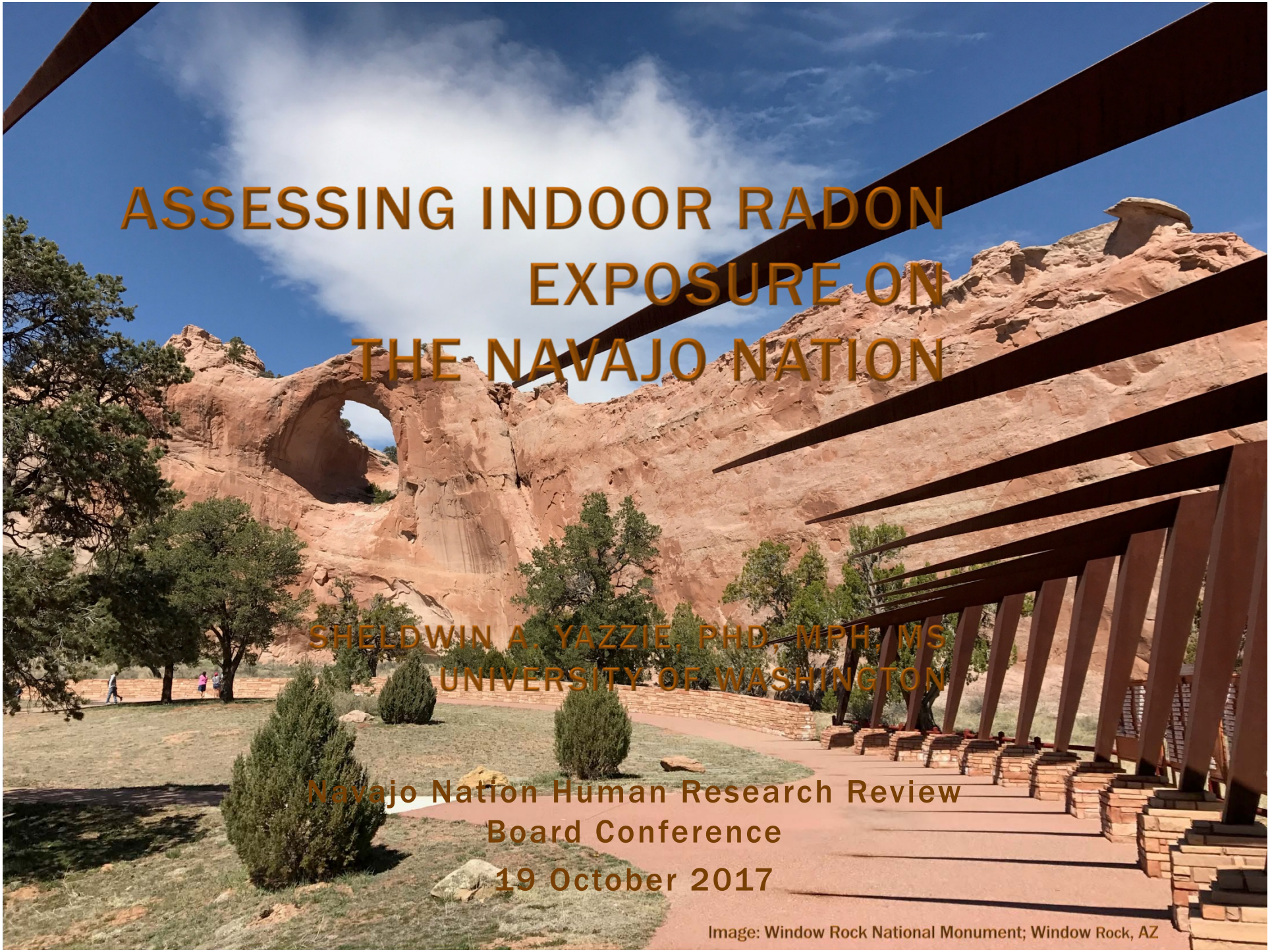

ASSESSING INDOOR RADON EXPOSURE ON THE NAVAJO NATION

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Navajo Nation Human Research Review Board Conference

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Image: Window Rock National Monument; Window Rock, AZ

PRESENTATION OVERVIEW

- Purpose
- Background
  - The Navajo Nation
  - Uranium Properties and Usage
  - Radon Properties and Health Effects
- AIMS
  - I Conduct An Indoor Radon Survey On The Navajo Nation
  - II Develop An Indoor Radon Prediction Model On The Navajo Nation
  - III Conduct A Validation Study
- Questions

BACKGROUND

THE NAVAJO NATION

- Largest Indian Reservation in the US
  - 27,000 square miles
  - Hopi Reservation
- Comprised
  - 5 BIA (Bureau of Indian Affairs) Agencies
  - 110 Chapters
- Reside on the Navajo Nation

Figure 1: Map of the US with the Navajo Nation Highlighted
Source: NNDOH (2013)

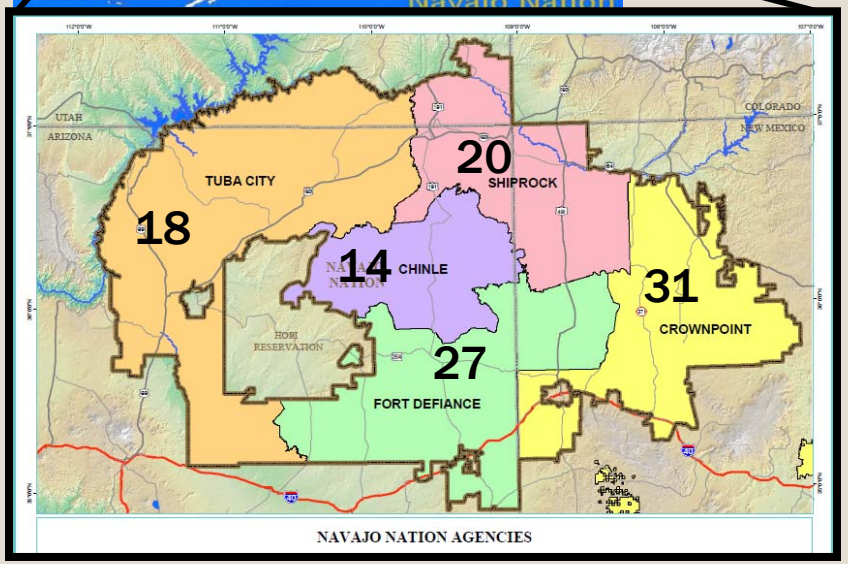


Figure 2: Map of the Navajo Nation Agencies
Source: EPA AUM and The Navajo Nation (Section 3)

ABANDONED URANIUM MINES (AUMS)

- Extensive uranium mining in the 1950s and 1960s
- Many of these mines abandoned around 1970
- 1993: Congressional subcommittee meeting on AUMs
- 1994: Navajo AUM Project
- Geographical Information Database
  - AUMs
  - Water sources
  - Nearby residence
  - Sediment Soil Uranium (ppm)

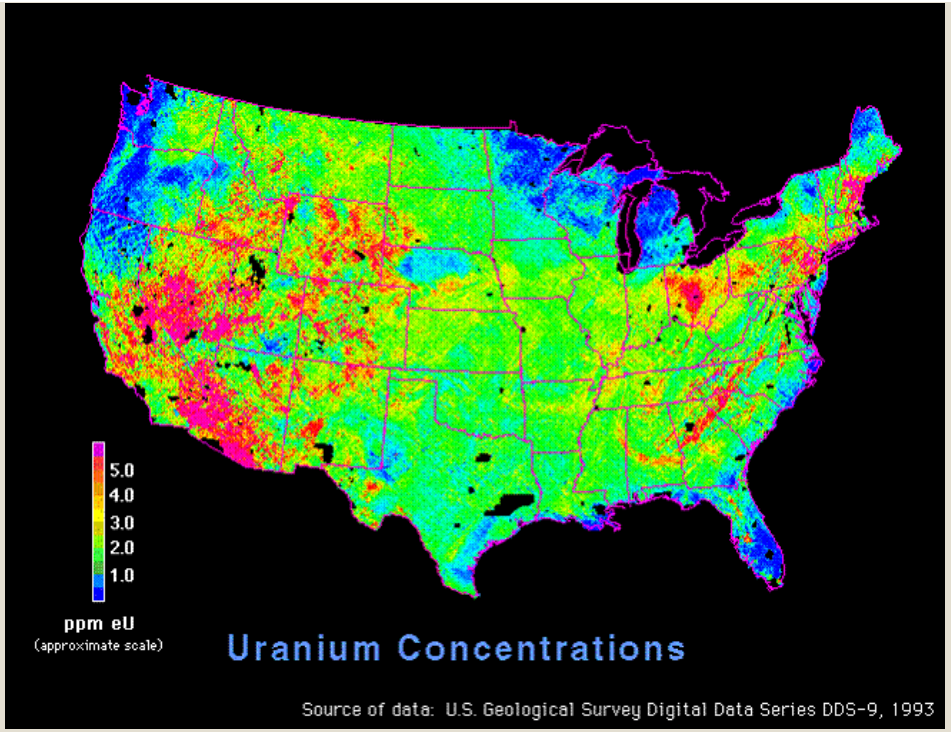


Figure 3: Map of US Uranium Concentration
Source: Uranium Resources and Environmental Issues (2013). Retrieved from http://energy.cr.usgs.gov/images/other/uranium/uranium_concentrations.gif

URANIUM (^{92}U)

- Naturally found in the environment
- Radioactive element
- Three naturally occurring isotopes
  - ^{238}U (99.274%)
  - ^{235}U (0.72%)
  - ^{234}U (0.0057%)
- Uses
  - Main: nuclear
  - Depleted: military
  - Enriched: nuclear weapons

