LIFE-RESPIRE Mid Term Conference - 11th of December 2018
Consiglio Nazionale delle Ricerche, Area della Ricerca ROMA 1

RESPIRE

Radon real time monitoring system

Geogenic Radon Potential (GRP)

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Radon r**E**al time monitoring **S**ystem and **P**roactive **I**ndoor **Re**mediation - LIFE16 ENV/IT/000553

LIFE-RESPIRE project objectives

- To provide an integrated geological / geochemical monitoring method of radon for the human health risk assessment due to natural radioactivity.
- To use new techniques for the mapping of Geogenic Radon Potential (GRP) and the identification of Radon Prone Areas (RPAs) in 4 significant areas, in Italy and Belgium, where an intelligent and adaptable hybrid Rn remediation system will be installed.
- To bridge the gap between research and politics by improving innovative solutions for land use planning and remediation of radon in workplaces and private dwellings.

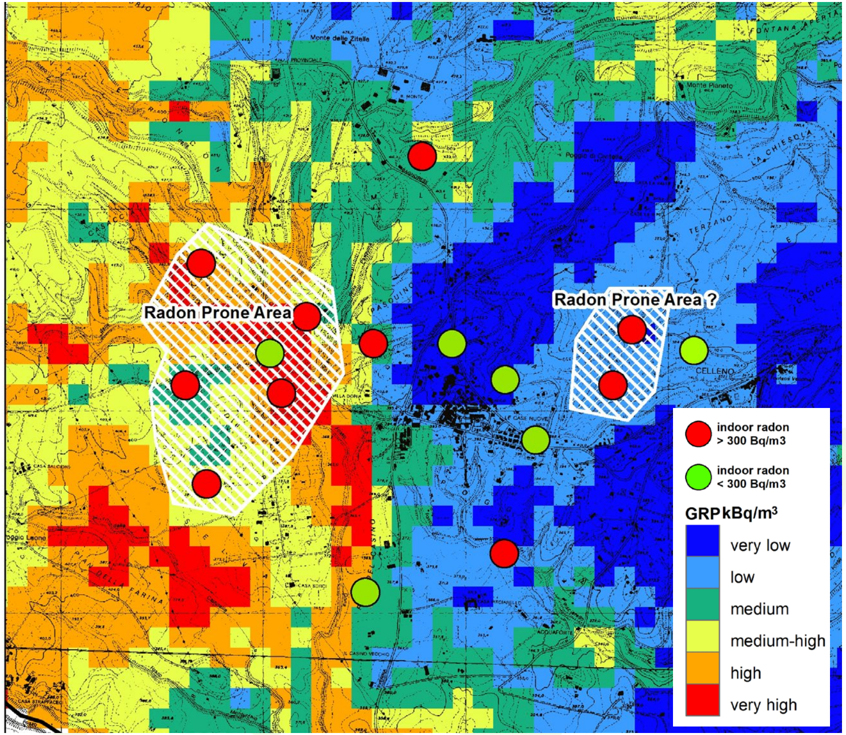
Geogenic Radon Potential and Radon Prone Areas

<u>Geogenic Radon Potential (GRP)</u> - GRP can be defined as 'what Earth delivers'; it defines the availability of radon generated in the ground for surface exhalation or infiltration into buildings. According to Neznal (2003):

$$GRP=C_{Rn}(soil)/[-\log_{10}(k)-10]$$

where $C_{Rn}(soil)$ is the radon concentration in soil air (kBq/m^3) and k is the permeability (m^2)

<u>Radon Prone Area (RPA)</u> - areas where indoor radon concentration is likely to be higher than the national average (ICRP, 2007), due to both geology and building characteristics. However, indoor radon levels are frequently disconnected from GRP because indoor radon concentrations are strongly influenced by anthropic factors, as well as meteorological parameters.



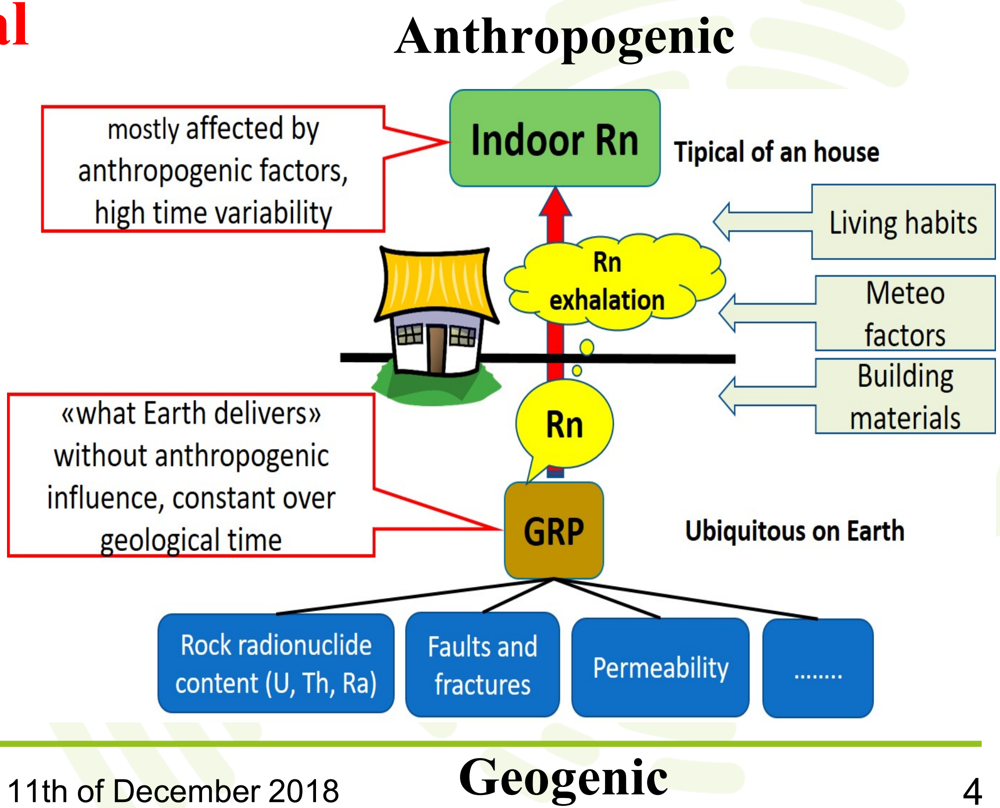
Radon: from rock to risk

Radon behaviour in the natural environment is very complex!!

It is defined by a lot of proxy variables which can interact in a complicate way.

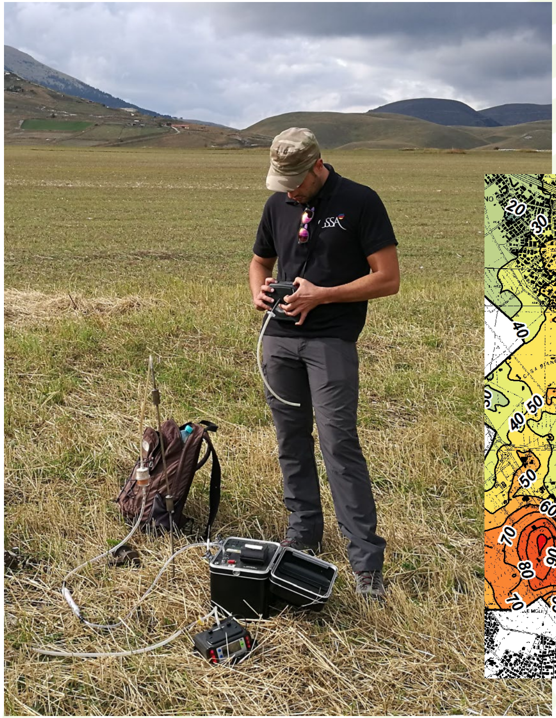
Results:

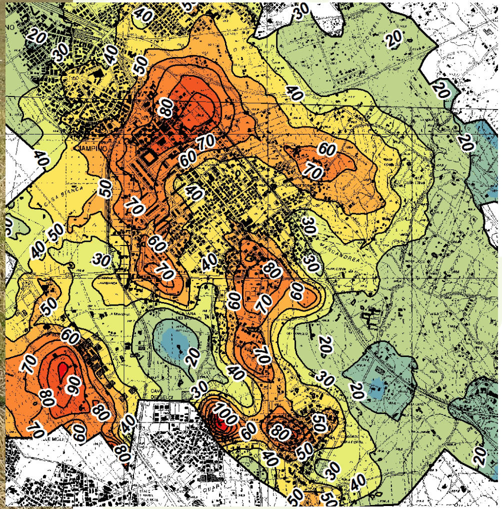
- **It is difficult to define the relationships between Rn and proxies;**
- **Rn (especially indoor Rn) shows a high spatial variability**



Estimating the Geogenic Radon Potential

- 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.



