A Model of Radon and a New Radon Map

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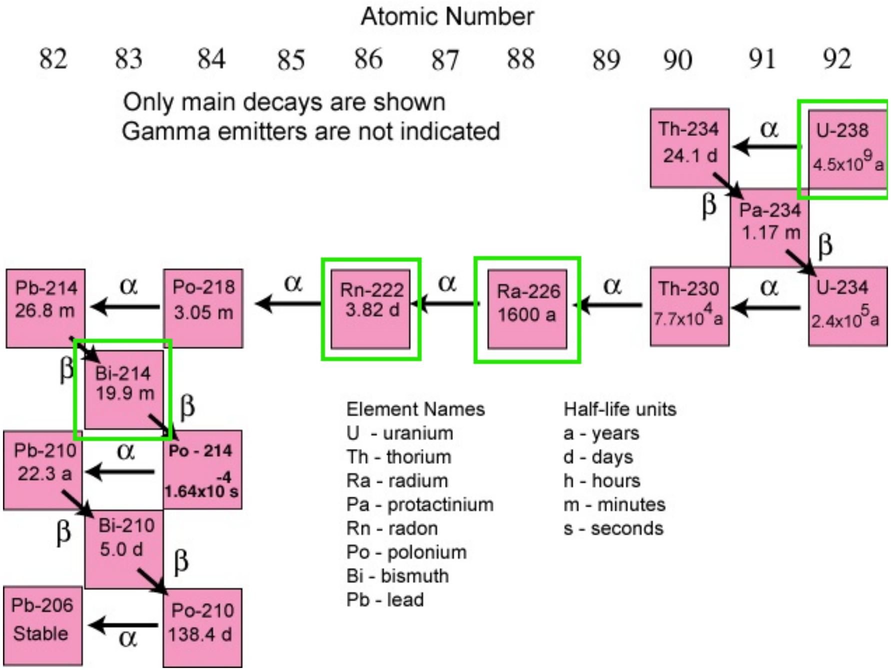
Main Challenges

How can we develop a generalized model of household indoor radon exposure that can be used to predict concentrations in areas without radon tests?

1. The distribution of geological units
2. The distribution of radon-producing elements (geochemistry)
3. Radon that has made it to the surface
4. Indoor Radon
   - 4.1 Omitted variables bias
   - 4.2 Radon testing sample selection

The Uranium-238 Decay Chain

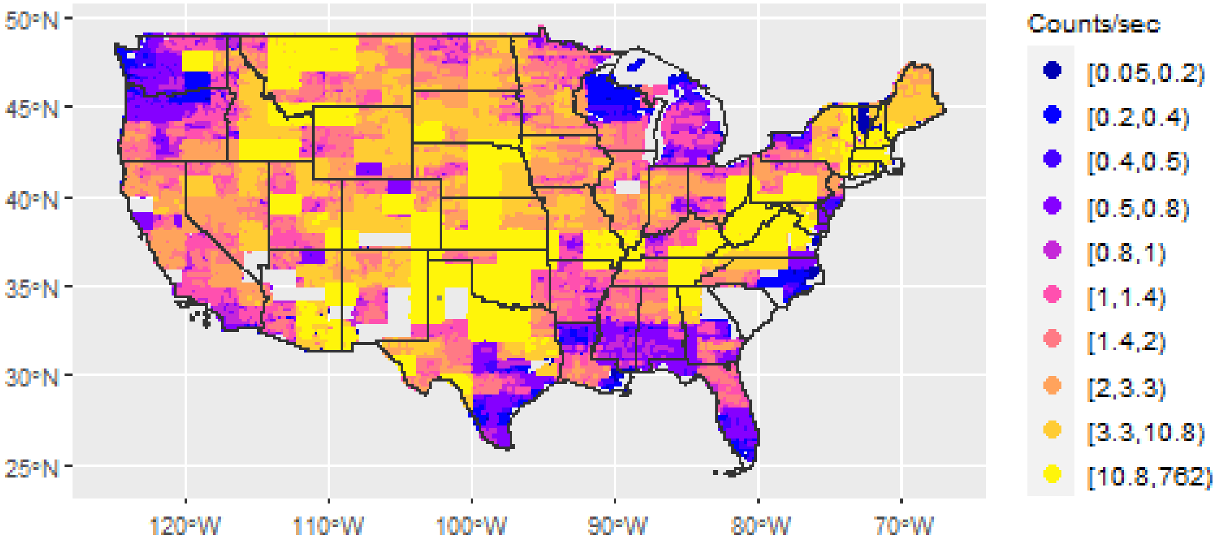


A Novel Approach to Radon Mapping

Atmospheric Bismuth-214 from the National Uranium Resource Evaluation (NURE)

