajo Nation. Instead 51 indoor radon measurements were collected between November 2014 and May 2015 within three agencies on the Navajo Nation using the Air Chek, Inc. Short Term Radon Kit.[51] The AirChek indoor radon kits were provided by the Institute for Tribal Environmental Professionals (ITEP) at the Northern Arizona University as part of graduate student educational support. The mission of the ITEP program is to "strengthen tribal capacity and sovereignty in environmental and natural resource management through culturally relevant education, research, partnerships and policy-based services."[52]

Instructions for the Air Chek radon test kit that were followed as closely as possible pertained to: 1) hanging indoor radon kits in the center of testing areas with a string from the ceiling, in attempt to capture the breathing zone of residents; 2) testing for a minimum of 3 days and not more than 7 days (testing days varied according to the weather and condition of roads to participant homes) ; 3) placing kits in home rooms where residents spent the majority of their time, usually the living room and bedroom; 4) avoiding placing kits in rooms with exhaust systems, usually in the kitchen or other utility rooms; 5) avoiding placing kits directly nears stoves or fireplaces, as such areas usually had associated exhaust systems; 6) informing participants that radon kits worked best if the home maintained a closed house condition as much as possible throughout the testing period, i.e., to limit the amount of time windows or doors were opened; 7) emphasizing radon kits were not to be disturbed; and 8) sending indoor radon kits to the AirChek laboratory for analysis immediately after the testing period .[53, 54] Participants also were advised to not operate or limit the amount of time any ceiling fans that might be used. Additional actions were taken to place kits as far away as possible from doorways, windows, and other vents.

Testing for indoor radon occurred mostly during the winter months with some homes measured in the early spring. Attempts were made to control for temperature changes by initially conducting home measurements in one agency per week followed and then changing to a different agency the following week. However, due to weather changes and effects on driving conditions attempts to vary indoor radon testing with each agency on a weekly basis was only carried out for three weeks.

Indoor Radon Kits

In each home, one radon text kit was placed in the living room, one in the bedroom, and an additional radon kit for quality control with every tenth radon sample (as practiced by the Navajo Nation Indoor Radon program). Also, a radon kit was placed in homes with a basement. Some residential units were made of single rooms, in which the home consists of one large room; therefore, only one radon kit was placed in these homes unless a quality control was required. A total of 10 indoor quality-control samples were obtained. In total, 110 indoor radon kit measurements were obtained among the 51 homes sampled; 51 living room measurements, 47 bedroom measurements, two basement measurements; and 10 quality control measurements. All indoor radon concentrations were measured in picocurie/liter (pCi/L).

Laboratory Analysis of Kits

Radon kits were picked up and sealed at the second home visit, and then sent to the Air Chek, Inc. Laboratory via FedEx in North Carolina for analysis. The short-term indoor radon kits utilizes charcoal to collect indoor radon gas over 3-7 days.[55] This type of testing is popular because of it is convenience and is one method used for indoor radon screening. The accuracy of the test can be increased by measuring different parts of the home simultaneously, as was done in this study. In the laboratory, radon concentration is measured by detecting gamma rays emitted by radon daughters using a sodium iodide scintillation detector.[55] This method provides an efficient means to reduce natural background radiation to provide an accurate assessment of net counts from the sample. The lower detection limit for Air Check indoor radon test kits in dry climates is 0.2 pCi/L.[55]

Living Room and Bedroom Indoor Radon Measurements

A total of 51-living room and 46-bedroom indoor radon measurements were measured in 51 homes. Measurements observed to be lower than the limit of detection (LOD) of 0.2 pCi/L were substituted using an accepted method.[55] In this method, these values were replaced with values calculated by taking the LOD and dividing by the square root of two (LOD/sqrt 2). In this project, seven living room samples and six bedroom samples were observed to be below the LOD and therefore substituted using the method explained above. One indoor radon sample was measured in a study room, instead of the bedroom at the request of the participant. This radon measurement was added to the total bedroom measurements bringing the total bedroom measurements to 47.

Combined Indoor Radon Measurements

A scatter plot was used to compare the correlation between both the non-log transformed and log-transformed living and bedroom indoor radon concentration measurements. This was done to compute a correlation coefficient to examine the relationship between indoor radon measurements taken in different parts of the home. The correlation coefficient computed was evaluated to assist in determining if all indoor radon samples for each home could be averaged to compute a combined mean indoor home radon concentration for each of the 51 homes.

Quality Control

A total of 10 quality control samples were collected. Quality control kits were: opened in the home providing brief exposure to the home indoor air, immediately sealed, positioned next to the indoor radon sample in the living room where it remained sealed during the testing period, and then sent to the laboratory for analysis at the end of the testing period. The intent of the quality control samples was to compare each quality control measurements with the respective kit it was placed next to during testing and to ensure the samples were not contaminated. Further, field quality control measurements are assessed by comparing the results to the lower limit detection of the indoor radon kit, a practice routinely done as part of quality control measures to ensure indoor radon kits used during testing were viable.[54] The quality control kits were not used as sample measurements, but merely as part of quality assurance practice to assess background exposure

2.3.6 Temperature Data

Historical temperature data during each home indoor radon testing period was obtained using two on-line weather data resources, "Weather Underground (WU)" and "The Weather Channel".[56, 57] The WU weather database collects information from over 140,000 weather stations with a spatial resolution of four kilometers.[56] The WU also generates hourly updates using data from personal weather stations, airports, and weather balloon data. The WU was acquired by the National Weather Channel (NWC) in 2012 to create a merger that would enhance both weather networks.[58] The merger combined two weather station with a broad network of weather stations and historical temperature data, which were ideal in obtaining historical weather data for this project.

Steps taken to obtain weekly temperature averages during indoor radon testing included the following. First, latitude and longitude coordinates were loaded into Google Maps tm to identify the name of the nearest town, including state and zip code. Second, this information was entered into WU along with the starting date for indoor radon testing. This provided an output of daily, weekly, and monthly temperature averages. The weekly temperature average was then selected as the temperature value during each appropriate household testing period.

The National Weather Channel (NWC) website was accessed only when weekly temperature averages were unavailable for some homes in WU. In this site, home coordinates were also used to identify the nearest town, state, and zip code. This information was then entered in the NWC site to obtain historical monthly temperature averages. Using this information, daily averages for the week period of indoor radon testing, a temperature average was then used as the temperature value during indoor radon testing.

2.3.7 Elevation Data

Elevation data for each home was ascertained using a handheld GPS Garmin eTrex20 device.[50] Elevation was collected to assist in assessing the relationship between indoor radon concentrations and temperature. It is well known at higher elevations that temperature decreases at a uniform rate, up to 39,000 feet, which is known as the adiabatic lapse rate.[59] In dry conditions, this uniform rate is equal to 5.5°/1,000 feet and in humid conditions the rate is 3.5°/1,000 feet.[59]

2.3.8 Protection of Human Subjects

Navajo Nation Human Research Review Board

The Navajo Nation Human Research Review Board (NNHRRB), established in 1996 on the Navajo Nation, was implemented to protect and ensure all research was done ethically in collaboration with the Navajo people.[60] Per NNHRRB protocol, an application was submitted, reviewed, and approved by the NNHRRB (#NNR-14.185T) prior to the initiation of any research activities.[61] This board is led by a Chairwoman, community members, health professionals, and scientists familiar with the Navajo Nation culture, language, and traditions. The NNHRRB mission states that research projects should promote the interests and visions of the Navajo people. To do this, agency resolutions in which research activities for this project was obtained. To successfully obtain an agency resolution, the research project was formally presented before a panel of agency officials and their respective community members. This open forum provided an opportunity for agency leaders and community members to openly express whether they agreed with this research project through a vote count. A favorable vote count then allowed agency leaders to sign a resolution approving research activities in those communities; an agency resolution must be signed and presented with each new NNHRRB application for final research approval. In doing so, this process builds and promotes partnerships between the Navajo people and their communities with researchers, some of whom may not be familiar with the Navajo people culture, language, and lifestyle. Ultimately, this creates a positive environment that encompasses, promotes, and encourages the interaction and sharing of ideas between the Navajo people and researchers intended to promote, strengthen, and improve the health of the Navajo people.

University of Washington Human Subjects Division

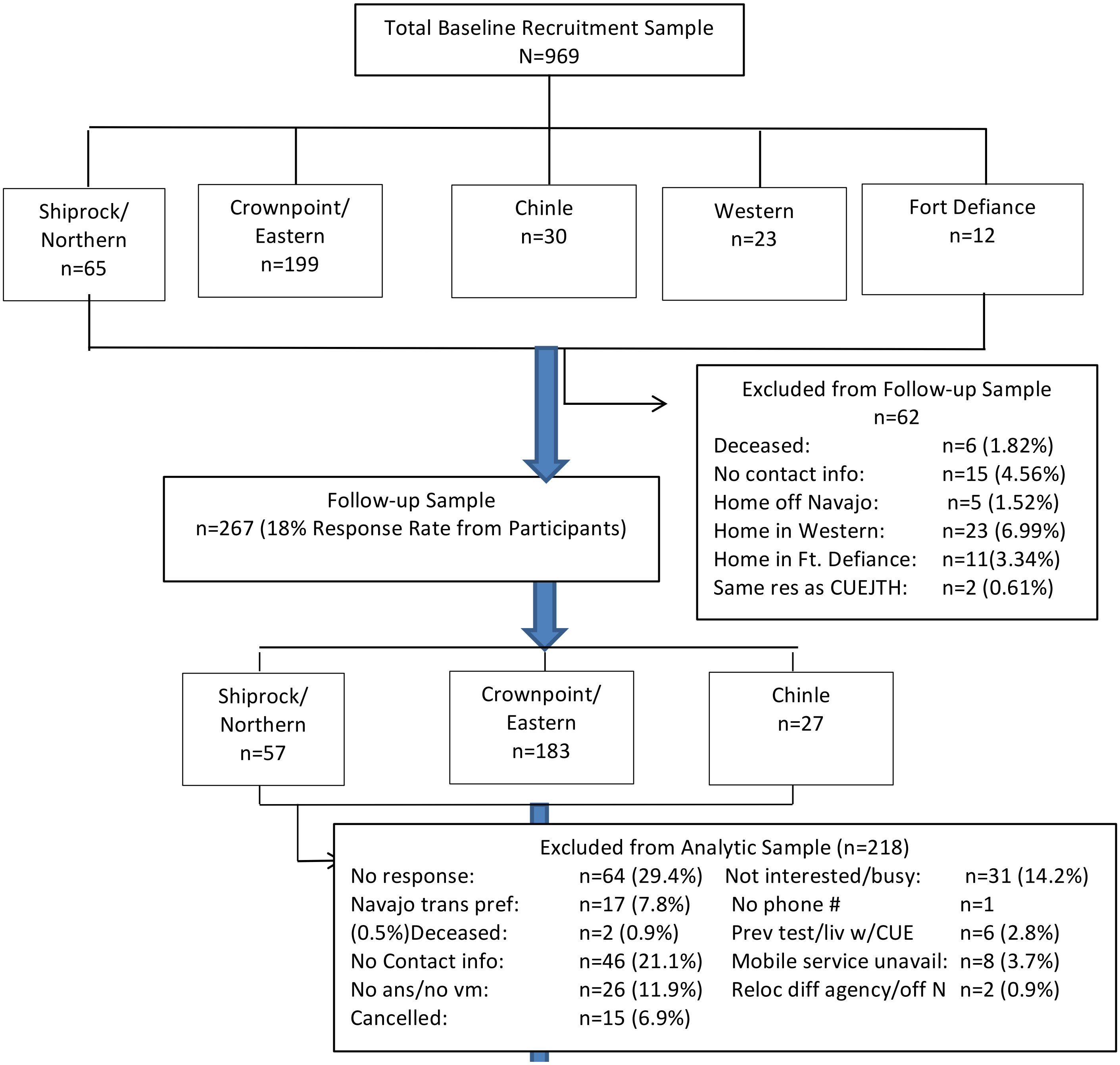
In addition, approval from the University of Washington Human Subjects Division (UW HSD) was obtained (IRB-EJ# 47652). The UW HSD worked in collaboration with the NNHRRB in the review and approval of research protocols to honor and protect the Navajo people.

2.4 RESULTS

2.4.1 Participants

The CUEJTH Program registered 964 participants through their community health surveys by December 2013. This dataset along with five additional participants who volunteered during this project brought the total recruitment sample size to 969 as seen in Figure 2. Among this group, only a certain proportion filled out research forms indicating a willingness to be contacted for potential participation in research projects. 329 participants filled research forms among the five Navajo Nation Agencies as follows: 1) Shiprock/Northern, 65, 2) Crownpoint/Eastern, 199, 3) Chinle, 30, 4) Western, 23, and 5) Fort Defiance, 12. We achieved a total participant response rate of 18%.

A total of 62 participants were excluded from the baseline recruitment sample. Exclusions were based on the following reasons (frequency, percentage): 1) deceased, n=6 (1.8%), 2) no current contact information, n=15 (4.6%), 3) residence off the Navajo Nation, n=5 (1.5%), 4) home in the Western Agency, n=23 (7.0%), 5) home in the Ft. Defiance Agency, n=11 (3.3%), and 6) same residence as another CUEJTH participant, n=2 (0.6%).



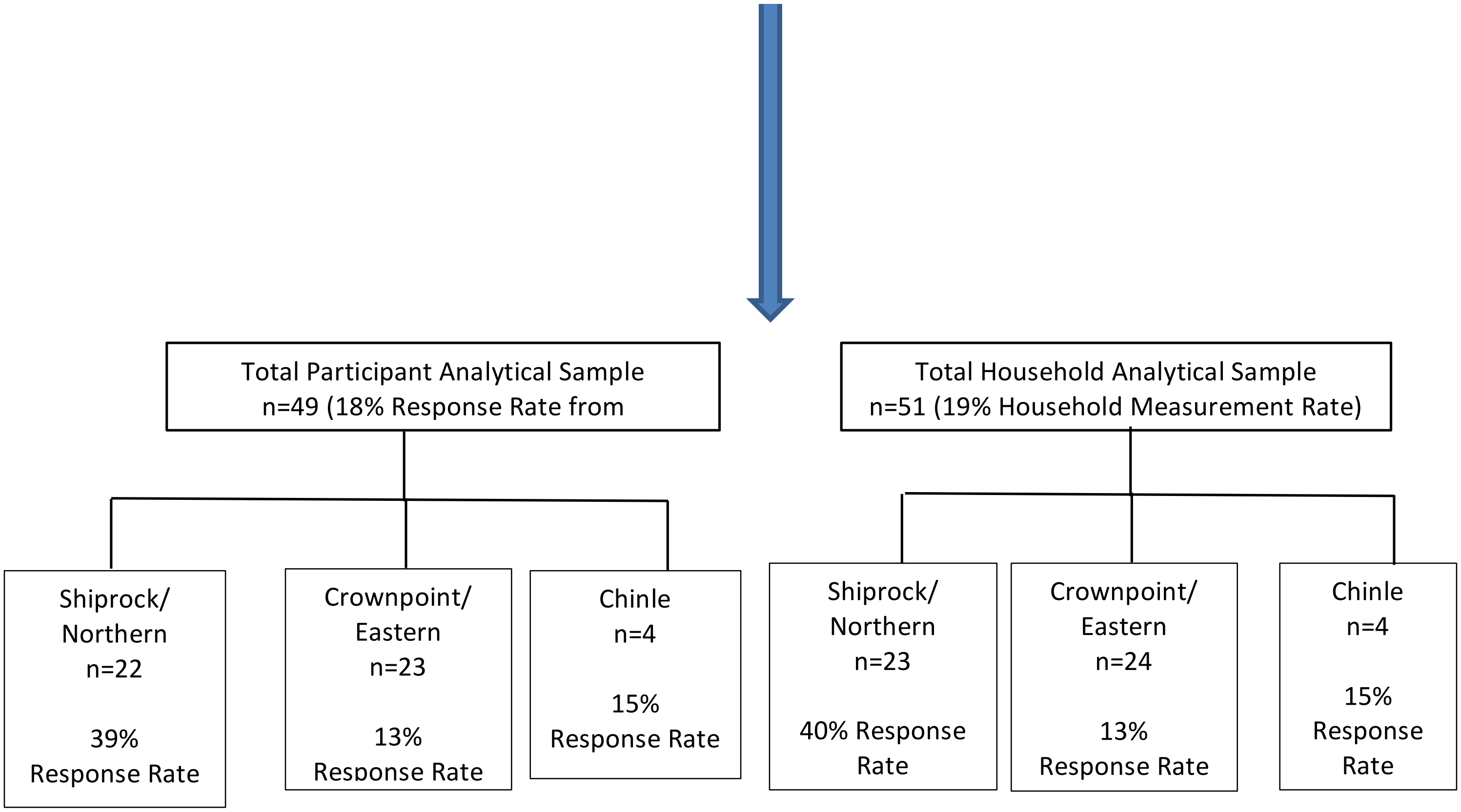
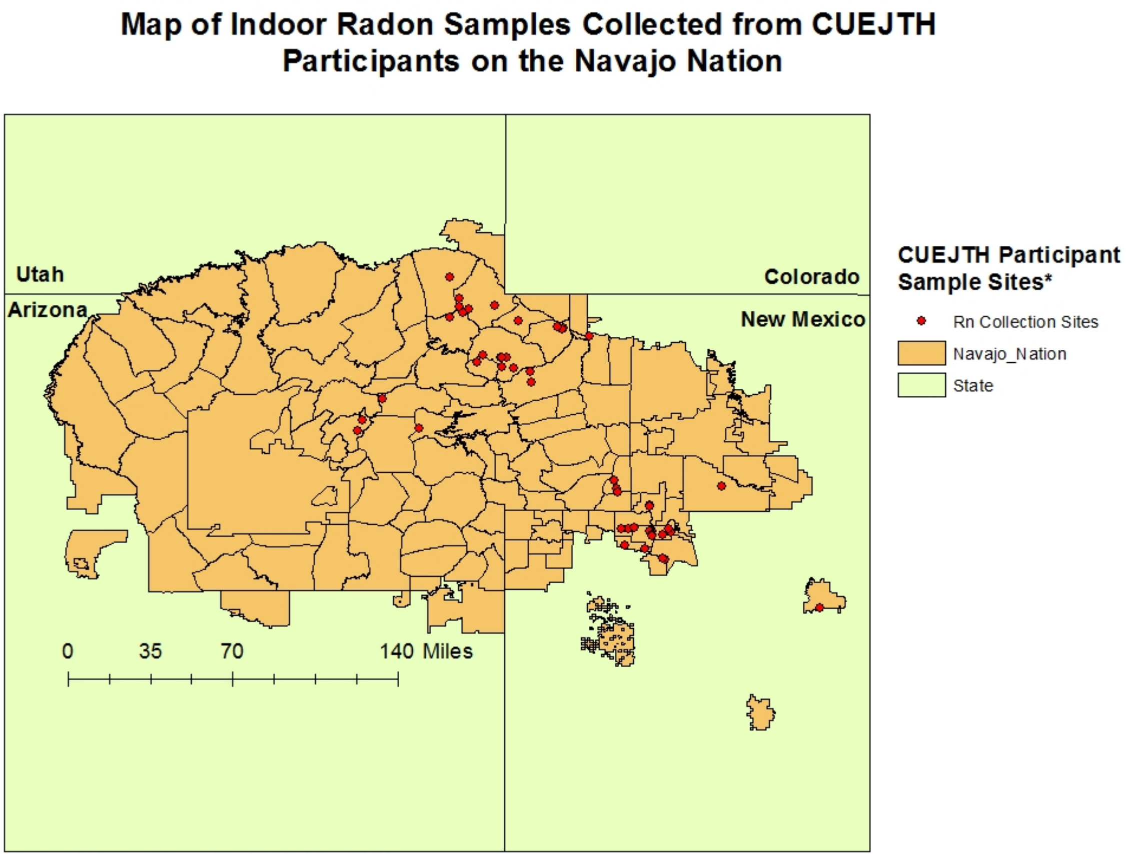


Figure 2: Flow diagram of CUEJTH participants

Accounting for these excluded individuals, the follow-up sample totaled 267 potential participants among the three agencies; 49 participants were successfully contacted. Two participants had two homes which were both measured giving the study a total household analytic sample of 51 homes. Therefore, this study had 49 total participants, 18% total participant analytical sample, and 51 homes measured for indoor radon, 19% total household analytical sample.

A figure diagramming the approximate residence of CUEJTH Participants within each agency on the Navajo Nation is shown below in Figure 3 (dithered to protect identity). This methodology is commonly done in public health to avoid any potential identification through reverse geocoding of known addresses with published geospatial maps.[62]



Temporal Range: November 2014 - May 2015
Production Date: October 22, 2016
Datum: NAD83
Projection: North American Albers Equal Area Conic
*Home location sites dithered

Figure 3: Map of Indoor Radon Samples Collected from CUEJTH Participants (red dots)

Follow-up Sample

After excluding 62 potential participants, 267 participants were used as the "follow-up" sample. From this follow-up group, 218 potential participants were excluded from the analytic sample for the following reasons, 1) no response after left voicemail and/or in-person messages, n=64 (29.4%), 2) Navajo translation preferred, n=17 (7.8%), 3) deceased, n=2 (0.9%), 4) no current contact information, n=46 (21.1%), 5) no answer or voicemail set up for working mobile numbers, n=26 (11.9%), 6) home visits cancelled by participant or due to weather, n=15 (6.9%), 7) participant too busy or not interested, n=31 (14.2%), 8) no phone number, n=1 (0.5%), 9) lived with other CUEJTH participant or home previously tested, n=6 (2.8%), 10) mobile service unavailable, n=8 (3.7%), and 11) participant relocated to another agency not approved or current residence off the Navajo Nation, n=2 (0.9%).

Analytic Sample for Participants

In this group 49 participants were successfully contacted by phone with a complete home indoor radon assessment conducted. These participants were distributed across the three approved agencies as follows, frequency (percentage): 1) Shiprock/Northern, n=22 (44.9%), 2) Crownpoint/Eastern, n=23 (46.9%), and 3) Chinle, n=4 (8.2%).

Analytic Sample for Households

Two individuals among the 49 participants owned and currently resided in two homes and requested that both their homes be tested. One participant was from the Shiprock/Northern Agency and the second participant was from the Crownpoint/Eastern Agencies. Including these two additional households brought the total analytic sample for households to 51 compared to 49 analytic samples for participants.

2.4.2 Basic Ventilation Characteristics by House Type

Table 5 Basic Ventilation Characteristics by House Type

Ventilation Characteristics	Mobile N=12 (%)	Hogan N=2 (%)	Wood N=27 (%)	Cement/Wood N=2 (%)	Concrete/Cement N=8 (%)
Crawl Space	100	50	41	0	38
Door Cracks/Shifted	25	0	22	0	0
Exhaust Fan	17	0	11	0	0
Visible Cracks in the Floor	42	0	56	50	63
Woodstove	75	100	93	50	100
Ceiling Openings/Cracks	58	50	59	50	75

Crawl Space

Table 5 provides a description of overall basic house characteristics for certain variables thought to be associated with indoor radon concentration levels. Crawl spaces were observed in all 12 mobile homes (100%) surveyed in this study. Other home categories with observed crawl spaces were as follows: one of two hogans (50%); 11 of 27 wood homes (41%); and three of eight concrete and cement homes (38%). In contrast, no homes made of cement and wood were observed to have a crawl space.

Cracked or Shifted Doors

Information was obtained on airflow or light shining through doors usually as a result of cracked or shifted doors. For example, over time some wood doors may have cracked or possibly shifted due to a shift in the foundation of the home. As a result, airflow could be felt by standing next to a shifted door merely by observing light shining through cracks of door side linings. Only two categories of home were observed to have cracked or shifted doors, mobile homes (25%) and wood homes (22%). The three remaining home categories were not observed to have cracks or shifts in their doors.

Home Exhaust Fans

Participants were asked if there was a main exhaust fan in the home. This did not include ventilation fans reported or observed in the bathrooms, laundry rooms, or above ovens. Only two home categories were observed to have some type of main exhaust fan, mobile (17%) and wood (11%) homes. The three remaining home categories did not have a main exhaust fan.

Visible Cracks in the Floor

The two hogans surveyed were the only homes in which no visible cracks were reported or observed in the floor. Otherwise, almost half of each of the remaining home categories either reported or were observed to have visible cracks in the floors as follows: mobile (42%); wood (56%); mix “cement and wood” homes (50%); and mix “concrete and cement” homes (63%).

Woodstoves

Woodstoves were reported and observed in all home categories. Mix “cement and wood” and mobile homes were two home categories least observed to have a wood stove compared to other homes, 50% and 75%, respectively. Wood homes almost all had a woodstove installed, 93%, while the remaining two home categories hogan and mix “concrete and cement” all had woodstoves installed.

Ceiling Openings or Cracks

In each home category, ceiling cracks and openings were observed in at least half or more of each home. Hogans and mix “cement and wood” homes each had at least 50% openings or cracks in their ceilings. Mobile homes and wood homes were observed to have ceilings with openings or cracks, 58% and 59%, respectively. Mix “concrete and cement” homes had the largest proportion of ceiling openings and cracks, 75%, compared to other home categories.

2.4.3 Mean Indoor Radon Concentration Results

Basic descriptive analyses were calculated for mean indoor radon concentration levels. Log transforming the mean indoor radon concentration levels showed a log normal distribution. The log-transformed indoor radon data was evaluated by graphing the log transformed data on a histogram and further evaluation by the Shapiro-Wilk test of normality. Following this observation, the geometric mean (GM) and geometric standard deviation (GSD) were computed and reported in Table 6.

The correlation coefficient (r) between living and bedroom indoor radon concentration comparing non-log transformed levels was r=0.98 (S.E.=0.03) and the correlation coefficient comparing the log-transformed data was 0.95 (S.E. =0.05). Based on these correlation results, it was decided to calculate and utilize a mean home indoor radon concentration for each home. We averaged all indoor radon home measurements to compute a mean indoor home radon concentration.

2.4.4 Mean Indoor Radon Concentration by House Type

Table 6 Mean Indoor Radon Concentration (pCi/L) by House Type

	N	GM	GSD	AM	SD	Min	Max
All Homes	51	1.2	2.6	1.6	1.2	0.1	6.3
Mobile	12	0.6	2.6	0.8	0.6	0.1	2.3
Hogan	2	2.0	1.0	2.0	0.0	2.0	2.0
Wood	27	1.2	2.5	1.6	1.0	0.1	3.4
Mix (Cement/Wood)	2	2.2	1.0	2.2	0.1	2.2	2.3
Concrete/Cement	8	2.6	1.6	2.9	1.5	1.4	6.3

GM=Geometric Mean; GSD=Geometric Standard Deviation; AM=Arithmetic Mean; SD=Standard Deviation

As shown in table 6 above, mobile homes had an overall geometric mean (GM) indoor radon concentration of 0.6 pCi/L and a geometric standard deviation (GSD) of 0.6, which was the lowest observed indoor radon concentration by home type. Hogan homes had an overall geometric mean indoor radon concentration of 2.0 pCi/L (GSD=1.0). Homes constructed primarily of wood had an overall geometric mean indoor radon concentration of 1.2 pCi/L (GSD=2.5). Homes with an observed mixture of cement and wood, referred to as mix cement and wood had an overall geometric mean indoor radon concentration of 2.2 pCi/L (GSD=1.0). The highest mean indoor radon concentration was observed in homes constructed mainly of cement and concrete with an geometric mean of 2.6 pCi/L (GSD=1.6).

2.4.5 Mean Indoor Radon Concentration by Ventilation

Ventilation was assessed by categorizing homes that were built directly on grade surfaces compared to homes not built directly on grade surfaces that had a crawl space. The radon concentration levels were then compared between these two categories providing one approach in assessing how ventilation is associated with the observed indoor radon concentration levels in the dataset. This comparison is shown in table 7 below.

Table 7: Mean Indoor Radon Concentration Levels [pCi/L] by Crawl Space

Crawl Space	Observations	AM	SD	Min	Max
Yes	27	1.2	0.84	0.14	2.9
No	24	2.1	1.3	0.14	6.3

A two sample t-test of the arithmetic mean indoor radon concentration levels by crawl space was assessed using the above data. The H0: B1=B2=0; HA: B1=B2≠0. Based on the two sample t-test results, there is strong evidence that the arithmetic mean indoor radon concentration across the homes with crawl space compared to homes with no crawl space are not equal (p=0.002).

2.4.6 Mean Indoor Radon Concentration by Agency

Table 8: Mean Indoor Radon Concentration [pCi/L]Levels by Agency

Agency	N	GM	GSD	AM	95% CI		SD	Min	Max
All	51	1.2	1.6	1.6	1.3	2.0	1.2	0.1	6.3
Shiprock/Northern	23	1.7	1.9	2.0	1.5	2.6	1.3	0.6	6.3
Crownpoint/Eastern	24	0.8	3.2	1.3	0.9	1.7	1.0	0.1	3.5
Chinle	4	1.4	1.5	1.4	0.5	2.3	0.6	0.9	2.2

In Table 8 by agency, the overall AM of mean indoor radon concentration was 1.6 pCi/L with a SD of 1.2. Highest to lowest AM (SD) of mean indoor radon concentration for each agency was as follows: Shiprock/Northern, 2.0 (1.3), Chinle, 1.4 (0.6), and Crownpoint/Eastern 1.3 (1.0).

Mean Indoor Radon Concentration below LOD

The Air Chek, Inc. home indoor radon test has a limit of detection of 0.2 pCi/L in dry climate, as in the Southwest where the Navajo Nation is located. Laboratory analysis report results returned from Air Chek, Inc. reported indoor radon measurements below the LOD as <0.3 pCi/L.[55] 11% of wood homes and 25% of mobile homes measured below the LOD. The remaining three home categories did not have indoor radon measurements below the LOD.

Action Limit

The action limit for indoor radon concentration is 4.0 pCi/L as set by the US EPA. 13% of concrete and cement homes were observed to have indoor radon concentrations above 4.0 pCi/L.