Figure 5: Yellowcake

Source: World Nuclear Association (2013). Retrieved from http://world-nuclear.org/Nuclear-Basics/How-is-uranium-ore-made-into-nuclear-fuel-/#.UmWtB_k7301

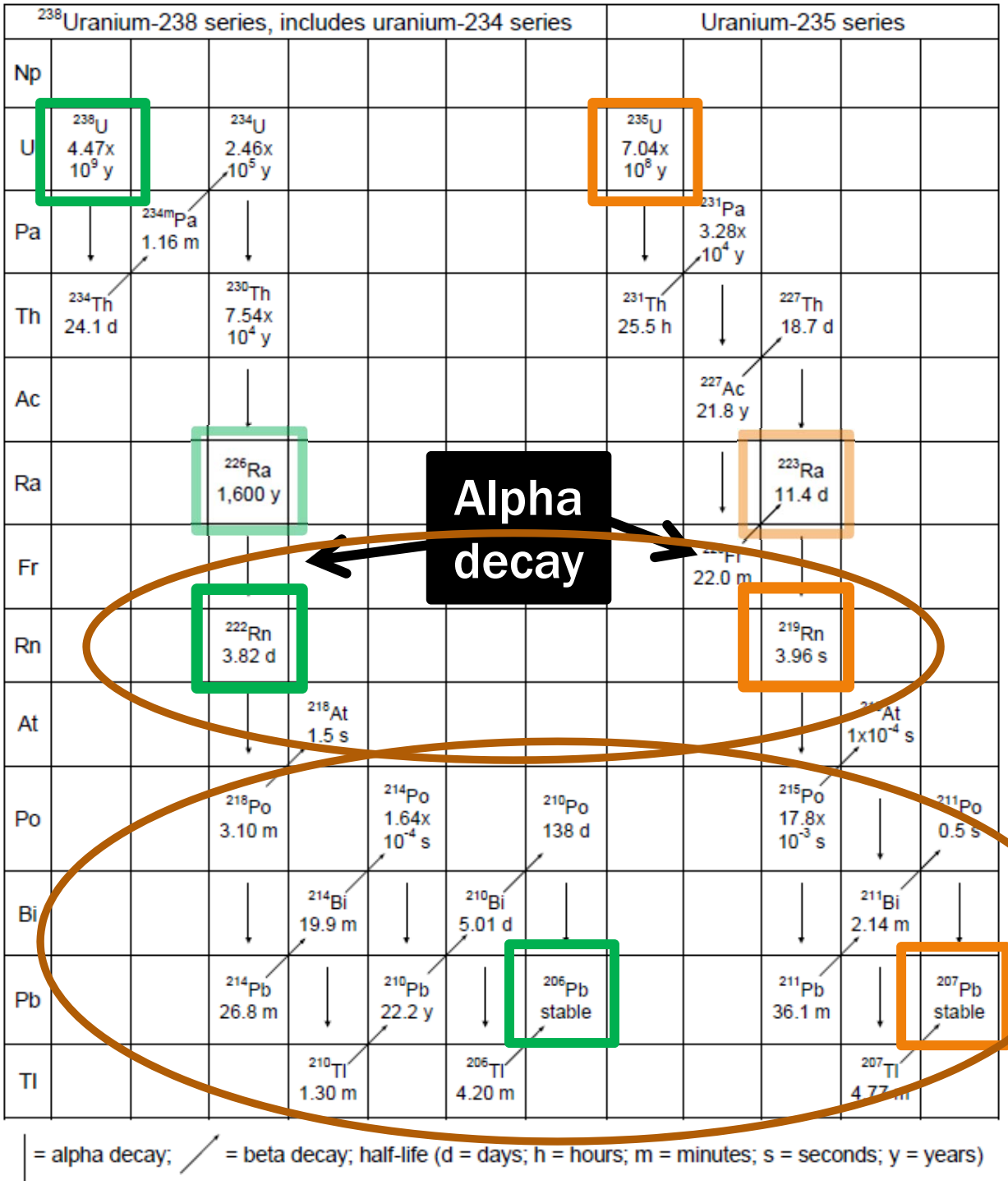


Figure 6: Uranium Decay Chain
Source: ATSDR (1999)

RADON

- Radioactive noble (inert) gas
- Decays quickly to progeny
  - ^{220}Radon ($PT_{1/2}$= 56 seconds)
  - ^{222}Radon ($PT_{1/2}$= 3.82 days)
- Properties
  - Heavy gas
  - Collects in basements
  - Colorless, odorless, and water soluble
- Emits alpha particle during decay
- Concentration in air
  - Radon pCi/L (1pCi/L=37 Bq/m^3)
  - Radon progeny: Working Level (WL) or Working Level Month (WLM)

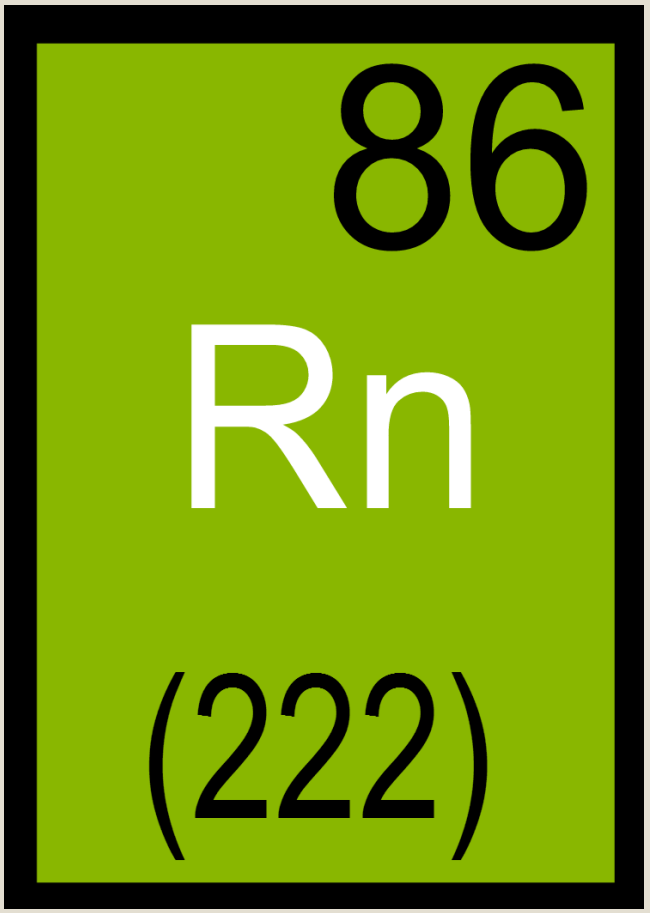


Figure 7: Radon Chemical Symbol
Source: Retrieved from
http://commons.wikimedia.org/wiki/File:Radon.svg

TOXICOLOGICAL PROFILE OF RADON

- Group 1 Carcinogen (IARC Monograph)
- Primary Route of Exposure
  - Inhalation of radon and radon progeny
- Radon progeny exposure in the respiratory tract
  - Unattached - very small particles
  - Attached due to electric charge to dust particles
- Clearance of particles
  - Mucociliary transport
  - Phagocytosis via lung macrophages
  - Transfer to other tissues

AIMS

- AIM 1: To conduct an indoor radon survey among a sample of CUEJTH participants
- AIM 2: To create a geospatial exposure prediction 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 prediction model against observed indoor radon concentrations

AIM - 1
METHODS

AIM 1 - INDOOR RADON SURVEY

- CUEJTH "CUE"
  - Program is sponsored by the Navajo Area Indian Health Service
  - Mission
- CUE Participants
  - Volunteers
  - Criteria

Figure 8: CUEJTH Logo
Source: Retrieved from http://hsc.unm.edu/pharmacy/healthyvoices/DiNEH_Documents/QUE_Presentation.pdf