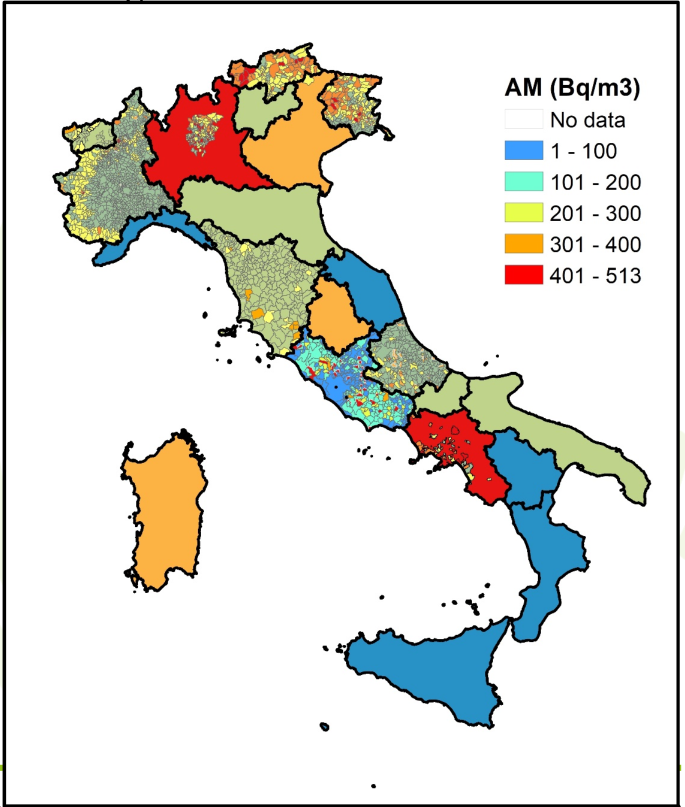


Available Rn indoor data at national scale

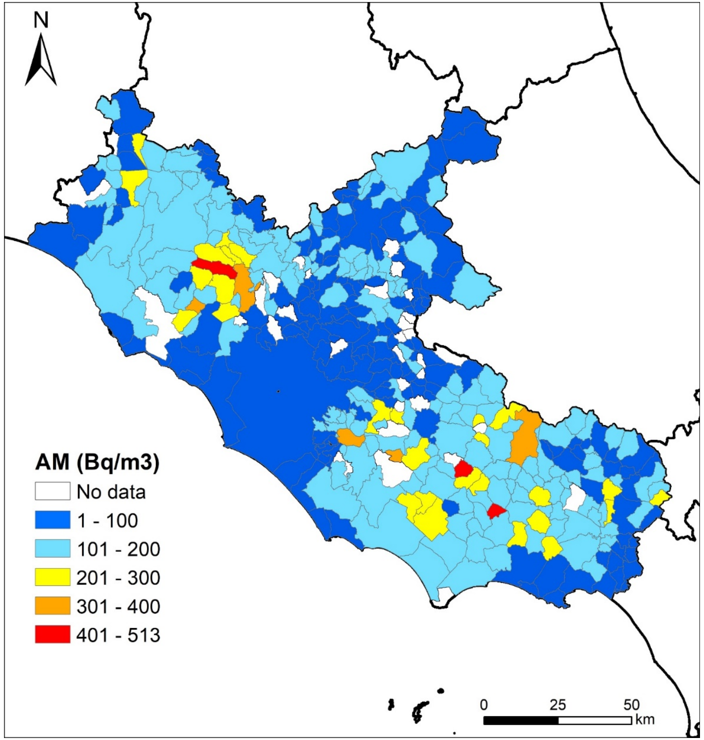
Region	Mun	Samples	AM	GM	Min	Max	STD
VDA	38	609	83	75	22	221	45
PIE	1206		88	82	28	847	47
LIG							
LOM	172	834	219	124	8	6514	361
TRE							
BOL	116	3265	227	135		2362	
VEN							
FVG	679*	2462	161	122	18	1812	145
ERO							
TOS	287	1981	51	40	9	344	45
MAR							
UMB							
LAZ	378	5281	121	86	4	2154	135
ABR	283	2205	65	53	1	1181	
MOL							
CAM	382		309	126	8	7784	816
PUG							
BAS							
CAL							
SIC	411		80		11	1197	
SAR							

Descriptive statistics (table on the left) have been calculated on the basis of data available from the regional ARPA sites

Average indoor Radon concentration in



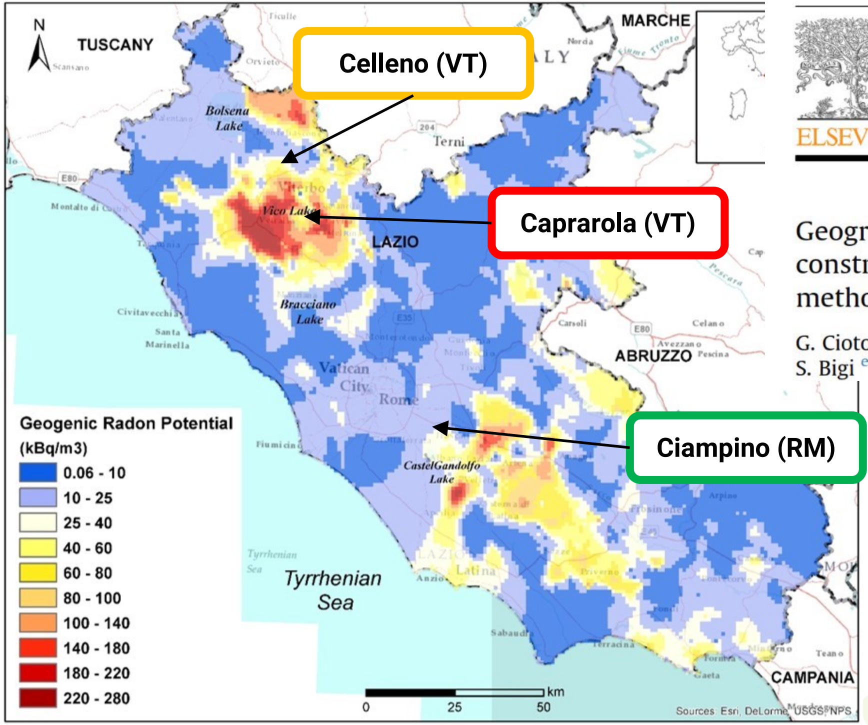
Available Rn indoor data at regional scale



Indoor Radon in Lazio region (ARPA Lazio, 2013)

	FR	LT	RI	RM	VT	TOT
N. Meas	1.288	675	1.036	1.418	864	5281
Min	4	5	6	5	6	4
Max	1.953	1.692	626	2.154	2.075	2154
AM	142	127	104	96	144	121
STD	148	142	78	122	170	135
GM	101	90	82	67	104	86
% > 100	51%	43%	38%	29%	51%	41%
% > 300	9%	7%	3%	4%	9%	6%
% > 500	**3%**	**2%**	**0%**	**1%**	**3%**	2%