Log Mean Home Indoor Radon Concentration vs Temperature

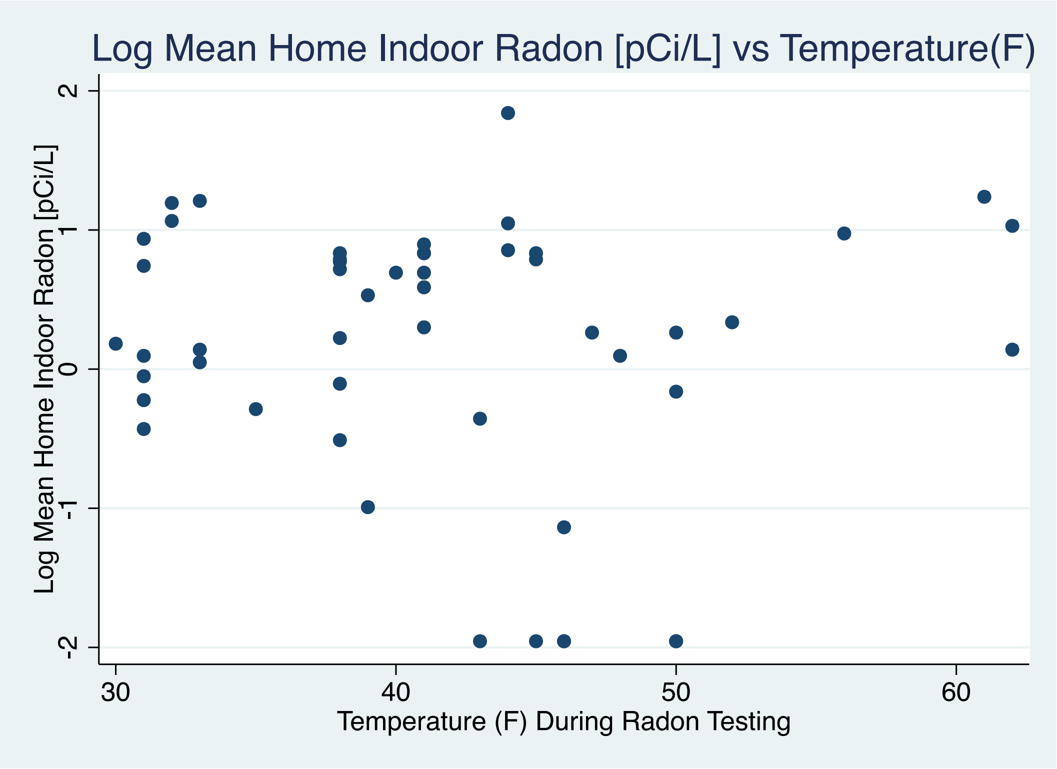


Figure 4 Log Mean Home Indoor Radon Concentration versus Temperature (°F)

The log mean indoor radon concentration as depicted in Figure 4 illustrates a small decrease in mean home indoor radon concentration at higher temperatures. Given the data collection period primarily during the Winter season months, the temperature range extends from roughly 30°F to 60°F. The correlation between between log mean indoor radon concentration and temperature was estimated to -0.10 (S.E.=0.14).

Log Mean Home Indoor Radon Concentration vs Elevation

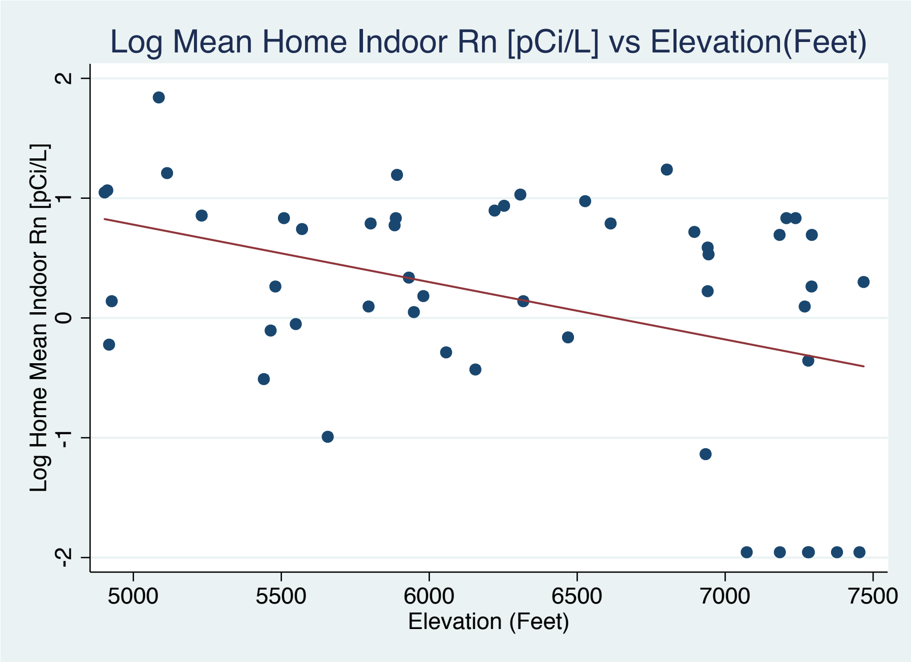


Figure 5 Log Mean Home Indoor Radon Concentration versus Elevation (Feet)

The log mean home indoor radon concentration values by elevation (feet) show a negative relationship in Figure 5. The correlation coefficient was estimated to be equal to -0.40 (S.E.=0.13).

2.5 DISCUSSION

Response Rate

The low household response rate of 19% was due to several factors. Almost one-third of potential participants did not respond; primarily due to unanswered messages left for this group (29%). Another factor was related to no current contact information for some participants (21%). Further, if these individuals did not recently visit their respective Indian Health Service clinic, then this would account for a lack of current information recorded in electronic health records. A certain proportion of participants, 14%, also stated they were not interested or too busy. Another group did not simply respond to voicemail message or other messages (12%).

The Navajo Nation access to broadband cellular phone usage is lower than the national average, 53% vs. 98%, as reported by the Navajo Times in April 2013.[63] This illustrates the proportion of residents living on the Navajo Nation without access to cell phones or Internet services. Access to land line telephones is higher on the Navajo Nation, 68%, but still lower than the national rate of 98%.[63] Compared to other tribal reservations and the U.S., the Navajo Nation is lagging behind in cellular phone and Internet access. Thus, limited access to cellular phone and land-use telephone services may partially account for the proportion of residents who were not contacted due to no current contact information, or who may not have responded to voice mail messages.

The indoor radon survey took place primarily during the winter season, a time when many residents were unavailable at home. As a result, many potential participants indicated their personal lives were too busy or unpredictable to state whether they would be available for two home visits. Others simply stated an appreciation for the project, but overall were not interested in their home being tested for indoor radon. Scheduled visits also were cancelled due to unforeseen family emergencies where the participant would be unavailable at home or if the weather did not permit a home visit.

Basic Ventilation Characteristics by House Type

All mobile homes measured had a crawl space compared to the other house types. This area of space between the soil and the foundation of the home may account for the observed lowest indoor radon concentration levels observed in this house type. In contrast, the two types of homes with higher levels of indoor radon concentrations had either none or less than half of the homes with crawl spaces, mixed homes with cement/wood and mixed homes with cement/concrete.

Other home characteristics associated with indoor ventilation included cracked or shifted doors, home exhaust fans, and openings or cracks in the ceiling. Mobile homes and wood homes were the only two house types observed to have cracked or shifted doors. Further, these two house types were also observed to have home exhaust fans while the house types did not. Ceiling cracks and openings were observed in all house types. Cracked and shifted doors along with home exhaust fans may also contribute to the lowest indoor radon concentration levels observed in mobile homes.

All house types except hogans were observed to have some visible cracks in the floor. These floor conditions could impact the amount of radon gas passing into the home from the soil if present. Only two hogans were measured for indoor radon levels in our survey of CUEJTH participants and combined the two hogans were observed to have higher levels of indoor radon concentration levels.

Averaging Mean Indoor Radon Concentration Results

The arithmetic mean indoor radon concentration for living rooms was 1.6 pCi/L (SD=1.1) with a geometric mean of 1.1 pCi/L (GSD=2.6). Also, there was a high correlation observed between living room and bedroom indoor radon measurements; thus allowing us to calculate an average home indoor radon measurements for each home. These correlation results also suggest the indoor radon concentration was fairly constant throughout the home.

Two homes had basements with with an arithmetic mean indoor radon concentration of 3.4 pCi/L (SD=0.1) and a geometric mean of 3.4 pCi/L (GSD=1.0). Because radon gas is denser than air, and tends to accumulate in higher concentrations closer to the surface, these basement indoor radon concentrations correlate with previously reported observations.[30]

Mean Indoor Radon Concentration Results by House Type

It has been previously documented house materials can impact the level of indoor radon conentrations.[64] Mobile homes had the lowest observed indoor radon concentration levels compared to the other house types. Mobile homes are manufactured homes and range in size from single wide to double wide homes, and can be longer than 40 feet in length and wider than 8 feet.[65] Because mobile homes are usually mounted on wheels and positioned above the surface, as was observed in all mobile homes for this study, there is no direct contact between the home foundation and ground surface. This creates a crawl space which is usually enclosed with various materials, such as vinyl siding or bricks.[65] This space underneath the home creates an opportunity for any potential radon gas emitted from the underground soil to potentially escape from underneath the home before entering and accumulating inside a mobile home. Therefore, this limits the amount of potential radon gas to enter the home leading to lower indoor radon concentrations as was observed in mobile homes.

Homes constructed primarily of wood had the next lowest observed indoor radon concentration levels. Homes engineered with wood in the structural component usually have deep cavities that require certain amounts of insulation to be layered in between the walls.[66] In the 1980s and 1990s, homes constructed with lumber were more poorly designed and did not offer much durability, compared to more durable materials such as concrete.[67] Depending on the insulation material and the amount of spacing between lumber used in the walls could create an environment in which any potential indoor radon gas may escape. Based on this knowledge of lumber use in home construction, it is probable to observe lower mean indoor radon concentration as observed in these wood-framed homes.

Homes with the third highest mean indoor radon concentration for this project were hogans. The hogan is a traditional type of Navajo home used for traditional ceremonies and often constructed with wood, bark, and mud.[68] Typically, hogans are round-shaped with an opening at the top with one opening doorway, always facing the east to greet the morning sunrise. The opening at the top is to allow smoke from a wood stove to escape out. The foundation of hogans usually consist of a hard-packed earthen floor, which could potentially increase the accumulation of radon gas emanating from the soil into the hogan.[69] Based on this structural design, any potential indoor radon gas could potentially escape through any openings in the structural walls not sealed or through openings at the top where smoke exits the home.

Homes constructed with a mixture of wood and cement had the second highest observed indoor radon concentration levels. Considering that homes built with cement are more durable and potentially more enclosed provides insight into the observed mean indoor radon concentration. Combined with lumber, these homes if potentially more insulated may potentially have higher indoor radon concentrations compared to mobile homes, or homes made up of only lumber as was observed in this study.

Homes constructed primarily of concrete and cement in this study had the highest observed mean indoor radon concentration levels. Homes primarily constructed with concrete and cement were observed to have these materials in both the foundation and structural walls. Such homes usually have a more solid structural component and commonly are used as structural materials because they provide greater resistance to certain weather conditions, such as heavy winds and rain according to the National Association of Home Builders.[70] Concrete and stones also can naturally contain radium and homes built mainly with concrete with reduced levels of fresh air entering the home have been observed to have problems associated with radon concentrations.[71] Homes with a more solid foundation and positioned above the ground surface, and in areas with potentially higher soil uranium concentrations could potentially have elevated indoor radon levels as observed in these homes. Further, if there are no cracks in the concrete slab foundation, then a home may be considered more tightly sealed which would then allow any potential radon gas beneath the home to accumulate inside the home.

Mean Indoor Radon Concentration by Agency

By agency, the Navajo Nation EPA indoor radon concentration levels fell outside the 95% CI of the CUEJTH indoor radon concentration levels. The CUEJTH mean indoor radon data provide different results by agency compared to the radon data obtained from the NN EPA. This could be because the time of year samples were taken or differences in procedures.

Mean Indoor Radon Concentration by Temperature

The indoor radon concentrations were primarily collected during the winter season extending from November 2014 through early May 2015. The flow of radon gas into the home is affected by the amount of radon gas that can enter the home, such as through cracks in the foundation or through spaces around pipes. This movement of gas is enhanced by pressure difference inside and outside the home. Temperature differences (i.e. indoor heating) can create a lower pressure environment inside the home compared to a higher pressure outside the home, which is known as the stack effect.[72] This then favors the movement of radon gas entering the home.

In this survey with CUEJTH participants, we collected most of the indoor radon measurements during the winter season. During colder conditions, home domestic behavior also differ than periods of warmer temperatures. For example, during colder conditions homeowners tend to keep windows and doors closed. Further, in the winter it may snow or rain more frequently, and these types of moisture naturally create a blanket over the soil which negatively impacts any soil emanation. This reduced level of soil breathing may favor any potential radon gas in the soil to move into the home. Taking this into consideration, we expected to observe higher indoor radon concentrations at colder temperatures compared to lower indoor radon concentrations at higher temperatures. This change in temperature between the outside and inside of the home affect the pressure difference that then draws radon gas into the home. Because we restricted our collection period to mainly the winter season, we did not observe a significant correlation between home indoor radon concentrations and temperature during testing. This is most likely due to our short testing period during the winter season.

Mean Indoor Radon Concentration by Elevation

The log transformed mean home indoor radon concentration plotted by elevation (feet) showed a negative relationship. At higher altitudes it is known temperature decreases uniformly which is known as the lapse rate.[59] Up to 10km, this lapse rate is equal to 6.5°C/1000 meters. Based on this knowledge, we would expect the mean indoor radon concentrations to increase at higher elevations, as is observed with lower temperatures. Further, these indoor radon measurements were collected during the winter season, a time when a home is more tightly sealed by closing windows and doors to keep warm air inside the home. These conditions also increase the stack effect inside the home; heating effect when warm air inside the home rises creating a vacuum inside the home that is replaced by outside air moving into the home.[33] Therefore, this indoor environment created by the cold temperature and domestic behaviors would potentially favor the accumulation of any indoor radon gas.

Limitations

Non-Response Bias

The overall response rate of 18% in this indoor survey may reflect several factors. One factor is the low availability of cellular phone usage on the Navajo Nation. Nearly half of the follow-up sample participants who were eligible had no first response or had any recent contact information. However, smaller proportions of these eligible participants stated they had no time or were too busy, even though they may have been interested in participating. All efforts were made in attempting to accommodate each participant with home visits; however, if the participant stated no interest then this decision was respected.

Interestingly, only a small proportion of participants who did not participate were not included because they may have preferred the Navajo language at the first phone call. Attempts were made in advance with each initial phone call to predict whether a participant may prefer Navajo; this preference was often indicated in their electronic health record which was accessed before the initial call when verifying and confirming contact information for participants. In such situations, initials phone calls were then scheduled with a Navajo translator on the phone to assist researcher in introducing and explaining the project in Navajo. These attempts were mostly successful if the participant answered the phone and was interested in the project.

Selection Bias

To reduce potential selection bias, CUEJTH participants were selected in a systematic approach. First, participants were only eligible if they filled out a form indicating a willingness to be contacted. Second, participants had to have homes located on the Navajo Nation. Third, participants had to have a residence located in one of the three approved agencies. Potential participants excluded from the survey were deceased, had no current contact information, residence was in an unapproved agency, resident with another CUEJTH participants, or had a home located off the Navajo Nation. Further, eligible participants were categorized within their respective agencies, chapter regions and then randomized.

2.6 CONCLUSIONS

This indoor radon survey with participants from the CUEJTH program provided updated information on indoor radon measurements for homes on the Navajo Nation. The arithmetic mean indoor radon concentration levels for homes in this study were observed to be higher than the US national mean indoor radon concentration levels. By house type, mobile homes were observed to have the lowest mean indoor radon concentration levels while homes constructed primarily with concrete and cement had the highest mean indoor radon concentration levels. Basic structural house characteristics collected as part of each home assessment survey provided some insight into the mean indoor radon concentration levels observed within each house type. For example, mobile homes were observed to have the lowest mean indoor radon concentration levels, an observation not surprising considering each mobile home was set on various types of support systems (e.g., cinder blocks) creating a crawl space between the floor of the home and the soil top. Further, crawl spaces enclosed with vinyl coverings provide a less tightly sealed space allowing any potential radon gas emanating from the soil underneath the home to exit through the crawl space; instead of radon gas entering the bottom of the home if the crawl space was tightly sealed.

The indoor radon concentration levels in this study agree with published information on the Navajo Nation. In regards to indoor radon concentration levels, the US EPA Map of Radon Zones categorizes the Navajo Nation as a Zone 2 region, which are areas with predicted average indoor radon levels ranging from 2.0 to 4.0 pCi/L. The southwestern region of the US is also known to have elevated levels of natural uranium in the soil. This observation along with the historical legacy of abandoned uranium waste piles throughout the Navajo Nation create an environment with potentially higher levels of indoor radon concentrations. This environmental concern has been raised in other communities surrounded by uranium mining and milling outside the Navajo Nation.

The findings of this indoor radon survey have a few potential public health implications for home owners on the Navajo Nation. First and foremost, radon education and testing on the Navajo Nation must continue through the Navajo Nation Environmental Protection Agency Radon Program. Second, homeowners must continue to be informed about the importance of adequate ventilation throughout the home, especially during colder temperatures when homes tend to be more tightly enclosed, i.e. windows and door shut. Third, the Navajo Nation is a geographical region historically impacted by abandoned uranium mines and natural elevated levels of soil uranium concentrations, which are two environmental indicators known to be associated with higher levels of indoor radon concentrations. Therefore, community educations programs, such as the CUEJTH program, must continue to be supported to provide communities with education and basic training surrounding uranium, such as testing homes for indoor radon levels.

2.7 Acknowledgements

The Community Uranium Exposure Journey To Healing Program staff, participants, current Medical Director, Dr. Linda Knedler, and former Program Director, Captain (Ret.) Lisa Allee, R.N. In addition, Ms. Dorena Benally, caseworker for the CUEJTH program, provided Navajo translation support. Support was also provided by the Navajo Area Indian Health Service Agency and the Navajo Area Indian Health Service Medical Director, Dr. Douglas Peter. Two institutional review boards approved this project, the Navajo Nation Human Research Review Board (#NNR 14.185) and the University of Washington (UW) Human Subjects Division (#47652-EJ). The UW Dissertation Academic Committee also provided guidance throughout this project. Community support throughout the Navajo Nation was very much appreciated: the three Navajo Nation Agencies in which this survey was conducted, Shiprock/Northern, Chinle, and Crownpoint/Eastern; the Navajo Nation Indoor Radon Program, Director Ms. Eugenia Quintana and staff member, Mr. John Plummer. Indoor radon kits were provided by Mr. Mansel Nelson, Senior Program Coordinator at the Tribal Environmental Education Outreach Program at Northern Arizona University. Navajo translation of consent forms in addition to translation support, were provided by Mr. Frank Morgan. Community support funding was provided by the Mayo Spirit of EAGLES Community Grant Award. Additional funding was also provided by the UW Biostatistics, Epidemiologic, and Bioinformatic Training in Environmental Health, the UW GO-MAP Dissertation Fellowship Award, and the Education and Research Center for Occupational Safety and Health Award through UW Department of Environmental & Occupational Health Sciences. A special recognition to family and friends for their abundant support; and a special thank you to both my father Mr. Ray Yazzie and dear friend Mr. Amin Eizadkhah for the generous use of their personal vehicles while traveling on the Navajo Nation conducting indoor radon surveys.

Chapter 3

EXPOSURE PREDICTION MODEL

3.1 ABSTRACT

Exposure to radon in non-occupational settings can potentially occur from naturally enriched soil with uranium or from anthropogenic hazardous waste, such as abandoned uranium mines (AUMs), or from uranium mine and mill tailings wastes.[4] Radon gas is a uranium decay product and causes lung cancer in smokers and non-smokers; therefore, it is imperative to identify homes with potentially higher radon levels.[4]

The Navajo Nation sits in a geographical region with naturally elevated levels of uranium along with a history of uranium mining. During the period of heightened uranium mining between 1944 and 1986, many tons of uranium were extracted from this region that resulted in over 500 AUMs along with their waste tailings. Some homes located near AUMs also used waste materials to construct their homes. Therefore, homes built on soil with naturally elevated levels of uranium, and if located proximal to AUMs with the chance of waste materials used in home construction creates concern for identifying homes on the Navajo Nation which may potentially have elevated levels of indoor radon gas.

We combined indoor radon data survey measurements collected across the Navajo Nation with available geographic land covariates thought to be associated with indoor radon to develop an indoor radon prediction model using land-use regression (LUR) in combination with Geographic Information Software (GIS). A two-step procedure to approximate Universal Kriging (UK) that combined LUR and GIS was used and evaluated by a ten-fold cross validation (CV)-$R^{2.}$ Based on two-step approach using LUR in combination with GIS, the CV-R^2 was 0.487.

3.2 INTRODUCTION

3.2.1 Overview of Radon Properties

The purpose of this project was to develop an indoor radon prediction model for homes on the Navajo Nation. Radon is a radioactive noble gas that is inert, colorless, odorless, denser than air, and soluble in water.[23] Radon forms from both the decay of uranium and thorium into radium followed then by formation of radon.[4] Radon itself also decays to other radioactive progeny which includes polonium-218, polonium-214, and bismuth-214. Radon decay progeny are electrically charged particles that are capable of attaching to dust or other ambient aerosols and surfaces. Therefore, inhalation of these charged particles may result in particle deposition in the nose, pharynx, and tracheobronchial tree.[6] Radon concentration in the air is measured in units of radioactivity per volume of air, pCi/L.[26] According to the USEPA, the average outdoor concentration of radon in the US is 0.4 pCi/L while the average indoor radon concentration is 1.3 pCi/L.[28]

3.2.2 Overview of Predictors of Home Radon Exposure

Previous studies have examined factors that contribute to elevated indoor radon levels.[72-74] Predictors of indoor radon concentrations include the pressure difference between the subsurface air and indoor air, building construction characteristics, geologic characteristics of the soil, the weather, groundwater movement, season, and residence proximity to AUMs.[26, 30, 32, 28] First, factors such as pressure differences may contribute to lower pressures inside the home compared to the outside. This pressure difference results in the movement of radon gas from the soil subsurface into the house through cracks and other openings in the underlying home structure, leading to increased indoor radon concentrations.[32] Second, homes built with materials contaminated with uranium also may contribute to elevated levels of indoor radon concentrations.

The IARC reported that sand tailings from uranium processes were often used in concrete as part of foundations in the western US during the 1960s.[13, 34] Third, another main source of indoor radon concentrations is from soil enriched with radium, a decay product of uranium. Soil enriched with uranium and thus radium would provide a source of radon gas that may enter the indoor air from cracks in the floor or walls. Further, soil characteristics such as a higher permeability and moderate moisture content both favor diffusion of radon from the soil into the air.[34] A fourth source of radon is radon dissolved in groundwater which is a consequence of surrounding rock enriched with radium-226 such as near uranium ore bodies often containing uranium-238 and radium-226.[12, 28, 34] Groundwater enhanced with radon that is brought into the home could be a source of radon gas when the water used for activities such as showering and laundering.[36]

Seasons in which windows and doors are closed could contribute to increased levels of indoor radon concentrations potentially elevating elevated health risks because of lower fresh air exchange to ventilate the interior space of the home. More specifically, depending on house preferences and habits, ventilation systems are a key factor that impacts the ventilation rate of a home which is the rate of air entry and exit from the home. In the winter time, ventilation systems are not used as often and if not used, then any radon gas entering the home potentially may accumulate with no way to exit the home; resulting in higher home indoor radon concentration levels during the winter time.[35] In addition, humidity and temperature affect the emission rate of radon from the soil, usually in the reverse direction. For instance, increased atmospheric pressure, rain, and snow may reduce the exit of radon gas from the soil surrounding the home.[34] As a consequence, this would increase the radon concentration in the soil during the winter season, leading to a higher concentration gradient between the soil and the home interior spaces. Last, individuals who live near uranium mines may also be potentially exposed to higher levels of radon compared to the general population.[26, 37]

3.2.3 Health Effects Associated with Radon

Radon Exposure and Lung Cancer in the Non-Occupational Setting

In the non-occupational setting, previous epidemiologic case-control studies show both positive and weak associations when examining radon concentration in residential indoors with lung cancer risk.[4, 30] Pooling the results of several case-control studies, investigators were able to estimate strong support for a positive association between residential radon and lung cancer risk, in both smokers and previous smokers.[4] In fact, the Agency for Toxic Substances and Disease Registry (ATSDR) reported there was a 25-fold higher risk of lung cancer associated with residential radon exposure among nonsmokers.[4] Radon-222 and its decay products have been classified as a Group 1 carcinogen by the International Agency for Research on Cancer (IARC).[42] Collectively, this information provides evidence that understanding factors that contribute to elevated indoor radon exposures, and targeting interventions for reducing indoor radon could potentially decrease the risk of lung cancer.

3.2.4 Brief Overview of Geospatial Prediction Model

In both exposure assessment and epidemiologic health studies, geographically mapping objects provides a means to predict certain exposure measurements.[73-75] In Switzerland, Huari et al. developed a model to predict residential household indoor radon concentrations.[73] Over 44,000 measurements collected as part of Switzerland's nationwide indoor radon program collected during the time period 1994-2004 was used. In this Swiss database, housing information is regularly collected that includes house type, year of construction, floor level of room in the building, and type of room. In addition, land covariates related to the tectonic type and soil texture were also used as predictors. A multivariable log-linear regression model was used with mean indoor radon concentration as the outcome, and predictors of indoor radon concentration related to housing characteristics and geology. In this study, 80% of the data was used for model development and the remaining 20% for testing. Model performance in this study was based on the adjusted R^2 when comparing predicted indoor radon concentrations with observed measurements. In their study, the authors stated their prediction model was robust and reported a Spearmen correlation coefficient value of .45 [95% CI: 0.44, 0.46] in their validation dataset when comparing their predicted measurements and observations; and a Spearman correlation coefficient of 0.44 [95% CI: 0.42, 0.46] for their validation dataset.[73] A similar study was also conducted in Canada using a geospatial approach which utilized existing residential radon measurement in combination with housing and geologic existing data to predict radon concentrations in areas without any indoor radon measurements.[72] In the U.S., states have conducted indoor radon surveys; however, there is limited studies on whether this information has been used to develop indoor radon prediction model which has been done in other countries.[29, 76] These studies provided a point on which to develop a framework for our indoor radon prediction model using residential indoor radon measurements combined with housing and geographical data.

3.3 METHODS

3.3.1 Study Design

In this study "Assessing Indoor Radon Exposure on the Navajo Nation", indoor radon data was collected and combined from two community health programs. The indoor radon data related to the home, "house covariates", was then combined with selected "land covariates" and then analyzed using ArcGIS. A land use regression model (LUR) was then used in combination with Geographic Information Software (GIS) software to develop an indoor radon prediction model using log mean indoor radon concentration as the outcome variable with selected house and land covariates as predictors.

Conceptual Framework

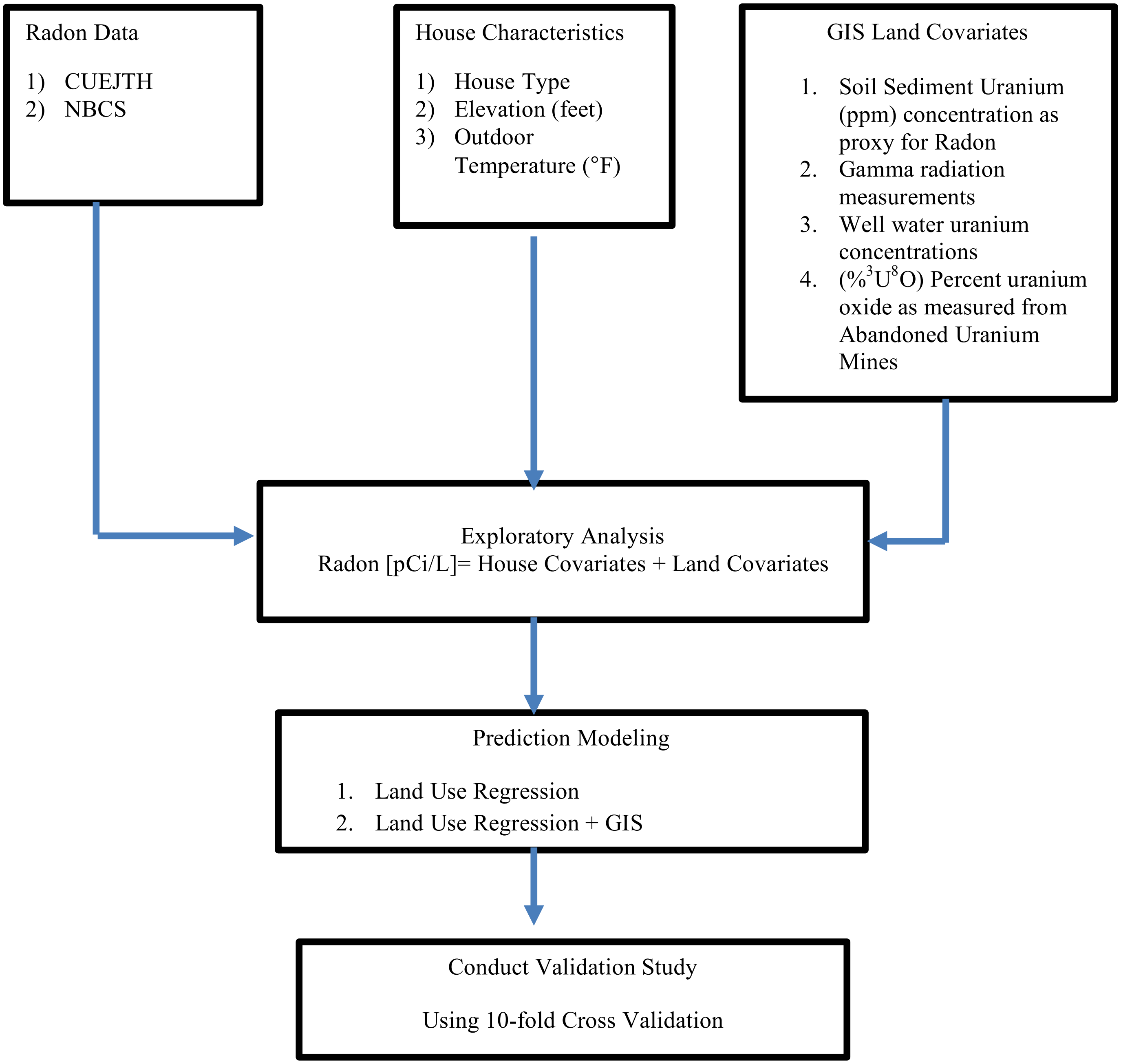


Figure 6: Flow Diagram in Developing Home Indoor Radon Prediction Model

3.3.2 Two House Indoor Radon Data Collection Surveys

Indoor Radon Survey with Participants from the CUEJTH Program

An indoor radon survey was conducted on the Navajo Nation with participants from the Community Uranium Exposure Journey To Healing Program (CUEJTH).[77] The CUEJTH program provides health monitoring, health promotion and health education to communities on the Navajo Nation who have been exposed to uranium. As previously described in chapter two, an indoor radon survey was conducted in three agencies on the Navajo Nation: Shiprock/Northern, Chinle, and Crownpoint/Eastern. In this survey, 51 home indoor radon surveys were conducted between November 2014 through May 2015. The Air Chek, Inc. short-term indoor radon kit was used to assess indoor radon for a minimum of three days and a maximum of seven days following the US EPA indoor radon protocol, which was adopted by the Navajo Nation Indoor Radon program.[51] The survey also captured basic housing characteristics including geographic coordinates (latitude and longitude) of the home. Briefly, houses were classified as mobile homes, hogan, wood, mixtures of wood and cement, and mixtures of concrete and cement. House elevation in feet was also recorded using a GPS device.