- Results are derived from counts per second of gamma radiation falling within specific energy windows
- Does not appear in the widely-used processed NURE data by (Duval et al., 2005)
- Some survey quadrangles (areas) lack measurements entirely
- Significant leveling and measurement errors

Atmospheric Bi-214 Measurements from NURE

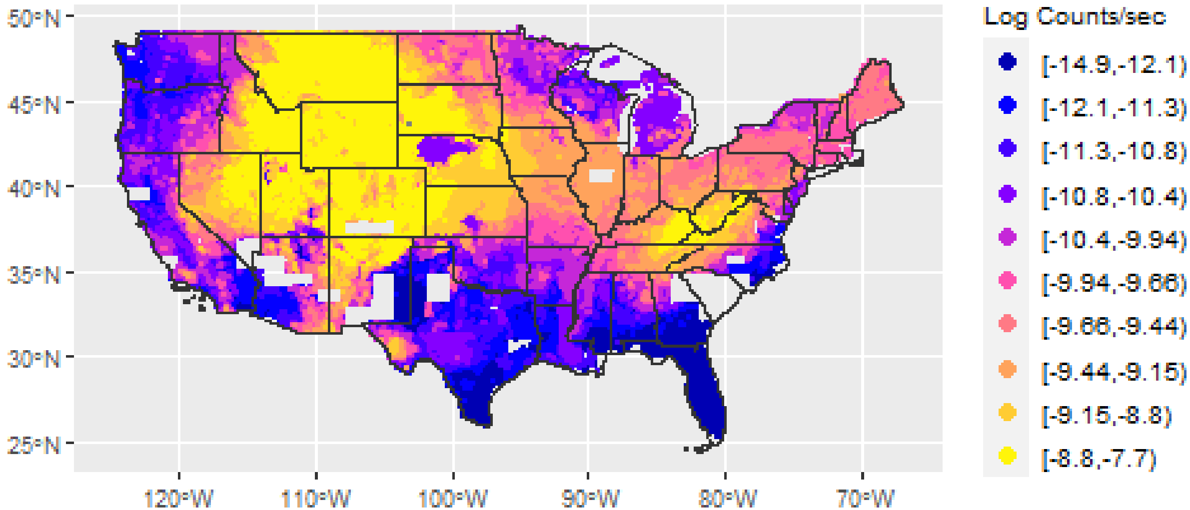


Notes: This Figure shows the 10 quantiles of the raw atmospheric bismuth-214 measurements in radioactive counts/second in the raw NURE data. Blue shades represent low radioactivity and yellow shades represent relatively high levels of radioactivity.

Modeling Atmospheric Bi-214

1. Geology lithology
2. Elevation, flow direction, slope, aspect, and terrain ruggedness from Danielson and Gesch, 2011
3. Physical and chemical soil characteristics from Soil Survey Staff, Natural Resources Conservation Service, 2016
4. Daily weather from Livneh et al., 2013
5. Land impervious measure from Dewitz and U.S. Geological Survey, 2021
6. Predicted geochemistry
   6.1 Quartz, aluminum, bismuth, calcium, cerium, iron, potassium, magnesium, niobium, phosphorous, lead, titanium, thallium, thorium, uranium, and yttrium
7. Flight line direction and altitude in NURE

PREDICTED ATMOSPHERIC BI-214



Notes: The final model is evaluated at the long-term weather normals so that the point predictions can be compared based on the mean distribution of weather across the US. Blue shades represent low radioactivity and yellow shades represent relatively high levels of radioactivity.

Modeling Indoor Radon

1. Individual homes from Zillow's ZTRAX database
    - Square footage, bathroom count, foundation type, number of stories, roof material type, basement indicator, interior floor materials, exterior wall materials, heating/AC, and more
2. 1.8 million individual radon test results from Alpha Energy Laboratories from 2005-2021
3. Daily weather, averaged over the last 3 days of the test from PRISM Climate Group, 2014
4. EPA Zone designations and CDC data on county testing rates (CDC, 2018)
5. Daily predictions of atmospheric bi-214 from the previous model

Indoor Radon Model Results

Nonparametric Local-linear Honest Random Forests

- Out-of-sample long-term alpha track tests: R-squared of 0.30
- Under-estimates short-term test results and long-term cumulative radioactive counts
- Accurately identifies 72 percent of tests above 2.7 piC/L