POPULATION PROPORTION BY REGION

Table 1: CUEJTH Population and Navajo Resident Proportion by Agency

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

*2010 US Census

MULTISTAGE SAMPLING

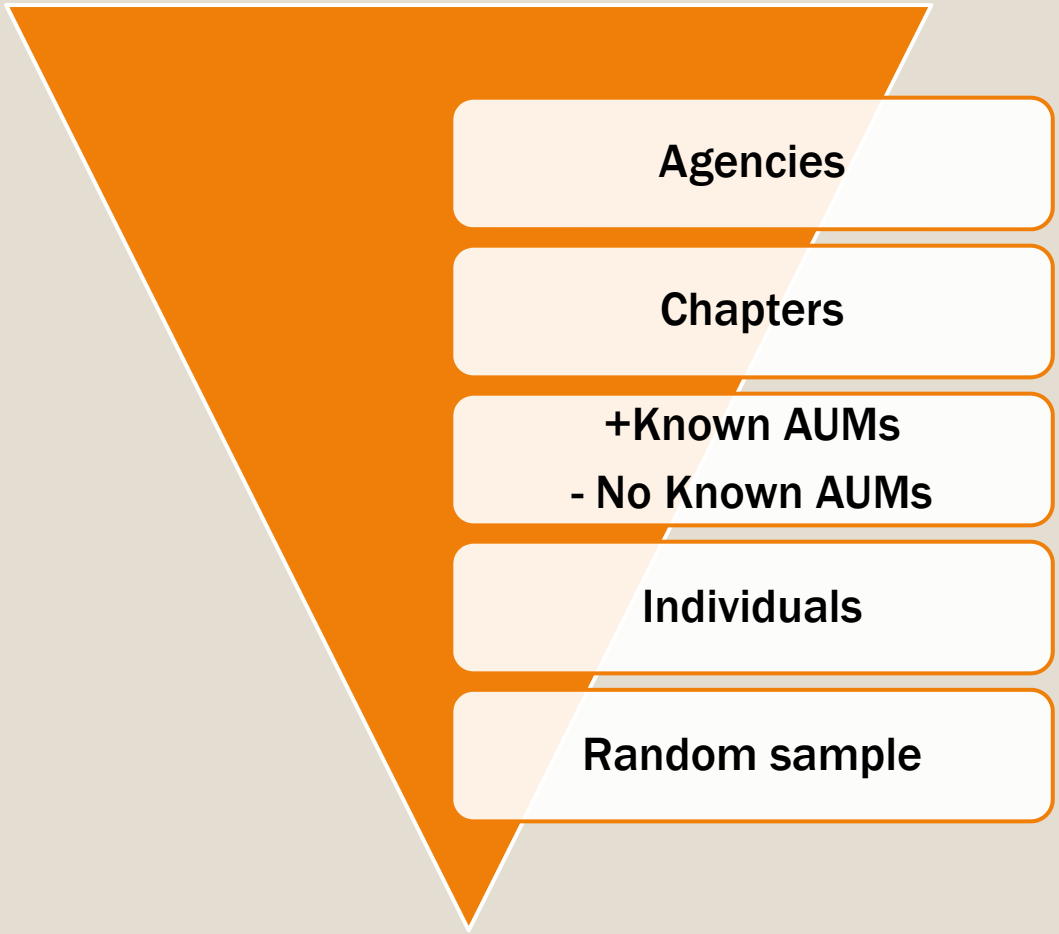


Figure 9: Sampling Strategy

DATA COLLECTION

- Phone Calls
  - Introduction
  - Oral Consent
- Two Visits Per Home
  - Written Consent
  - Home characteristics
    - Developed
    - Type of home
    - Ventilation characteristics
  - Indoor Radon Samples
  - Geolocation
    - Latitude/Longitude
  - Elevation (Feet)
  - Temperature (°F) retrospective

Figure 10: House Cartoon
Source: Google Images

Figure 11: Garmin GPS Device
Source: Google Images

HOUSE TYPE

- Mobile Homes
- Hogan
- Wood
- Mix (Wood/Cement)
- Mix (Concrete/Cement)

Figure 12: Mobile Home
Source: Google Images

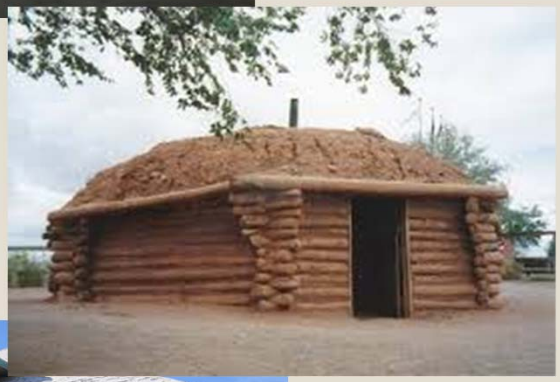


Figure 13: Hogan
Source: Google Images

Figure 14: Concrete/Cement
Source: Google Images

PREDICTORS OF RADON EXPOSURE

- Home type
  - Proximity to AUMs
- Pressure difference
- Soil characteristics
- Groundwater
  - Movement/displaces radon
  - Absorbs radon
- Weather

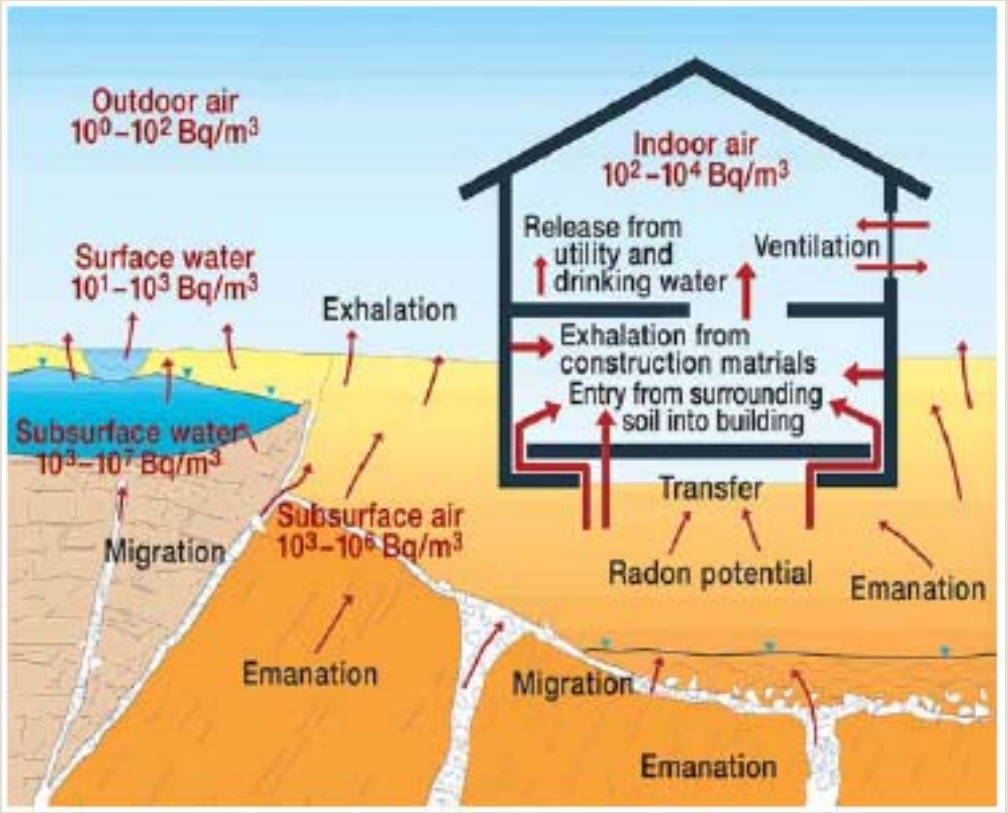


Figure 15: Radon In The Environment
Source: Schmid K., Kuwert T., & .Drexler H. (2010)

INDOOR RADON SURVEYS

- Navajo Nation Air & Toxic Department
- US EPA Protocol
  - Locations to be tested
- Type of kit
  - Short term
  - Testing time: 3-7 days
- Measures Indoor Radon Concentration
  - Units (pCi/L)

Step 1: Fill it out

Step 2: Hang it up

Step 3: Close it up

Step 4: Mail it in

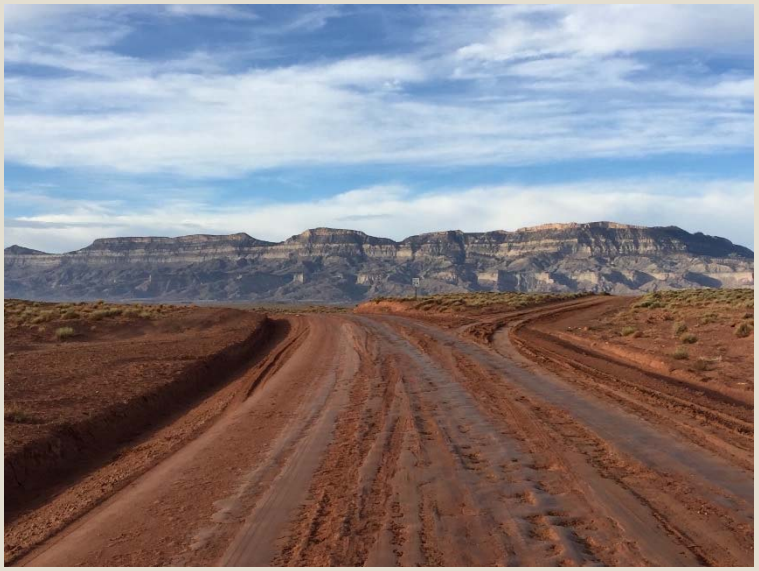
Figure 16: AirChek Short-Term Radon Test Kit Instructions
Source: Retrieved from http://www.radon.com/radon/radon_airchek.html