Navajo Birth Cohort Study Home Environmental Assessments

An indoor radon survey was also conducted as part of the Navajo Birth Cohort Study (NBCS), which is an epidemiologic study being conducted on the Navajo Nation.[78] In this study, trained Navajo staff conducted Home Environmental Assessments (HEAs) for each study participant in all five BIA Agencies on the Navajo Nation: Shiprock/Northern, Crownpoint/Eastern, Chinle, Fort Defiance, and Tuba City/Western to evaluate environmental exposure to toxicants. One HEA goal is to evaluate exposure to indoor radon. HEAs were conducted by Southwest Research and Information Center (SRIC) staff.[79]

In the NBCS study, indoor radon concentration measurements (pCi/L) were collected throughout the year using short term indoor radon kits.[80] Radon canisters intended for short-term testing ranging from two to seven days were purchased from the Radon Testing Corporation of America (RTCA).[80] These canisters, like the Air Chek radon test kits, used charcoal to absorb radon gas present in the home. The canisters were then analyzed using a sodium iodide detector at the RTCA laboratory. Trained staff placed charcoal canisters on solid surfaces following the manufacturer's recommended protocol. Charcoal canisters were placed in 2 rooms where residents spent most of the time, usually a living room and bedroom. The canisters were positioned away from windows, fireplaces, and other ventilation sources. A blank canister was measured every 5th or 6th home; blank canisters were opened for roughly three seconds, sealed, and placed next to an open canister during the testing period. At the end of the testing period, canisters were picked up by field staff and shipped directly to the RTCA for analysis.

The mean indoor radon concentration (pCi/L) measurements were examined using basic descriptive statistics. In the combined dataset, the lognormality of the mean indoor radon concentration was examined by plotting the distribution of measurements on a histogram and QQ plot with a Shapiro-Wilk test. The mean indoor radon concentrations (pCi/L) collected in our study and the NBCS study were also compared.

In the NBCS home survey, field staff observed and documented the home type. The NBCS classified each home using the following scheme: 1) single-story cement slab, 2) single-wide mobile home, 3) double-wide mobile home, 4) hogan, 5) wood frame, stucco, 6) adobe, 7) logs and mud, and 8) cement/cinder block. Home location (latitude and longitude coordinates) was recorded at the front entrance to the home using a Garmin eTrek 10 GPS (WGS84 datum), conducted in the same manner as the CUEJTH radon survey by field staff. House elevation was also recorded using the GPS device. Elevation was checked against the National Elevation dataset.

The NBCS collected additional data in their home survey assessment that was not available to our study. The additional data included gamma survey reading measurements recorded in mircoroetgen per hour (μR/hr) inside and outside the house. Dust wipe samples were also collected. The source of domestic water and usage information was also collected.

3.3.3 House Type

House type information collected in the indoor radon survey with CUEJTH participants, “CUEJTH dataset”, were combined with housing type information collected from the NBCS study, “NBCS dataset”, in the following manner. First, mobile home physical make-ups were recorded similarly in both home survey assessments using a generalized definition of a manufactured home as described by the U.S. Department of Housing and Urban Development as homes “built in the controlled environment of a manufacturing plant and transported in one or more sections on a permanent chassis”.[81] In the CUEJTH dataset, mobile homes were identified based on their structural make-up in align with mobile homes, in that these homes generally were transported to their residential site, sat on wheels above the ground soil, and enclosed with skirting materials. Manufactured homes can be single-wide or double-wide mobile homes; and in the NBCS dataset, mobile homes were classified as either single-wide or double-wide. Based on this information, the NBCS mobile home classification was collapsed into a general mobile home category and combined with mobile homes in the CUEJTH dataset.

The second house type was the hogan, a traditional home on the Navajo Nation. Hogans are usually made of logs or mud, cone-shaped, and the floor is generally hard-packed soil.[68] These homes generally have one door, traditionally facing the east direction for morning blessings. Also, there is generally one opening in the ceiling for stove pipes. In the indoor radon survey with CUEJTH participants, hogans were recognizable based on these basic structural characteristics. In the NBCS home survey, data collected included a “Hogan” category. In addition, two additional categories were available that included, “logs and mud” and “adobe in the NBCS dataset. Since adobe is generally made up of mud, NBCS homes marked as either logs and mud or adobe were categorized as hogan, and combined with the other homes categorized as hogan in the CUEJTH dataset.

The third house type were homes categorized as wood homes which were constructed mostly of wood materials. This was based on home observation as well as information obtained from the homeowner. The structural make-up were observed to be mostly wood materials and sat on solid foundation above the soil top. In the NBCS home survey, home surveys included a house type category of “wood frame, stucco”; therefore, these homes were considered wood homes. Using this information, we combined the wood frame, stucco homes in the NBCS study with the homes categorized as wood homes in the CUEJTH dataset.

The fourth house type were homes categorized as both wood and cement. In the CUEJTH dataset, these homes were categorized based on the proportion of structural materials making up the majority of the home. For example, some of these homes had half of the home layered with cement blocks around the home, and the remainder made up of wood. In these instances, we categorized these homes as “mixed homes, wood and cement”. In the NBCS home survey sheet, the field data collectors sometimes marked multiple categories for some homes. For example, some homes were marked as “wood frame, stucco”, “single-story cement slab”, or “cement/cinder block”; therefore, these homes in the NBCS dataset were categorized as mixtures of wood and cement, as was done in the CUEJTH dataset.

The fifth house type were homes categorized as mixtures of concrete and cement. In the study with CUEJTH participants, some homes were structurally made up mostly of concrete and cement materials. In these homes, we categorized these homes as mixtures of concrete and cement. In the NBCS home survey, these homes were labeled as “single-story cement slab” and “cement/cinder block”. Using this information from the NBCS survey, we combined these mixtures of homes in the NBCS dataset with those categorized as mixtures of concrete and cement in the CUEJTH dataset.

3.3.4 Temperature Data

Temperature measurements during radon testing period were collected retrospectively from a weather data resource, Weather Underground, that provided weekly average temperature recordings in areas where homes were located.[56] Temperature data are collected from over 42,000 weather stations nationwide located at airports, personal weather stations, and weather stations managed by the National Oceanic and Atmospheric Administration. To do this, the latitude and longitude home coordinates were entered into Google Maps™ to obtain the name of the nearest town and/or zip code. This information was then entered in the Weather Underground web page which then provided the weekly average temperature (°F) during the radon testing period.

Scatter plots of log mean indoor radon concentration versus temperature (°F) during indoor radon testing were created for CUJETH homes assessed in this project, homes in the NBCS home assessment, and also for both datasets combined. In each scatter plot, a correlation coefficient was calculated to assess the relationship between the log mean home indoor radon concentration and temperature.

3.3.5 Elevation

Scatter plots of log mean indoor radon concentration versus elevation (feet) were created for CUJETH homes assessed in this project, homes in the NBCS home assessment, and also for both datasets combined. In each scatter plot, a correlation coefficient was calculated to assess the relationship between the log mean home indoor radon concentration and elevation of the home.

3.3.6 Model Selection Process for Subject Covariates

House Type

We conducted basic descriptive statistics for each home type. This included the arithmetic mean (AM), arithmetic standard deviation (ASD), geometric mean (GM), and geometric standard deviation. These descriptive statistics were calculated independently for each dataset, the CUEJTH and NBCS, and also for the combined dataset. The log mean indoor radon concentration was also explored by house type. This information was then used to create an ordinal variable for house type.

Temperature

The scatter plots were used to assess the trends between log mean home indoor radon concentration [pCi/L] and temperature during radon testing. Correlation coefficients were used to asses the slope when assessing each scatter plot.

Elevation

Similar to temperature, scatter plots were created comparing the relationship between log mean home indoor radon concentration [pCi/L] and the elevation of the home (feet). Correlation coefficients were used to assess the slope when comparing each scatter plot. Additional analysis was explored by creating a scatter plot between diffusion and temperature (Appendix J).

A summary of the covariates associated with each home or “subject covariates” selected as predictors of indoor radon concentration [pCi/L] are summarized in Table 9 below.

Table 9 House Covariates Used to Develop Indoor Radon Prediction Model

Variable	Data Type	Unit of measurement
House Type	Categorical	1 Mobile Home 2 Hogan 3 Wood 4 Mix Wood/Cement 5 Concrete/Cement
Mean Temperature During Radon Testing Period	Continuous	°F
Elevation of home	Continuous	Feet

3.3.7 Description of GIS Based Land Covariates

Based on previous prediction models in air pollution and more specifically studies related to predicting home radon concentrations, land covariates thought to be related to uranium and therefore also potentially as a source of home indoor radon exposure were explored as potential predictor covariates. Moreover, land covariates were considered as predictors of home indoor radon levels if available for the Navajo Nation. The land covariates used in this model were found by accessing the geographic information system database developed by the Environmental Protection Agency for the Navajo Nation, titled "Navajo Nation AUM Screening Assessment Report and Atlas with Geospatial Data".[18] Each of the following land covariates (total terrestrial gamma activity, percent of uranium oxide measured at abandoned uranium mines, soil sediment uranium concentration, and uranium measurements collected from water resources) were explored as potential predictors for indoor radon exposure by mapping in ArcGIS 10.2. Each land covariate was mapped and overlaid on the Navajo Nation borders.

Total Terrestrial Gamma Activity

Total terrestrial gamma activity as recorded from aerial surveys collected near uranium mining areas on the Navajo Nation was considered but not used. This data was collected by the Department of Energy Remote Sensing Laboratory located in Las Vegas, Nevada that was funded by the Region 9 US EPA. Aerial surveys were targeted primarily at geographic regions on the Navajo Nation where uranium mining sites were located. These surveys included all radioactivity and Bismuth-214 (^{214}Bi) radioactivity, which is a radionuclide in the ^{238}U decay chain series; therefore, radioactivity measurements recorded from ^{214}Bi could be considered as a proxy for potential uranium resources in these uranium mining areas. Thus, high gamma activity near potential uranium sources could also be a proxy as a source of home indoor radon levels. This land covariate was not included in the final model because the dataset was incomplete compared to other land covariate that provided more coverage across the Navajo Nation.

Percent of Uranium Oxide at Abandoned Uranium Mine Production Sites

Uranium production on the Navajo Nation was mapped in the EPA database. In this database, uranium production was mapped diagramming the geolocation of each uranium production site. At each uranium production site, the quantity of uranium produced in pounds as well as the percent of uranium oxide (%U^3O^8) produced was provided.

Soil Sediment Uranium Concentration

This database included points of soil sample sites collected on the Navajo Nation as part of the National Uranium Resource Evaluation (NURE) program initiated by the US Department of Energy. The aim of the NURE program was to identify as many uranium resources as possible in the US which was carried out by the Hydrogeochemical and Stream Sediment Reconnaissance (HSSR) program. Sampling was collected from stream sediments and soils. Sampling began in 1975 and ended early in 1980 as a result of lack of funding support. This soil data was specific to the Navajo Nation and soil sediment sites provided coverage for most of the Navajo Nation.

Uranium Measurements Collected from Water Resources

Uranium concentration in water in parts per billion (ppb) was also measured by delayed neutron counting as part of the NURE program. As with soil, the NURE program sampled water sources which included surface and groundwater. These uranium measurements collected from water resources on the Navajo Nation were explored as a potential indoor radon predictor because well water is sometimes stored inside homes without water plumbing. Water stored in the home is one potential source of indoor radon exposure if any water was obtained from wells with elevated levels of uranium.[26] This land covariate was not included in the final model because the dataset was incomplete compared to other land covariate that provided more coverage across the Navajo Nation.

3.3.8 Model Selection of GIS Based Land Covariates

The process used to explore each of the GIS based land covariates were as follows. First, each land covariate was imported into ArcMap and spatially mapped over the Navajo Nation that included the corresponding geolocation of each home. Second, buffer distances ranging from 0.5km up to 30.0km were drawn around each home location. Third, using the Intersect tool in ArcMap, attribute features captured within each corresponding buffer distance was exported into a spreadsheet and analyzed in Stata13. Attributes captured included each corresponding home location (latitude and longitude), house type, temperature (°F), elevation (Feet), and each respective land covariate. Fourth, at each buffer distance basic descriptive statistics were calculated for each land covariate. Univariate and bivariate analyses were also conducted. Scatter plots were created between the log mean home indoor radon concentration [pCi/L] and each land covariate, in addition to correlation coefficients to observe trends. Fifth, multivariate regression models were explored within each buffer distance to assess the level of significance of each GIS land covariate and the level of significance for each subject covariate (house type, temperature (°F), elevation (Feet)).

At each buffer increment, the following observations were noted. First, the number of homes in this study that were captured. Second, trends and correlation coefficients were observed in each scatter plot. Third, the significance level of each land covariate and overall model performance as indicated by the Adjusted-R^2 were noted. These evaluation parameters were used in this exploratory analysis of each GIS based land covariate to decide on whether to potentially include each GIS based land covariate as a potential predictor of indoor radon concentration [pCi/L] in the final prediction model. Table 10 below summarizes briefly each GIS based land covariate explored and whether it was included in the final prediction model.

Table 10 GIS Based Land Covariates Considered as Radon Indoor Predictors

Variable	Brief description	Unit of Measurement	Scientific Meaning	Final Selection Status
Terrestrial Gamma Radioactivity	Radioactivity Measurements Near Uranium Mining Areas	KeV	Gamma Radioactivity Correlated with Uranium	Explored, Not Used
Percent of Uranium Oxide	Percent of Uranium Oxide	(%U^3O^8)	Correlates with Quality of Uranium Measured at Abandoned Uranium Mines	Explored, Not Used
Soil Sediment Uranium Concentration	Measured in Sediment Soil	parts per million (ppm)	Natural Uranium in Soil is a Precursor to Radon Gas Production	Explored and Included in Analysis
Uranium Measurements Collected from Water Resource	Measured in Water	parts per billion (ppb)	Potential Source of Indoor Radon if Stored Inside the Home	Explored, Not Used

3.4 Statistical Analysis

3.4.1 Brief Over of Analytic Steps

The following steps were performed in the statistical analysis as described below. First, indoor radon data collected among participants from the CUEJTH study and the NBCS study were combined. Second, an exploratory spatial analysis of selected land covariates thought to be related to radon gas exposure was conducted. In this exploratory analysis, home locations were spatially mapped and at each home location land covariate attributes were extracted. This allowed us to understand how each land covariate was associated with indoor radon concentrations and how much data was available for each home location. Third, based on the exploratory analysis in ArcGIS, predictor variables were selected and included in a baseline land use regression (LUR) model. Fourth, using ten-fold cross-validation in the baseline land use regression model, the cross-validated residuals were imported into ArcMap to create a smooth surface. Lastly, cross-validated residual estimates were extracted for each home and used to to calculate a final cross-validated log mean indoor radon concentration estimate. Step by step approach is outlined in Appendix L.

Cross validation is a method used to obtain an obtain an out of sample estimate by dividing a dataset into two partitions, one is a training dataset and the other is a validation or test dataset. In this approach, the training data is used to build a model and the remainder group, the validation or test group, is used to evaluate the model. A ten-fold cross validation approach is commonly used in which the dataset is split into ten distinct groups and examined in ten iterations. In the first iteration, 90% of the data are used as the training dataset to fit the model and the remaining 10% is used as the validation or test dataset that is used to develop predictions.[82] This method provides a prediction for each observation that was predicted on an out of sample group. See Appendix A for illustration of ten-fold cross validation.

3.4.2 Combined Indoor Radon Data

This dataset consists of 51 home indoor radon measurements from the CUEJTH program and 279 home indoor radon measurements from the NBCS for a total of 330 indoor radon measurements located throughout the Navajo Nation (Figure 7). The dataset used in this analysis was restricted to 289 homes that had one or more soil sediment samples within 25 km of the residence.

3.4.3 Exploratory Analysis of Land Covariates Using GIS

For each land covariate, buffer distances between 0.5km to 30.0km were drawn around each home location. The intersect feature in ArcGIS was then used to capture intersecting regions between each buffer distance and corresponding land covariate. An output table was then created for each home location that had the following attributes: mean log indoor radon concentration, house type, temperature during testing (°F), elevation of home (feet), and corresponding land covariate attribute. Basic descriptive analysis was done for each land covariate to examine overall distribution characteristics. Log normal distribution for each land covariate was used in the LUR if observed to follow a log normal distribution. Our approach did not have any specific set of criteria as this was an exploratory analysis. We aimed to collect a large enough fraction of homes, 80% or more, with each predictor variable. This was done by assessing the predictor variable performance at various buffer distances drawn around each home. Essentially, there was a trade-off between distance and the precision of the estimate for each predictor variable.

3.4.4 Model Selection using Land Use Regression

At each buffer distance, a land use regression (LUR) model was created and examined. For each LUR model, the outcome was the mean log indoor radon concentration with predictors as house type, temperature during radon testing (°F), elevation of house (feet), and the land covariate. The level of significance was examined for each predictor variable and the overall fit of the LUR model was assessed by assessing the adjusted-R^2 and root mean square error. Based on these overall performance measures, the buffer zone in which the predictors were most associated with indoor radon concentration (pCi/L) was selected.

3.4.5 Land Use Regression Model

A LUR model was fitted to the log mean indoor radon concentration (pCi/L) for each home location as the response variable and type of home, elevation of home (feet), average temperature during testing period (°F), the average sediment soil uranium concentration (ppm) as captured within a 25 kilometer (km) buffer distance around each home, and an interaction term between average soil sediment uranium concentration (ppm) and type of home as predictor variables. This interaction term was included in the LUR model because we observed that the relationship between the outcome variable log mean indoor radon concentration and the soil sediment uranium concentration differed by house type.

3.4.6 Final Land Use Regression Model Equation

Final land use regression model with selected predictor variables known to be associated with indoor radon exposure is written as follows:

$$\mathrm{E[Y|X]} = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 (X_1 * X_4) + \varepsilon$$

Y represents the outcome of the average log mean home indoor radon concentration [pCi/L] given the predictor value of X as follows:
X_1= House Type (5 categories)
X_2= Temperature (°F) during radon testing
X_3= Elevation of home (Feet)
X_4= Sediment soil uranium concentration (ppm)
X_1*X_4= House type*sediment soil uranium concentration

3.4.7 Two Step Approach to Approximate Universal Kriging

A two-step approach that approximates Universal Kriging (UK) was used that combines LUR and GIS (A detailed step by step analysis using the two-step approach is described in Appendix K). In the first step, the LUR model was fitted as stated above and out of sample predictions were generated using ten-fold cross-validation (as described above in section 3.4.1). In the second step, the cross validated LUR predictions were used to calculate cross-validated LUR residual estimates for each observation by taking the difference for each observation and predicted value; thus generating cross-validated LUR residuals (described in Appendix K). The cross-validated LUR residual predictions were then imported into ArcMap and mapped. Ordinary kriging was then used to create a smoothed surface of the cross-validated LUR residuals. At each home location, smoothed cross-validated LUR residual estimates were then extracted from this smooth surface.

A table and box plot were generated of the smoothed cross-validated LUR residual estimates to illustrate how the Kriged estimates varied across each of the five Navajo Nation agencies.

To approximate universal kriging estimates of log mean indoor radon concentrations, the cross-validated predicted estimates from the LUR model were added with the cross-validated LUR residual kriged estimate for each home that was extracted from the smoothed map. Correlation between the observed mean log indoor radon concentrations and cross-validated predicted mean indoor radon concentrations as calculated from the two-step LUR approach was evaluated by calculating a correlation coefficient and generating a scatter plot.

3.4.8 Model Prediction Map of Mean Indoor Rn[pCi/L] for Concrete/Cement Homes

A model prediction map of the mean indoor radon concentration was created using the two-step approach as described above as an approximation to universal kriging. In this method, the mean indoor radon concentration [pCi/L]was estimated for concrete/cement homes at 48°F across the Navajo Nation.

3.4.9 Model Performance Using Cross Validation

Model prediction performance was evaluated using two methods. First, the prediction performance of the LUR model was evaluated using an in-sample assessment by calculating the R^2 and root mean square error (RMSE). Second, the two-step modeling approach was evaluated using ten-fold cross validation, in which 90% of the data were used to train the model while the remaining 10% of the data was used to test the data. Cross validated R^2 (CV-R^2) and root mean square error (RMSE) estimates were generated and compared to the in-sample assessment R^2 and RMSE.

3.5 RESULTS

3.5.1 Individual Dataset Comparison of Mean Home Indoor Log Radon Concentration [pCi/L]

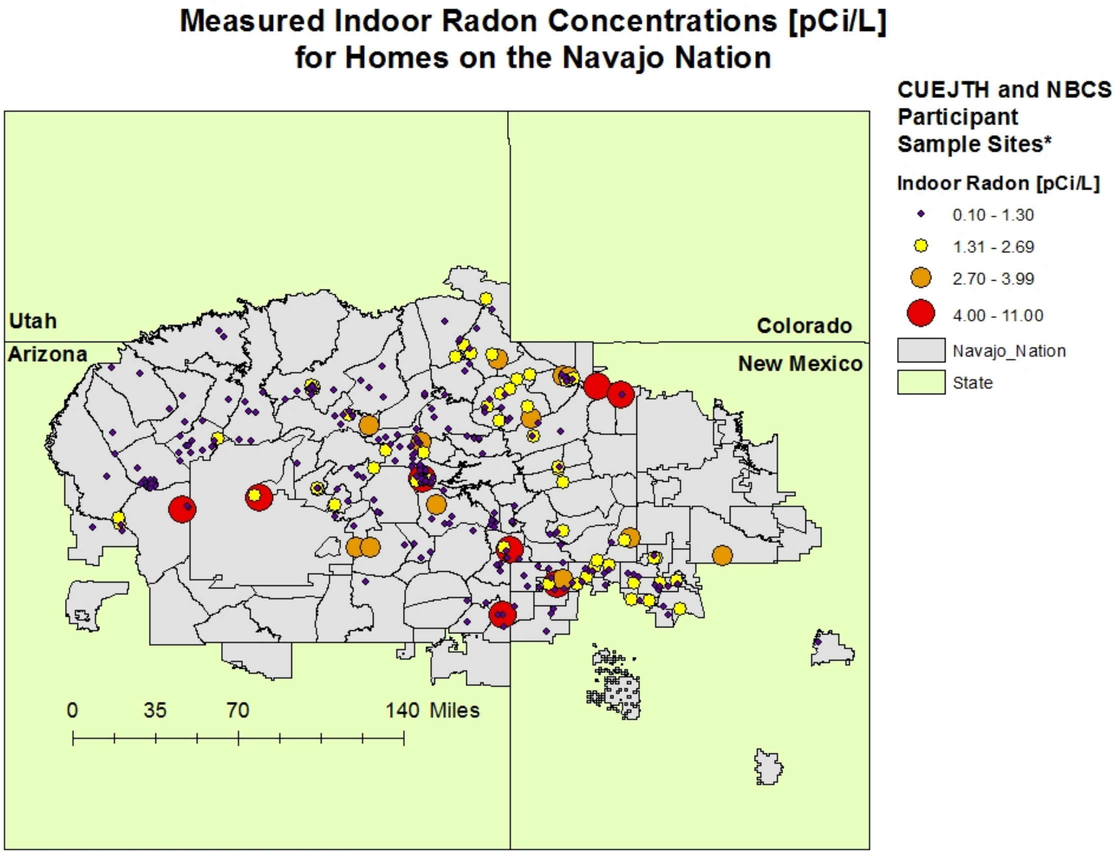
In Table 11 below, the home mean indoor log radon concentration (pCi/L) for each dataset are provided for comparison. In the CUEJTH study, we measured 51 homes from CUEJTH participants while the NBCS had 279 homes. By house type, mobile homes were observed to have the lowest GM in both the CUEJTH and NBCS homes, 0.6 pCi/L (GSD=2.6) and 0.3 pCi/L (GSD=2.0), respectively. In the CUJETH dataset, concrete and cement homes had the highest mean log indoor radon concentration with a GM of 2.6 pCi/L (GSD=1.6). However, in the NBCS dataset, concrete and cement homes and wood homes were observed to have the highest log mean indoor radon concentration, GM=0.7 pCi/L (GSD=5.2) and GM=0.7 pCi/L (GSD=2.5), respectively.

Table 11: CUEJTH and NBCS Home Indoor Radon Concentration (pCi/L) Comparisons by House Type

	CUEJTH	NBCS	CUEJTH		NBCS		CUEJTH				NBCS			
	n	n	GM	GSD	GM	GSD	AM	SD	Min	Max	AM	SD	Min	Max
Indoor Radon	51	279	1.2	2.6	0.5	2.7	1.6	1.2	0.1	6.3	0.9	1.1	0.1	10.0
Type of Home														
Mobile	12	57	0.6	2.6	0.3	2.0	0.8	0.6	0.1	2.3	0.4	0.3	0.1	1.5
Hogan	2	20	2.0	1.0	0.6	2.5	2.0	0.0	2.0	2.0	0.8	0.6	0.1	2.5
Wood	27	76	1.2	2.5	0.7	2.5	1.6	1.0	0.1	3.4	1.1	1.1	0.1	5.7
Mix (Cement/Wood)	2	122	2.2	1.0	0.6	2.9	2.2	0.1	2.2	2.3	1.0	1.4	0.1	10.0
Concrete/Cement	8	4	2.6	1.6	0.7	5.2	2.9	1.5	1.4	6.3	1.6	2.2	0.1	4.8

3.5.2 Combined Dataset: House Type and Mean Log Indoor Radon Concentration

A total of 330 mean indoor log indoor radon concentrations were used in the exploratory analysis using GIS (Figure 7).



Temporal Range: April 2013 - June 2015
Production Date: October 3, 2016
Datum: NAD83
Projection: North American Albers Equal Area Conic
*Home location sites dithered

Figure 7: Mean Indoor Radon Concentrations [pCi/L] for Homes on the Navajo Nation

By house type, as seen in Table 12 below, there were 69 mobile homes, 22 hogans, 103 mobile homes, 124 homes observed to be mixtures of cement and wood, and 12 homes made up primarily of concrete and cement.

Table 12: Combined Home Indoor Radon Concentrations [pCi/L] by House Type

	n	%>4 pCi/L	GM	GSD	AM	SD	Min	Max
Indoor Radon	330	2.4	0.6	2.8	1.0	1.2	0.1	10.0
Type of Home								
Mobile	69	0.0	0.3	2.2	0.4	0.4	0.1	2.3
Hogan	22	0.0	0.7	2.6	0.9	0.7	0.1	2.5
Wood	103	1.9	0.8	2.6	1.2	1.1	0.1	5.7
Mix (Cement/Wood)	124	3.2	0.6	2.9	1.1	1.4	0.1	10.0
Concrete/Cement	12	16.7	1.7	3.1	2.4	1.8	0.1	6.3

*LOD (CUEJTH)=0.2 pCi/L
*LOD(NBCS)=0.1 pCi/L

In the combined dataset (Table 12 above), mobile homes had the lowest observed mean log indoor radon concentration [pCi/L] while concrete/cement homes had the highest level of mean log indoor radon concentration, GM=0.3 pCi/L (GSD=2.2) and GM=1.7 pCi/L (GSD=3.1), respectively. The remaining house types had the following mean indoor log radon concentrations: hogan, GM=0.7 pCi/L (GSD=2.6); wood homes, GM=0.8 pCi/L (GSD=2.6); and mixed homes of cement and wood had a GM of 0.6 pCi/L and GSD=2.9. The distribution of radon concentration for the combined dataset had an overall geometric mean (GM) of 0.6 pCi/L and a geometric standard deviation (GSD)=2.8. The proportion of homes that measured above the Environmental Protection Agency's action limit of 4.0 pCi/L was observed in both mixed homes of cement/wood and concrete and cement homes, 3.2% and 16.7%, respectively.

The Shapiro-Wilk test of the raw mean indoor radon concentration was statistically significant indicating the data did not follow a normal distribution pattern (W=0.70; p<0.001). Based on the histogram in Figure 8 below and the Shapiro-Wilk test, it was determined the mean indoor radon concentration for the combined dataset followed a log normal distribution.

