Relationships between geogenic radon potential and gamma ray maps with indoor radon levels at Caprarola municipality (central Italy).

1Ruggiero L., 1Bigi S., 2Brilli M., 2,3Ciotoli G., 4Dehandschutter B., 3Galli G.,
2Giustini F., 1Lombardi S., 3Lucchetti C., 2Pennica F., 3Pizzino L., 3Sciarra A., 2Sirianni P., 1Tartarello M. C., 2Voltaggio M.

1 Dipartimento di Scienze della Terra, Sapienza-Università di Roma, DST-Sapienza, Italy
2 National Research Council, Institute of Environmental Geology and Geoengineering, CNR-IGAG, Italy
3 Istituto Nazionale di Geofisica e Vulcanologia, Italy
4 Federal Agency for Nuclear Control - Belgium
The LIFE-Respire partnership

**DURATION:**
Start date 01/09/2017  End date 31/08/2020

Centro di Ricerca, Previsione, Prevenzione e Controllo dei Rischi Geologici, Sapienza Università di Roma, Rome – Italy (project leader)

Istituto di Geologia Ambientale e Geoingegneria, Consiglio Nazionale delle Ricerche, Rome - Italy

Istituto Nazionale di Geofisica e Vulcanologia, Rome - Italy

Federal Agency for Nuclear Control, Brussels, Belgium

Elica S.p.A., Fabriano (AN), Italy
The LIFE-Respire project objectives

**Radon rEal time monitoring System and Proactive Indoor Remediation**

1. **To demonstrate in 4 significant areas**, with different GRP in Italy and Belgium, a cost-effective and eco-friendly solution for Rn real-time measurement and remediation to keep indoor Rn levels below 300 Bq/m³ level (as indicated in European Directive 2013/59/EURATOM).

2. **To realize and install an intelligent and adaptable hybrid Rn remediation system** composed by sensors, an Air Quality Balancer (called SNAP) and an external additional fan-system (eolian and/or electric) working on positive pressure method.

3. **To construct a real time LIFE-RESPIRE geodatabase** of collected continuous Rn measurements, coupled with other geological and geochemical data, as well as building characteristics.

4. **To provide local authorities with Rn hazard guidelines**, i.e., guidance about Indoor Radon Abatement Acts, and about the risk, measurement and remediation of radon in workplaces and schools; **and real-time WebGis radon maps** for land use planning and health risk assessment, helping to prepare relevant national action plans (Articles 54, 74 and 103 in 2013/59/EURATOM).
Respire project activities

Preparatory actions

A1 Caprarola Site Characterization

A2 Permissions for Demonstration cases implementation

Implementation actions

B1 Prototype assembly and tests

B2 Implementation of demonstration cases including remediation measures

B3 Monitoring and WebGis

B4 Replicability potential evaluation and demonstrative case in Belgium

Monitoring of the impact of the project actions

C1 Monitoring of project impact indicators and LCA

C2 Socio-economic impact assessment

E Management

Public awareness and dissemination of results

D1 Dissemination planning and execution

D2 Networking
Objectives

1. To construct the geogenic radon potential (GRP) map of the Caprarola municipality (northern Lazio, central Italy) by using multivariate regression model (Empirical Bayesian Kriging Regression, EBKR).

2. To study the relationships between:
   • GRP and Rn indoor
   • Terrestrial gamma dose rate and Rn indoor
   • Indoor gamma dose rate and Rn indoor.
The Geogenic Radon Potential (GRP) defines the availability of radon generated in the ground for surface exhalation or infiltration into buildings.

**GRP of an area is directly measurable in the field by the Rn concentrations in the soil pores.** These quantities actually are available only regionally and/or locally.

Other factors control the GRP of a region: the source and the transport in the ground.

The transport is additionally affected directly/indirectly by factors related to tectonics, and geodynamic features i.e., active faults, seismicity, geothermal activity and volcanism.
The indoor radon mapping problem

- The spatial distribution of indoor Rn samples at large scale is often clustered.