TRAVELING ON THE NAVAJO NATION

TRAVELED NEARLY 20,000 MILES IN 5.5 MONTHS

Images 3-5: Self-portraits on the Navajo Nation

TRAVELING ON THE NAVAJO NATION



Images 6-9: Self-portraits on the Navajo Nation

RESULTS

RESULTS - PARTICIPANTS

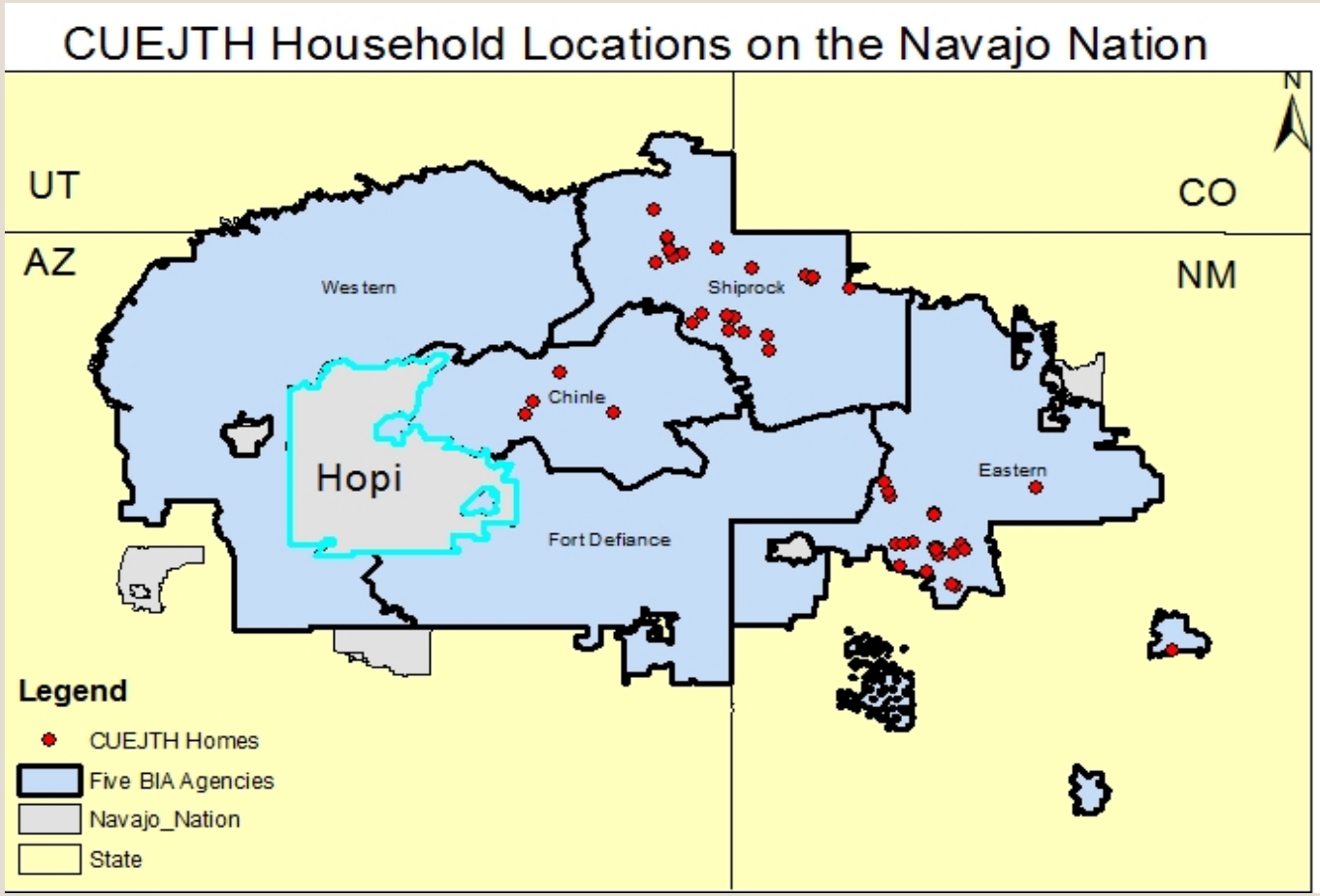


Figure 17: CUEJTH Homes Across the 5 Navajo Nation BIA Agencies

RESULTS - PARTICIPANTS

Table 2: CUEJTH Household Analytic Sample

Agency	Shiprock/Northern	Crownpoint/Eastern	Chinle/Central
Total Participants	65	199	30
Available for Follow-Up	57	183	27
Homes Sampled	23	24	4
Measurement Rate (%)	40	13	15

PROPORTION OF HOMES WITH CRAWL SPACE

Table 3: Proportion of Home Types with Crawl Space

Type of Home	Crawl Space N=51	Crawl Space (%)
Mobile	12	100
Hogan	2	50
Wood	27	41
Mix (Cement/Wood)	2	0
Mix (Concrete/Cement)	8	38

MEAN INDOOR RADON [PCI/L] BY HOUSE

Table 4: 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
Wood	27	1.2	2.5	1.6	1.0	0.1	3.4
Hogan	2	2.0	1.0	2.0	0.0	2.0	2.0
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

LOG MEAN HOME INDOOR RN [PCI/L] VS TEMPERATURE (°F)

- Scatter plot comparing log mean indoor radon [pCi/L] vs temperature (°F)
- Slope, m= -0.10
- Temperature restriction

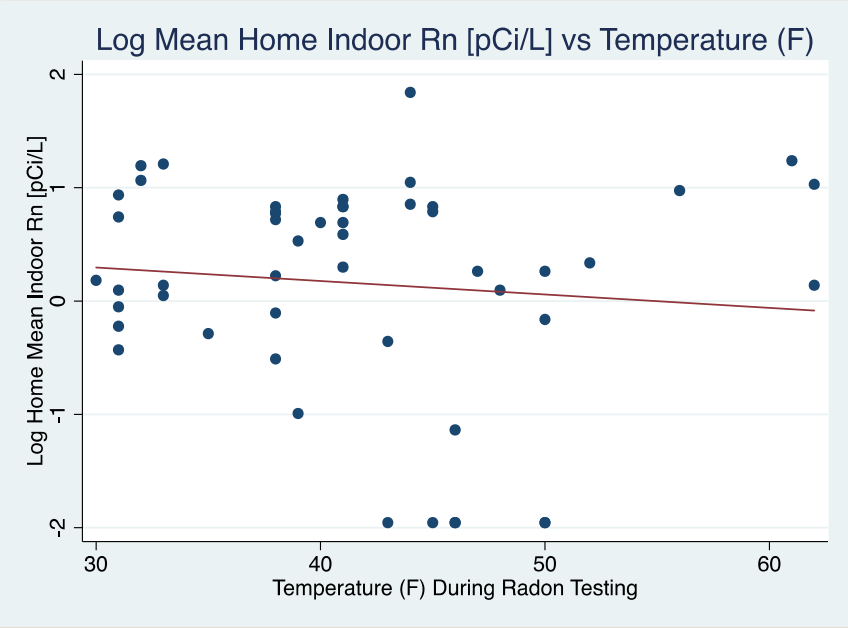


Figure 18: Log Mean Indoor Radon [pCi/L] vs Temperature (°F)

LOG MEAN HOME INDOOR RN [PCI/L] VS ELEVATION (FEET)

- Scatter plot comparing log mean indoor radon [pCi/L] vs elevation (feet)
- Slope, m= -0.40

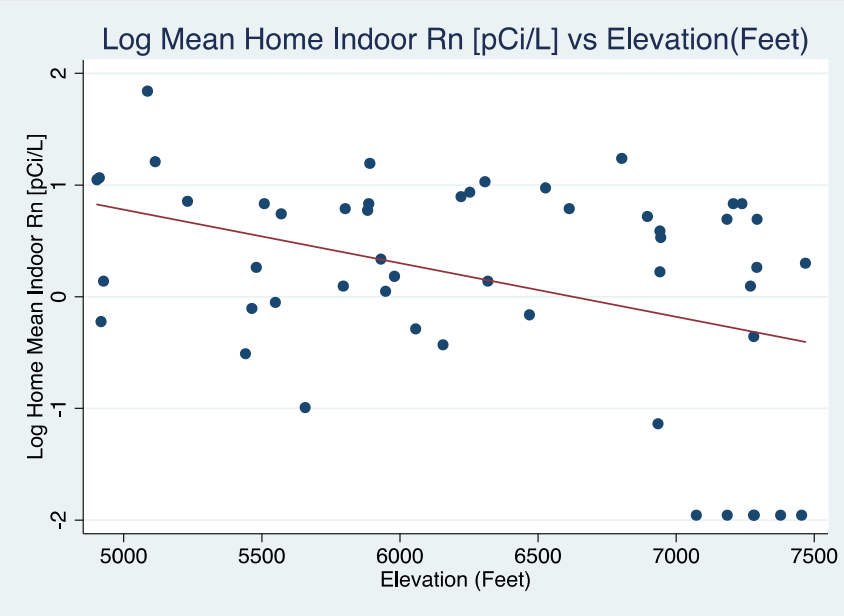


Figure 19: Log Mean Indoor Radon [pCi/L] vs Elevation (Feet)

CONCLUSIONS – AIM 1

- Mean Indoor Radon Concentration Levels
  - Mobile Homes observed to have lowest levels
  - Concrete/Cement homes to have highest levels
- Effect of Temperature
- Effect of Elevation
- Key Take Home Messages
  - House type observed to be associated with indoor radon [pCi/L]
  - Temperature observed to be associated with indoor radon [pCi/L]
  - Elevation not as strong association, but related to temperature

AIM - 2

AIM 2 – EXPOSURE PREDICTION MODEL

- AIM 2: To create a geospatial exposure prediction model characterizing potential exposure to indoor radon for residents of the Navajo Nation
- Background Previously Observed
  - Navajo Nation has varying indoor radon levels across agencies
  - Different Geographic regions have different prevalence of AUMs (GIS database)
  - Soil Sediments and water surveys conducted show wide variations across regions
- Geospatial Predictors of Indoor Radon Exposure
  - Previous study like Swiss study of residential indoor radon
- To develop a similar geospatial model on the reservation we need:
  - Larger sample size
  - Across all five agencies on the Navajo Nation
- SOLUTION: Navajo Birth Cohort Study (NBCS)
  - Approach, combine NBCS with CUEJTH data to build geospatial model
  - Assess
    - Collections methods- need similar across two studies
    - Similar classification of home type

NAVAJO BIRTH COHORT STUDY

- Epidemiologic study being conducted on the Navajo Nation
- Home Environmental Assessments
  - Trained field staff
  - Conducted across all 5 Navajo Nation BIA Agencies
- Collected Indoor Radon Measurements
  - Collected throughout the year
  - Similar method as with CUEJTH home indoor radon kits
- House Information
  - Type (similar categories as with CUEJTH homes)
  - Geolocation (latitude and longitude)
- Elevation (Feet)
- Temperature (°F)

COMBINED HOUSE CLASSIFICATION

- CUEJTH – previously described
- NBCS
  - Reclassified using same categories as CUEJTH
- Lost some detail on house characteristics
  - Crawl space about NCBS home
  - Ventilation
  - Other detailed (windows, shifted doors, cracked floors)
- Successfully harmonized NBCS home categories with CUEJTH homes