Indoor Radon Model Results

Parametric Poisson Structural Model

- Significant positive sample selection
  - Every 10 percent increase in the test probability increases indoor radon levels by 11.5 percent
- Homes with more bathrooms, larger square footage, and multiple stories produce lower indoor radon concentrations
- Slap, pier, and stone foundations reduce indoor radon levels
- Basements increase indoor radon levels by a factor of 1.5 (e.g. 2 piC/L in the first floor implies 3 piC/L in the basement)

Radon-Attributed Lung Cancer Deaths

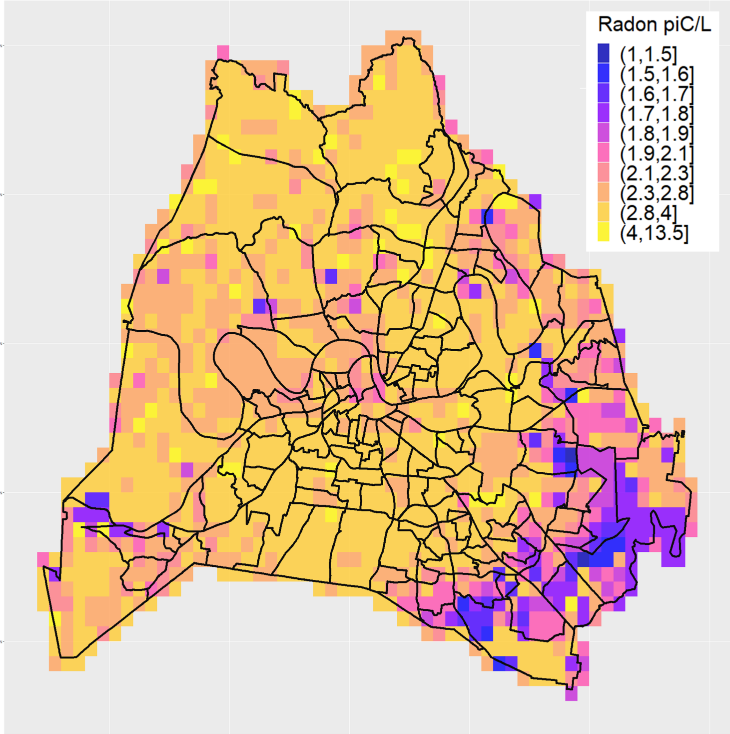
- Predicted long-term radon for 74 million single-family homes in Zillow's database
- Apply the EPA's linear dose-response model for lung cancer risk due to radon exposure[1]
- Use two exposure scenarios
  1. 100 percent first-floor exposure
  2. 60 percent of the time individuals are exposed to first-floor radon and 40 percent to basement levels of radon
- Implied radon-attributed fraction between 24 and 28 percent: 30,000-35,000 yearly radon-attributed lung cancer deaths

[1] Refer to the EPA's table here: https://www.epa.gov/radon/health-risk-radon

Cost-Effective Targeted Radon Remediation

- Predicted long-term radon for 74 million single-family homes in Zillow's database
- Remediation threshold of 2.7 piC/L,
- Reduce yearly radon-attributed lung cancer deaths by approximately 8,800
- The total costs would amount to approximately $3.02 billion
- Approximately $354,545 per avoided **lung cancer death**
  - Denman et al., 2013 find remediation using a 5 square km map of radon produces over $1 million per avoided **lung cancer case**

Square Kilometer Map of Davidson County



Additional Model Application - Home Sales

Does radon matter and are consumers willing to pay to avoid the risk and if so, at what price?

- 165,000 single-family residential transactions from 2001-2018, Davidson County (Nashville, TN)
- Increasing the radon levels above median risk (2-2.3 piC/L) *reduces* the sale price by about $3500 relative to the mean sale price
- Reducing indoor radon levels to those below the median risk *increases* the sale price of a home by $2100

Additional Model Application - Lung Cancer among US Veterans

- Over 400,000 veterans living in South East Central Census region
- Predicted long-term residential indoor radon concentrations generate a significant risk of lung cancer
  - A 10% increase in long-term first-floor radon exposure increases lung cancer risk by 6.2%
- Veteran populations with increased risk of lung disease (COPD, smoking, etc.) have a significantly increased risk of radon-attributed lung cancer

Future Work

Significant work to be done to refine our predictive models and fully characterize the distribution of indoor radon

- Random sampling
- Short-term versus long-term or continuous monitoring
- We need to understand how individuals respond to radon tests
    - How can we induce consumers to perform testing and subsequently install mitigation systems if high radon is revealed?
    - Optimal policy?

Questions

Thank You!

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