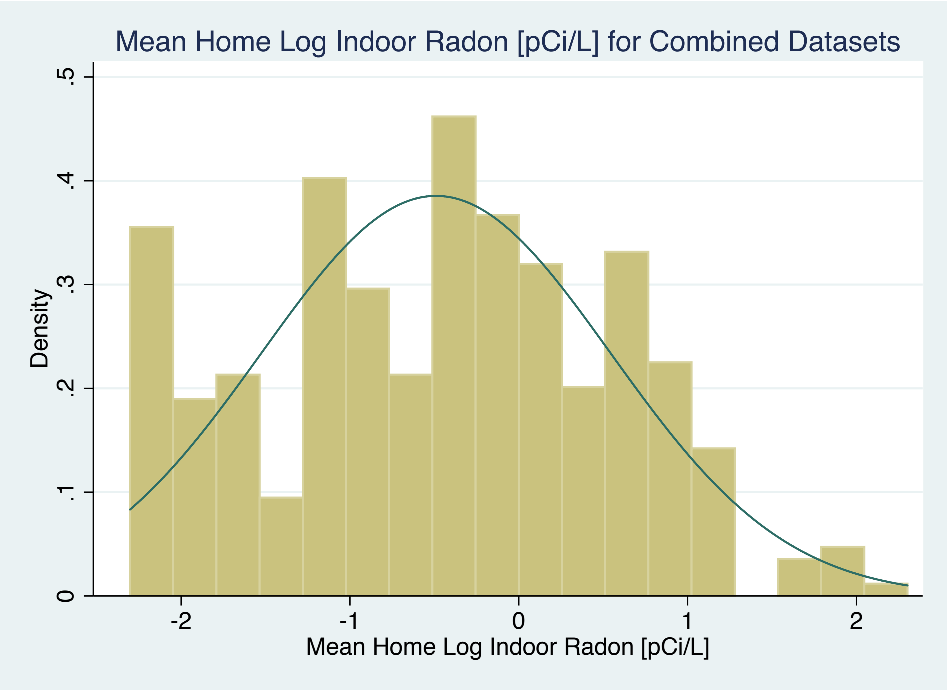


Figure 8: Histogram of Mean Home Log Indoor Radon Concentration [ln pCi/L] for Homes in both the CUEJTH and NBCS Datasets

A comparison of the mean log indoor radon concentration (pCi/L) by house type is plotted in a box plot in Figure 9 below. In this box plot, mobile homes are observed to have the lowest mean log indoor radon concentration (pCi/L) while concrete and cement homes have the highest mean log indoor radon concentration (pCi/L). Hogans are observed to have a higher mean log indoor radon concentration (pCi/L) compared to mobile homes and mixed homes of cement and wood. Homes made primarily of wood are observed to have a higher mean indoor radon concentration compared to both hogans and homes mixed with cement and wood.

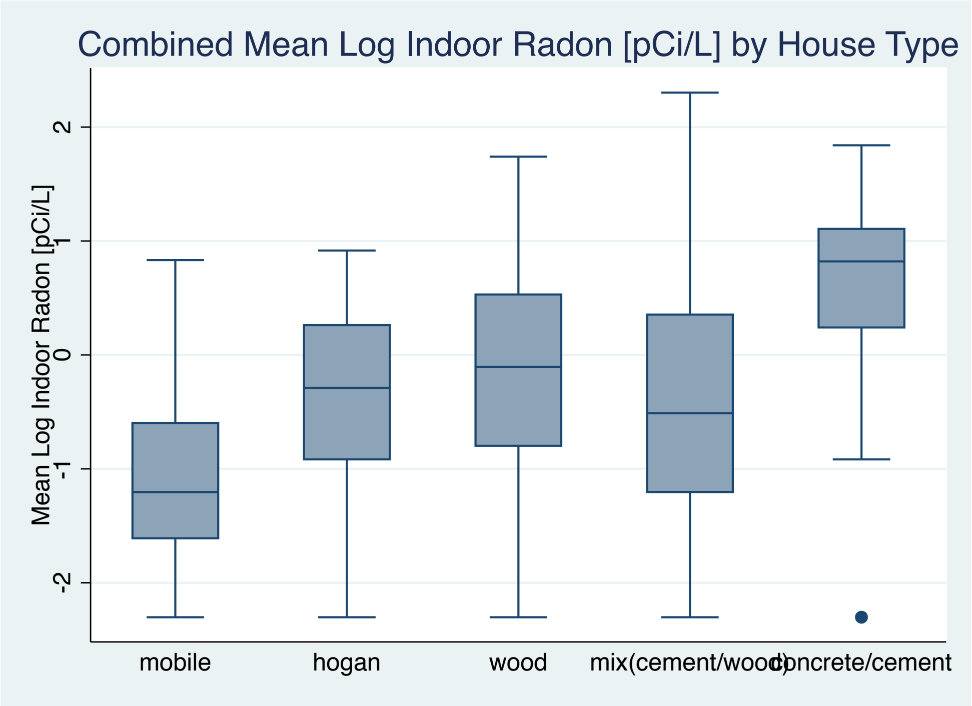


Figure 9: Box Plot Comparisons of Mean Home Log Indoor Radon [pCi/L] by House Type in the Combined Dataset

3.5.3 Temperature

In Figure 10 below, the association between the log mean home indoor radon concentration and temperature (°F) during radon testing for the combined dataset is plotted. The red squares highlight the CUJETH home radon sample measurements while the blue squares highlight the NBCS radon samples. The overall slope correlation for the combined dataset is -0.37 (S.E.=0.05). The CUEJTH samples were collected mainly during the winter months when it is colder. The scatter plot indicates the CUEJTH samples are consistent with the overall data. In Appendix F, scatter plots for the individual datasets are provided.

We conducted an additional analyses assessing the relationship between diffusion and temperature (Appendix J) since radon gas enters the home through diffusion. Diffusion is increases with temperature raised to the 1.5 power and changes inversely with pressure. Based on this relationship, we would expect diffusion to not increase linearly with increasing temperature or height.[83] In our scatter plot shown in Appendix J, we observed a linear relationship between diffusion and temperature (Kelvin) raised to the 1.5 power; therefore, we were able to use a linear model to approximate the effect of temperature.

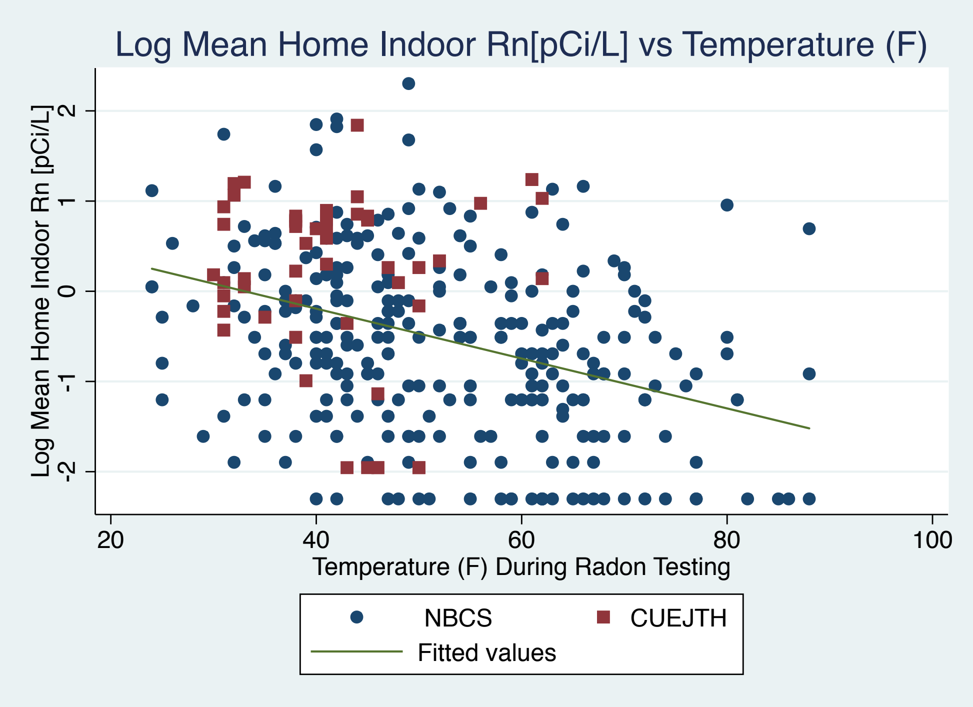


Figure 10: Mean Home Log Indoor Radon Concentration [pCi/L] versus Temperature (°F); Red Squares, CUEJTH homes; Blue Squares, NBCS homes

3.5.4 Elevation

In Figure 11, the association between the log mean home indoor radon concentration and elevation (Feet) for the combined dataset is provided. The red squares highlight the CUJETH home radon sample measurements and the blue squares highlight the NBCS radon samples. By dataset, the CUEJTH mean log indoor radon concentration measurements are observed to be in the higher levels. This is consistent with the overall data since the CUEJTH samples were mainly collected during the winter months when it is colder. The overall slope correlation for the combined dataset is .06 (S.E.=0.06). Scatter plots for the individual datasets are provided in Appendix G.

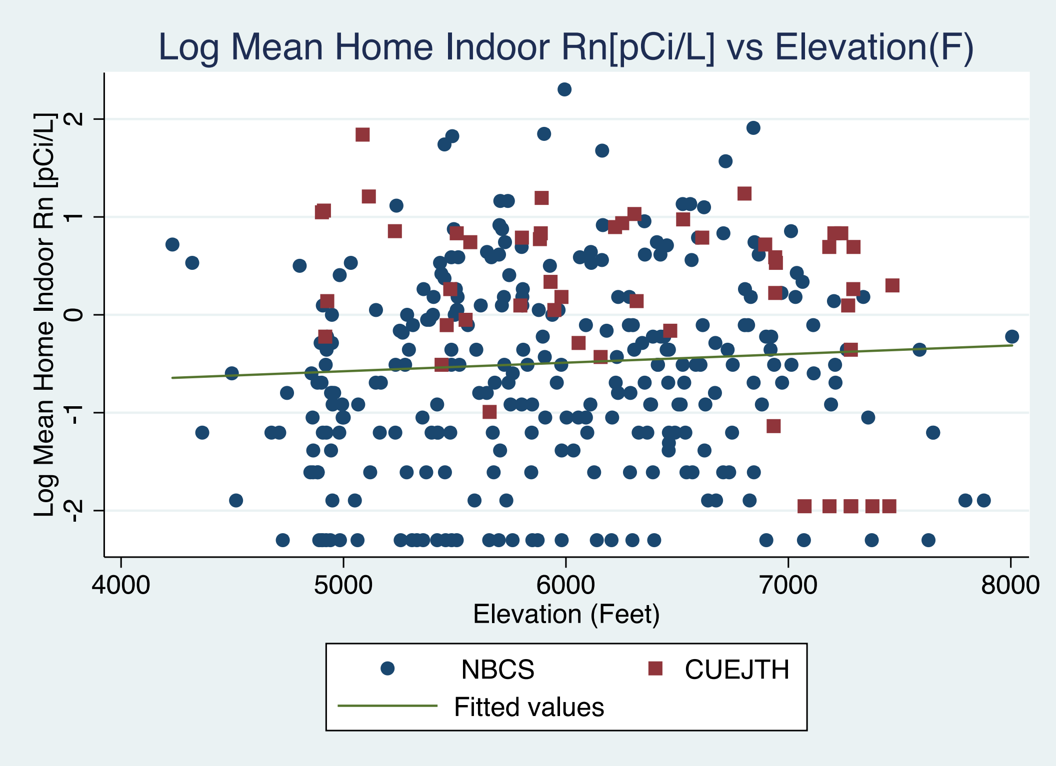


Figure 11: Mean Home Log Indoor Radon Concentration [pCi/L] versus Elevation (Feet); Red Squares, CUEJTH homes; Blue Squares, NBCS homes

In an additional analysis, the LOD values were excluded from the CUEJTH dataset to assess the overall effect on the slope between log mean indoor radon concentration (pCi/L) and elevation in the CUEJTH dataset as well as the combined dataset. The effect of this analysis on the slope in the CUEJTH dataset and the combined dataset is illustrated in appendix H and appendix I, respectively.

3.5.5 Model Selection of GIS Based Land Covariates

Terrestrial Gamma Radioactivity

In Appendix B, the performance of the GIS based land covariate terrestrial gamma radioactivity (38-3026 keV) "gross counts" is illustrated. In this table, we observe a range of homes that captured at least one gross count sample when various buffer distances were drawn around each home, from 13 homes at 0.5 km up to a maximum of 243 homes. We also observed a larger number of gross count samples that were captured when larger diameter buffer distances were drawn around each home. The performance of the GIS based land covariate for terrestrial gamma radioactivity when included in the land use regression model reached a level of significance when captured within a 3 km of a home and remained significant up to 30 km. In addition, the overall land use regression model reached a maximum adjusted-R^2 of 19.55 at a range of 5 km; at this buffer distance only 43 homes out of the 330 homes captured at least one gamma terrestrial radioactivity sample count. The level of significance for terrestrial gamma radioactivity over varying buffer distances is also illustrated in Appendix C.

Percent Uranium Oxide, %U^3O^8

In Appendix D, the performance of the GIS based land covariate for the quality of uranium ore at abandoned uranium mines, measured as percent uranium oxide (%U_3O_8) is illustrated. In this table, we observe a range of homes that captured at least one sample of percent uranium oxide as measured near an abandoned uranium mine when various buffer distances were drawn around each home, from 3 homes at 0.5 km up to a maximum of 238 homes. We also observed a larger number of %U_3O_8 samples that were captured when larger diameter buffer distances were drawn around each home. In this data, we observed multiple measurements captured around each home at larger buffer diameters. This reflects that some homes were proximal to more than one abandoned uranium mine, and therefore captured multiple measurements within that buffer zone. To address these multiple measurements, an average of all $\%U_3O_8$ measurements captured around each home was averaged to avoid multiple samples.

The performance of the GIS based land covariate for $\%U_3O_8$ when included in the land use regression model reached a level of significance when captured within a 4 km of a home and was no longer significant between buffer distances ranging from 5km to 15 km. After 15km, the $\%U_3O_8$ remained significant up to 30 km. The overall land use regression model performance remained relatively stable when evaluated by the adjusted-R^2. The level of significance for $\%U_3O_8$ over varying buffer distances is also illustrated in Appendix E.

Uranium Measurements Collected from Water

The water sample measurements provided no scientifically meaningful data to report. The scatter plots explored between the water samples and the log mean indoor radon concentration did not follow any particular trend. The land use regression models for the water sample measurements were also not significant.

Sediment Soil Uranium Concentration (ppm)

In Table 13 below, the performance of the GIS based land covariate for the average sediment soil uranium concentration as measured in parts per million (ppm) is illustrated. In this table, we illustrate the number of sediment soil uranium samples captured when various buffer distances are drawn around each home, and report the performance of the overall land use regression model by listing the adjusted-R^2 at each buffer distance. We observe a large proportion of homes that captured at least one sample of sediment soil uranium concentration when various buffer distances were drawn around each home, from 26 homes at 0.5 km up to a maximum of 289 homes. We also observed a larger number of sediment soil uranium concentration samples that were captured when larger diameter buffer distances were drawn around each home. In this data, we observed multiple measurements captured around each home at larger buffer diameters. To address these multiple measurements of sediment soil samples, an average of all sediment soil uranium (ppm) measurements captured around each home within each respective buffer was used to generate one sediment soil uranium measurement for each home in the modeling to avoid multiple samples.

Table 13: Number of Sediment Soil Uranium Concentration (ppm) Samples Captured within Various Buffer Distances Around Each Home

Buffer Distance (km)	Samples	No. of Homes	p-value	Adj-R2
0.5	29	26	0.790	0.0365
1	101	71	0.305	0.1714
1.5	231	135	0.668	0.2636
2	433	180	0.133	0.2479
3	915	242	0.098	0.2125
4	2086	251	0.090	0.2262
5	3191	253	0.101	0.2235
7.5	7195	257	0.000	0.1981
10	13154	263	0.000	0.2031
12.5	20476	265	0.000	0.2153
15	28681	271	0.000	0.2212
17.5	38123	275	0.000	0.2198
20	48476	281	0.000	0.2242
22.5	60235	286	0.000	0.2249
25	7339	289	0.000	0.227
27.5	88657	289	0.000	0.2292
30	104512	289	0.000	0.2303

Model: y= log mean indoor radon concentration (pCi/L)
Predictors: House Type; Temperature (ºF); Elevation (Feet), Sediment Soil Uranium (ppm)

The performance of the GIS based land covariate for sediment soil uranium concentration (ppm) when included in the land use regression model reached a level of significance when captured within a 7.5km of a home and remained significant at buffer distances up to 30km (Figure 12 below). The overall land use regression model performance remained relatively stable when evaluated by the adjusted-R^2.

The level of significance for sediment soil uranium concentration over varying buffer distances is illustrated in Figure 12. The p-value is the observed performance of the sediment soil uranium concentration (ppm) as a predictor of mean indoor radon concentration at each buffer distance.

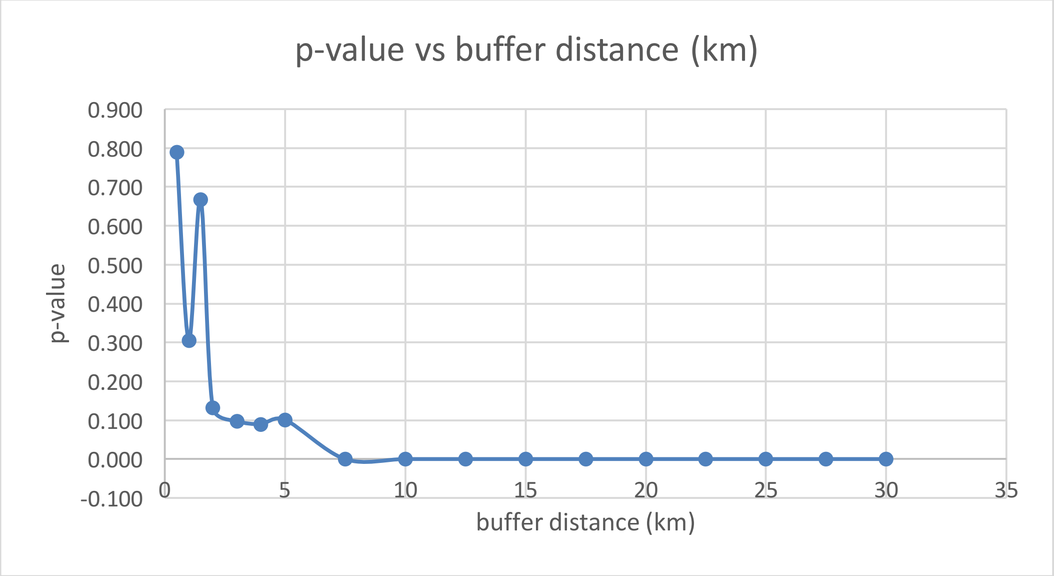


Figure 12: Estimated P-Value Performance of Sediment Soil Uranium (ppm) at Buffers Distances Around Each Home

3.5.6 Land Use Regression Model

A total of 289 mean log indoor radon concentrations were used in the LUR model as shown in Table 14 below. By home type, there were 59 mobile homes, 22 hogans, 101 homes constructed primarily of wood, 95 homes constructed of both cement and wood, and 12 homes constructed primarily of concrete and cement. The average outdoor air temperature (°F) during the week of testing was negatively associated with mean log indoor radon concentration as illustrated in Figure 10 ($p<0.001$), while elevation (feet) was not significant as shown in Figure 11.

House type was coded as an ordinal variable, 1-5, and the LUR results illustrated a near-linear pattern. Based on this observation, a scatter plot was made between log mean home indoor radon concentration [pCi/L] versus average sediment soil uranium concentrate made to include an interaction term between average sediment soil uranium concentration (ppm) and house type. Including the interaction terms also provided an improvement in the adjusted-R^2.

Table 14: Performance of Predictor Variables in the Land Use Regression Model (R^2=0.336)

Predictor Variables in the Baseline LUR Model	N	Coef.	SE	p
Home type (categorical)	289			
Mobile (Reference)	59	-	-	-
Hogan	22	-.22	.70	.75
Wood	101	.28	.54	.60
Mix (cement/wood)	95	-.15	.51	.77
Mix (concrete/cement)	12	.05	.49	.92
Mean Temperature (°F)		-0.03	.004	<0.001
Elevation (Feet)		-.0001	.0001	0.188
Average Sediment Soil Uranium (ppm)*		.022	.15	0.88
Mix (cement/concrete)*Average Sediment Soil Uranium (ppm)	(12)	0.54	0.21	0.012
Mix (cement/wood)*Average Sediment Soil Uranium (ppm)	(95)	0.36	0.18	0.051
Hogan*Average Sediment Soil Uranium (ppm)	(22)	0.36	0.26	0.167
Wood*Average Sediment Soil Uranium (ppm)	(101)	0.17	0.19	0.378

*Average of sediment soil samples within a 25km buffer zone around home

The p-values in Table 14 reflect the magnitude of the coefficient and the standard error reflects the uncertainty in the coefficient. The coefficients reflect a modest slope and their respective standard errors reflect the variability of the radon levels within each home. The variability is also related to the number of homes within each home category and the within group variability within each home category. The interaction terms between home type and average sediment soil uranium concentration (ppm) indicates the influence on the mean indoor log radon concentration (pCi/L) that changes depending on the house type. In Table 14, the interaction between average sediment soil uranium concentration (ppm) and concrete homes on indoor radon concentration (pCi/L) was significant ($p<0.05$). The influence of house type and average sediment soil uranium concentration (ppm) on indoor radon concentration (pCi/L) is plotted in Figure 13. The slope directions in Table 14 with respect to mean temperature during radon testing (°F) is negative. The slope directions for each interaction term for soil sediment concentration with house type were positive.

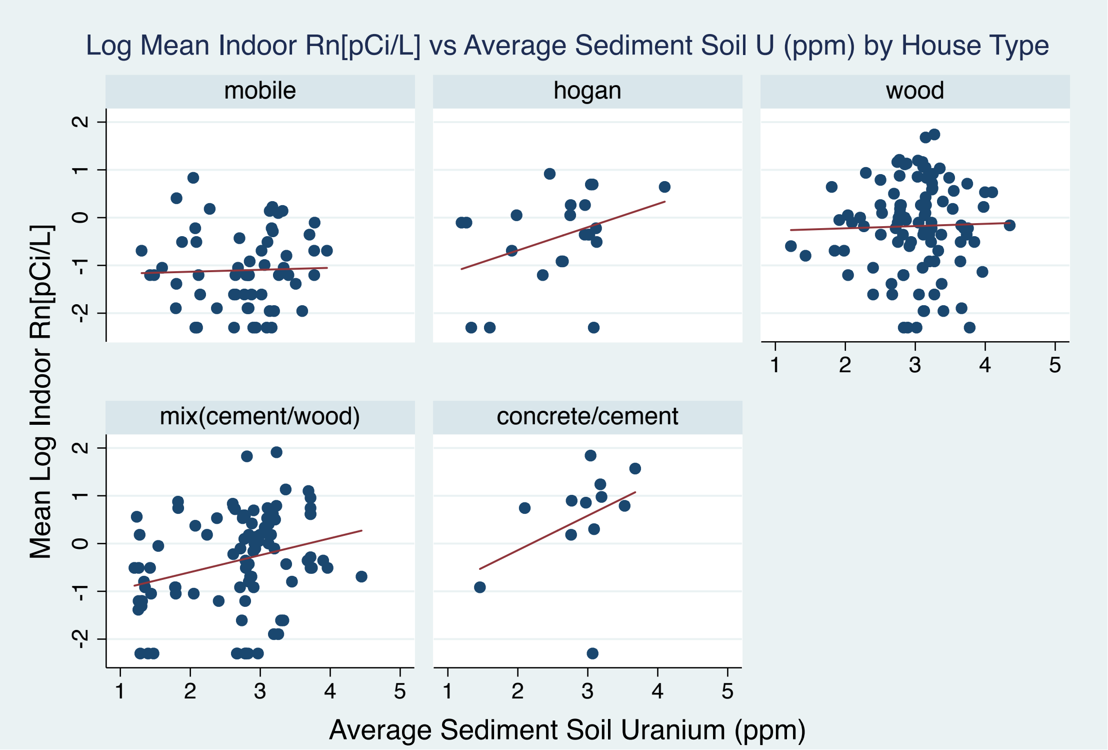
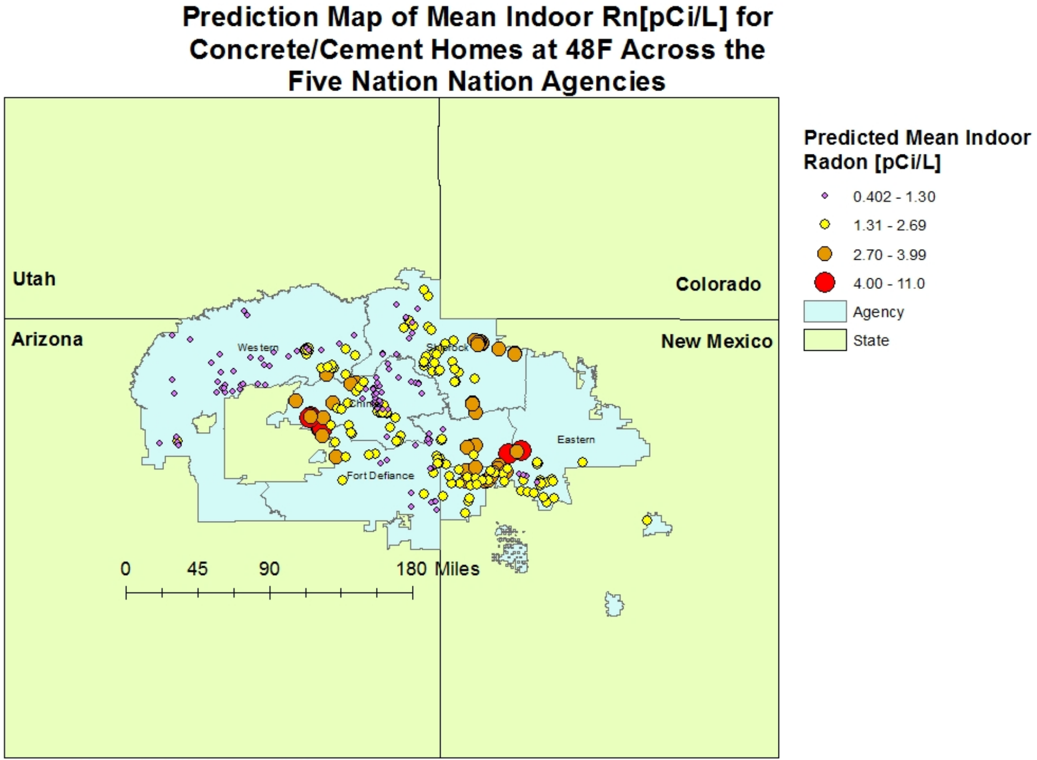


Figure 13: Mean Log Indoor Radon Concentration (pCi/L) vs Average Sediment Soil Uranium Concentration (ppm) by House Type

3.5.7 Model Prediction Map of Mean Indoor Rn[pCi/L] for Concrete/Cement Homes



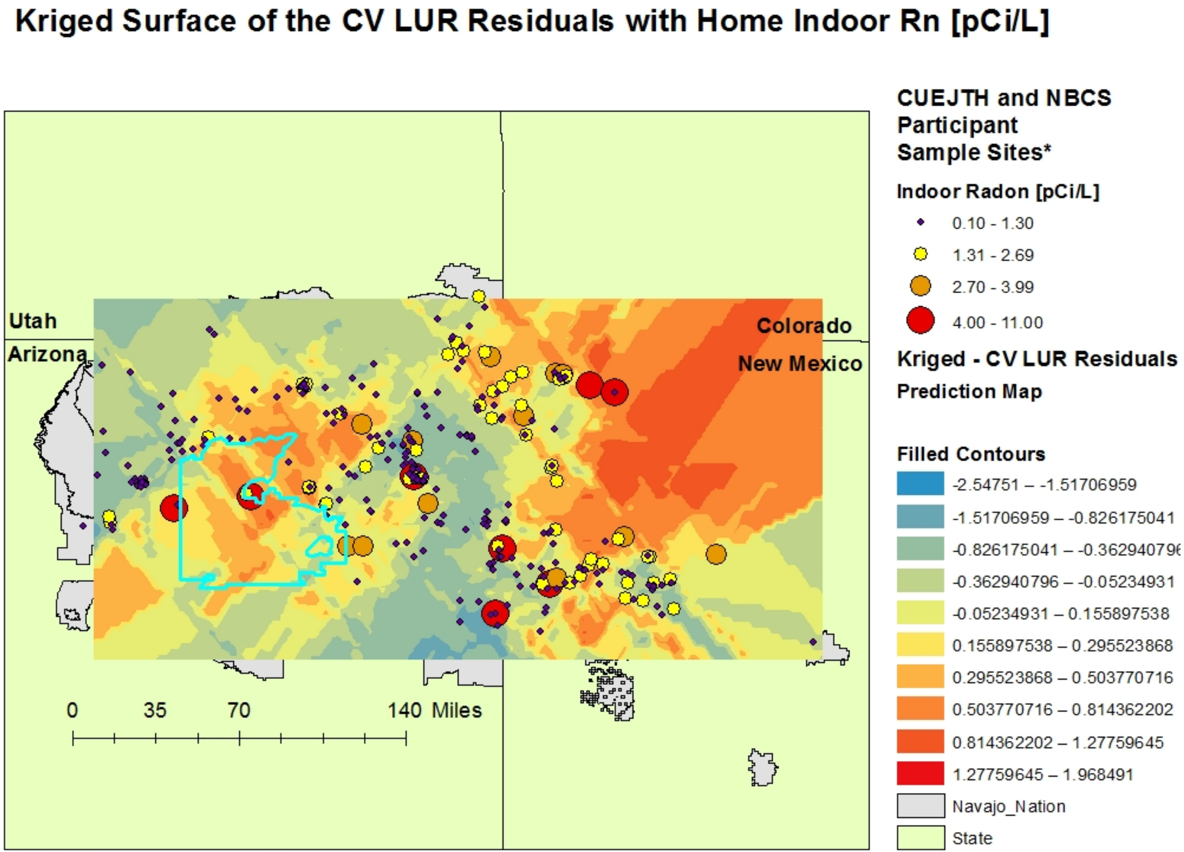
Temporal Range: April 2013 - June 2015
Production Date: October 22, 2016
Datum: NAD83
Projection: North American Albers Equal Area Conic

Figure 14: Model Prediction Map Illustrating the Mean Indoor Radon Concentration [pCi/L] for Concrete/Cement Homes at 48°F Across the Five Navajo Nation Agencies

Figure 14 above illustrates the spatial distribution of mean indoor radon concentration when holding the temperature constant at 48°F and house type constant as all concrete/cement homes. This figure illustrates there is clustering of concrete/cement homes with similar mean indoor radon concentrations [pCi/L] across the five agencies. In the Western Agency, the predicted mean indoor radon concentration [pCi/L] are predicted to be less than 1.3 pCi/L. In comparison, there are clusters of homes that fall with the mean indoor radon concentration [pCi/L] range between 1.31 pCi/L and 2.69 pCi/L in the Shiprock, Chinle, and Eastern Agencies. There are also clusters of concrete/cement homes with predicted mean indoor radon concentration levels that lie above 2.70 pCi/L in the western part of the Chinle Agency, eastern part of the Shiprock Agency, eastern region of the Fort Defiance Agency, and the western portion of the Eastern Agency.