SWISS STUDY OF INDOOR RADON - 1

- Large population-based residential study of radon levels (Huari et al., 2013)
- Developed predictions of indoor radon
- Used multivariate log-linear model
- Predictors of indoor radon
  - Building type
  - Soil texture and composition
  - Building age
  - Degree of urbanization
  - Floor of the building

SWISS STUDY OF INDOOR RADON - 2

- Similar results between model and measurements
  - Model-based mean = 84.1 Bq/m^3
  - Prediction-based model = 78 Bq/m^3
- Advantages:
  - 1) Model-based allows prediction of radon exposures at other sites
  - 2) Measurement-based approach- assess radon exposure distribution
- Based on this model's performance, we felt a similar model developed for the Navajo Nation could predict indoor radon levels.
- Implication – could assist the Navajo Nation EPA indoor radon program to identify areas with potentially high levels of indoor radon

METHODS

STUDY DESIGN

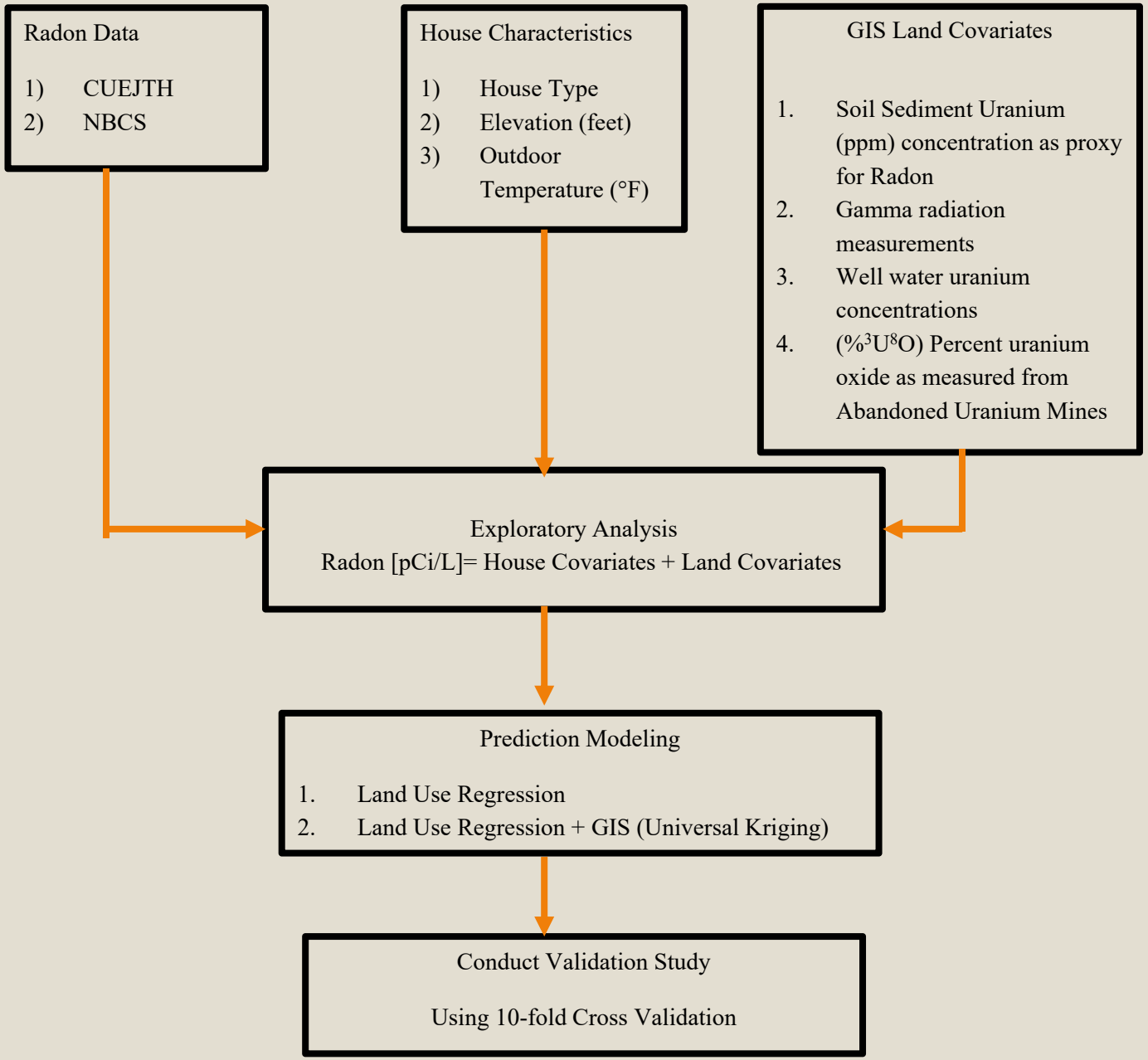


Figure 20: Flow Diagram in Developing Home Indoor Radon Prediction Model

ANALYSIS OF "HOUSE" COVARIATES IN THE COMBINED DATA SETS

- Bivariate analyses
- Correlation Coefficients
- Land Use Regression Model

Table 5: 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

MODEL SELECTION FOR GIS BASED "LAND" COVARIATES

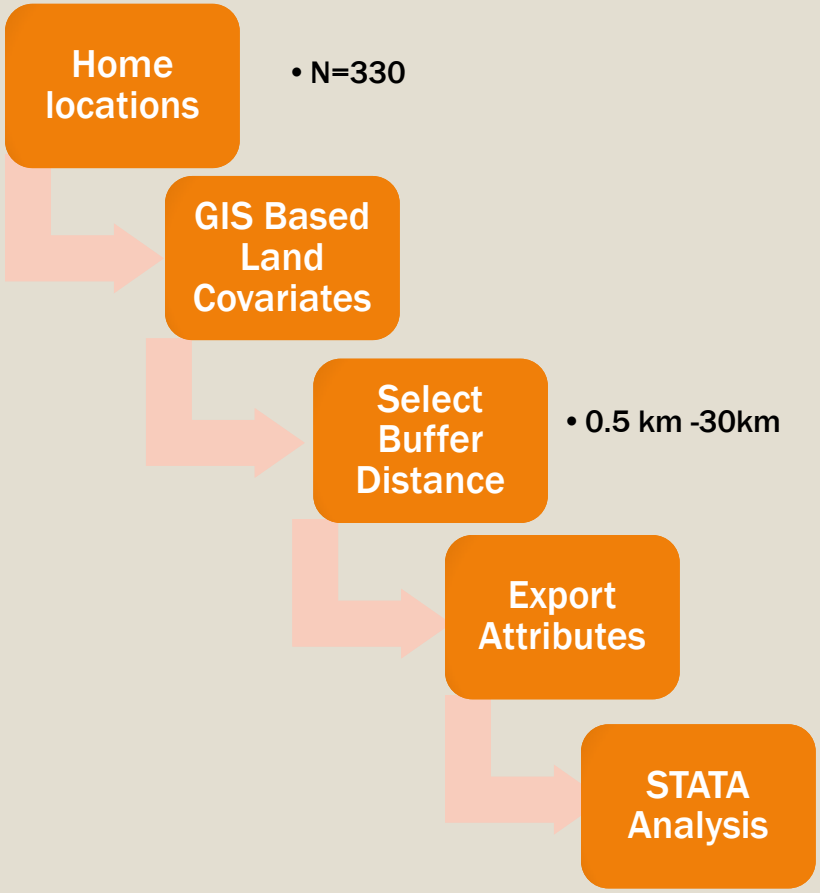


Figure 21: Flow Diagram in Model Selection for GIS Based "Land" Covariates

- Possible GIS Covariates
  - Terrestrial Gamma Radioactivity
  - % Uranium Oxide, $\%U^3O^8$
  - Uranium Measurements Collected from Water
  - Sediment Soil Uranium Concentration (ppm)

SELECTION OF GIS BASED "LAND" COVARIATES

Table 6: 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

LAND USE REGRESSION (LUR) MODEL

- **Land Use Regression Model**
  - **Combines House + GIS Covariates**

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

- 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

APPROXIMATION OF UNIVERSAL KRIGING

- Combination
  - Land Use Regression (LUR)
  - GIS
- LUR with Cross-Validation (CV)
  - Generate out of sample CV predictions
  - Generate out of sample CV LUR residuals
  - Import CV LUR residuals - ArcMap
  - Smooth CV LUR residuals using ordinary kriging in ArcMap
  - Extract CV LUR residual estimate for each home
- Evaluate Model Performance
  - Measured Indoor Radon
  - Predicted Indoor Radon

  (CV predicted + CV LUR residual estimate)

Figure 22: Kriging
Source: esri (2014)

RESULTS

COMBINED INDOOR RADON DATA

- CUEJTH
  - 51 homes
  - 3 BIA Agencies
- NBCS
  - 289 homes
  - 5 BIA Agencies
- Total 330 homes