- Indoor Rn usually shows strong variability at least on short geographic scale (i.e., non-autocorrelated and non-stationary spatial behavior) because of its multifactorial dependence (i.e., physical, meteorological and anthropic parameters).

- The direct interpolation of indoor Rn values beyond the boundary of an urban area could be a difficult and non-robust procedure to accomplish.
The radon mapping problem

- Alternative approaches consider the construction of Geogenic Radon Potential (GRP) maps by using available geological and geochemical information (i.e., rock permeability, faults, radionuclide content, etc.), calibrated by using soil gas radon.

- These data are more suitable to construct GRP maps because they are characterised by:
  - higher spatial autocorrelation
  - lower variability
  - not depend by anthropogenic factors
Methods

How Empirical Bayesian Kriging Regression works

- Empirical Bayesian Kriging Regression (EBKR) combines ordinary least square (OLS) regression and simple kriging to provide accurate predictions of moderately non-stationary data at a local level. It accounts for these local effects by dividing the input data into subsets of a given size before doing any modeling.

- EBKR estimates the semivariogram through a process of subsetting and repeated simulations and transforms the proxy variables into their principal components, that are used as the explanatory variables in the regression model. The PCs transformation also solves the problem of multicollinearity because each PC is uncorrelated with the others.

- Each principal component captures a certain proportion of the total variability of the explanatory variables; (in general few principal components up to 70% of the total variability).
Empirical Bayesian Kriging Regression

Methods

Advantages of EBKR

- Requires minimal interactive modelling
- Allows accurate predictions of non-stationary data
- Uses local models to capture small scale effects
- More accurate than other kriging methods for small datasets

Disadvantages of EBKR

- Processing is slower than other kriging methods
- Anisotropy is unavailable

The study area

Caprarola municipality (central Italy)

The study area is located about 100 km N of Rome, in central Italy.

Area: 58 km$^2$
Population (2017): 5417
Density: 94/ km$^2$
Methods

Geological setting

- volcanic rocks (tuffs and lavas), outcropping in whole area.
- sedimentary rocks (recent and lake deposits, mainly outcropping in the Western sector of the area.

• The volcanic products are particularly enriched on natural radionuclides, and they were traditionally used as building materials in the old center of the Caprarola village.

Simplified geology of the Caprarola municipality modified after the Geological Map of the Lazio Region (scale 1:25000) (Cosentino and Pasquali, 2012).

△ Soil samples
Methods
The Proxy variables

- Radionuclide content in Bq/kg (226Ra, 238U, 232Th, 40K) averaged on lithological types. 16 samples (high-resolution gamma spectrometer equipped with a low-background HPGe coaxial detector, GEM – EG&G ORTEC)

- **EMAN** = Emanation coefficient, averaged on lithology →
  \[ \eta = \frac{Rn_{cp}}{Rn_{tot}} = \frac{\text{Rn amount in connected pores}}{\text{total Rn amount}} \]  
  (Sasaki et al., 2004)

- **Diffusive RnFLUX** from the soil, averaged on lithology and calculated by →
  \[ J = \eta \rho_p (1 - \varphi) 226\text{Ra} \sqrt{\lambda D_0} e^{-\left(6\varphi R_s + 6\varphi^1 14\varphi\right)} \]  
  (Voltaggio et al., 2006)

- **GAMMA** = Terrestrial gamma dose rate → 187 samples
  (NaI γ-ray portable scintillator Scintrex GRS-500) Ordinary Kriging

- **CO2** = soil-gas CO₂ concentration → 178 samples (Draeger X-am 7000) Ordinary Kriging

- **Perm** = Permeability of soil/rocks → (measured in the field at the soil gas sampling points)
### Results