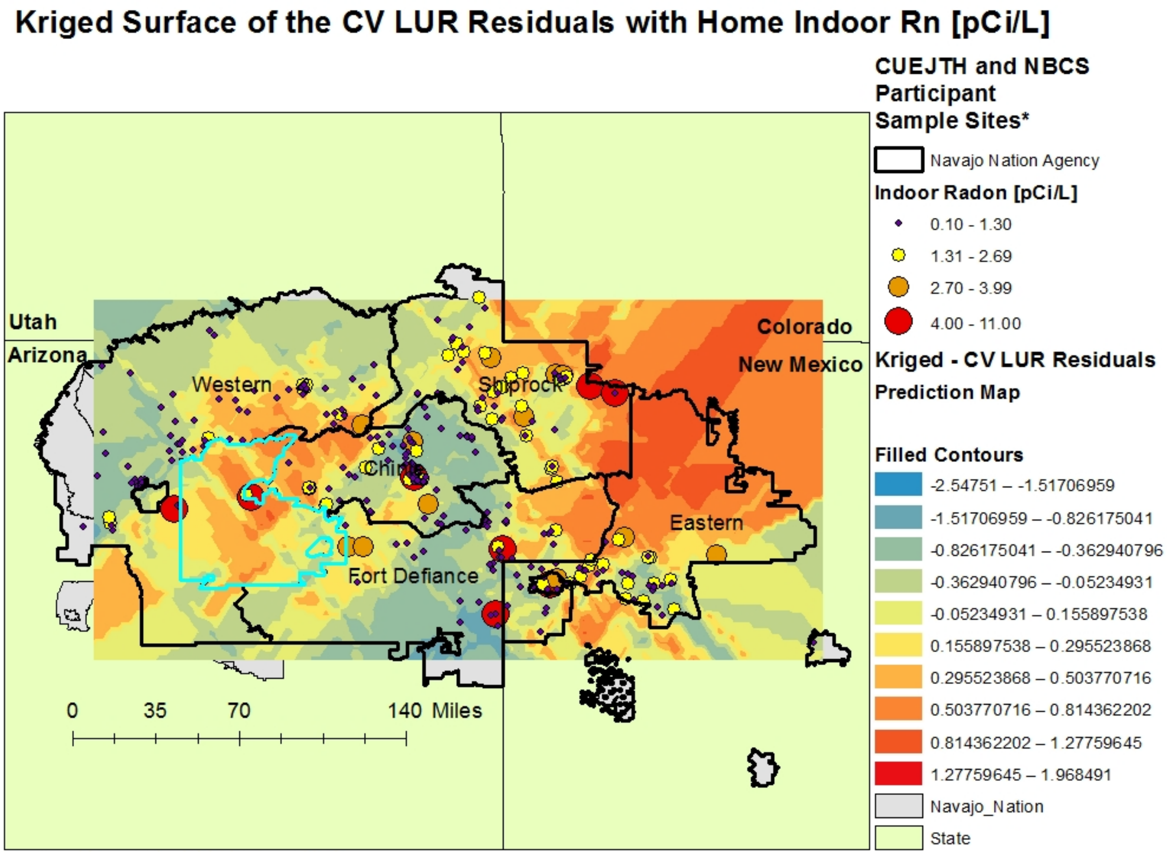
3.5.8 Semivariogram of the Cross Validated LUR Residuals

The semivariogram of the cross validated LUR residuals shown in Figures 15, 16, and 17 demonstrate spatial correlation. In Figure 15, the Kriged surface of the cross validated residuals illustrate a spatial pattern over the various geographic regions on the Navajo Nation. This spatial pattern is also highlighted in Figure 16 in which the Kriged surface is outlined by the five Nation Nation Agencies: Shiprock/Northern, Crownpoint/Eastern, Fort Defiance, Western, and Chinle.



Temporal Range: April 2013 - June 2015
Production Date: April 19, 2017
Datum: NAD83
Projection: North American Albers Equal Area Conic
*Home location sites dithered

Figure 15: Kriged Surface of CV LUR Residuals Using Ordinary Kriging in ArcMap



Temporal Range: April 2013 - June 2015
Production Date: October 3, 2016
Datum: NAD83
Projection: North American Albers Equal Area Conic
*Home location sites dithered

Figure 16: Kriged Surface of CV LUR Residuals Using Ordinary Kriging Overlaying the Five Navajo Nation Agencies

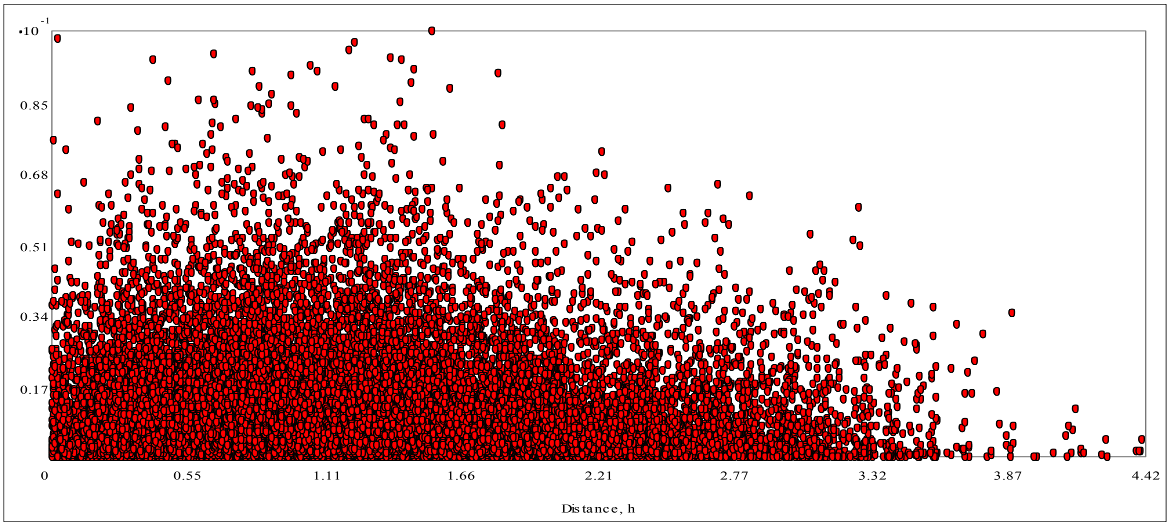


Figure 17: Semivariogram of Cross Validated LUR Residuals

Table 15 also lists the number of homes captured within each of the five agencies. The arithmetic mean and standard deviations are also provided for each agency and also plotted in box graphs for comparison in Figure 18. The cross validated LUR residual estimates were also plotted in a Q norm plot in Figure 19.

Table 15: Cross Validated LUR Residuals Estimates Extracted via Ordinary Kriging by Agency

Agency	N	AM	ASD	Min	Max
	330	-0.063	0.373	-1.112	0.976
Shiprock/Northern	50	0.208	0.220	-0.290	0.583
Crownpoint/Eastern	60	0.024	0.415	-1.044	0.976
Chinle/Central	105	-0.083	0.352	-0.897	0.643
Western	86	-0.211	0.371	-0.725	0.566
Fort Defiance	29	-0.199	0.275	-1.112	0.317

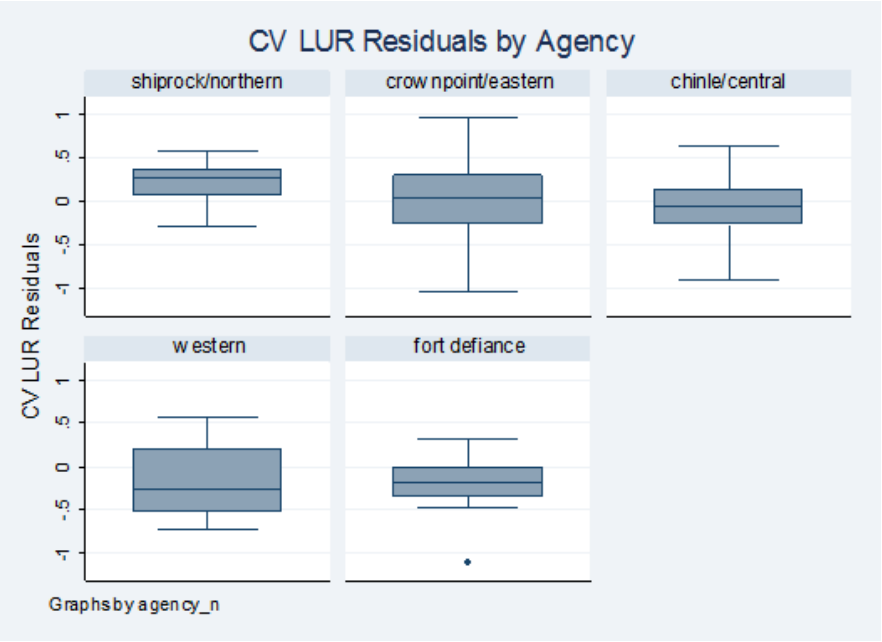


Figure 18: Cross Validated LUR Residuals Estimates Extracted via Ordinary Kriging by Agency

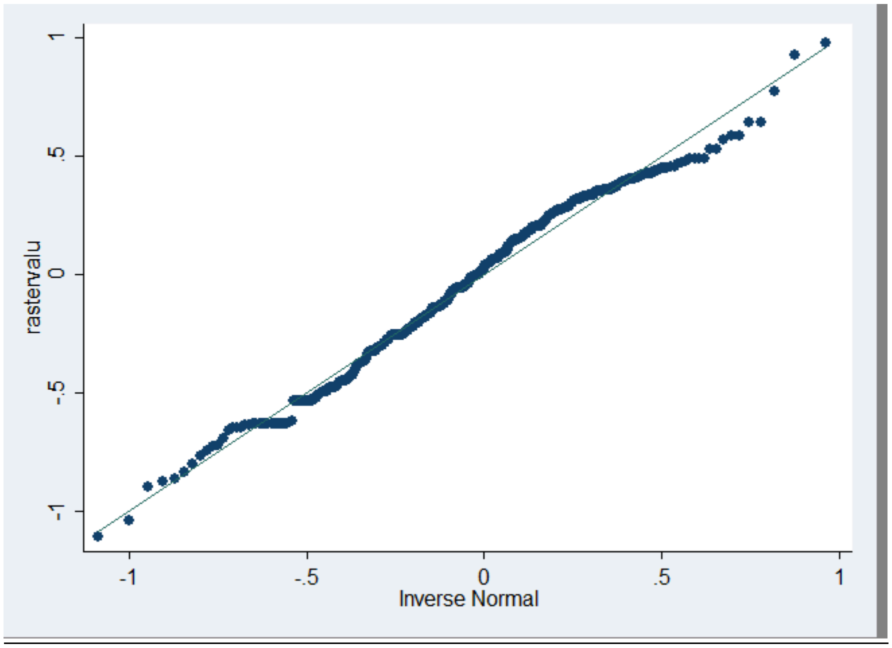


Figure 19: Q Norm Plot of Cross Validated LUR Residuals Estimates Extracted via Ordinary Kriging

3.5.9 Exponential Model of Semivariogram

We observe in Figure 20 using an exponential model that the curve pattern of the semivariogram illustrates a spatial pattern. At smaller distances between points, the semivariance between points is smaller which is indicated by smaller values on the y-axis and therefore more similar. In contrast, at farther distances the semivariance between two points increases indicating points farther away are not as similar which is indicated by larger semivariance values on the y-axis. The parameter estimates for the semivariogram using an exponential model are listed in Table 16. The range in kilometers is 0.003, the partial sill is 0.82, and the nugget is 0.19.

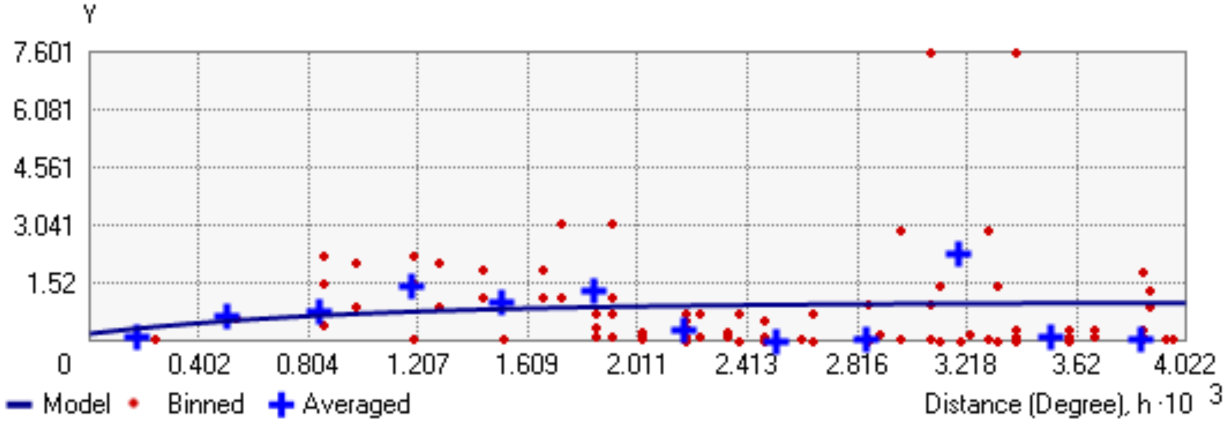


Figure 20: Semivariogram Model using an Exponential Model

Table 16: Parameters for Semivariogram Using an Exponential Model of Log Indoor Radon (pCi/L)

Parameters	
Range in kilometers	0.002921669
Partial Sill	0.8216544
Nugget	0.19099396

Ascertained from ArcMap

3.5.10 Performance Evaluation of Prediction Model

The prediction of indoor radon concentration (pCi/L) was evaluated by comparing the CV-R^2 calculated using the cross-validated predicted estimates to the in-sample predictions from the LUR model (Table 17). The CV-R^2 and RMSE calculated using the two-step approach compared to the in-sample R^2 and RMSE were, 0.49 (0.73) and 0.28 (0.86), respectively. The scatterplot in Figure 21 shows a positive correlation between the cross-validated predicted estimates using the two-step approach versus the observed mean log indoor radon concentrations with a CV-R^2=0.49.

Table17: Measures of Model Performance using CV-R^2 and RMSE

	CV-R^2	RMSE
Land Use Regression Model	0.284	0.861
2-Step Approach	0.487	0.729

*289 homes

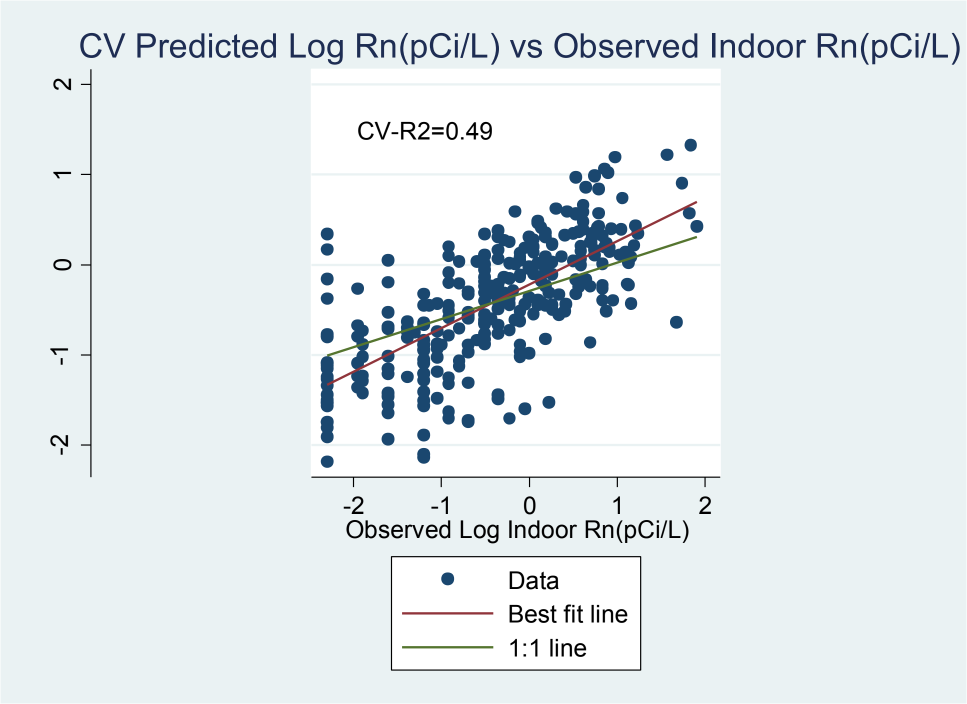


Figure 21: Scatterplot of Predicted Log Indoor Rn (CV Predicted LUR + CV Predicted Residuals as Estimated from ArcMap Using Ordinary Krging) vs Observed Log Indoor Rn (pCi/L)

3.6 DISCUSSION

The modeling approach used in this study to predict indoor radon concentration levels in homes across the Navajo Nation appears to be effective. The combination of covariates included in the two-step approach using the land use regression model and ordinary kriged estimates were effective at capturing variability based on the cross-validated R^2 estimates.

Combining the two individual indoor radon datasets for our analysis was justified in our observations. Combining the NBCS indoor radon data with the CUEJTH indoor radon dataset increased the overall sample size to 330. In our data collection with participants from the CUEJTH program, we were only permitted to obtain indoor radon measurements in three of the five Navajo Nation agencies; whereas, the NBCS collected indoor radon measurements across all five Navajo Nation agencies. Therefore, our combined dataset has measurements across the five geographic regions.

The findings in the combined datasets provide evidence that the type of home and where a home is located affect indoor radon concentration levels. House type was categorized based on common structural characteristics observed at each home assessment. Log mean indoor radon concentrations observed within each house type align with common expectations. For example, mobile homes generally are set on foundation blocks above the ground creating an air space between the soil and bottom floor of a home. Therefore, mobile homes usually have lower indoor radon levels because any radon emanating from the soil beneath the home would most likely escape to the outside air through crawl spaces. In addition, traditional Navajo homes, hogans, are built with logs or mud and hard packed soil forms the floors.[69] Traditionally, hogans lacked windows with only a center opening in the ceiling, fit for a wood heating or cooking stove pipe. Hogans also constructed in geographic regions with elevated levels of natural sediment soil uranium concentrations would potentially have higher indoor radon concentration levels. Based on this common structural make-up of a hogan, it is reasonable to expect such homes to have higher indoor radon concentration levels that rest directly on the soil surfaces compared to mobile homes as observed in the combined datasets. Homes constructed primarily of wood materials also were observed to have higher mean log indoor radon concentrations compared to mobile homes and hogans. Homes constructed of wood materials generally are more tightly sealed because of better insulation, caulking, and tighter sheathing materials compared to those used in mobile homes and hogans; and wood is often laminated providing more tightly sealed home environments.[84] Therefore, higher indoor radon levels in wooden homes as observed in the combined datasets seems reasonable. Another category of homes in the combined datasets were homes with mixed construction of either wood and concrete, or with concrete and cement. In general, homes constructed with concrete are more durable, often were more tightly sealed and provided efficient insulation; and when used in combination with cement provides a durable and insulated indoor environment.[85] As a note, some building materials also contain low amounts of radioactive materials, such as concrete, brick, or granite. These materials contain trace amounts of naturally occurring elements like uranium which could decay into radon gas and contribute to indoor radon levels.[86] In the combined datasets, homes constructed primarily of concrete and cement had the highest indoor radon concentration levels compared to the other home types.

By house type, the log mean indoor radon concentration levels by house type might appear different, but are actually quite similar. However, a direct comparison cannot be made without some temperature or seasonal adjustment. In Table 11, the GM for the NBCS indoor radon concentration levels [pCi/L] are lower compared to the CUEJTH indoor radon levels. This is most likely because the NBCS indoor radon measurements were collected all year long and also cover a wider geographic range, i.e., across all five Navajo Nation agencies. In comparison, the CUEJTH home indoor radon concentration levels [pCi/L], particularly with reference to the arithmetic mean are higher, an observation most likely related to the collection of these samples primarily during the winter months. A fair comparison of the mean indoor radon concentration levels between the two datasets would require adjusting for temperature and elevation, or possibly restricting the temperature range in the NBCS dataset to the same temperature range as in the CUEJTH dataset.

The relationship between log mean indoor radon concentration (pCi/L) and temperature (ºF) during radon testing was stronger in chapter three compared to the weaker association observed in chapter two. In both datasets, we observed a negative association between log mean indoor radon concentration (pCi/L) and temperature during radon testing. In chapter two with the CUEJTH dataset, we observed higher indoor radon concentration (pCi/L) levels compared to the NBCS dataset. However, the weaker negative association observed in chapter 2 is most likely due to two factors. One is the smaller sample size of 51 homes as measured from the CUEJTH participants compared to the larger sample size in chapter 3 as a result of the additional 279 home indoor radon measurements from the Navajo Birth Cohort participant homes. Second, there is a restriction of temperature range in which indoor radon samples were measured in CUEJTH participant homes, which were measured mainly during the winter months (November through early May). In comparison, indoor radon measurements from NBCS study participant homes were collected year-round, which provided a much larger range in temperature range. As a result, the negative association between log mean home indoor radon [pCi/L] in the CUEJTH homes is not as strong as the negative association observed in the NBCS participant homes. By combining the dataset, we observe that the indoor radon concentration levels [pCi/L] follow the same negative linear direction when compared to temperature (°F).

As an additional analysis, we plotted the relationship between diffusion and temperature. We did this to examine the relationship between diffusion and temperature as diffusion increases with temperature raised to the 1.5 power.[83] Diffusion also changes inversely with pressure; and pressure decreases with elevation in atmospheres and altitude in feet. As we observed in the scatter plot provided in Appendix J, as expected we observed there is an approximately linear increase in diffusion with increasing temperature over a range of temperature in our study. Although the underlying relationship between temperature and diffusion was non-linear over our limited range of temperature changes, it appears that a linear relationship provides an appropriate model.

Regarding elevation, we observed the overall expected relationship in the combined dataset with a slightly positive slope. Temperature levels at higher elevation levels are generally colder and therefore we would expect high indoor radon concentration levels. In the CUEJTH dataset, we observed a slope trend in the opposite direction compared to the overall dataset as illustrated in Appendix G. This is most likely due to the LOD values in the CUEJTH dataset observed at higher elevations that are affecting the direction of slope, and this effect is apparent in the smaller CUEJTH dataset. We excluded the LOD values in the CUEJTH dataset to observe the overall effect of the slope trend in both the CUEJTH dataset and in the combined dataset, Appendix H and I, respectively. In the CUEJTH dataset after removing the LOD values, we observe a less negative association between elevation and log mean indoor radon concentration (pCi/L) levels. Overall, we observed a more positive slope trend in the combined dataset when comparing log mean indoor radon concentration (pCi/L) levels and elevation (feet).

In the exploratory selection of GIS based land covariates, terrestrial gamma radioactivity was explored but not selected in the final model. This covariate was explored because the data represented radiological survey measurements near potential uranium mines. Using gamma radiological survey measurements is not a novel tool, but has been used by the NURE program when exploring for geographic regions for natural uranium resources. In New Jersey, a study was done to examine the correlation between gamma radioaeriological surveys with indoor radon levels. Investigators used previously collected gamma measurements from the NURE program in New Jersey for efficiency. They found a correlation between indoor radon levels and gamma measurements within half-mile of homes.[87] However, based on our exploratory analysis, this covariate was not considered because only 243 homes out of our 330 homes captured at least one sample radiologic survey reading when a 30 km buffer diameter was drawn around the home. Selecting this covariate would have excluded over ¼ of homes in our final land use regression model.

The second GIS based land covariate explored but not used was the percent uranium oxide (%U_3O_8) that was measured at abandoned uranium mines on the Navajo Nation. These measurements were taken from abandoned uranium mines on or within one mile of the Navajo Nation. Also provided in this dataset was the amount of uranium in pounds that was mined. We explored the %U_3O_8 because this could be correlated with the quality of uranium ore at the abandoned uranium mine. The covariate showed some promising results when explored in the land use regression models within each buffer zone. However, when included with other covariates, this covariate did not remain significant and therefore was an unreliable predictor that was likely collinear with other variables. Further, at the largest buffer distance around a home of 30km, only 238 of our homes had a $\%U_3O_8$ measurement. The percent of uranium oxide taken from these points at abandoned uranium mines may not truly reflect the actual amount of natural uranium near homes. This may be one reason why this covariate did not remain a significant predictor.

The third GIS based land covariate we explored but did not include in our model was uranium measurements collected from water samples. It is well established that radon gas dissolves in ground water and when stored in homes, as is the custom on the Navajo Nation in homes not connected to public water supplies, are potential sources of indoor radon exposure. The use of the stored water through agitations, such as bathing or washing, can release radon gas into the air becoming a potential source of airborne exposure. Our evaluation of the uranium as measured in water samples produced no scientifically meaningful associations. This may reflect the fact that the GIS water radon values we obtained were not matched to households, and may reflect wells that are not used for home water supplies. Thus we expect that the GIS data are highly misclassified as a predictor of indoor radon levels. The scatter plots did not show any particular trend or associations nor did the prediction levels of this covariate produce any levels of significance.

In this study, the average sediment soil uranium concentration (ppm) was an important predictor of indoor radon concentration levels which we included in our final land use regression model. This GIS based land covariate provided a sample sediment soil uranium concentration (ppm) for 289 of the 330 homes in the combined dataset when a 25 km buffer diameter was drawn around each home.

Unfortunately, some homes were not adjacent to a sediment soil sample which was our justification for reducing the number of homes in our final land use regression model from 330 homes to 289 homes. We observed that reducing the number of homes to 289 did not affect the model performance. It was not surprising that this covariate was a significant predictor because a main source of indoor radon concentrations is from soil enriched with radium, a decay product of uranium.[4, 35] Soil enriched with uranium and thus radium would provide a source of radon gas that may enter the indoor air from cracks in the floor or walls. Further, soil characteristics such as a higher permeability and moderate moisture content both favor diffusion of radon from the soil into the air.[34]

In the final land use regression model, an interaction term was included between the type of home and average sediment soil uranium concentration (ppm). During our analysis, we plotted the log mean indoor radon concentration versus sediment soil uranium concentration (ppm) and observed that the slopes differed by house type. To include this effect in our model, we included an interaction term to capture the influence of both predictors on indoor radon concentration levels. This interaction between house type and average sediment soil uranium concentration (ppm) was significant in this study.

The semivariogram of the cross validated land use regression residuals and the map of the smooth Kriged surface of the cross validated land use regression residuals indicate a spatial pattern. We overlaid the Kriged surface area across the five Navajo Nation agencies and observed that each agency has a different spatial pattern. To gain insight into this, we calculated the arithmetic means of the cross validated land use regression residuals estimates that we extracted for each home. We compared the arithmetic means of the cross validated land use regression residual estimates by agency and conclude that our prediction model is performing better in some agencies compared to others. The cross validated residual estimates indicate there are regional differences across the five agencies that exist even after accounting for house type, temperature (ºF) during radon testing, elevation, and the sediment soil uranium concentration (ppm) the house sits above in the land use regression model. This regional difference in residuals suggests that potentially, other geographic predictor variables may be found that explain home radon levels.

The use of the two-step approach in improving the predictive power has been successfully used by other researchers investigating outdoor air pollution.[75] In this approach, the ordinary kriging function in the ArcGIS software was used to create a smooth surface of the LUR model cross validated residuals. This provided an opportunity to include the spatial correlation between the residuals in the prediction model. This two-step method markedly improved the CV-R^2 and RMSE compared to the LUR prediction model alone that did not account for the spatial correlation. Adding the spatial correlation of the LUR model cross validated residuals was important in predicting indoor radon concentration because this allowed spatial structure to be included in the model.

A few limitations may include the following characteristics. First, sediment soil uranium data on the Navajo Nation was limited in the western region. Given this limitation, some homes in this study were excluded because no sediment soil uranium samples were captured within a 25 kilometer buffer distance. Nonetheless, excluding these homes only reduced the sample size by 12%. Thus, a majority of the homes in this dataset were used in the prediction model. Second, other related predictor variables related to potential indoor radon concentration levels were considered but not included due to a lack of data for all homes. For example, the percent of uranium oxide in the form of uranium oxide (%U_3O_8) produced at Abandoned Uranium Mines on the Navajo Nation was explored. Total terrestrial gamma activity measured at the ground surface, which were calculated from aerial radiological surveys was also examined. Third, comparison to a Universal Kriging (UK) prediction model might be more advantageous. In UK, the geographic coordinates are simultaneously taken into account along with the covariates in the overall prediction model. In previous studies, the UK method has been suggested to perform slightly better than the two-step approach used in this study.

A few strengths in this study include the following. First, the combined dataset between the CUEJTH and NBCS provided a large dataset. This combined dataset provided coverage across all five agencies on the Navajo Nation. Therefore, this combined dataset could be considered generalizable to all areas on the Navajo Nation. Second, samples were collected using the same types of short-term indoor radon kits between the two studies. Also, samples were collected throughout the year taking into account seasonal variation. Third, basic home characteristics were collected during indoor radon assessments. By taking into account these characteristics, home type was included as an indicator variable which proved to be a critical predictor. Fourth, the coverage of sediment soil uranium samples was abundant for homes included in the prediction model. These sediment soil uranium samples, which are related to a main source of indoor radon concentration in homes, were included in the prediction model.

Our results could assist the Navajo Nation in prioritizing future studies including collecting additional indoor radon measurements. First, we observed that house type is a major predictor for indoor radon concentration (pCi/L) levels. We observed in both datasets that some types of homes have higher levels of indoor radon concentration, such as homes primarily made of either cement and wood or concrete and cement. Second, the performance of the interaction term in the land use regression model between house type and sediment soil uranium concentration (ppm) were significant for one particular house type and marginally significant for another house type, mixed concrete/cement and mixed cement/wood, respectively. Third, the cross validated residual estimates show that our prediction model over predicts in the Shiprock/Northern Agency, and under predicts in the Western and Fort Defiance Agencies, and performs reasonably well in the Crownpoint/Eastern and Chinle/Central Agencies. Using this information, the Navajo Nation Environmental Indoor Radon Program and the Navajo Nation Housing

Authority could aim at pushing for homeowners living in these two types of mixed homes to potentially test their home for indoor radon levels.