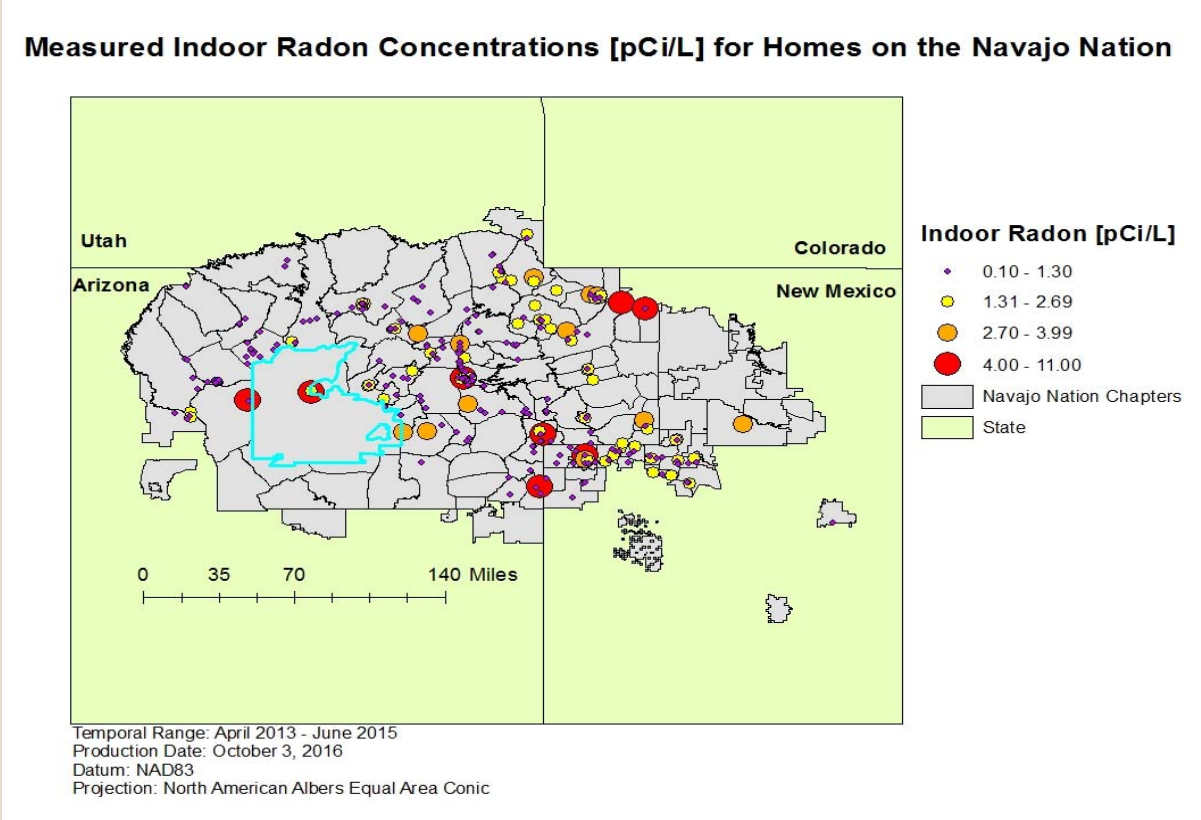


Figure 23: Mean Indoor Radon Concentrations [pCi/L] for Homes on the Navajo Nation

COMPARISON OF INDOOR RADON DATA

Table 7: 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

COMBINED INDOOR RADON DATA

Table 8: 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

BOX PLOT COMPARISONS OF MEAN HOME LOG INDOOR RADON [PCI/L] BY HOUSE TYPE IN THE COMBINED DATASET

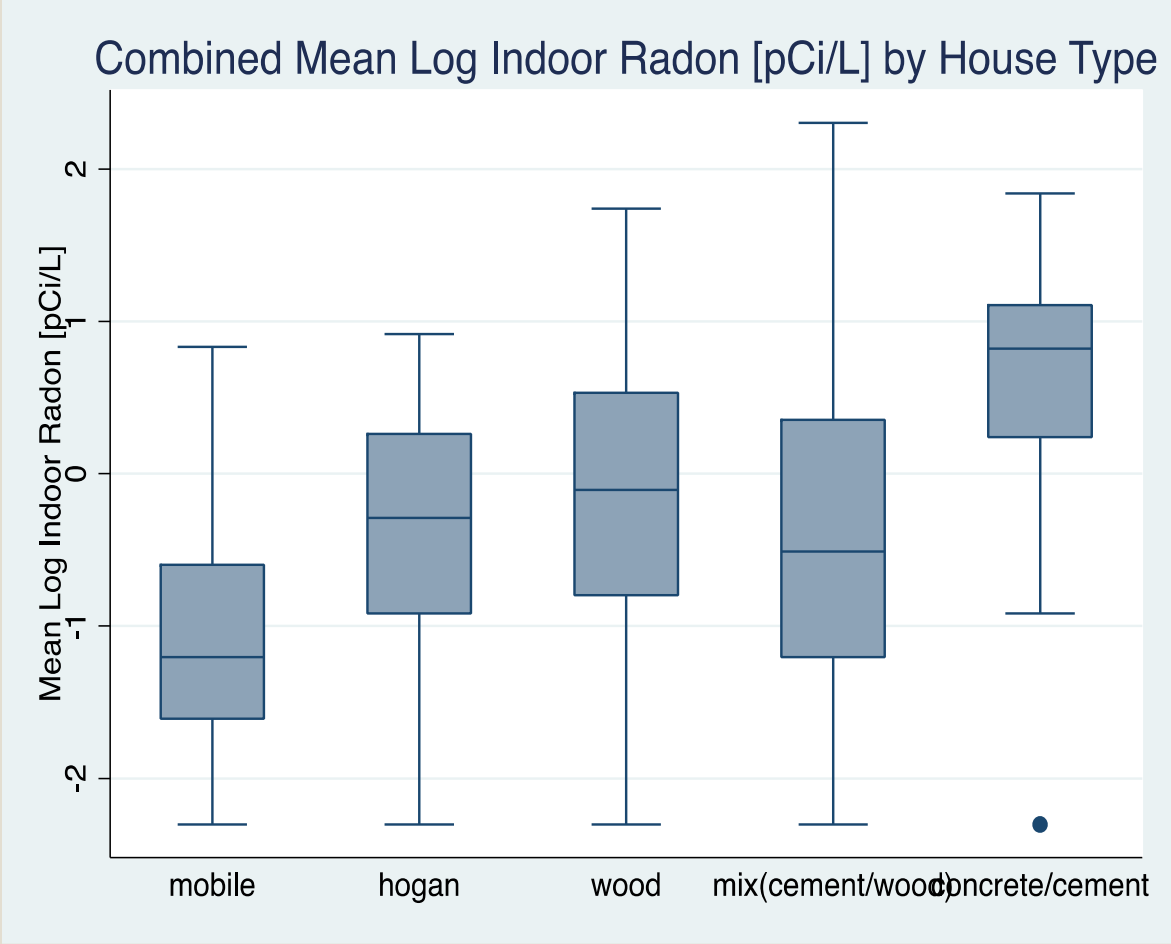


Figure 24: Box Plot Comparisons of Mean Home Log Indoor Radon [pCi/L] by House Type in the Combined Dataset

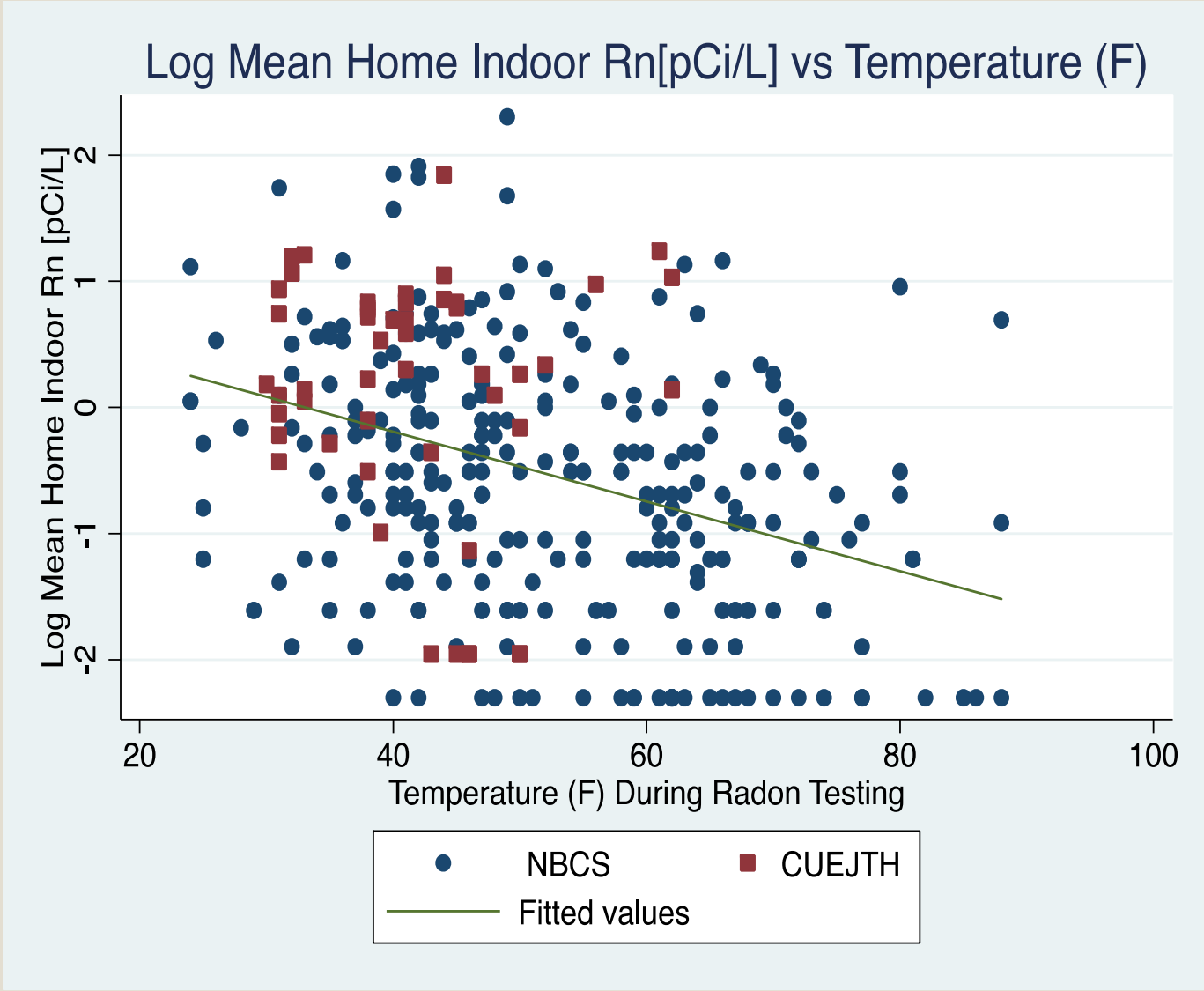


Figure 25: Mean Home Log Indoor Radon Concentration [pCi/L] versus Temperature (°F); Red Squares, CUEJTH homes; Blue Squares, NBCS homes