The starting point
The Geogenic Radon potential map of the Lazio region



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ELSEVIER

Geographically weighted regression and geostatistical techniques to construct the geogenic radon potential map of the Lazio region: A methodological proposal for the European Atlas of Natural Radiation

G. Ciotoli [a, b, *], M. Voltaggio [a], P. Tuccimei [c], M. Soligo [c], A. Pasculli [d], S.E. Beaubien [e], S. Bigi [e]

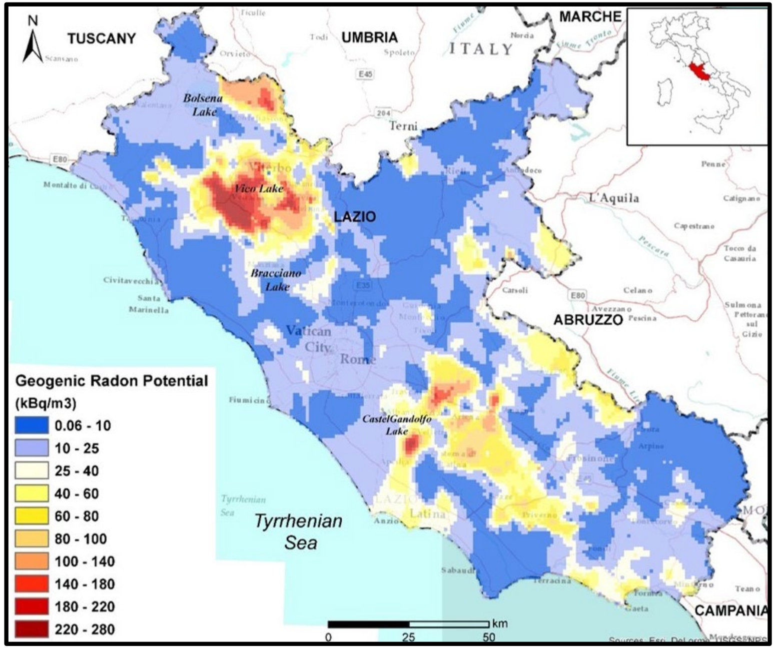
High Rn potential

Medium Rn Potential

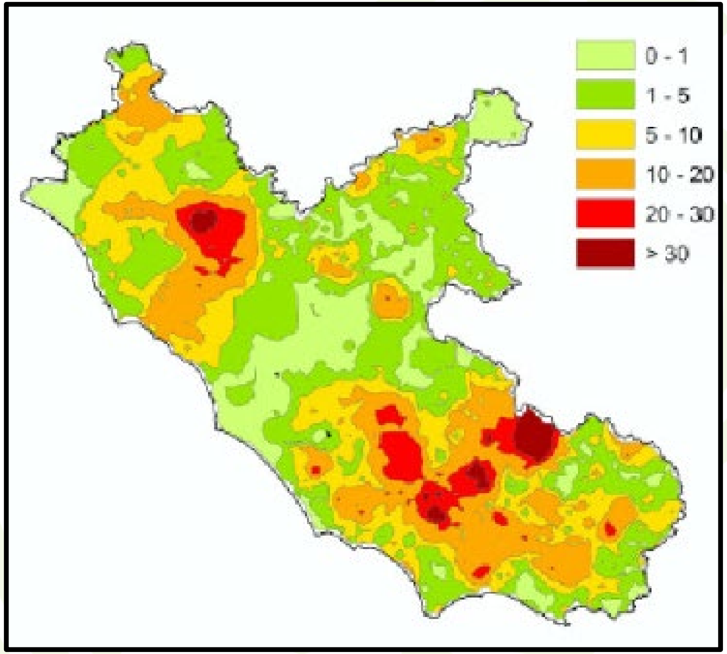
Low Rn Potential

The startin point
Comparison between GRP and RPA maps of Lazio region

Geogenic Radon Potential map of Lazio region



Map of the probability to exceed the threshold of 300 Bq/m^3 (ISPRA, 2013)



The LIFE-Respire geodatabase

The LIFE-Respire geodatabase includes:

- available data from previous research projects conducted by the RESPIRE Consortium
- available data provided by other public institutions

Data are provided as:

- Vector format (points, lines, polygons shapefile)
- Raster (grid, tiff, jpg, ecc.)
- Datasheet format (excel, csv)

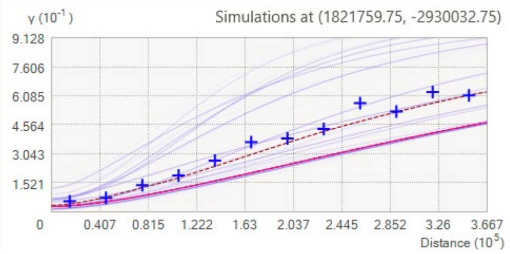
All data are organized as georeferenced layers in a GIS environment, in the WGS84-UTM33 system, ready to be uploaded to the RESPIRE WebGIS and adapted to the European Reference System (ETRS89) as required by the European Directive 2007/2 / EC INSPIRE.

Base cartography

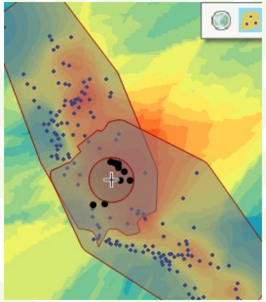
- Technical map of the Lazio Region, scale 1:5000 in vector (shapefile) and raster (tif) formats
- Digital Terrain Model in a grid format having 20x20 m cell resolution
- Map of the Homogeneous Geological Units derived from the Geological Map of the Lazio Region (scale 1:25,000) in vector format (Cosentino and Pasquali, 2012)
- Map of the main faults of Lazio Region
- Map of the Hydrogeological Complexes (in terms of aquifer potential) as defined in the Hydrogeological map of the Lazio Region (scale 1:25,000) in vector format (Capelli et al., 2012)

New spatial technique for the mapping of the GRP

- Empirical Bayesian Kriging Regression (EBKR) combines ordinary OLS regression and simple kriging to provide accurate predictions of moderately non-stationary data at a local level
- EBKR estimates the semivariogram through a process of subsetting and repeated simulations
- EBKR uses the principal components of the explanatory variables in the regression model, to solve the problem of multicollinearity
- Each principal component captures a certain proportion of the total variability of the explanatory variables; generally, most of the information can be captured in just a few principal components (up to 70% of the total variability)



Simulated semivariograms. Empirical semivariances fall in the middle of the spectrum



Prediction with subsets

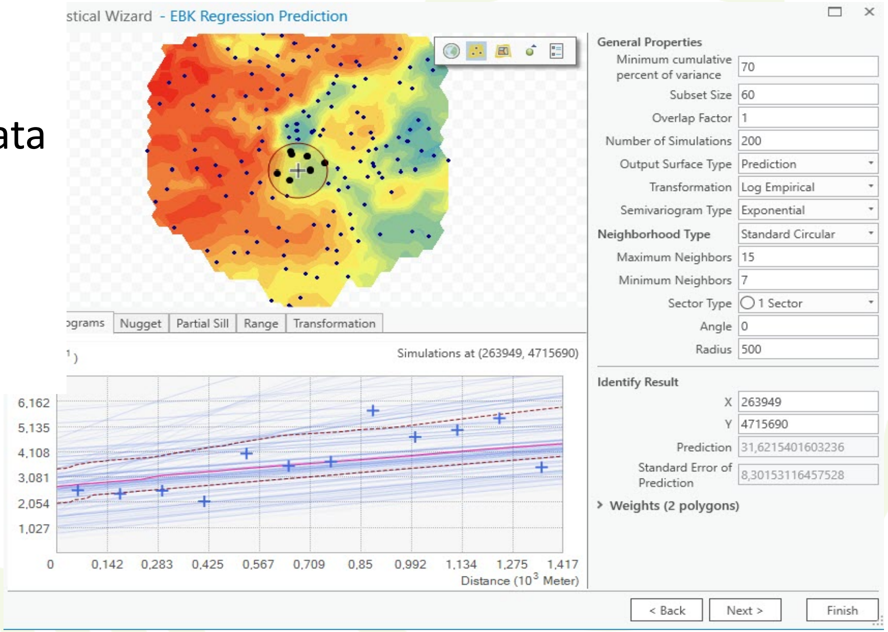
New spatial technique for the mapping of the GRP