Our study was similar to the Swiss study conducted by Huari et al. in that it used a multivariable log-linear regression model to predict residential radon levels. In the Swiss study as in our study, house type was included as a predictor. However, no interaction term was included in the Swiss study. Another similarity between their study and our study is the use of soil data. The Swiss study used soil texture as a predictor because it affects gas and water permeability of soil; therefore, this would potentially affect the flow of radon gas from the soil into a home. In the Swiss study, the floor level of the radon measurements was included as a predictor. This relates to how radon levels are usually lower in upper levels of multi-story homes. However, on the Navajo Nation, multi story homes are very uncommon, and this was not a useful factor in the data. The model selection of the predictors were also chosen based on known published literature as well as the adjusted R^2 value, two criteria we also used in our exploratory analysis of our GIS based land covariates. Model evaluation in the Swiss study was done by comparing predicted indoor radon measurements with observed indoor radon measurements, as we did in our study. The Swiss investigators used box plots to compare their predicted and measured indoor radon concentration measurements and calculated a Spearman correlation coefficient to compare the predicted with measured indoor radon levels. They also used a sophisticated method of incorporating cross-validation with subsampling. In their cross validation, they used 80% of the data to develop the model and 20% to validate the model. This was largely due to the much larger number of homes in the Swiss study. In our cross validation method, we used 90% of data to develop the land use regression model and the remaining 10% to validate the model ten-fold. We then repeated this technique with the land use regression residuals.

Overall, the main results in this study coincide with previously reported studies and common knowledge. It is well known that the construction of a home is related to indoor radon concentration levels.[4, 32, 35, 73] Specifically, the ventilation system and building substructure that may affect air pressure differences that push air from the soil into a home. Also, The U.S. Environmental Protection Agency published a fact sheet titled "Radionuclides (including Radon, Radium and Uranium)" which states that residents who live near uranium mines may be exposed to elevated levels of radon gas compared to the general population.[5] In this study, proximity and uranium oxide concentrations in nearby mines were not important predictors of indoor radon levels. Further, the cross-validated R^2 in this study coincide with similar studies, such as those used in predicting outdoor air pollution. Moreover, results from this study could potentially be used in health studies to examine the association between residential radon concentrations and lung cancer mortality on the Navajo Nation which has been previously done by other researchers in the U.S. and Europe.[41]

3.7 CONCLUSIONS

One of the main take home messages from this study is that indoor radon concentration levels are related to house type and the location of the house. At each home location, we observed there were other geospatial factors to consider other than the soil uranium concentration. We were able to capture the microclimate around each home which included the temperature during radon testing and elevation of the home, both factors included in the model. The indoor radon database used in this study provided an opportunity to use house type as a predictor of indoor radon concentration and results agree with similar studies examining associations between house type and indoor radon concentrations. Second, a primary predictor of indoor radon concentration, soil sediment uranium samples, was included in this prediction model. Taking this one step further, the prediction model developed in this study incorporated an interaction term between house type and soil sediment uranium concentrations, reflecting differences in how soil uranium levels can contribute to radon movement and accumulation in indoor spaces.

Moreover, the model performance of the indoor radon prediction model agrees with other environmental studies that developed prediction models. These study findings could assist the Navajo Nation Environmental Radon Program in encouraging homeowners, who have not tested their homes for indoor radon gas and living in geographic regions predicted to potentially have higher radon gas levels, to test their homes. The geographical spatial pattern variations observed in the Kriged surface maps provide a foundation to continue indoor radon testing and to prioritize data collection in homes across all agencies.

3.8 ACKNOWLEDGEMENTS

Home indoor radon surveys collected by two community health programs on the Navajo Nation (NN) provided data for this project: The Community Uranium Exposure Journey To Healing Program and the Navajo Birth Cohort Study. This project received approval from two institutional review boards: the NN Human Research Review Board (#NNR 14.185) and the University of Washington (UW) Human Subjects Division (#47652-EJ). Content expertise and guidance was provided by faculty, co-investigators, peers, and community members encompassing, but not limited to the following. First, the student Dissertation Academic Committee Chair and student advisor, Professor Michael G. Yost who provided considerable enthusiasm and encouragement. Second, the University of New Mexico Community Environmental Health Program (UNM CHEP) in partnership with the Southwest Research and Information Center in Albuquerque, NM. A special thank you to Joseph Hoover, a postdoc geographer working with the UNM CHEP who provided guidance in geospatial methods. Funding support for this project was provided by: The Mayo Clinic Spirit of EAGLES Community Grant Award; the UW Biostatistics, Epidemiologic, and Bioinformatic Training in Environmental Health Training Grant; the UW Graduate Opportunities and Minority Achievement Program Dissertation Fellowship Award; and the Education and Research Center for Occupational Safety and Health Award at the UW. Also, special recognition to my family (Father-Ray and partner Jean; Sisters-Raina and family, Reiko, and Shihomi; Brother-Sterling; Aunts Elsie, Jayne, Ella and Cheryl; and Uncle Chuck), dear friends (Amin, Sara, Lynnette, Selina, Jack, and Mam), peers (Archana, Melody, and Ed), mentors (Amanda Fretts; Antonio J. Neri; Scott Davis; and Charles Wiggins), and mentor/colleague Kevin English for their abundant support. Finally, a dedication of this dissertation to Mom – Sue, who passed at an early age from breast cancer. Her motherly love and affection along with her strong wish for her children to learn and achieve without limits will forever be felt and shared.

3.9 APPENDIX

Appendix A: Illustration of Ten-Fold Cross-Validation

Dataset is split into 10 random equally size groups for ten iterations.

T=Training; V=Validation/Test

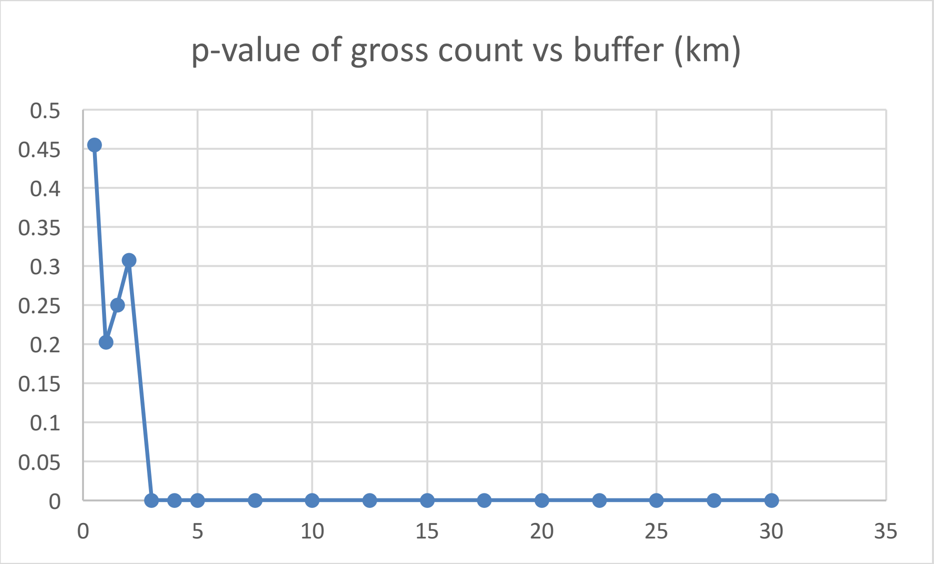
V	T	T	T	T	T	T	T	T	T
T	V	T	T	T	T	T	T	T	T
T	T	V	T	T	T	T	T	T	T
T	T	T	V	T	T	T	T	T	T
T	T	T	T	V	T	T	T	T	T
T	T	T	T	T	V	T	T	T	T
T	T	T	T	T	T	V	T	T	T
T	T	T	T	T	T	T	V	T	T
T	T	T	T	T	T	T	T		T
T	T	T	T	T	T	T	T	T	V

Appendix B: Overall Performance of Terrestrial Gamma Ray Counts (38-3036 keV) by Estimated p-Value and Adj-R^2

Buffer Size (Km)	Gross Count Samples	No. of Homes	p-value	Adj-R^2
0.5	124	13	0.455	0.1522
1	342	14	0.202	0.1484
1.5	623	19	0.250	0.1264
2	977	24	0.307	0.1453
3	2001	28	0.0001	0.1801
4	3326	32	0.0001	0.1941
5	5052	43	0.0001	0.1955
7.5	18987	108	0.0001	0.1265
10	47919	133	0.0001	0.1241
12.5	64194	168	0.0001	0.1207
15	86780	184	0.0001	0.1355
17.5	116570	195	0.0001	0.1258
20	145850	202	0.0001	0.1111
22.5	187727	214	0.0001	0.0807
25	244991	222	0.0001	0.0581
27.5	303751	236	0.0001	0.0526
30	377397	243	0.0001	0.0502

Model: y= log mean indoor radon concentration (pCi/L)
Predictors: House Type; Temperature (ºF); Elevation (Feet); and Terrestrial Gamma Radioactivity

Appendix C: Estimated P-Value Performance of Terrestrial Gamma R Radioactivity at Buffers Distances Around Each Home

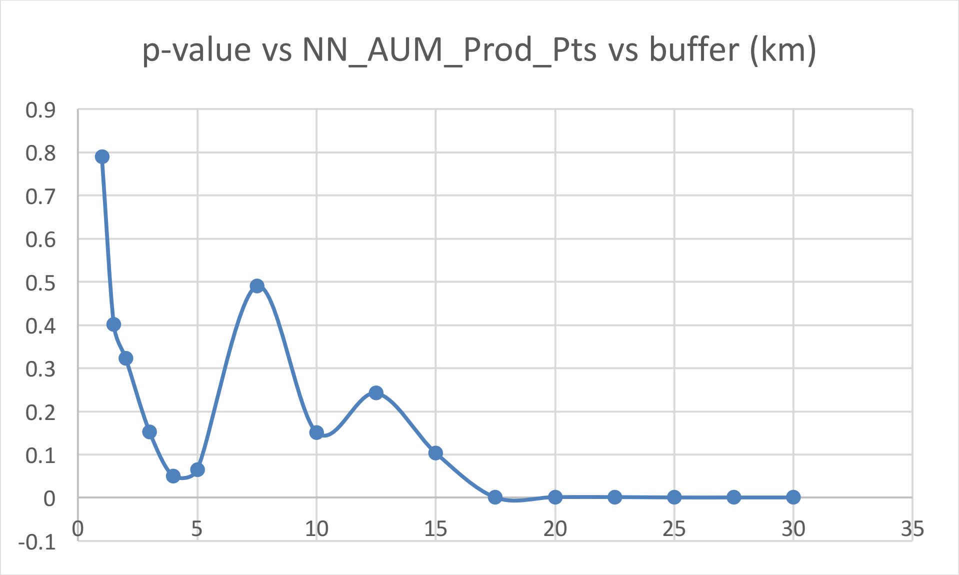


Appendix D: Overall Performance of Percent Uranium Oxide (%U_3O_8) by Estimated p-Value and Adj-R^2

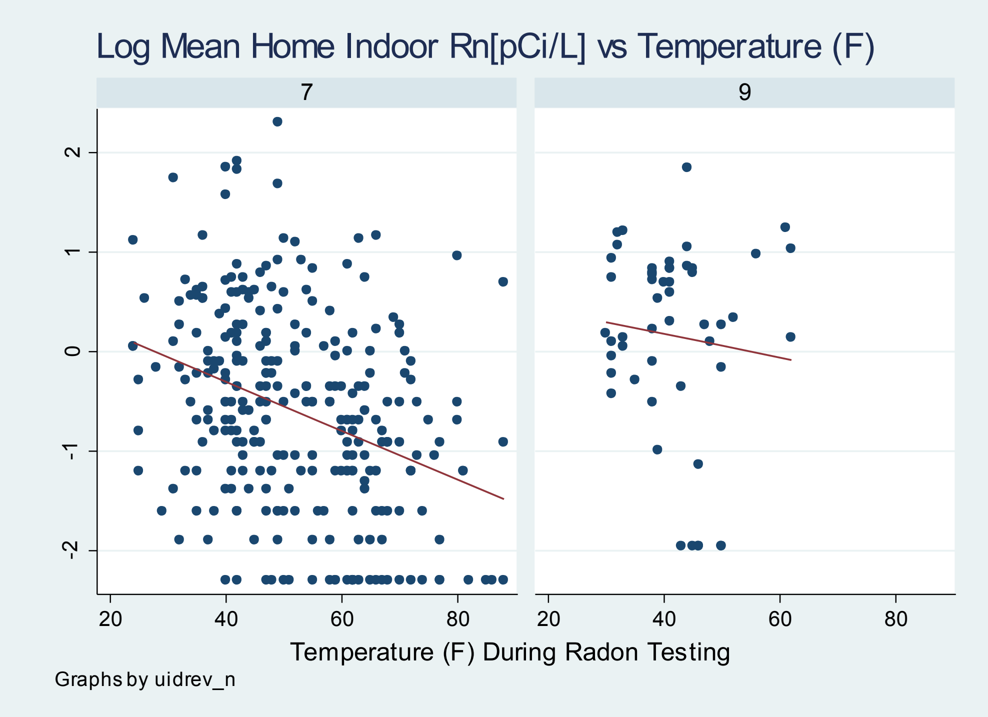
Buffer Size (km)	Samples	No. of Homes	p-value	Adj-R^2
0.5	4	3	NA	NA
1	9	6	0.789	0.3656
1.5	22	10	0.401	0.5476
2	33	11	0.323	0.6283
3	69	23	0.152	0.3149
4	132	36	0.049	0.341
5	201	45	0.065	0.0121
7.5	470	74	0.490	0.2351
10	746	85	0.151	0.2767
12.5	1227	95	0.242	0.3268
15	1788	121	0.103	0.3607
17.5	2425	155	0.0001	0.3556
20	3192	174	0.001	0.3857
22.5	4005	195	0.001	0.4011
25	4752	214	0.0001	0.4022
27.5	5725	225	0.0001	0.3920
30	6816	238	0.0001	0.3796

Model: y= log mean indoor radon concentration (pCi/L)
Predictors: House Type; Temperature (ºF); Elevation (Feet), U_3O_8lbs, and %U_3O_8

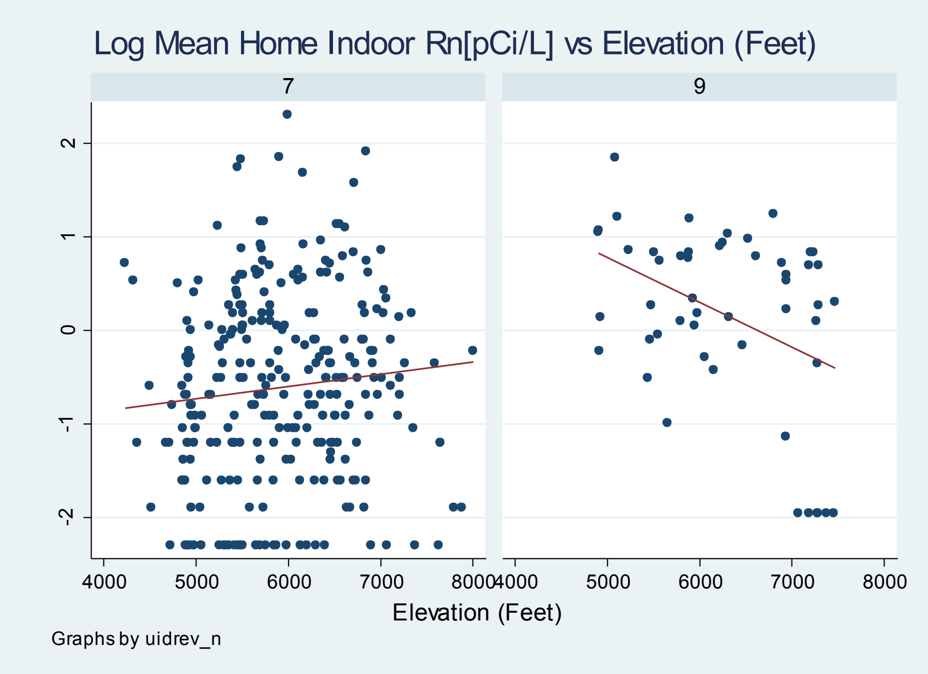
Appendix E: Estimated P-Value Performance of %U_3O_8 at Buffers Distances Around Each Home



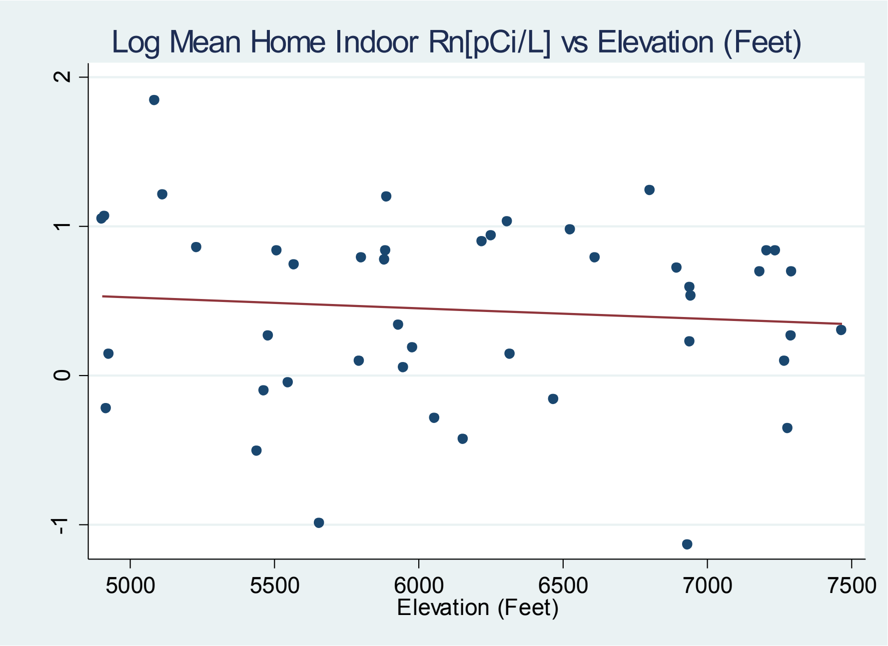
Appendix F: Log Mean Home Indoor Radon Concentration [pCi/L] versus Temperature (°F) for both the CUEJTH and NBCS Homes



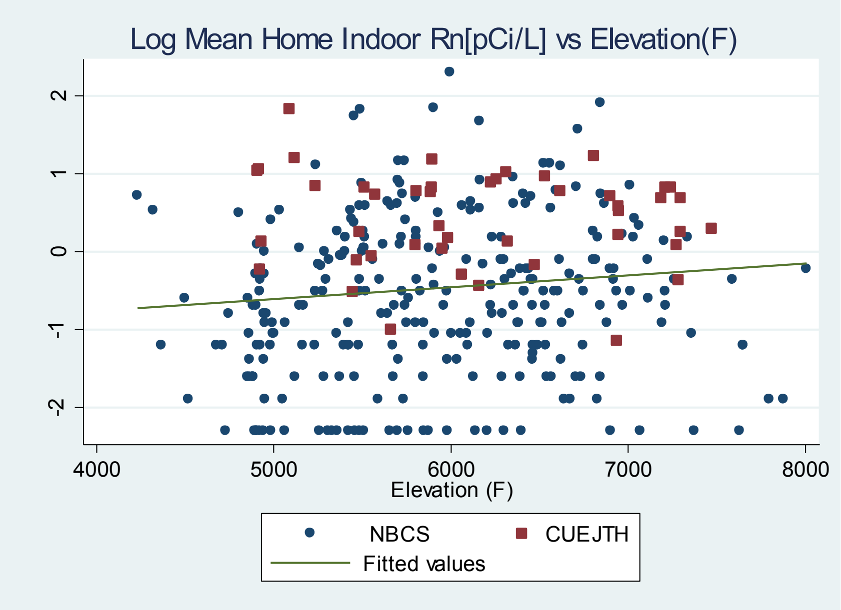
Appendix G: Log Mean Home Indoor Radon Concentration [pCi/L] versus Elevation (Feet) for both CUEJTH and NBCS Homes



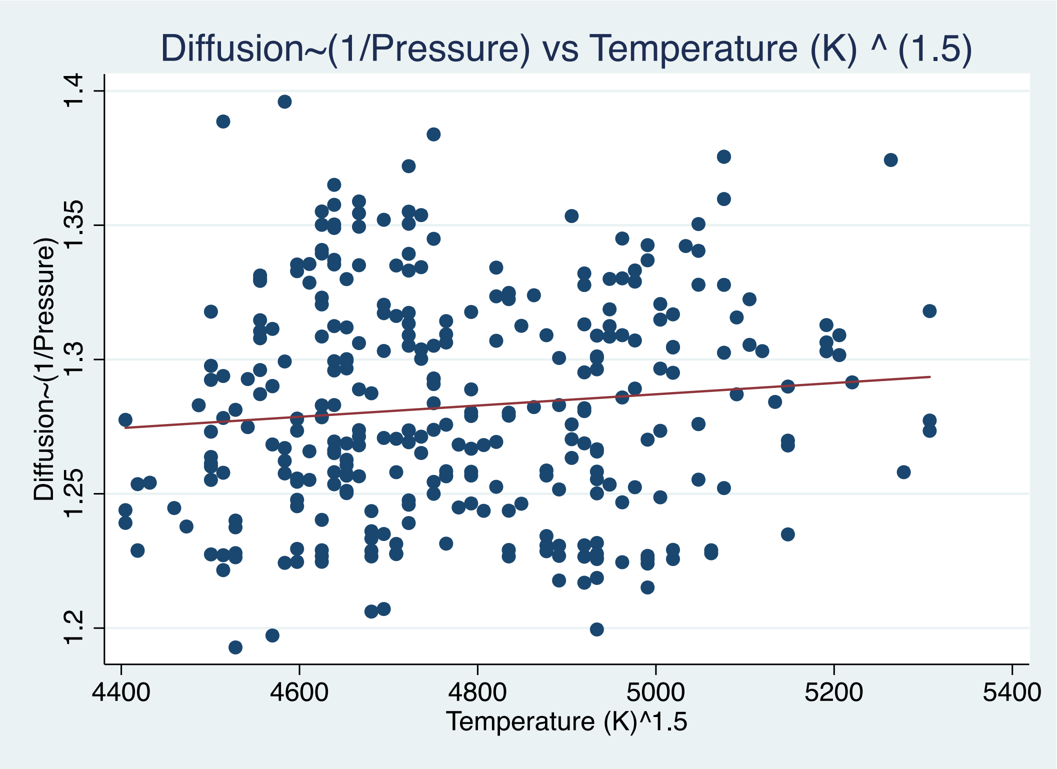
Appendix H: Log Mean Home Indoor Radon [pCi/L] versus Elevation in the CUEJTH Dataset After Excluding the LOD values



Appendix I: Log Mean Home Indoor Radon [pCi/L] versus Elevation in the Combined Dataset After Removing the LOD values from the CUEJTH Dataset



Appendix J: Scatterplot of Diffusion versus Temperature(°F)



Appendix K: Detailed description of the two-step approach conducted used to approximate Universal Kriging (UK) combining LUR and GIS

1. First step

a. The land use regression model fitted as stated below

```
********************************************************************************
**11-17-16 Baseline model; correct approach and confirmed by LS
********************************************************************************
```

xi: regress ln_rn_1x_n mean_temp1_rev ned_elevation_n i.home3a_n*u_dn_ppm, robust

Dependent variable	ln_rn_1x_n	Mean indoor log radon concentration (pCi/L)
Predictor	mean_temp1_rev	Outdoor mean temperature (°F) during radon testing
Predictor	ned_elevation_n	Elevation of home (feet)
Predictor	i.home3a_n	Type of home (categorical)
Predictor	u_dn_ppm	Sediment soil uranium concentration (ppm)
Interaction	i.home3a_n*u_dn_ppm	Interaction term for house type and sediment soil uranium concentration (ppm)

b. STATA OUTPUT from step (1a) above

```
. xi: regress ln_rn_1x_n mean_temp1_rev ned_elevation_n i.home3a_n*u_dn_ppm, robust
i.home3a_n        _Ihome3a_n_1-5      (naturally coded; _Ihome3a_n_1 omitted)
i.ho~a_n*u_dn~m   _IhomXu_dn__#       (coded as above)

Linear regression                                      Number of obs =     289
                                                       F( 11,   277) =   17.61
                                                       Prob > F      =  0.0000
                                                       R-squared     =  0.3385
                                                       Root MSE      =  .84522

------------------------------------------------------------------------------
             |               Robust
  ln_rn_1x_n |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
mean_temp1_rev |  -.0282054    .003854    -7.32   0.000    -.0357921   -.0206186
ned_elevation_n | -.0000949    .000072    -1.32   0.188    -.0002365    .0000467
_Ihome3a_n_2 |  -.2231908   .6960891    -0.32   0.749    -1.593487    1.147106
_Ihome3a_n_3 |   .2847556   .5434844     0.52   0.601    -.7851288     1.35464
_Ihome3a_n_4 |  -.1485978   .5061132    -0.29   0.769    -1.144915    .8477191
_Ihome3a_n_5 |   .0512018   .4866204     0.11   0.916    -.9067421    1.009146
    u_dn_ppm |   .0223986   .1522172     0.15   0.883    -.2772508     .322048
_IhomXu_dn__2 |   .3585228   .2589815     1.38   0.167    -.1512991    .8683448
_IhomXu_dn__3 |   .1681956   .1903327     0.88   0.378    -.2064866    .5428778
_IhomXu_dn__4 |   .3610594   .1838554     1.96   0.051    -.0008719    .7229908
_IhomXu_dn__5 |   .5361933   .2120032     2.53   0.012     .1188513    .9535353
       _cons |   .8771574   .5841593     1.50   0.134    -.2727983    2.027113
------------------------------------------------------------------------------
```

c. The land use regression model was used to generate ten-fold cross-validate predictions.

```
******************************************************************************
**11-16-16 feedback from LS- cv approach is appropriate below
**save cv residual predictions using cross validation
******************************************************************************
set seed 1000
*out-of sample assessments**
*Try to manually cross-validate this model using the code given above.
*use this part when I want to leave one group out**
xtile randgroup=uniform(), nq(10)
gen cv_fitted=.
*next section doesn't change*
forvalues i=1/10 {
*first do the regression on the training data
qui xi: regress ln_rn_1x_n i.home3a_n u_dn_ppm mean_temp1_rev ned_elevation_n
home3a_n#c.u_dn_ppm if randgroup !=`i'

*then predict on the test data
qui predict cv_fittedi
*then fill in the cv_fitted vector
qui replace cv_fitted = cv_fittedi if randgroup==`i'
qui drop cv_fittedi
}


*
*calculating summary statistics from the cross-validation results:
egen ln_rn_1x_n_avg=mean(ln_rn_1x_n)
*the following is the MSE of the data
*take the square root to get the RMSE
egen MSEln_rn_1x_n= mean((ln_rn_1x_n-ln_rn_1x_n_avg)^2)
*the following is the MSE of the predictions:
egen MSEests= mean((ln_rn_1x_n-cv_fitted)^2)
*MSE-based R2
gen MSER2 = max((1 - MSEests/MSEln_rn_1x_n),0)
*the following shows the calculated variables
*    (as one line of Stata code)

display MSEln_rn_1x_n ",  MSE = " MSEests ",  MSE-based R2 =  " MSER2
display "RMSE =  " sqrt(MSEests)
/*
1.0351986,  MSE = .ln7410602,  MSE-based R2 =  .28413716
. disy "RMSE =  " sqrt(MSEests)
RMSE =  .86084853
```

*

d. STATA Output from step (1c) above on ten fold cross-validation

```
. ****************************************************************************
. **11-16-16 feedback from LS- cv approach is appropriate below
. **save cv residual predictions using cross validation
. ****************************************************************************
. set seed 1000

. *out-of  sample assessments**
. *Try to manually cross-validate this model using the code given above.  Compare
. *   the CV R2 and RMSE to your in-sample estimates.
. *use this part when I want to leave one group out**
. xtile randgroup=uniform(), nq(10)

. gen cv_fitted=.
(289 missing values generated)

. *next section doesn't change*
. forvalues i=1/10 {
  2. *first do the regression on the training data
. qui xi: regress ln_rn_1x_n i.home3a_n u_dn_ppm mean_temp1_rev ned_elevation_n home3a_n#c.u_dn
> _ppm if randgroup !=`i'
  3. *then predict on the test data
. qui predict cv_fittedi
  4. *then fill in the cv_fitted vector
. qui replace cv_fitted = cv_fittedi if randgroup==`i'
  5. qui drop cv_fittedi
  6. }

.
```

```
. *calculating summary statistics from the cross-validation results:
. egen ln_rn_1x_n_avg=mean(ln_rn_1x_n)

. *the following is the MSE of the data
. *take the square root to get the RMSE
. egen MSEln_rn_1x_n= mean((ln_rn_1x_n-ln_rn_1x_n_avg)^2)

. *the following is the MSE of the predictions:
. egen MSEests= mean((ln_rn_1x_n-cv_fitted)^2)

. *MSE-based R2
. gen MSER2 = max((1 - MSEests/MSEln_rn_1x_n),0)

. *the following shows the calculated variables
. *    (as one line of Stata code)
.
.
. display MSEln_rn_1x_n ",  MSE = " MSEests ",  MSE-based R2 =  " MSER2
1.0351986,  MSE = .7410602,  MSE-based R2 =  .28413716

. display "RMSE =  " sqrt(MSEests)
RMSE =  .86084853
```

2. Second step
   a. The ten-fold cross-validated predictions from step 1b above were then used to calculate ten-fold cross-validated residual estimates.
   b. Residuals are the difference between observed and fitted values.[88]

Cross-Validated LUR residual=(observed-fitted)