**Response variable: Soil gas radon**

<table>
<thead>
<tr>
<th>Soil gas radon sampling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil gas and permeability measurements</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Main statistics</th>
<th>N</th>
<th>Mean (95% CI)</th>
<th>GM (95% CI)</th>
<th>Min</th>
<th>Max</th>
<th>St.dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{222}$Rn (kBq/m$^3$)</td>
<td>180</td>
<td>157 (143-172)</td>
<td>130 (118-143)</td>
<td>17</td>
<td>865</td>
<td>99.2</td>
</tr>
<tr>
<td>$^{220}$Rn (kBq/m$^3$)</td>
<td>180</td>
<td>314 (286-341)</td>
<td>259 (235-286)</td>
<td>34</td>
<td>&gt;1000</td>
<td>183</td>
</tr>
<tr>
<td>CO$_2$ (% v/v)</td>
<td>178</td>
<td>0.68 (0.61-0.65)</td>
<td>0.55 (0.49-0.61)</td>
<td>0.06</td>
<td>3.1</td>
<td>0.47</td>
</tr>
<tr>
<td>K (m$^2$)</td>
<td>157</td>
<td>1.19E-11</td>
<td>4.13E-13</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TGDR (μS/h)</td>
<td>187</td>
<td>0.36 (0.34-0.38)</td>
<td>0.34 (0.33-0.36)</td>
<td>0.15</td>
<td>0.97</td>
<td>0.11</td>
</tr>
<tr>
<td>$^{226}$Ra (Bq/kg)</td>
<td>16</td>
<td>149 (120-179)</td>
<td>79</td>
<td>318</td>
<td>57</td>
<td></td>
</tr>
<tr>
<td>$^{238}$U (Bq/kg)</td>
<td>16</td>
<td>181 (142-219)</td>
<td>85</td>
<td>369</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>$^{232}$Th (Bq/kg)</td>
<td>16</td>
<td>253 (200-307)</td>
<td>23</td>
<td>481</td>
<td>104</td>
<td></td>
</tr>
<tr>
<td>$^{40}$K (Bq/kg)</td>
<td>16</td>
<td>744 (611-877)</td>
<td>317</td>
<td>1236</td>
<td>249</td>
<td></td>
</tr>
<tr>
<td>$^{222}$Rn Emanation</td>
<td>16</td>
<td>0.087 (0.076-0.099)</td>
<td>0.046</td>
<td>0.14</td>
<td>0.021</td>
<td></td>
</tr>
<tr>
<td>$^{222}$Rn flux (Bq/m$^2$/day)</td>
<td>16</td>
<td>7291 (6209-8373)</td>
<td>3730</td>
<td>11482</td>
<td>2030</td>
<td></td>
</tr>
</tbody>
</table>
Results - Proxy variable maps

Radionuclide content (U, K, Ra, Th)

Emanation coefficient
Results

Permeability – Terrestrial gamma dose rate
Results - Empirical Bayesian Kriging Regression

Cross validation results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inside 90 Percent Interval</td>
<td>90.740</td>
</tr>
<tr>
<td>Inside 95 Percent Interval</td>
<td>95.061</td>
</tr>
<tr>
<td>Mean Error</td>
<td>-0.543</td>
</tr>
<tr>
<td>Root-Mean-Square (RMS) Error</td>
<td>29.248</td>
</tr>
<tr>
<td>Mean Standardized Error</td>
<td>-0.007</td>
</tr>
<tr>
<td>RMS Standardized Error</td>
<td>0.956</td>
</tr>
</tbody>
</table>

Root Mean Square Standardized Error: This value should be close to 1
Results - Map of the GWR Rn estimates

• Simple Kriging have been applied to map the estimated values by GWR.

<table>
<thead>
<tr>
<th>Parameter</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Error</td>
<td>0.200</td>
</tr>
<tr>
<td>RootMeanSquare (RMS)</td>
<td>29.84</td>
</tr>
<tr>
<td>RMS Standardised</td>
<td>0.900</td>
</tr>
<tr>
<td>Average Standard Error</td>
<td>29.02</td>
</tr>
</tbody>
</table>
Results

Geogenic Radon Potential

[Map showing areas with different radon potential levels, with Vico lake and Ronciglione highlighted.]
Results – Radon Indoor Survey

Preliminary and short-time indoor radon measurement surveys were carried out in the Municipality of Caprarola by using charcoal canisters, in order to select buildings in which integrated seasonal radon measurements (in winter and summer) will be conducted.