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 EKBR

- Processing is slower than other kriging methods
- Anisotropy and cokriging are unavailable



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Previous studies carried out in the municipalities involved in the LIFE-RESPIRE project

Comune di
Celleno

CITTÀ DI
CIAMPINO
CITTA' METROPOLITANA DI ROMA CAPITALE

Municipality of Celleno (VT, Italy)

Available data

	Samples	Variables	Results
Soil gas (CERI, CNR-IGAG)	204	^{222}Rn, ^{220}Rn, CO_2, O_2, CO_2 flux	Maps of soil gas concentrations
High-resolution gamma spectrometry (CNR-IGAG)	20	activity concentrations of radionuclides ^{238}U, ^{226}Ra, ^{232}Th e ^{40}K in soil/rock samples	Maps of activity concentrations of radionuclides
Terrestrial gamma dose (CNR-IGAG)	77	TGDR	Map of terrestrial gamma dose rate
Groundwater (CERI, INGV)	17	Chemical composition of water samples (major, minor and trace elements); dissolved Rn	Dissolved Rn in groundwater
Indoor Rn (CNR-IGAG)	40 private and public dwellings	^{222}Rn	Preliminary evaluation of indoor radon levels for the selection of buildings

The proxy variables

- **Radionuclide content in Bq/kg (226Ra, 238U, 232Th, 40K) averaged on lithological types.** 20 samples (high-resolution gamma spectrometer equipped with a low-background HPGe coaxial detector, GEM – EG&G ORTEC)
- **EMAN =** Emanation coefficient, averaged on lithology $\longrightarrow$ $\eta = \frac{Rn_{cp}}{Rn_{tot}} = \frac{Rn\ amount\ in\ connected\ pores}{total\ Rn\ amount}$ (Sasaki et al., 2004)
- **Diffusive RnFLUX** from the soil, averaged on lithology and calculated by

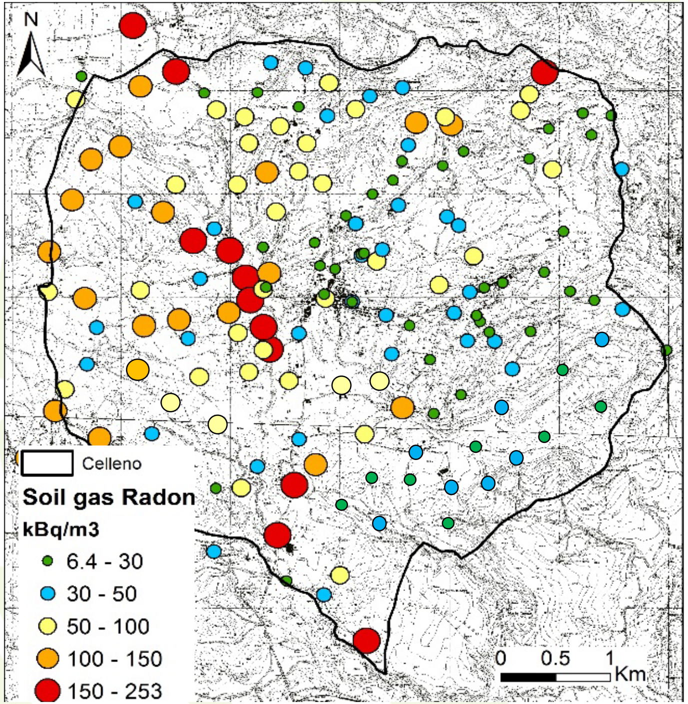
  $$J = \eta\rho_p(1-\varphi)\,226Ra\sqrt{\lambda D_0\, e^{-\left(6\varphi R_s+6R_s^{14\varphi}\right)}}$$ (Voltaggio et al., 2006)

- **GAMMA = Terrestrial gamma dose rate** → 80 samples (NaI γ-ray portable scintillometer Scintrex GRS-500)
- **CO2 =** soil-gas CO_2 concentration → 230 samples (Draeger X-am 7000) Ordinary Kriging
- **TPI** (topographic position index) derived from the Digital Terrain Model → (20x20m) of Lazio region (proxy of the meteo parameters)
- **Perm** = Permeability of soil/rocks → (map of the hydrological complexes; Capelli et al., 2012)

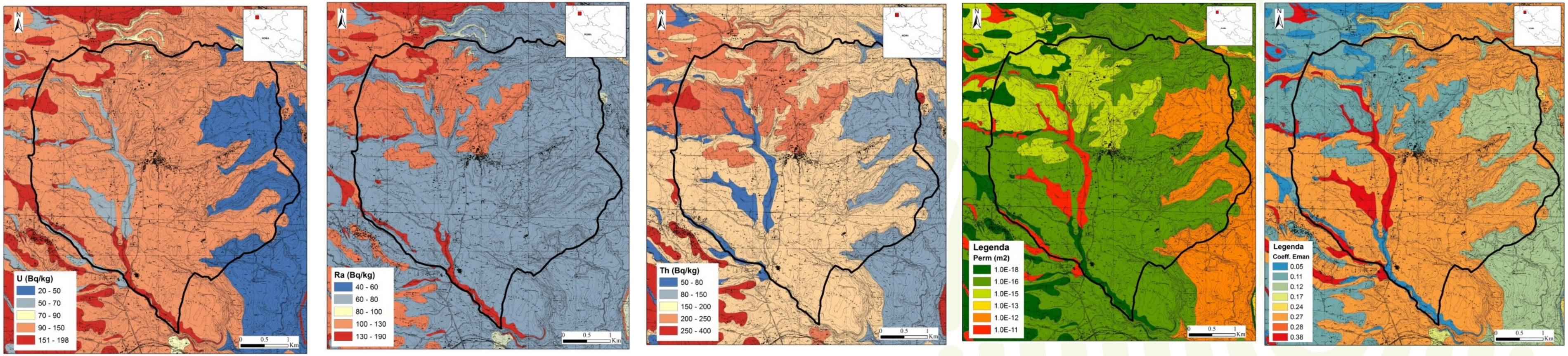
Response variable: soil gas radon

	N	Mean (95% CI)	Min	Max	Stdev
^{222}Rn (kBq/m^3)	**230**	**60 (52.8-66.8)**	**6.4**	**253**	**48.75**
CO_2 (%, v/v)	230	3.3 (3.0-3.6)	0.3	11.0	2.2
TGDR (mSv/h)	80	0.229 (0.218-0.239)	0.130	0.417	0.046
^{226}Ra (Bq/kg)	20	122.2 (90.1-154.3)	46	295	68.6
^{238}U (Bq/kg)	20	124.1 (93.9-154.2)	42	281	64.3
^{232}Th (Bq/kg)	20	222.1 (186-258.2)	78	365	77.1
^{40}K (Bq/kg)	20	965.9 (716.1-1216)	299	2480	533.5
^{222}Rn Emanation	20	0.109 (0.069-0.148)	0.033	0.38	0.085
^{222}Rn flux (Bq/m^2/day)	20	6284 (4684-7883)	1866	17779	3417