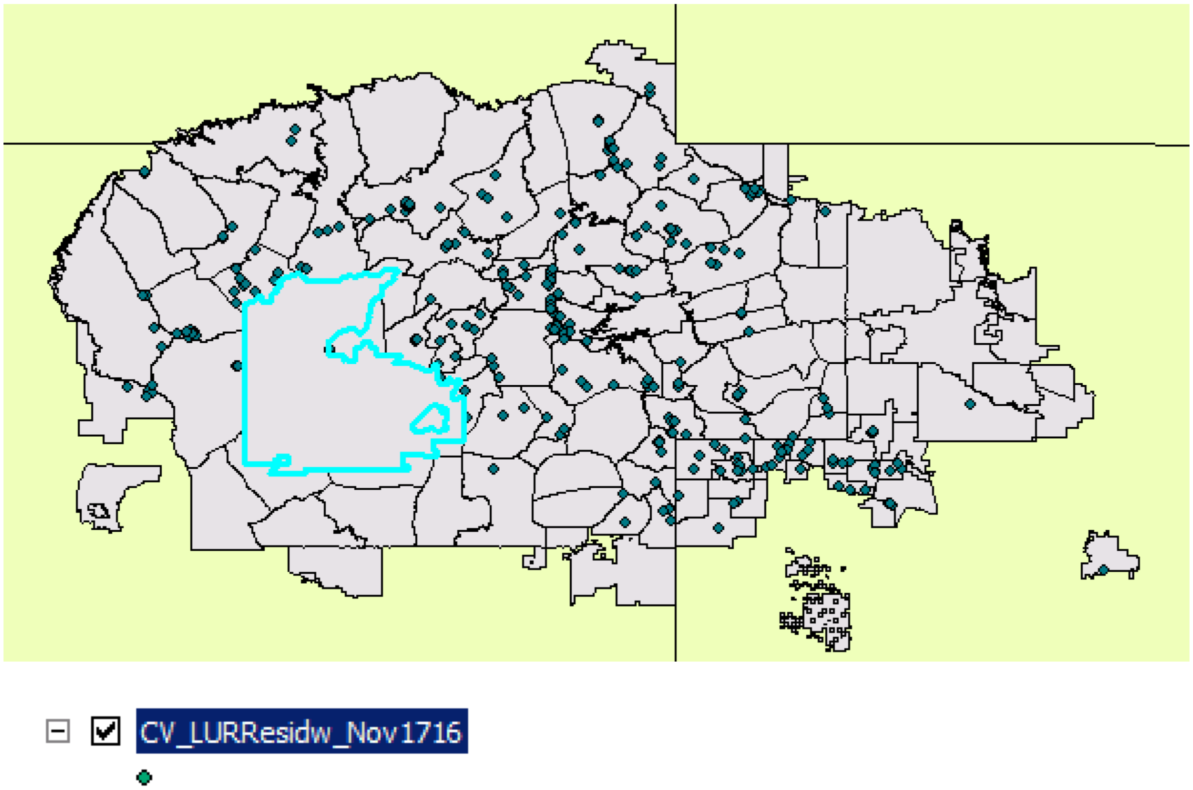
$$\text{Cross} - \text{Validated LUR residual}_{\text{i}} = \text{y}_{\text{i}} - \hat{\text{y}}_{\text{i}}$$

   c. Stata command and output for Step 2b

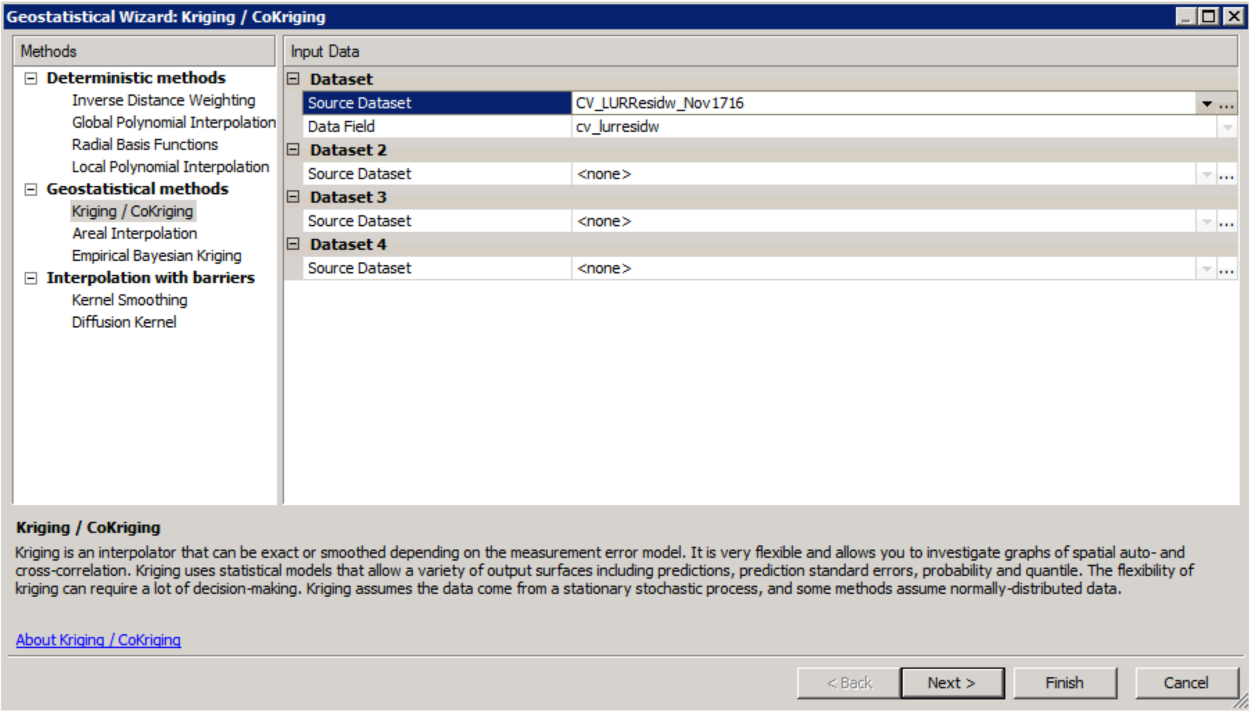
```
. *cross validated residuals defined as the difference between the obesrved and fitted values
. gen cv_lurresidw=(ln_rn_1x_n)-(cv_fitted)
```

3. Third Step- the cross-validated LUR residual predictions from step 2b were then imported into ArcMap and mapped.
   a. Steps to import cross validated residuals

      Steps: Import dataset with cross-validated LUR residuals from step 2b
      Display x,y table
      x=longitude
      y=latitude
      NAD83
   b. Map generated below displaying cross-validated LUR residuals across the Navajo Nation



4. Fourth step
    a. Select source datafile containing the cross-validated LUR residuals in ArcMap
    b. ArcMap steps using the Geostatistical Analyst/Geostatistical Wizard tools to export shape file with cross-validated LUR residuals



Dataset
Source Dataset: CV_LURResidw_Nov1716
Data Field: cv_lurresidw

Dataset 2
Source Dataset: <none>

Dataset 3
Source Dataset: <none>

Dataset 4
Source Dataset: <none>

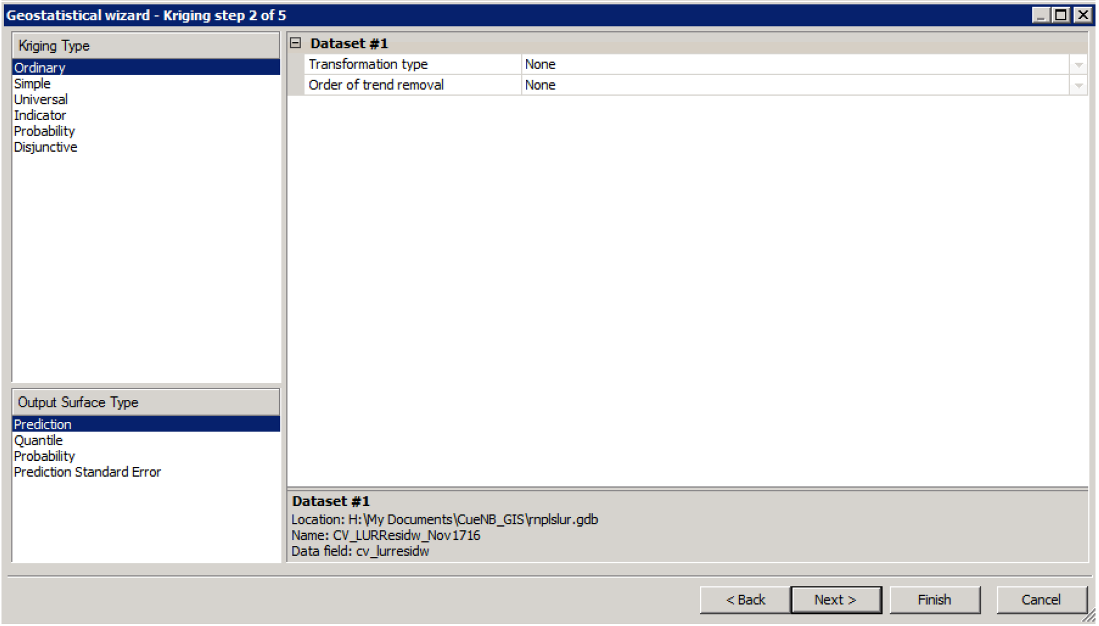
Kriging / CoKriging

Kriging is an interpolator that can be exact or smoothed depending on the measurement error model. It is very flexible and allows you to investigate graphs of spatial auto- and cross-correlation. Kriging uses statistical models that allow a variety of output surfaces including predictions, prediction standard errors, probability and quantile. The flexibility of kriging can require a lot of decision-making. Kriging assumes the data come from a stationary stochastic process, and some methods assume normally-distributed data.

5. Fifth step
    a. In ArcMap using the Geostatistical Analyst tool, ordinary kriging was then used to create a smoothed surface of cross-validated LUR residuals.
    b. ArcMap steps using Geostastistical Analyst

Source: Select dataset containing cross-validated LUR residual data
Datafield: Select cross-validated residuals
Ordinary Kriging
Transformation type: none
Prediction
Prediction map created of cross-validated LUR residuals
Export to raster to use in step 6

c. ArcMap showing selection of ordinary kriging and prediction surface



Kriging Type

- Ordinary
- Simple
- Universal
- Indicator
- Probability
- Disjunctive

Output Surface Type

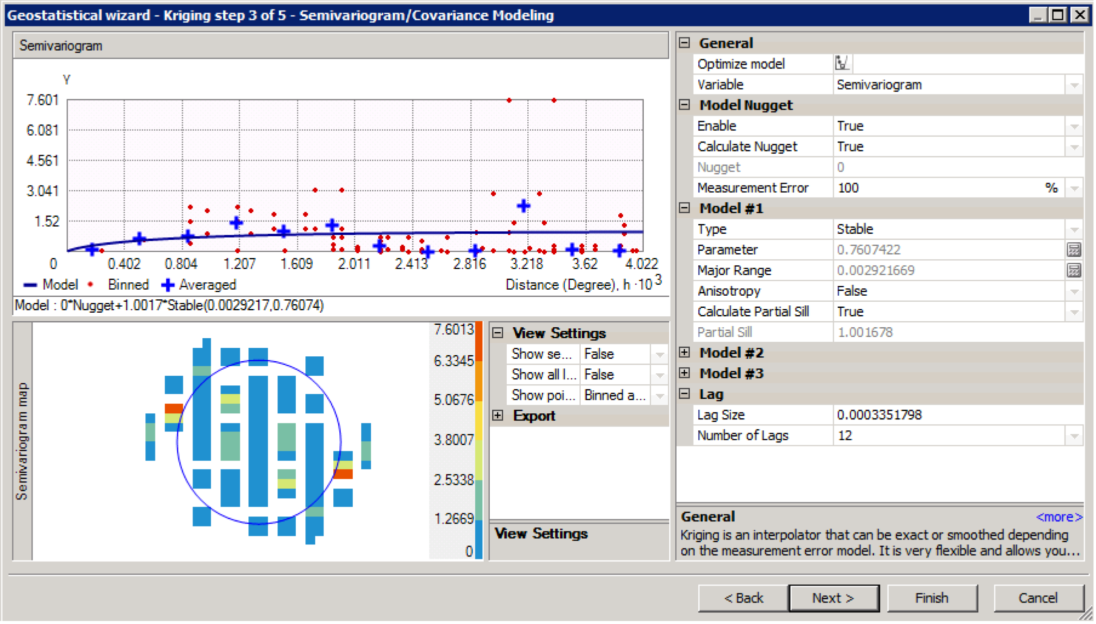
- Prediction
- Quantile
- Probability
- Prediction Standard Error

Dataset #1

Transformation type	None
Order of trend removal	None

Dataset #1
Location: H:\My Documents\CueNB_GIS\rnplslur.gdb
Name: CV_LURResidw_Nov1716
Data field: cv_lurresidw

d. Empirical Semivariogram[89]- default view



Model : 0*Nugget+1.0017*Stable(0.0029217,0.76074)

View Settings

Show se...	False
Show all l...	False
Show poi...	Binned a...

General

Optimize model	
Variable	Semivariogram

Model Nugget

Enable	True
Calculate Nugget	True
Nugget	0
Measurement Error	100 %

Model #1

Type	Stable
Parameter	0.7607422
Major Range	0.002921669
Anisotropy	False
Calculate Partial Sill	True
Partial Sill	1.001678

Model #2

Model #3

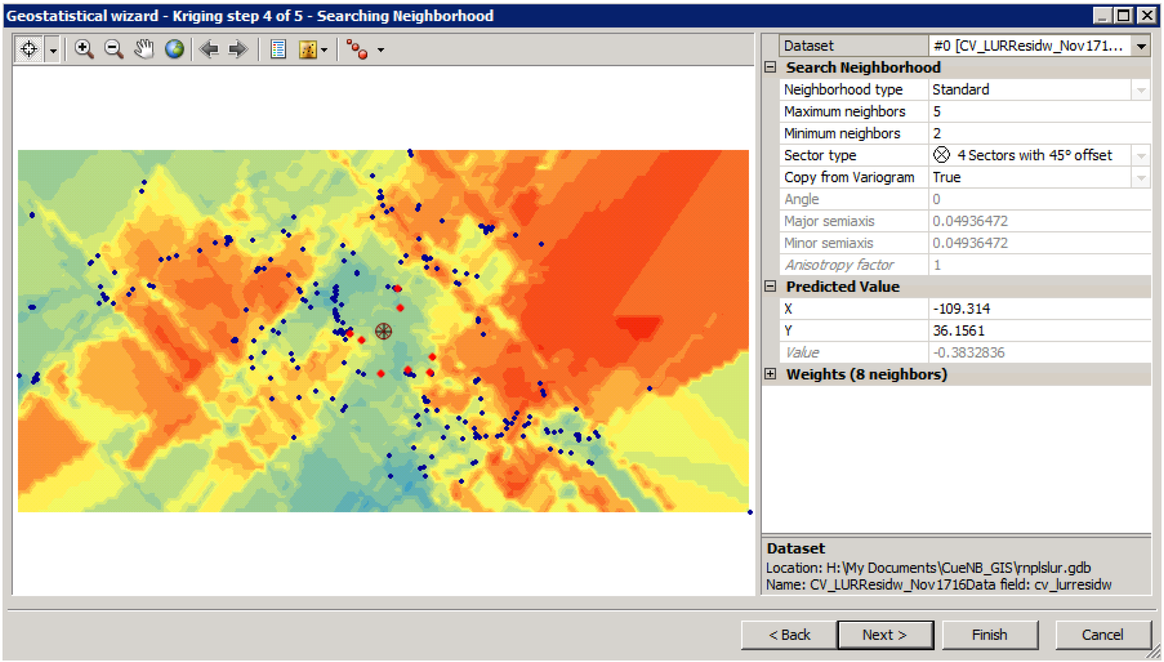
Lag

Lag Size	0.0003351798
Number of Lags	12

General <more>
Kriging is an interpolator that can be exact or smoothed depending on the measurement error model. It is very flexible and allows you…

Default view shows binned (red dots) and average values (+).

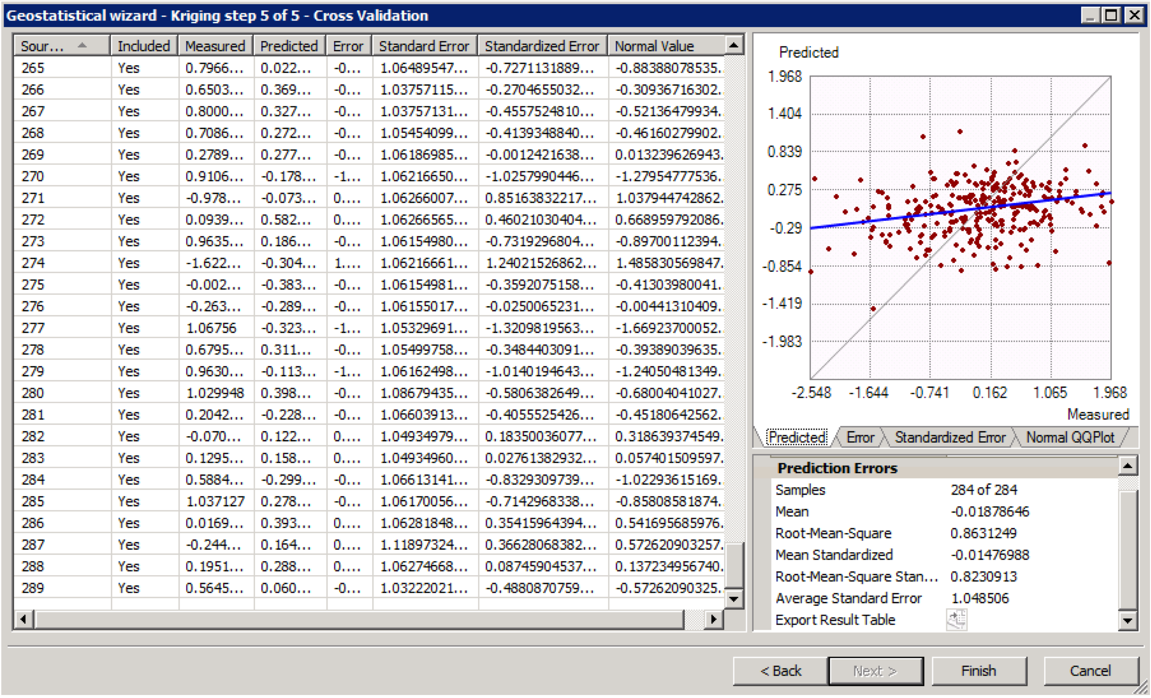
e. Smooth surface created from ordinary kriging. Used to extract prediction values of cross-validated land use regression residuals.



Dataset	#0 [CV_LURResidw_Nov171...
Search Neighborhood	
Neighborhood type	Standard
Maximum neighbors	5
Minimum neighbors	2
Sector type	⊗ 4 Sectors with 45° offset
Copy from Variogram	True
Angle	0
Major semiaxis	0.04936472
Minor semiaxis	0.04936472
Anisotropy factor	1
Predicted Value	
X	-109.314
Y	36.1561
Value	-0.3832836
Weights (8 neighbors)	

Dataset
Location: H:\My Documents\CueNB_GIS\rnplslur.gdb
Name: CV_LURResidw_Nov1716Data field: cv_lurresidw

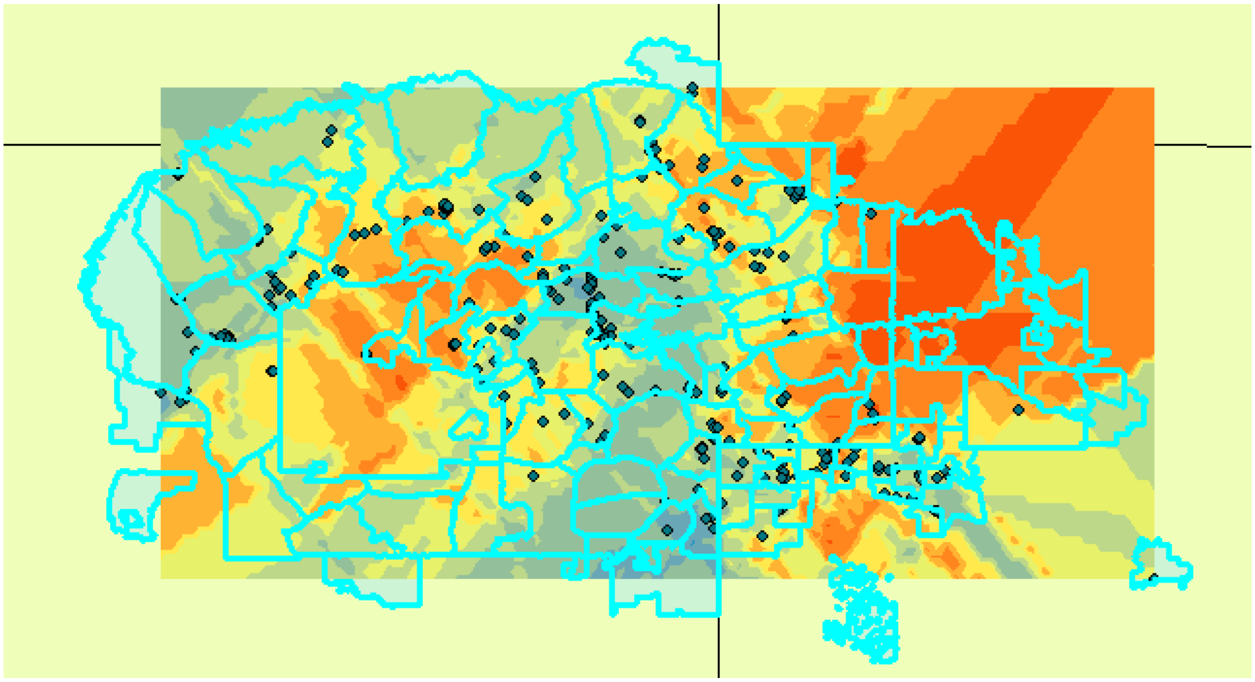
f. Cross validation results created in ArcMap



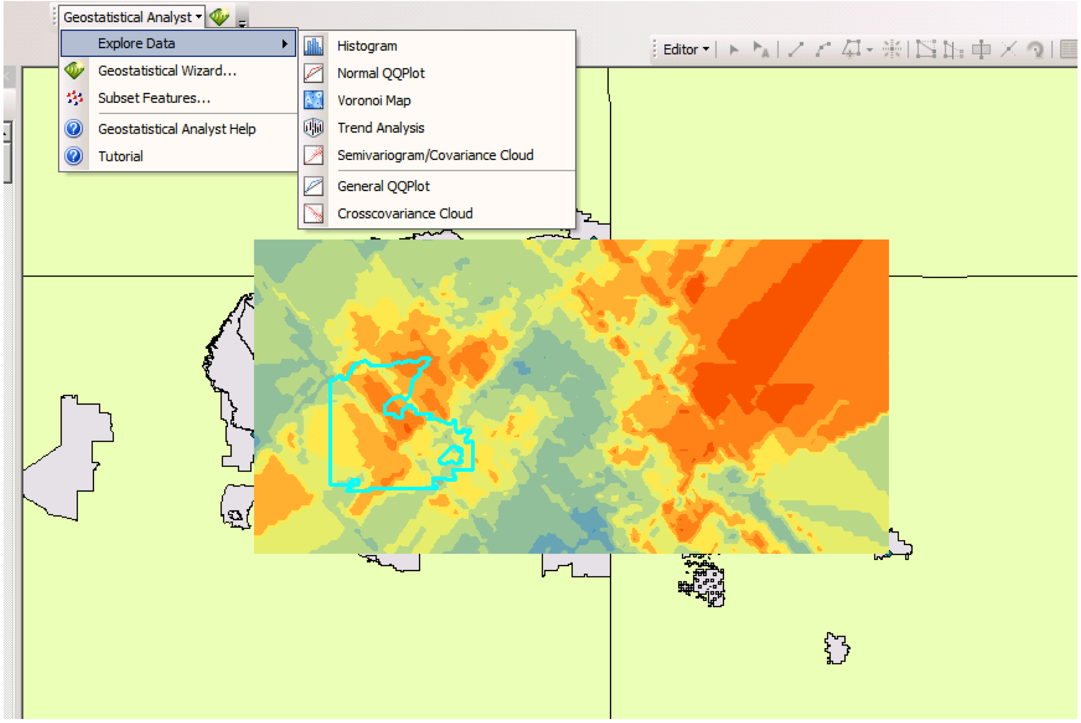
Sour...	Included	Measured	Predicted	Error	Standard Error	Standardized Error	Normal Value
265	Yes	0.7966...	0.022...	-0...	1.06489547...	-0.7271131889...	-0.88388078535.
266	Yes	0.6503...	0.369...	-0...	1.03757115...	-0.2704655032...	-0.30936716302.
267	Yes	0.8000...	0.327...	-0...	1.03757131...	-0.4557524810...	-0.52136479934.
268	Yes	0.7086...	0.272...	-0...	1.05454099...	-0.4139348840...	-0.46160279902.
269	Yes	0.2789...	0.277...	-0...	1.06186985...	-0.0012421638...	0.013239626943.
270	Yes	0.9106...	-0.178...	-1...	1.06216650...	-1.0257990446...	-1.27954777536.
271	Yes	-0.978...	-0.073...	0....	1.06266007...	0.85163832217...	1.037944742862.
272	Yes	0.0939...	0.582...	0....	1.06266565...	0.46021030404...	0.668959792086.
273	Yes	0.9635...	0.186...	-0...	1.06154980...	-0.7319296804...	-0.89700112394.
274	Yes	-1.622...	-0.304...	1....	1.06216661...	1.24021526862...	1.485830569847.
275	Yes	-0.002...	-0.383...	-0...	1.06154981...	-0.3592075158...	-0.41303980041.
276	Yes	-0.263...	-0.289...	-0...	1.06155017...	-0.0250065231...	-0.00441310409.
277	Yes	1.06756	-0.323...	-1...	1.05329691...	-1.3209819563...	-1.66923700052.
278	Yes	0.6795...	0.311...	-0...	1.05499758...	-0.3484403091...	-0.39389039635.
279	Yes	0.9630...	-0.113...	-1...	1.06162498...	-1.0140194643...	-1.24050481349.
280	Yes	1.029948	0.398...	-0...	1.08679435...	-0.5806382649...	-0.68004041027.
281	Yes	0.2042...	-0.228...	-0...	1.06603913...	-0.4055525426...	-0.45180642562.
282	Yes	-0.070...	0.122...	0....	1.04934979...	0.18350036077...	0.318639374549.
283	Yes	0.1295...	0.158...	0....	1.04934960...	0.02761382932...	0.057401509597.
284	Yes	0.5884...	-0.299...	-0...	1.06613141...	-0.8329309739...	-1.02293615169.
285	Yes	1.037127	0.278...	-0...	1.06170056...	-0.7142968338...	-0.85808581874.
286	Yes	0.0169...	0.393...	0....	1.06281848...	0.35415964394...	0.541695685976.
287	Yes	-0.244...	0.164...	0....	1.11897324...	0.36628068382...	0.572620903257.
288	Yes	0.1951...	0.288...	0....	1.06274668...	0.08745904537...	0.137234956740.
289	Yes	0.5645...	0.060...	-0...	1.03222021...	-0.4880870759...	-0.57262090325.

Prediction Errors	
Samples	284 of 284
Mean	-0.01878646
Root-Mean-Square	0.8631249
Mean Standardized	-0.01476988
Root-Mean-Square Stan...	0.8230913
Average Standard Error	1.048506
Export Result Table	

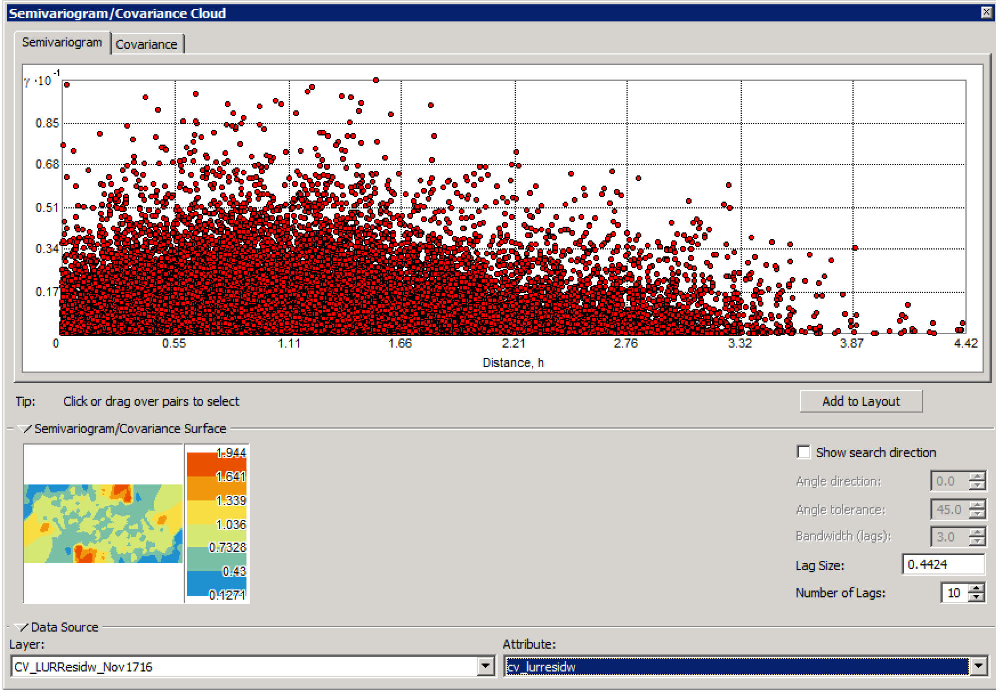
g. Smoothed surface of cross-validated LUR residuals across the Navajo Nation outlined in turquoise).