<table>
<thead>
<tr>
<th>Caprarola</th>
<th>N</th>
<th>AM (95% CI)</th>
<th>GM(95% CI)</th>
<th>Median</th>
<th>Min</th>
<th>Max</th>
<th>Std.Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor Rn Bq/m³</td>
<td>82</td>
<td>677(491-863)</td>
<td>405(320-512)</td>
<td>364</td>
<td>14</td>
<td>5800</td>
<td>835</td>
</tr>
</tbody>
</table>

About 65% of the measured buildings are above the limit indicated in European Directive 2013/59/EURATOM.
Results (preliminary indoor radon survey)

GRP vs Indoor Rn

TGDR vs Indoor Rn

Coef of determination, R-squared = 0.836547
## Results – Indoor Gamma Dose Rate

<table>
<thead>
<tr>
<th>Location</th>
<th>N</th>
<th>AM (95% CI)</th>
<th>GM (95% CI)</th>
<th>Median</th>
<th>Min</th>
<th>Max</th>
<th>Std.Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGDR μS/h</td>
<td>116</td>
<td>0.48 (0.45-0.51)</td>
<td>0.46(0.43-0.49)</td>
<td>0.49</td>
<td>0.18</td>
<td>0.84</td>
<td>0.16</td>
</tr>
</tbody>
</table>

1 = center of the room, on the floor  
2 = center of the room, 1 mt above the floor  
3 = 1.5 mt from the walls  
4 = on the walls
Results (preliminary indoor radon survey)

IGDR vs Indoor Rn

The graph shows a good relationship between indoor gamma dose rate and indoor radon concentrations, thus confirming the contribution of the building materials for the Caprarola site.
Conclusions

The application of multivariable spatial techniques seems to be more appropriate to construct maps of the radon potential. The EBKR model has proven to be the best spatial regression model among the other classical (OLS) and spatial (GWR) model estimation.

GRP values estimated in correspondence of IR measurements at ground floors and cellars do not show a clear correlation with the IRC. However, IRC above 600Bq/m³ show a positive correlation with the terrestrial gamma dose values thus suggesting that in this case IRC could be mainly due to the radon emanation from the building materials (mainly tuff) rather than the geogenic potential of the soil and outcropping rocks.

The good relationship between indoor gamma dose rate and IRC confirms the contribution of the building materials for the Caprarola site.
THANK YOU FOR THE ATTENTION!!

www.liferespire.it  www.liferespire.eu
## Principal Component Analysis Results

<table>
<thead>
<tr>
<th>Factor</th>
<th>Factor Loadings (Varimax raw)</th>
<th>Extraction: Principal components (Marked loadings are &gt;.700000)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40-K</td>
<td>0.738</td>
<td>Factor - 1</td>
</tr>
<tr>
<td></td>
<td>-0.762</td>
<td>Factor - 2</td>
</tr>
<tr>
<td></td>
<td>-0.168</td>
<td>Factor - 3</td>
</tr>
<tr>
<td>EmanationCoeff</td>
<td>0.273</td>
<td></td>
</tr>
<tr>
<td>Pemeability</td>
<td>-0.194</td>
<td></td>
</tr>
<tr>
<td>226-Ra</td>
<td>0.778</td>
<td></td>
</tr>
<tr>
<td>Rn in the Pore</td>
<td>0.036</td>
<td></td>
</tr>
<tr>
<td>232-Th</td>
<td>0.054</td>
<td></td>
</tr>
<tr>
<td>220-Rn</td>
<td>0.638</td>
<td></td>
</tr>
<tr>
<td>238-U</td>
<td>0.105</td>
<td></td>
</tr>
<tr>
<td>DTM</td>
<td>0.105</td>
<td></td>
</tr>
<tr>
<td>Cumulative Expl.Var (%)</td>
<td>30.3</td>
<td></td>
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<tr>
<td></td>
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</table>

Cumulative Expl.Var (%): 30.3% for Factor 1, 56.7% for Factor 2, 66.8% for Factor 3.