Soil gas radon samples



Celleno (VT, central Italy) – Proxy variables



Radionuclide content (U, Ra, Th) **Permeability (m2)** **Emanation coefficient**

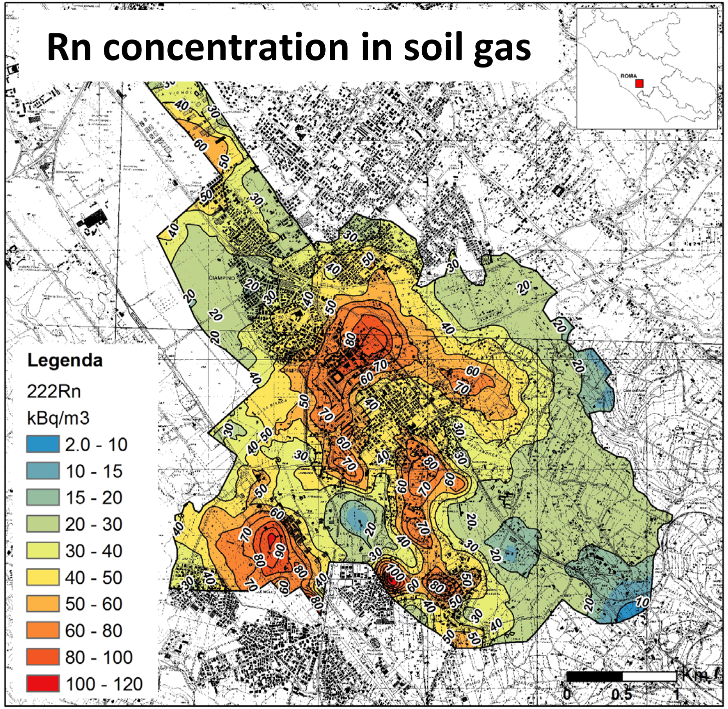
Giustini F., Ciotoli G., Rinaldini A., Ruggiero L., Voltaggio M.
Mapping the geogenic radon potential and radon risk by using Empirical Bayesian Kriging regression: a case study from a volcanic area of central Italy.
Science of Total Environment (accepted for publication)

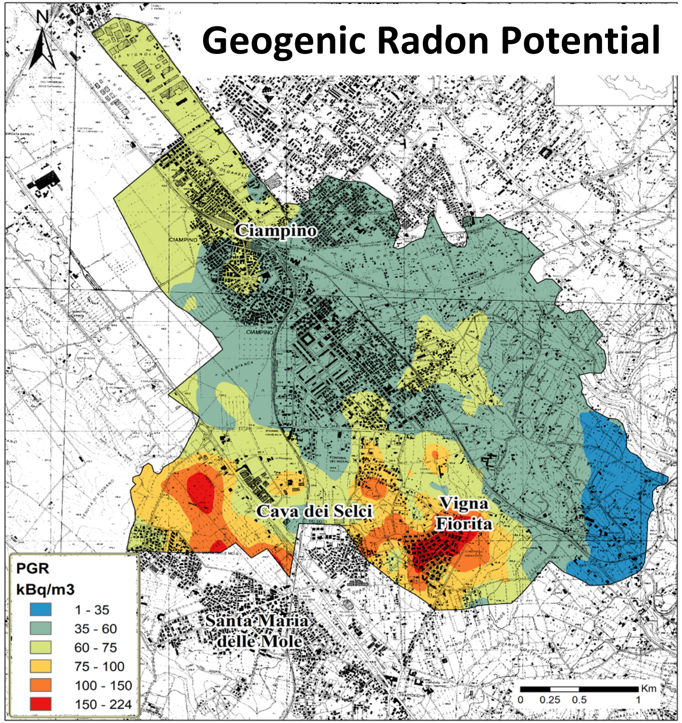
Municipality of Ciampino (Rome, Italy)

Available data

	Samples	Variables	Results
Soil gas (CERI)	425	^{222}Rn, CO_2, He, CH_4, CO_2 flux	Maps of soil gas concentrations
High-resolution gamma spectrometry	Data from literature	^{238}U, ^{226}Ra, ^{232}Th	Maps of activity concentrations of radionuclides
Groundwater (INGV)	86	T, pH, redox potential and alkalinity; dissolved Rn and CO_2	Dissolved Rn in groundwater
Indoor Rn (INGV)	67 private and public dwellings	^{222}Rn	Preliminary evaluation of indoor radon levels for the selection of buildings

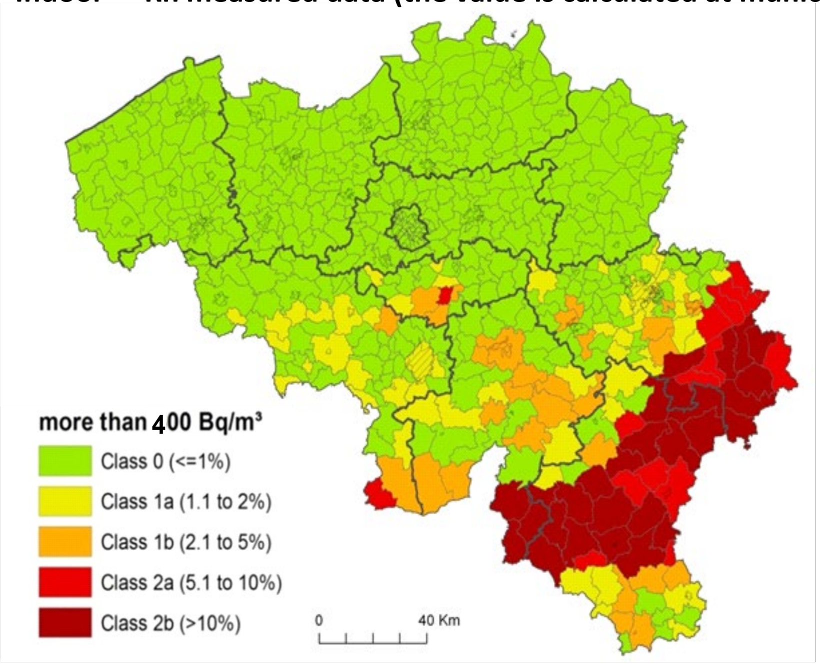
Comune di Ciampino (Roma, Italia)

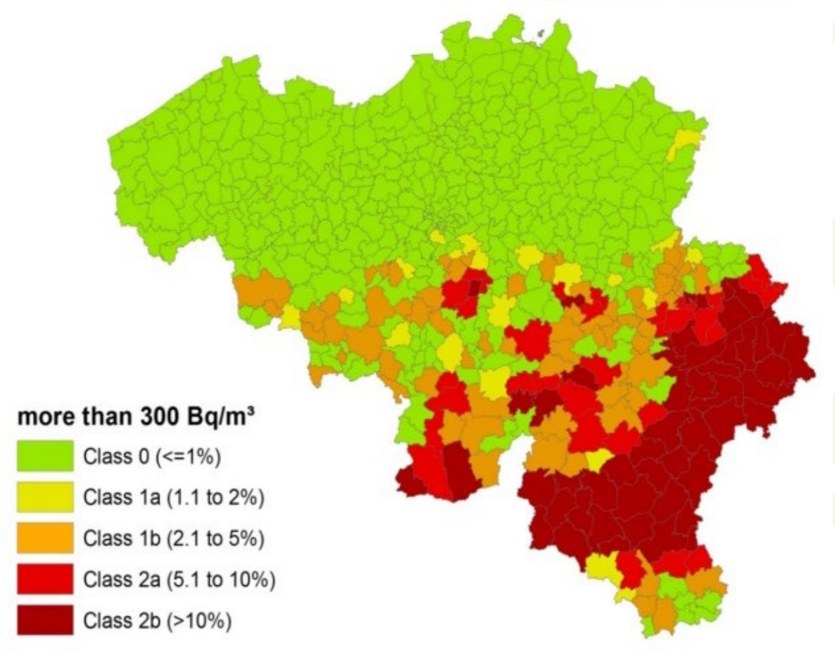




Ardenne region (Belgium)