6. Exploring the semivariogram of the cross-validated residuals
    a. In ArcMap using the Geostatistical Wizard tool "Semivariogram/Covariance Cloud



b. Semivariogram of cross-validated residuals



Tip: Click or drag over pairs to select

☐ Show search direction

Angle direction: 0.0

Angle tolerance: 45.0

Bandwidth (lags): 3.0

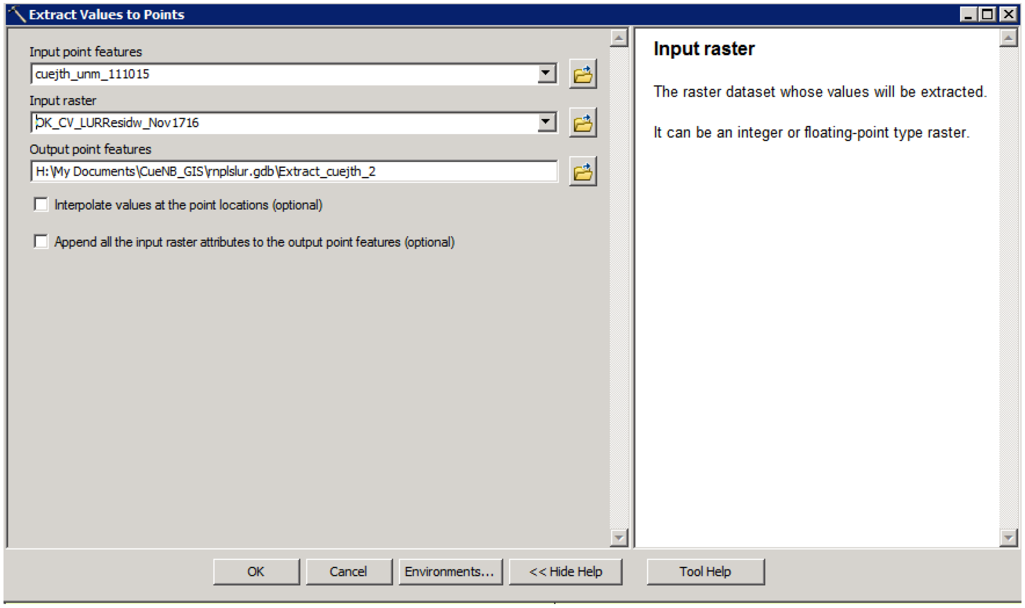
Lag Size: 0.4424

Number of Lags: 10

Layer: CV_LURResidw_Nov1716

Attribute: cv_lurresidw

7. Sixth step
   a. Using the smoothed map from step 5d above created, a cross validated LUR residual estimates for each home was then extracted using the Spatial Analyst tool.
   b. Spatial Analyst tool in ArcMap
      The function "Extract Values to Points" was used to extract a cross-validated LUR residual estimates for each home



Input point features: cuejth_unm_111015

Input raster: OK_CV_LURResidw_Nov1716

Output point features: H:\My Documents\CueNB_GIS\rnplslur.gdb\Extract_cuejth_2

☐ Interpolate values at the point locations (optional)

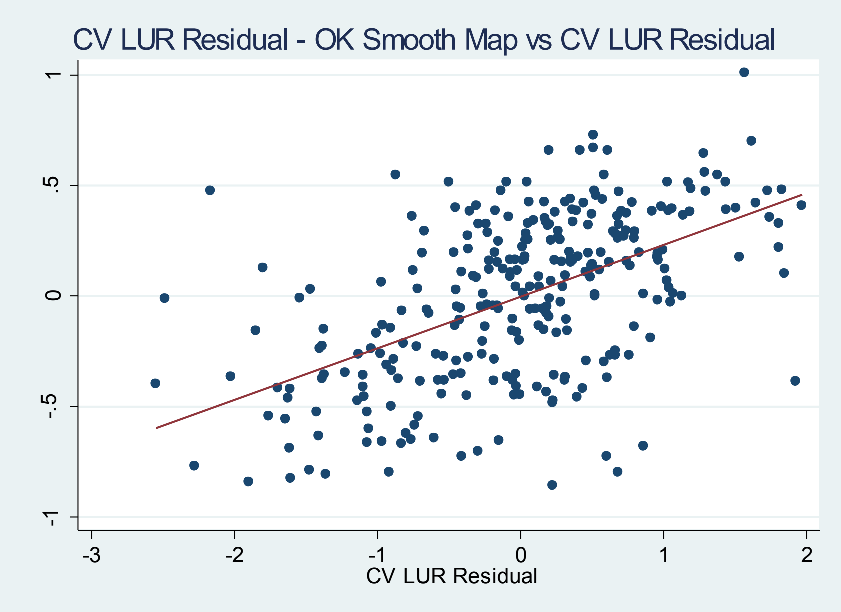
☐ Append all the input raster attributes to the output point features (optional)

Input raster

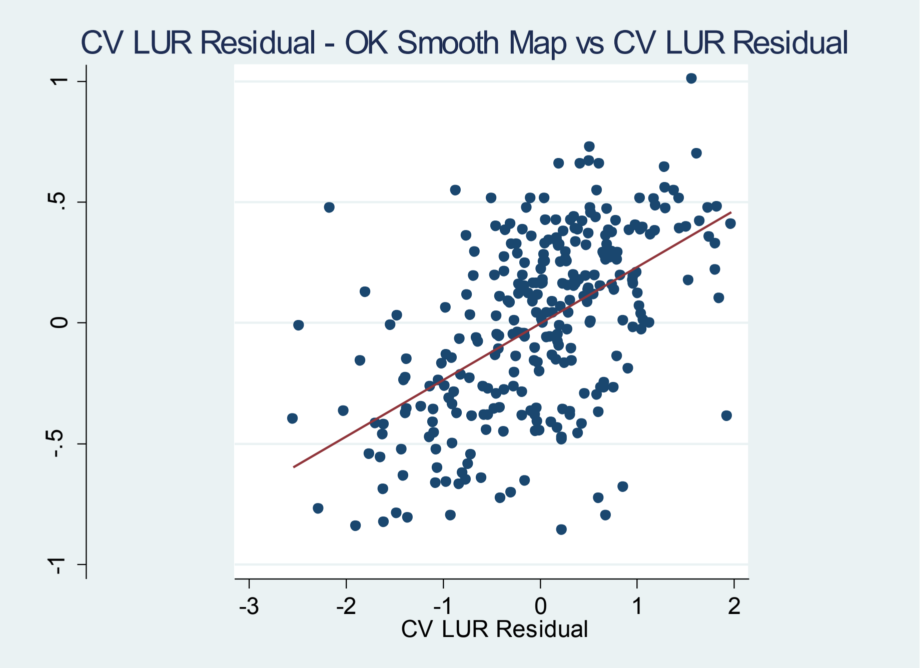
The raster dataset whose values will be extracted.

It can be an integer or floating-point type raster.

8. Logic check step
    a. Double check cross-validated LUR estimates input into ArcMap are different from cross-validated LUR estimates extracted from smooth map created by ordinary kriging
    b. Scatter plot created in Stata



    c. 1:1 scale



9. Seventh step
    a. To approximate universal kriging estimates of log mean indoor radon concentrations, the the cross-validated predicted estimates from the LUR model (step 1b) were added with the cross-validated LUR residual kriged estimate (step 6b) for each home that was extracted from the smoothed map.
    b. Stata steps
        i. Merge two datasets containing cross-validated predictions from step 1b with cross-validated LUR residual estimates EXTRACTED from smoothed map that was created by ordinary kriging
        ii. Generate a new variable “yhat_pred=(cv predicted “fitted”+ cv lur residual estimate from smoothed map created by ordinary kriging)”
        iii.
    c. $\hat{y}_{\text{predicted}} = \hat{y}_{\text{mean from LUR (step 1b)}} + \hat{y}_{\text{residual from ordinary kriging (step 6b)}}$
    d. Stata output command

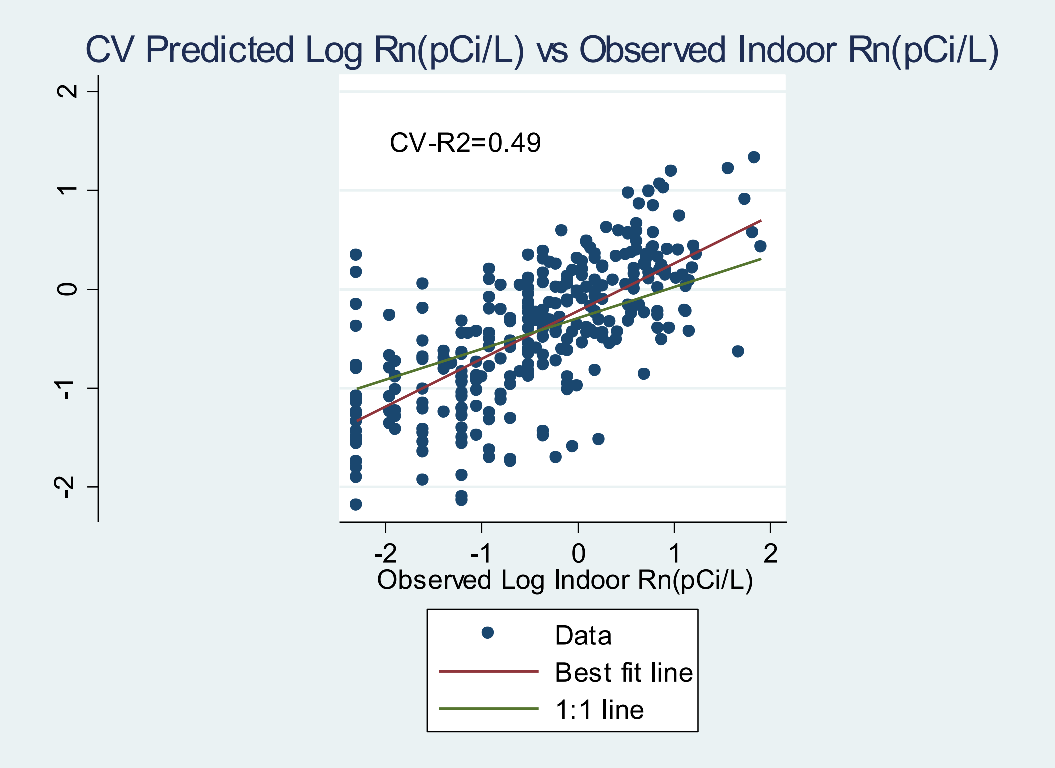
```
. gen yhat_pred=cv_fitted+ok_cvlurresidw
```

10. Eighth step
    a. Evaluation of cross validated predictions calculated in step 7b
    1.) Created scatter plot
    2.) Calculate correlation coefficient
    3.) Calculate Root Mean Square Error (RMSE)

    b. Create a scatter plot comparing observed mean log indoor radon concentrations with the cross validated predictions (step 7b), “yhat_pred=(cv predicted “fitted”+ cv lur residual estimate from smoothed map created by ordinary kriging)”.

```
. twoway (scatter yhat_pred ln_rn_1x_n, sort xtitle("Observed Log Indoor Rn(pCi/L)") ytitle("CV
>  Predicted Log Rn(pCi/L)")) (lfit yhat_pred ln_rn_1x_n) (lfit cv_fitted ln_rn_1x_n), yscale(r
> ange(-2 2))xscale(range(-2 2)) scale(1) aspectratio(1) ///
> title("CV Predicted Log Rn(pCi/L) vs Observed Indoor Rn(pCi/L)")legend(order(1 "Data" 2 "Best
>  fit line" 3 "1:1 line") rows(3)) ///
> text(1.5 -2.0 "CV-R2=0.49", place(e))
```

c. Stata scatter plot output



Best fit line:Data observations

1:1 line: Estimated for cross-validated predictions vs observations

d. Calculate correlation coefficient, cross validated predictions vs log mean indoor radon observations

1.) Stata command

```
. corr yhat_pred ln_rn_1x_n
(obs=289)

             | yhat_p~d ln_rn_~n
-------------+------------------
   yhat_pred |   1.0000
  ln_rn_1x_n |   0.6975   1.0000
```

2.) Correlation= .6975

3.) R^2=$(0.6975)^2$

R^2=0.4865

CV-R^2=0.487

e. Calculate RMSE

1.) Root Mean Square Error (RMSE) Equation

$$\mathrm{RMSE} = \sqrt{\left(\left(\frac{1}{\mathrm{n}}\right)\sum\nolimits_{\mathrm{i}} (\mathrm{y_i} - \mathrm{yhat_i})^2\right)}$$

Assesses deviation around the best-fit line (between cross-validated predictions and observed log mean indoor radon concentrations.

2.) Stata command

```
. **compte RMSE=sqrt( (1/n)sum(observed-predicted)^2 )
. gen obs_pred2=(ln_rn_1x_n-yhat_pred)^2

.
end of do-file

. do "C:\Users\shyazzie\AppData\Local\Temp\7\STD00000000.tmp"

. display r(sum)
.

. *153.64598
.
end of do-file

. do "C:\Users\shyazzie\AppData\Local\Temp\7\STD00000000.tmp"

. display sqrt(153.64598/289)
.72914127
```

3.) RMSE= 0.729

Chapter 4: Summary and Findings

4.1 Summary

This dissertation project was undertaken to provide analytic support to the Community Uranium Exposure Journey To Healing (CUEJTH) Program, to conduct an indoor radon survey on the Navajo Nation, and to develop an indoor radon prediction model for homes on the Navajo Nation. The CUEJTH program is sponsored by the Navajo Area Indian Health Service and provides health monitoring, health promotion and health education related to uranium to communities across the Navajo Nation. Elevated levels of natural uranium in the soil and rocks in this Southwest region of the US historically created an ideal area for uranium mining. An environmental legacy to this era between 1944 to 1986 was the mining of over 30 million tons of uranium and abandonment of over 500 uranium mines and their wastes on the Navajo Nation.[90]

Many family members worked in these uranium mines and oftentimes lived in proximity to uranium mines with their families. Abandoned uranium waste materials were also sometimes used in the construction of nearby homes. Therefore, exposure to uranium and one of its decay product radon gas outside the uranium mines in the non-occupational set the stage for this dissertation project. Moreover, properties of radon gas such as no odor or taste, and its ability to diffuse from soil into homes highlight the importance of conducting radon surveys in this region. By conducting an indoor radon survey, this project provided participants from the CUEJTH program with a current indoor radon survey of their home and ultimately these radon surveys supported the mission of the CUEJTH program related to education of uranium exposure, specifically radon exposure. In addition, the indoor radon surveys collected as part of this dissertation project was used to develop an indoor radon prediction model.

The indoor radon survey for this dissertation, "Assessing Indoor Radon Exposure on the Navajo Nation", was facilitated with volunteers from the CUEJTH program. The Navajo Nation Environmental Protection Agency Radon Program routinely conducts radon tests in public buildings; however, home testing is only done at the request of the homeowner.[48] By offering radon testing to CUEJTH volunteers, this project benefitted homeowners by providing them with current radon testing, and the radon results also contributed to the Navajo Nation Radon Program database; specifically in regards to additional home indoor radon measurements since only public buildings are routinely tested. By offering homeowners radon testing, homes with potentially high indoor radon levels could be identified and scheduled for additional testing and home mitigation if necessary.

In this radon survey, a total of 51 home indoor radon survey measurements were conducted in three of the five agencies on the Navajo Nation. The results of this survey concur with other published indoor radon surveys. Log mean indoor radon concentrations (pCi/L) differed by house type which could be rationalized scientifically. For instance, it is known that ventilation throughout a home provides better air flow into and out of the home; therefore, homes with more ventilation could potentially have lower indoor radon levels compared to homes with less ventilation. In alignment with this relationship between ventilation and indoor radon levels for this study was that the structural make-up of a house also affects indoor radon levels; in this dissertation study, mobile homes had lower indoor radon concentration levels compared to homes mixed with concrete and cement (generally more tightly sealed). It is also scientifically reasonable to conclude mobile homes would have lower indoor radon concentration levels since they generally sit above crawl spaces creating an outlet for any potential radon gas emanating from the soil underneath the home from entering the home.

This indoor radon survey is unique to the Navajo Nation in several ways. First, housing characteristics were collected simultaneously during indoor radon testing using a standardized survey to record information about the general condition of the home; such as age, construction materials, and overall ventilation. Second, the geolocation (latitude and longitude) and elevation (feet) of each home were recorded. Collecting specific housing information selected a priori as predictor variables thought to be associated with indoor radon concentration was essential in developing an indoor radon prediction model for the Navajo Nation. Third, this study is also distinctive through its collaboration with an ongoing epidemiological study, the Navajo Birth Cohort Study (NBCS) at the University of New Mexico Community Health Environmental Program (UNM CHEP). The NBCS conducts home exposure assessments (HEA) as part of its study in examining the association between uranium exposure and birth outcomes. The NBCS HEAs involves collecting home indoor radon measurements (pCi/L), housing information such as type of home, geolocation (latitude and longitude), and elevation (feet). Temperature data (°F) during home indoor radon testing for this study and the NBCS was ascertained retrospectively through a reliable weather database system.

Combining the indoor radon data from this dissertation study and the NBCS created a radon database set that: 1) had a large number of home indoor radon measurements providing a large sample size, 2) had geocoded (latitude and longitude) locations of each home indoor radon measurement ideal for creating a spatial map of indoor radon measurements across the Navajo Nation, 3) provided a larger coverage area across the Navajo Nation, 4) had year-round indoor radon measurements accounting for temperature and seasonal changes. Taking these factors into account, it is reasonable to infer the combined indoor radon dataset is more generalizable across the Navajo Nation.

The indoor radon prediction model developed in this dissertation project is the first to be conducted on the Navajo Nation. Using previously collected geographic coded land covariates in combination with the combined geocoded indoor radon dataset from this dissertation study and the NBCS provided the essential elements to develop an environmental indoor radon prediction model which has

has been done in other studies.[72-74] Specifically, house type, temperature (°F) during radon testing, elevation (feet) of the home, in addition to land covariate average sediment soil uranium concentration (ppm), and an interaction term between house type and average soil sediment uranium concentration (ppm) were used as predictors in developing the indoor radon prediction model. Using a two-step methodological which combined land use regression with ordinary kriging using GIS software produced a model that explains almost 49% of the variability.

4.2 Strengths & Weaknesses

There are several strengths to this dissertation study. One strength of this study lies in the dataset and the performance of the indoor radon prediction model. The combined indoor radon dataset provided a large sample size that was geocoded and covered all five of the Navajo Nation agencies. In addition, including house type as a predictor was advantageous to the model because it is well established that house type, i.e., condition, age, and ventilation, influence indoor radon concentration levels. Further, soil sediment uranium concentration level that was geocoded across the Navajo Nation was a principal predictor because radon gas is a decay product of uranium, and it is well-established that soil uranium concentrations is a major factor that contributes to indoor radon concentration levels. With these key elements in place, spatially mapping these covariates across the Navajo Nation using GIS software was instrumental in developing a prediction model.

A second strength is that the radon database organized for this project is unique to the Navajo Nation. Discussions with the Navajo Nation Environmental Protection Agency Radon Program and more recently with the US Department Of The Interior Indian Affairs Geospatial Support Program indicate this indoor radon database is unique and valuable as a model moving forward.[48, 91] The Navajo Nation does not routinely collect housing survey information in detail as did this study, and to restate does not routinely test homes and only does so at the request of homeowners. Therefore, this indoor radon database will provide the Navajo Nation with a sample database to model for their own program, to collect detailed housing information at the time of indoor radon testing, as is done in other national registry programs, i.e. Canada, Finland and Sweden.[72, 92] [74]

There are a few potential limitations to this study. One might be in regards to participants from the CUEJTH program. Volunteers from this program participated in CUEJTH education activities related to uranium; therefore, majority of participants had some knowledge about the effects of uranium and less so about radon exposure. As a result, these individuals may not necessarily be representative of the general population of the Navajo Nation. Another potential limitation to the indoor radon survey conducted for this dissertation may be been in regards to the data collection period that was conducted primarily during the winter season. House behavior patterns in the winter season may have influenced indoor radon concentration levels as higher because residents most often keep a more tightly sealed home during this colder time of the year.

Potential limitations to the indoor radon prediction model may lie with the limited number of land covariates. In regards to the sediment soil uranium concentrations, a limited number of samples were available for a portion of the western region of the Navajo Nation. As a result, a small percentage of homes were not included in the indoor radon prediction model. In addition, a number of radon gas predictors were considered, e.g., percent uranium oxide $(\%^3U^8O)$, but were not included due to a limited number of samples to provide adequate coverage for the number of homes across the Navajo Nation. Last, the two-step approach using land use regression in this model has been suggested to approach that of universal kriging, but in theory would be improved using this method.

4.3 Suggested Future Research

One potential area would be to include additional land covariates related to indoor radon concentration levels in the prediction model. For example, similar indoor radon prediction models while few and not generalizable to the Navajo Nation, utilized other geological characteristics such as soil permeability. Another next step would be to continue collecting indoor radon measurements for the general population of the Navajo Nation, that is to expand testing outside both the CUEJTH and NBCS participants. In addition, staff members at the Navajo Nation Environmental Protection Agency Radon Program could be trained on how to classify homes providing an opportunity to apply this model to more homes and places. Finally, the results based on the two-step approach used in this study could be compared to the universal kriging methodological approach.

4.4 Conclusions

The results of this study are in alignment with well-established literature related to indoor radon concentration levels. For instance, house type matters and in this study variations in indoor radon concentration levels differed by house type. Further, sediment soil uranium concentration is a known primary predictor of indoor radon gas and this relationship was observed in this study. More importantly, an interaction term in this model allowed the preservation of the association between soil sediment uranium concentration and indoor radon concentration levels to differ by house type. Finally, one of the most important messages of this dissertation study is that house type and place of house matters. Taking this message into account, this indoor radon prediction model could assist the Navajo Nation Environmental Radon Program in encouraging homeowners, who have not tested their homes for indoor radon gas and living in geographic regions predicted to potentially have higher radon gas levels, to test their homes.

Bibliography

1. Five-Year Plan and Report to Address Impacts of Uranium Contamination, 2008-2012.
2. Addressing Uranium Contamination on the Navajo Nation.
3. Toxicological Profile For Uranium 2013.
4. Toxicological Profile For Radon. 2012.
5. Radionuclides (including Radon, Radium and Uranium). 2014.
6. Archer VE, Gillam JD and Wagoner JK. Respiratory disease mortality among uranium miners. *Ann N Y Acad Sci*. 1976;271:280-93.
7. Gilliland FD, Hunt WC, Archer VE and Saccomanno G. Radon progeny exposure and lung cancer risk among non-smoking uranium miners. *Health Physics*. 2000;79:365-72.
8. Gilliland FD, Hunt WC, Pardilla M and Key CR. Uranium mining and lung cancer among Navajo men in New Mexico and Arizona, 1969 to 1993. *Journal of Occupational and Environmental Medicine*. 2000;42:278-83.
9. Gottlieb LS and Husen LA. Lung cancer among Navajo uranium miners. *Chest*. 1982;81:449-52.
10. Samet JM, Kutvirt DM, Waxweiler RJ and Key CR. Uranium mining and lung cancer in Navajo men. *N Engl J Med*. 1984;310:1481-4.
11. Roscoe RJ, Deddens JA, Salvan A and Schnorr TM. Mortality among Navajo uranium miners. *American Journal of Public Health*. 1995;85:535-40.
12. (U.S.) NRC. *Health Effects Of Exposure To Radon*. Washington, D.C.: National Academy of Sciences; 1999.
13. Brugge D and Buchner V. Health effects of uranium: new research findings. *Rev Environ Health*. 2011;26:231-49.
14. ATSDR. Toxicological profile for Uranium. 1999.
15. Uranium: Its Uses and Hazards. 2017.
16. Brugge D and Goble R. The history of uranium mining and the Navajo people. *Am J Public Health*. 2002;92:1410-9.
17. Dawson SE and Madsen GE. Psychosocial and health impacts of uranium mining and milling on Navajo lands. *Health Phys*. 2011;101:618-25.
18. USEPA. Navajo Nation AUM Screening Assessment Report and Atlas with Geospatial Data. 2007.
19. CERCLA Overview. 2014.
20. Uranium Toxicity: What Are the Routes of Exposure for Uranium? 2014.
21. Brugge D, de Lemos JL and Oldmixon B. Exposure pathways and health effects associated with chemical and radiological toxicity of natural uranium: a review. *Rev Environ Health*. 2005;20:177-93.
22. Pinney SM, Freyberg RW, Levine GE, Brannen DE, Mark LS, Nasuta JM, Tebbe CD, Buckholz JM and Wones R. Health effects in community residents near a uranium plant at Fernald, Ohio, USA. *Int J Occup Med Environ Health*. 2003;16:139-53.
23. RADON: Chemical and Physical Data.
24. Brill AB, Becker DV, Donahoe K, Goldsmith SJ, Greenspan B, Kase K, Royal H, Silberstein EB and Webster EW. Radon update: facts concerning environmental radon: levels, mitigation strategies, dosimetry, effects and guidelines. SNM Committee on Radiobiological Effects of Ionizing Radiation. *J Nucl Med*. 1994;35:368-85.
25. Axelson O. Cancer risks from exposure to radon in homes. *Environ Health Perspect*. 1995;103 Suppl 2:37-43.
26. Frumkin H and Samet JM. Radon. *CA Cancer J Clin*. 2001;51:337-44, 322; quiz 345-8.
27. EPA Assessment of Risks from Radon in Homes. 2003.
28. Radiation Protection: Radon. 2013.
29. McLemore V. Radon Availability in New Mexico. 1994.

30. Schmid K, Kuwert T and Drexler H. Radon in indoor spaces: an underestimated risk factor for lung cancer in environmental medicine. *Dtsch Arztebl Int*. 2010;107:181-6.
31. Radon Toxicity: What Are the Routes of Exposure to Radon? 2014.
32. Alexander WG and Devocelle LL. Mapping Indoor Radon Potential Using Geology and Soil Permeability. *1997 International Radon Symposium*. 1997.
33. Department BRH. Why Do Radon Levels Inside a Home Fluctuate So Much? 2017.
34. Occurrence, Exposure and Analysis. 2014.
35. Nazaroff WW and Anthony V. Nero J. *Radon And Its Decay Products In Indoor Air*. New York: John Wiley & Sons; 1988.
36. Prevention CfDCa. Radon and Drinking Water from Private Wells. 2017.
37. Momcilovic M, Kovacevic J, Tanic M, Dordevic M, Bacic G and Dragovic S. Distribution of natural radionuclides in surface soils in the vicinity of abandoned uranium mines in Serbia. *Environ Monit Assess*. 2013;185:1319-29.
38. Branion-Calles MC, Nelson TA and Henderson SB. A geospatial approach to the prediction of indoor radon vulnerability in British Columbia, Canada. *Journal of exposure science & environmental epidemiology*. 2015.
39. Nazaroff WW. Radon Transport From Soil To Air. *Review of Geophysics*. 1992;30:137–160.
40. Health Effects of Exposure to Radon: BEIR VI (Free Executive Summary). *Committee on Health Risks of Exposure to Radon*. 1999.
41. Turner MC, Krewski D, Chen Y, Pope CA, 3rd, Gapstur S and Thun MJ. Radon and lung cancer in the American Cancer Society cohort. *Cancer Epidemiol Biomarkers Prev*. 2011;20:438-48.
42. IARC Monographs on the Evaluation of Carcinogenic Risks to Humans. 2014.
43. EPA. National Residential Radon Survey: Summary Report. October 1992.
44. A Citizen's Guide to Radon. 2014.
45. Navajo Nation. 2014.
46. Demographic Analysis of the Navajo Using 2010 Census and 2010 American Community Survey Estimates.
47. Navajo Population Profile 2010 U.S. Census. 2013.
48. Agency NNEP. Radon Program. 2016.
49. Inc. RE. E-PERM Systems. 2017.
50. GARMIN. eTrex20. 2015.
51. Air Chek, Inc. Radon Facts and Top-Rated Radon Test Kits.
52. Welcome to the Institute for Tribal Environmental Professionals. 2017.
53. Additional Radon Testing Information. 2015.
54. Protocols for Radon And Radon Decay Product Measurements in Homes. 1993.
55. Air Check I. Analytical Procedures and Comparisons. 2015.
56. Weather Underground. 2015.
57. The Weather Channel. 2015.
58. Wunderground.com sold to The Weather Channel Companies. 2017.
59. Kaur H. Environmental Chemistry. 2010.
60. Navajo Nation Human Research Review Board. 2014.
61. Navajo Human Research Review Board IRB Research Protocol Application. 2014.
62. Zandbergen PA. Ensuring Confidentiality of Geocoded Health Data: Assessing Geographic Masking Strategies for Individual-Level Data. *Adv Med*. 2014;2014:567049.
63. Landry A. Indian Country left on far side of digital divide. *Navajo Times*. 2013.
64. Radford EP. Potential health effects of indoor radon exposure. *Environ Health Perspect*. 1985;62:281-7.
65. Safety and Health in Manufactured Structures. 2015.

66. Concrete Block vs Engineered Wood Frame. 2015.
67. Smulski S. Durability of Energy-Efficient Wood-Frame Houses. 2015.
68. Navajo Homes - Hogans. 2015.
69. THE NAVAJO INDIAN HOGAN: Shelter And Center of Their World.
70. Concrete Building Systems. 2015.
71. Basic Radon Facts. 2015.
72. Branion-Calles MC, Nelson TA and Henderson SB. A geospatial approach to the prediction of indoor radon vulnerability in British Columbia, Canada. *J Expo Sci Environ Epidemiol*. March 25, 2015.
73. Hauri DD, Huss A, Zimmermann F, Kuehni CE and Roosli M. A prediction model for assessing residential radon concentration in Switzerland. *J Environ Radioact*. 2012;112:83-9.
74. Hauri DD, Huss A, Zimmermann F, Kuehni CE and Roosli M. Prediction of residential radon exposure of the whole Swiss population: comparison of model-based predictions with measurement-based predictions. *Indoor Air*. 2013 Oct;23:406-16.
75. Mercer LD, Szpiro AA, Sheppard L, Lindstrom J, Adar SD, Allen RW, Avol EL, Oron AP, Larson T, Liu LJ and Kaufman JD. Comparing universal kriging and land-use regression for predicting concentrations of gaseous oxides of nitrogen (NOx) for the Multi-Ethnic Study of Atherosclerosis and Air Pollution (MESA Air). *Atmospheric environment (Oxford, England : 1994)*. 2011;45:4412-4420.
76. Liu KS, Chang YL, Hayward SB, Gadgil AJ and Nero AV. The distribution of lifetime cumulative exposures to radon for California residents. *J Expo Anal Environ Epidemiol*. 1993;3:165-79.
77. Community Uranium Exposure Journey To Healing Program. 2014.
78. Navajo Birth Cohort Study. 2016.
79. Southwest Research and Information Center. 2015.
80. Radon Testing Corporation of America. 2015.
81. Development USDoHaU. HUD-Manufactured Housing and Standards --Alternative Construction Introduction. 2017.
82. Sheppard L and Seixas N. ENVH 556: "Occupational Exposure Analysis". 2015.
83. Diffusion Coefficient. 2017.
84. Wood. 2016.
85. The Pros & Cons of Concrete Block House Construction. 2016.
86. Radiation from Building Materials. 2017.
87. Muessig KW. Correlation of Airborne Radiometric Data and Geologic Sources With Elevated Indoor Radon in New Jersey. 1988.
88. Vittinghoff E, Glidden DV, Shiboski SC and McCulloch CE. *Regression Methods in Biostatistics: Linear, Logistic, Survival, and Repeated Measures Models*: Springer; 2005.
89. Fitting A Model to the Empirical Semivariogram. 2017.
90. Navajo Nation: Cleaning Up Abandoned Uranium Mines. 2017.
91. Branch of Geospatial Support. 2017.
92. Makelainen I, Arvela H and Voutilainen A. Correlations between radon concentration and indoor gamma dose rate, soil permeability and dwelling substructure and ventilation. *The Science of the total environment*. 2001;272:283-9.