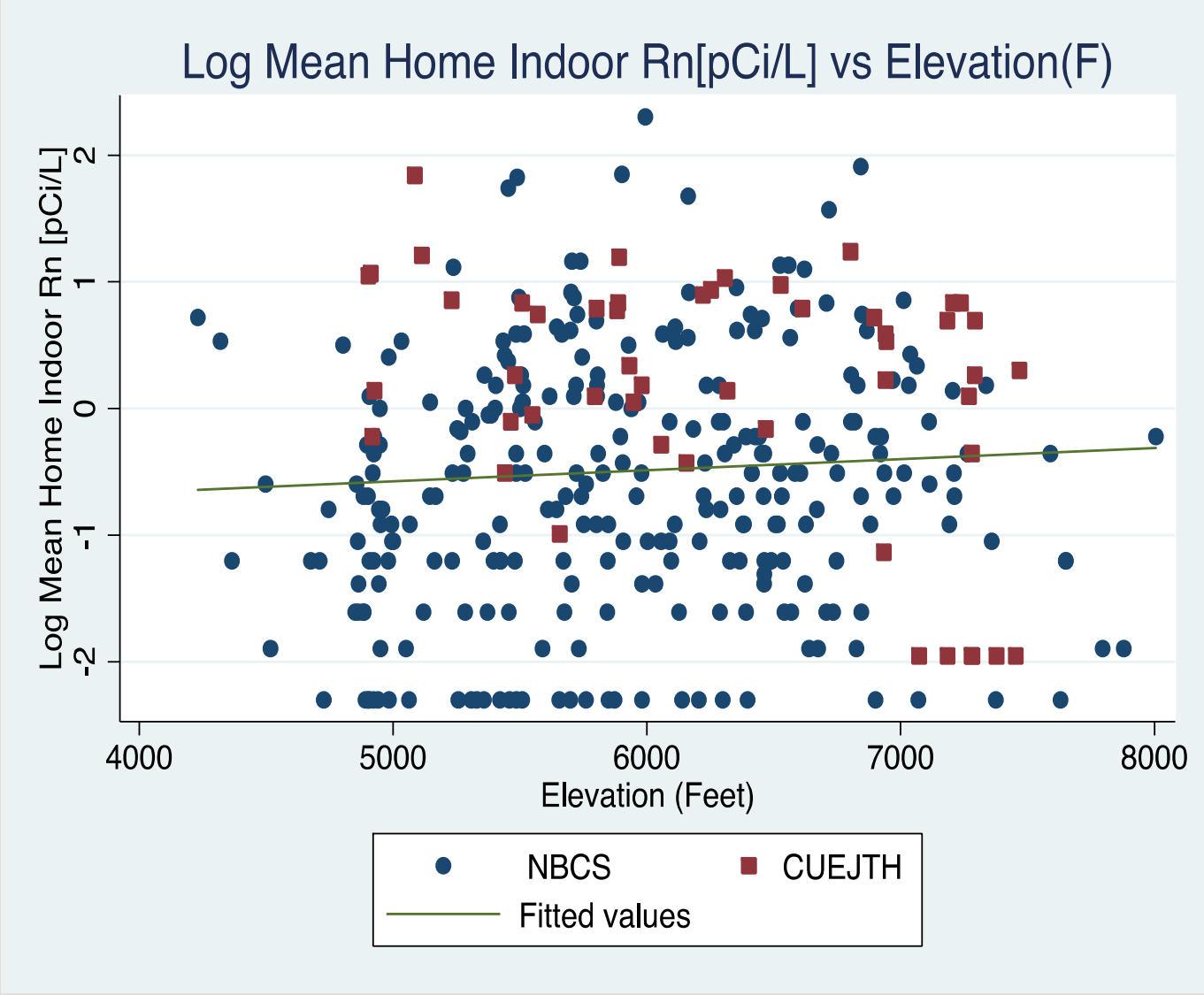


Figure 26: Mean Home Log Indoor Radon Concentration [pCi/L] versus Elevation (Feet); Red Squares, CUEJTH homes; Blue Squares, NBCS homes

SEDIMENT SOIL URANIUM (PPM)

Table 9: Sediment Soil Uranium Concentration (ppm)

Buffer Distance (km)	Samples	No. of Homes	p-value	Adj-R2
0.5	29	26	0.790	0.0365
1.0	101	71	0.305	0.1714
1.5	231	135	0.668	0.2636
2.0	433	180	0.133	0.2479
3.0	915	242	0.098	0.2125
4.0	2086	251	0.090	0.2262
5.0	3191	253	0.101	0.2235
7.5	7195	257	<0.001	0.1981
10.0	13154	263	<0.001	0.2031
12.5	20476	265	<0.001	0.2153
15.0	28681	271	<0.001	0.2212
17.5	38123	275	<0.001	0.2198
20.0	48476	281	<0.001	0.2242
22.5	60235	286	<0.001	0.2249
25.0	73339	289	<0.001	0.2270
27.5	88657	289	<0.001	0.2292
30.0	104512	289	<0.001	0.2303

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

EFFECT OF SOIL SEDIMENT URANIUM (PPM) IS DIFFERENT BY HOUSE TYPE

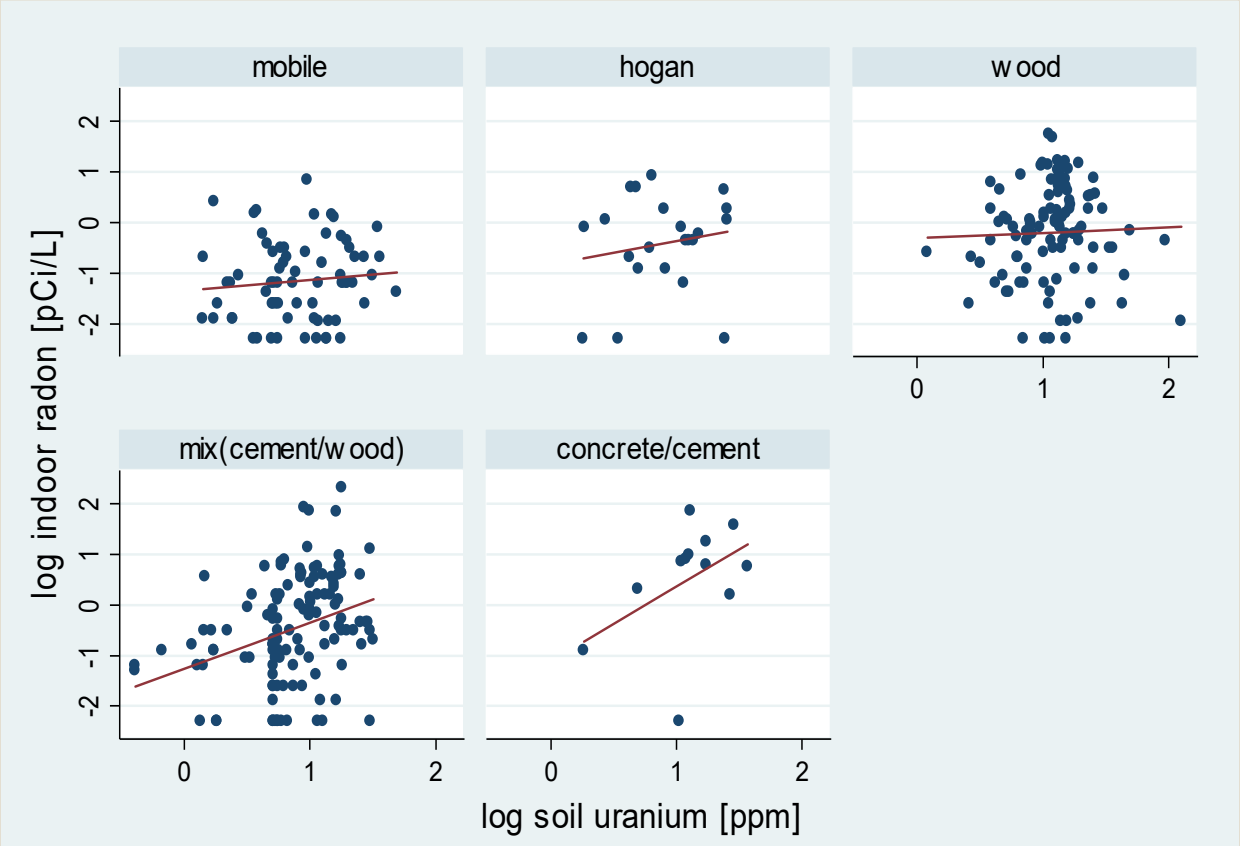


Figure 27: Mean Log Indoor Radon Concentration (pCi/L) vs Average Sediment Soil Uranium Concentration (ppm) by House Type