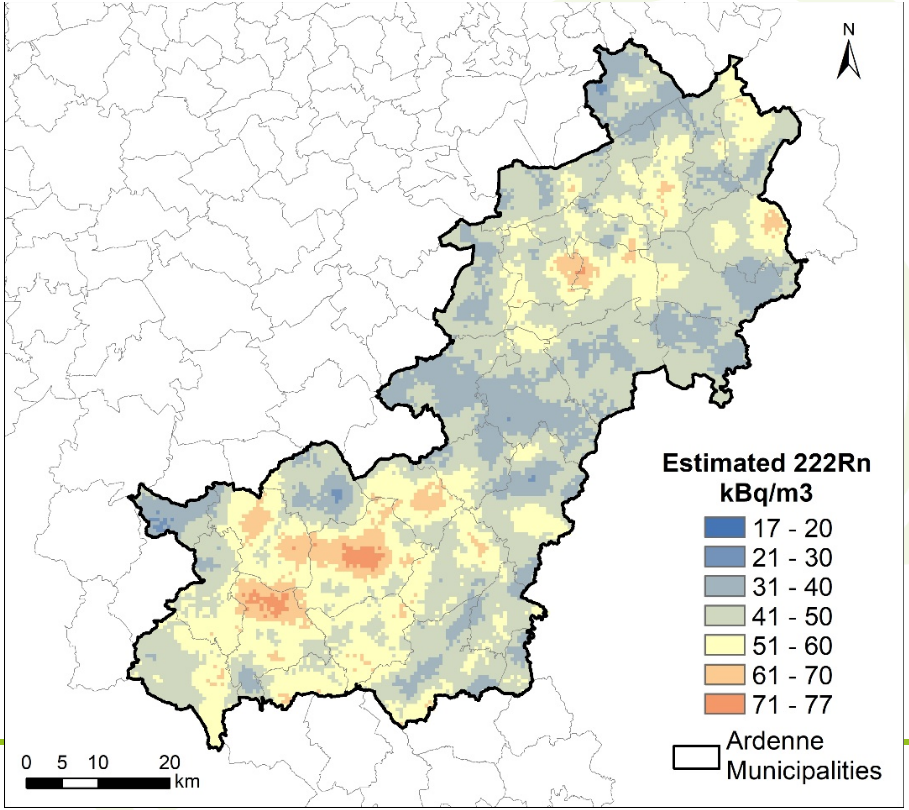
Indoor ^{222}Rn measured data (the value is calculated at municipality level)





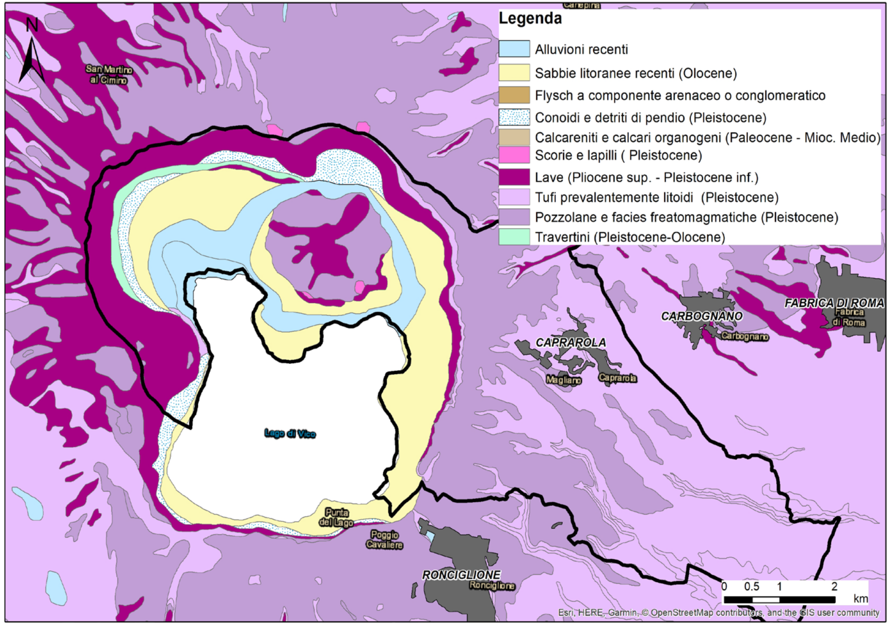
Ardenne Region (Belgium)

Contour map of soil-gas radon



New studies carried out in the municipality of Caprarola (VT)

Life-Respire field surveys and available data



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

Geological setting

Volcanic rocks (tuffs and lavas) of Cimino volcanic complex (~ 0.90-1.30Ma) outcrop in whole area. The volcanic products are particularly enriched on natural radionuclides. Sedimentary rocks (recent and lake deposits) mainly outcrop in the western sector of the area.

The Cimino complex consists of a series of rhyodacitic domes and ignimbrites emplaced along a NW–SE trending fracture zone. At the end of the activity a central volcano, emitting latitic and olivine-latitic composition lavas, developed.

Several thermal springs (from 25.3 °C to 62.2 °C) and gas vents occur in the area, suggesting the migration of thermal and deep fluids towards the surface from a reservoir hosted in the Mesozoic unit.

Life-Respire field surveys and available data

Table shows the field surveys conducted at the municipality of Caprarola (~ 50 km^2)

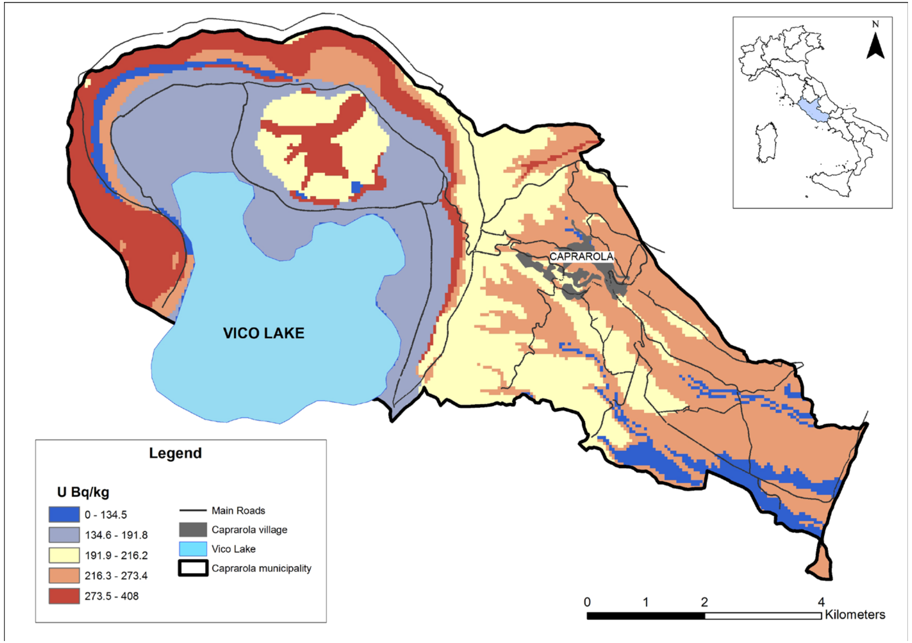
Survey	Samples	Variables	Results
Soil gas (CERI, IGAG)	181	^{222}Rn, ^{220}Rn, CO_2, O_2, flusso di CO_2	Maps of soil gas concentrations
Soil permeability (CERI with University of ROMA TRE - Prof.ssa P. Tuccimei)	181	Permeabiliy	Map of soil permeability
• High-resolution gamma spectrometry (IGAG) • Terrestrial gamma dose (IGAG) • Gamma Indoor (IGAG)	19 187 117	Activity concentrations of radionuclides ^{238}U, ^{226}Ra, ^{232}Th e ^{40}K in soil/rock samples, emanation coefficient, TGDR	Maps of activity concentrations of radionuclides Map of terrestrial gamma dose rate
Groundwater (CERI, INGV)	38	Chemical composition of water samples (major, minor and trace elements); dissolved Rn	Dissolved Rn in groundwater
Indoor Rn (CERI, INGV, IGAG)	80 (34 public and private sites)	^{222}Rn	Preliminary evaluation of indoor radon levels for the selection of buildings

Field surveys and laboratory analysis

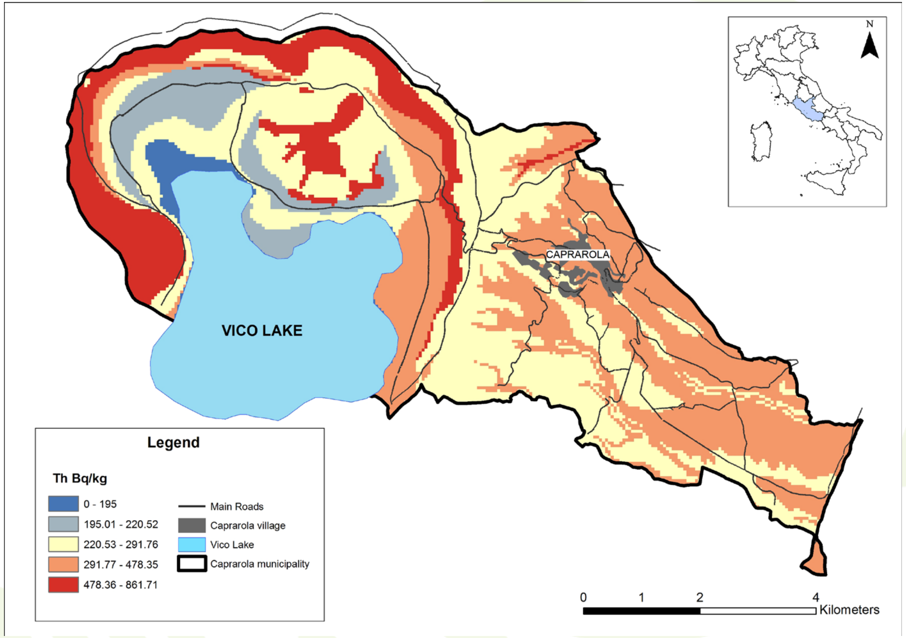
- Soil gas sampling (181 sites)
- Measurements in the field of CO_2, O_2, CH_4, H_2, H_2S concentrations, ^{222}Rn, ^{220}Rn, CO_2 flux and soil permeability
- Collection of soil and rock samples in order to determine the activity concentrations of radionuclides ^{238}U, ^{226}Ra, ^{232}Th and ^{40}K
- Laboratory measurements of CO_2, N_2, O_2, He, Ne, CH_4 concentrations