LAND USE REGRESSION MODEL

Table 10: 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			-
Wood	101			-
Mix (cement/wood)	95			-
Mix (concrete/cement)	12			-
Mean Temperature (°F)		-0.03	.004	<0.001
Elevation (Feet)		-.0001	.0001	0.188
Average Sediment Soil Uranium (ppm)*				-
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

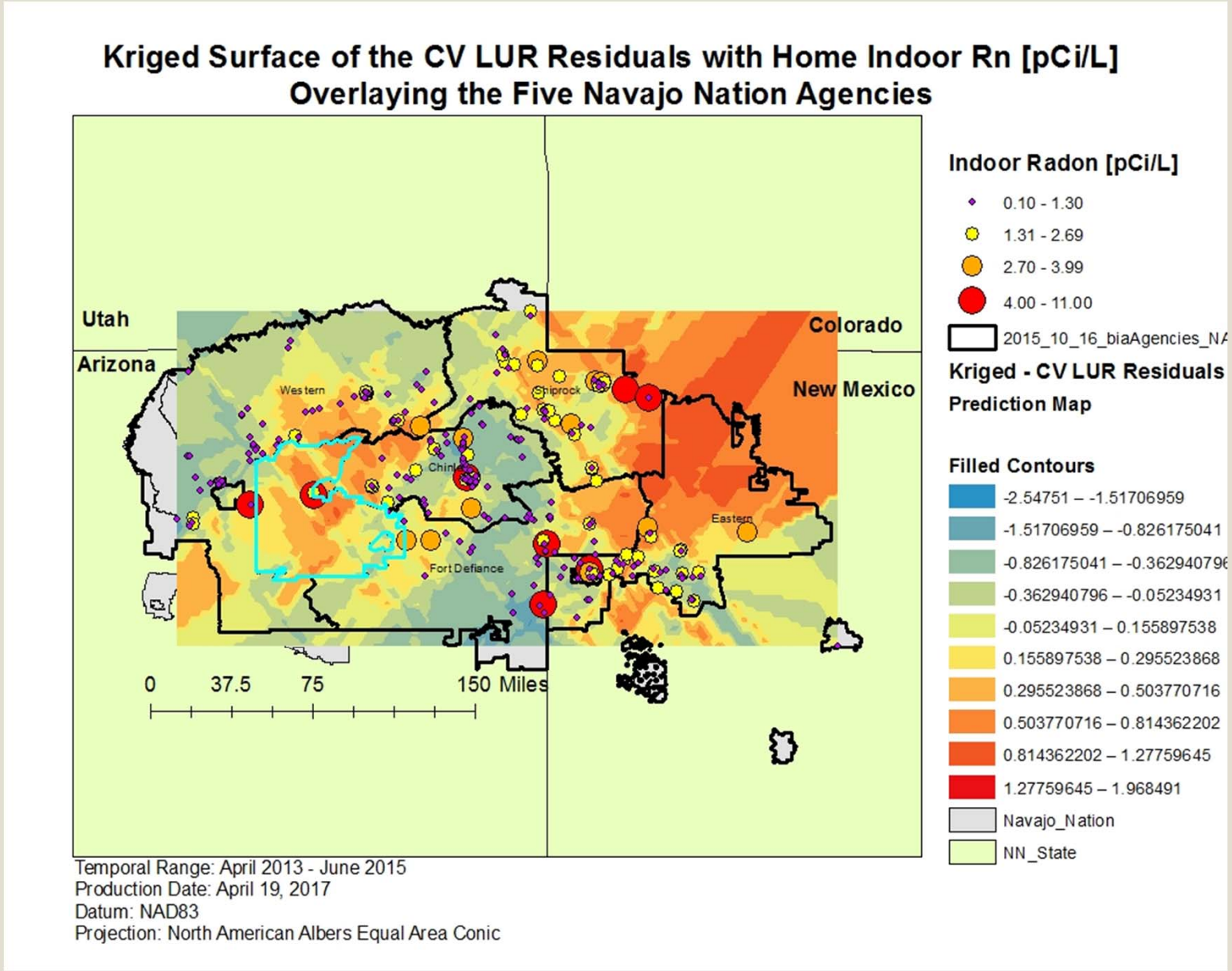


Figure 28: Kriged Surface of CV LUR Residuals Using Ordinary Kriging Overlaying the Five Navajo Nation Agencies

AIM 3 – PREDICTION MODEL PERFORMANCE

Table 11: Measures of Model Performance Using CV-R^2

	CV-R^2
Land Use Regression Model	0.284
2-Step Approach (LUR + GIS)	0.487

*289 homes

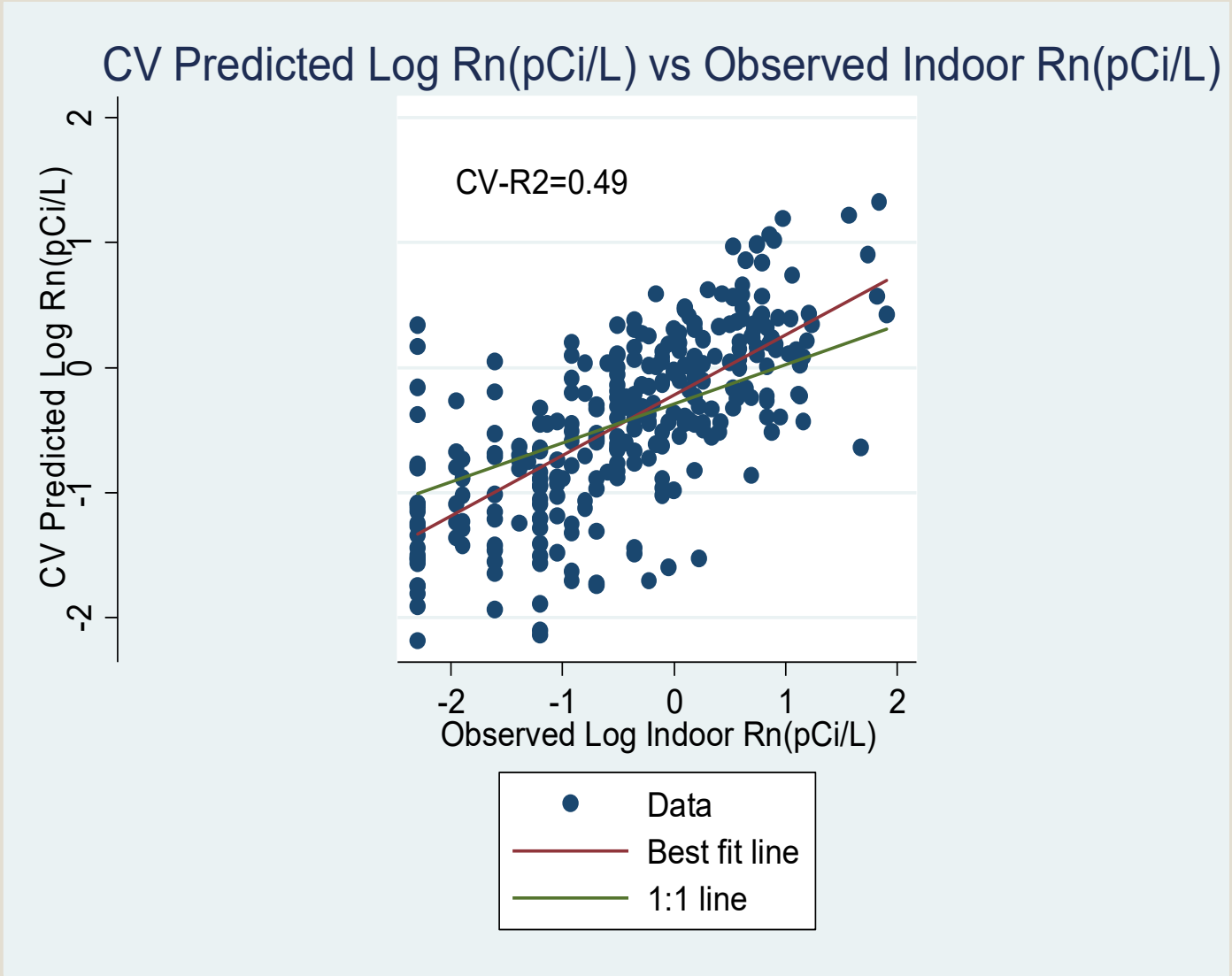


Figure 29: Scatterplot of Predicted Log Indoor Rn (CV Predicted LUR + CV Predicted Residuals as Estimated from ArcMap Using Ordinary Kriging) vs Observed Log Indoor Rn (pCi/L)

DISCUSSION

DISCUSSION

- The modeling approach
  - Appears to be effective
    - Swiss study: adjusted R^2=0.20
    - The combination of LUR covariates & universal kriging approximation
- Justification for Combining Two Indoor Radon Datasets
  - Similarities in House Type
  - Temperature
  - Elevation
- Exploratory Selection of GIS Based Land Covariates
  - Captured Spatial Structure
  - Sediment Soil Uranium Concentration (ppm)
    - Major contributor to model
    - Interaction with house type
- Semivariogram
  - Illustrates spatial correlation- two adjacent points are more similar compared to two points further apart

DISCUSSION

- Strength
  - Combining two indoor radon datasets created larger sample size
  - Better spatial coverage across the Navajo Nation
  - Similar indoor radon kits used in both datasets
  - Similar categorization of house types
- Limitations
  - Sediment soil uranium concentration not available for Western region of the Navajo Nation
    Excluded some homes and reduced sample size by 12%
  - Universal Kriging method might be more advantageous
- Implications
  - Assist the Navajo Nation in identifying certain house types or regions with potentially higher levels of indoor radon
  - Prioritize regions on the Navajo Nation for indoor radon testing
  - Encourage homeowners to test for indoor radon levels

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