Proxy Variables

Map of the Uranium content in the different lithologies

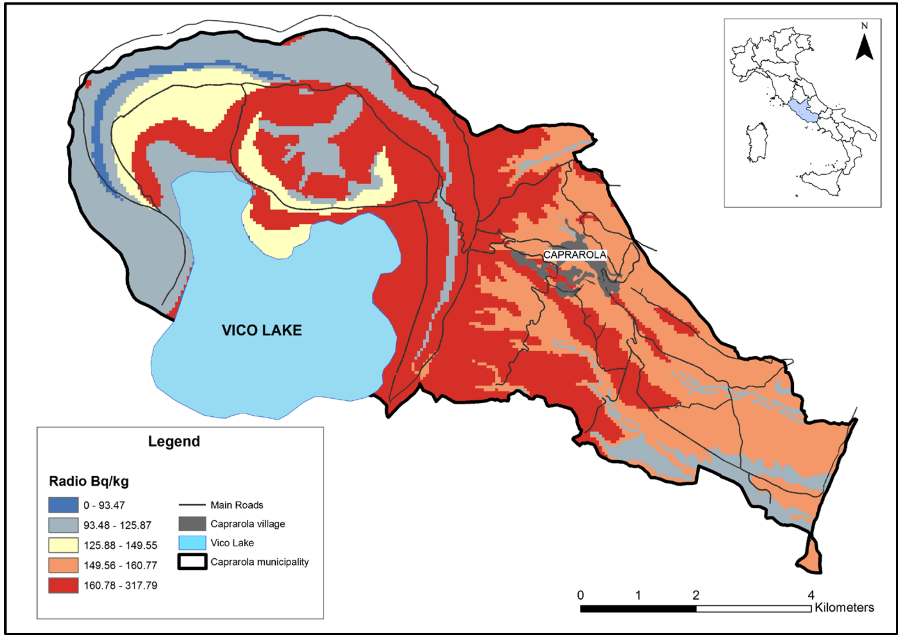


Map of the Thorium content in the different lithologies

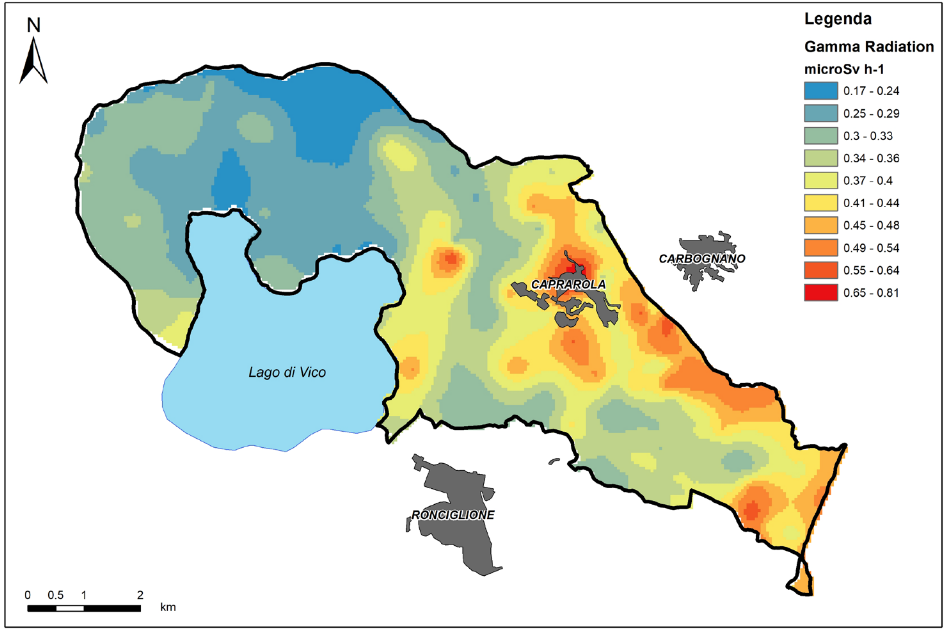


Proxy Variables

Map of the Radio content in the different lithologies



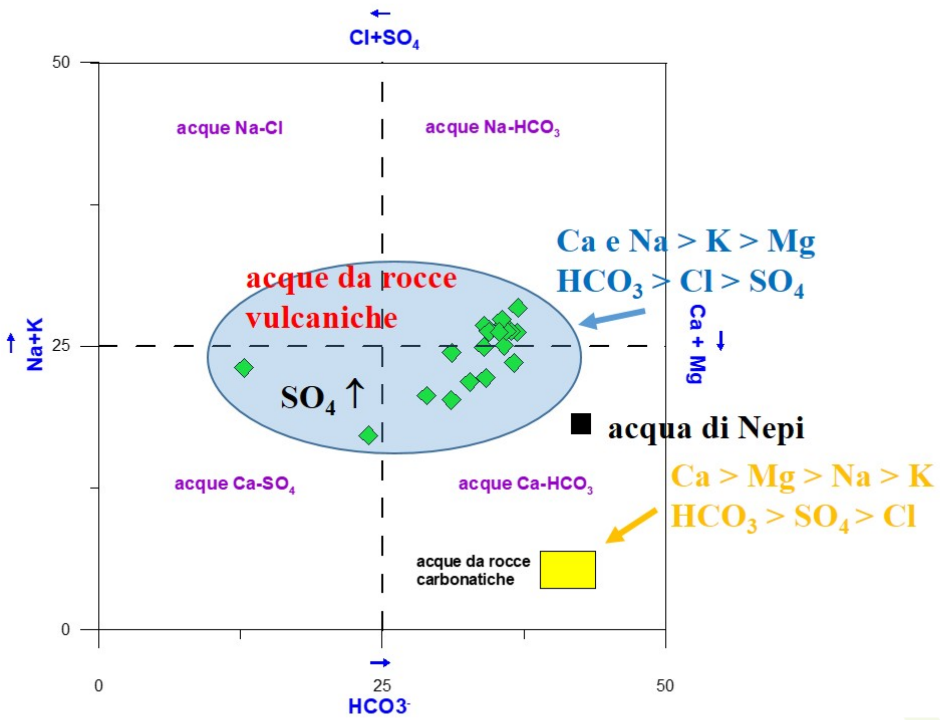
Map of the terrestrial gamma dose rate



Groundwater

- 19 water samples were collected from 2 springs and 17 domestic and agricultural wells;
- Water temperature, pH, electrical conductivity, alkalinity were determined in situ;
- Major anions and cations (Ca, Mg, K, Na, Cl, SO_4), minor and trace elements (Al, B, Ba, SiO2, Li, Fe, Mn, U, As and Sr) were measured to determine the levels of natural contaminants;
- Stable isotopes of C (to identify the source of dissolved CO_2), O e H (to determine the origin of water);
- Analysis of dissolved gases (CO_2, N_2, O_2, He, Ne, CH_4, H_2);
- Analysis of dissolved radon.

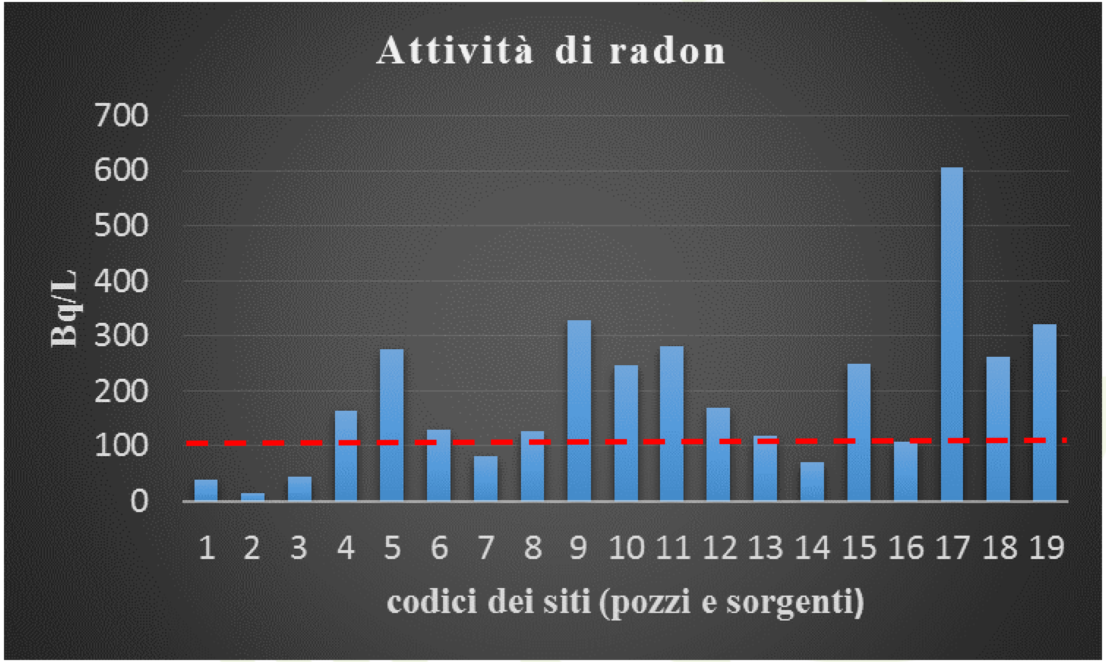
Groundwater chemistry



- **Groundwaters display low salinity and pH from slightly basic to slightly acid (from 6.5 to 7.5); their temperatures range between 9 and 16°C.**
- **Groundwaters interact with volcanic rocks and result enriched in Na e K.**

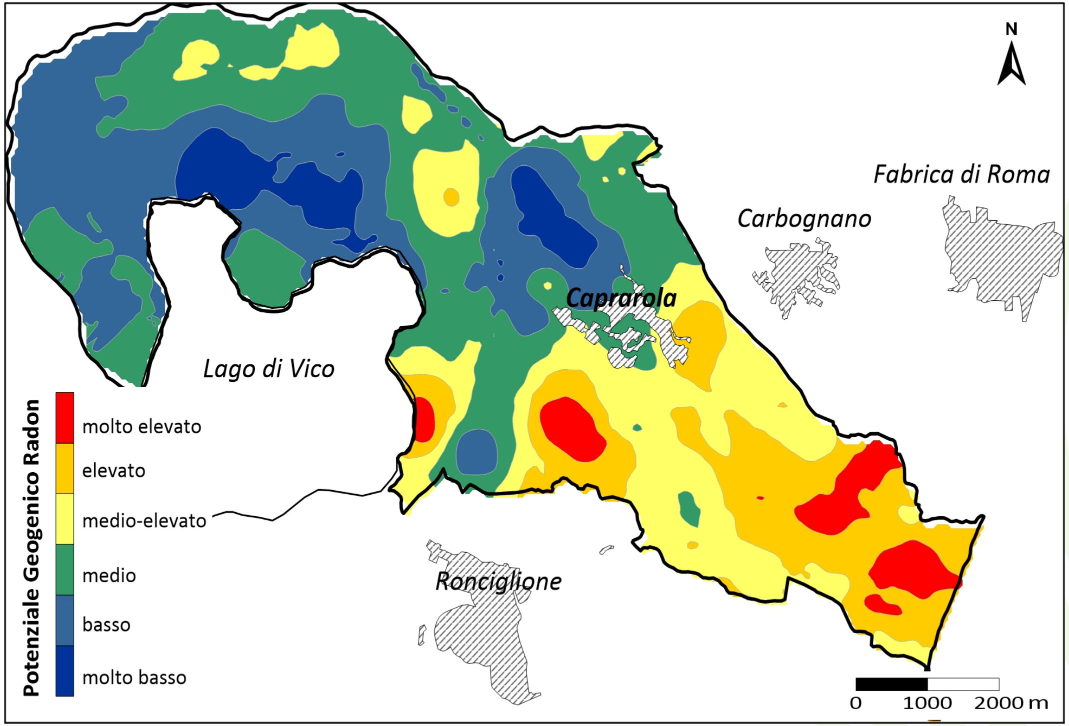
^{222}Radon in groundwater

Radon (Max admitted activity, D.L. 28/2016): 100 Bq/L.



Municipality of Caprarola (VT, Italy)

Results



Map of Geogenic Radon Potential of the Caprarola municipality

Preliminary results

- The municipality of Caprarola is characterized by high natural radioactivity, as already highlighted in the Geogenic Radon Potential map of Lazio region (Ciotoli et al., 2017).
- The content of natural radionuclides (U, Th e Ra) varies from medium to high values, particularly in the south-eastern sector of the municipality (i.e., east of the Vico lake), where consequently most of the high values of soil-gas radon were detected.
- Groundwaters are enriched in dissolved radon, sometimes above the threshold value of 100 Bq/L.

Preliminary results

- The Geogenic Radon Potential map does not indicate health risk areas, but it highlight areas where the presence of high indoor radon values is most likely.
- The map can be used by the local administrations for land use planning, and for the selection of areas where more detailed indoor radon monitoring will be carried out.

RESPIRE
Radon real time monitoring system

The modelling of the Geogenic Radon Potential!!

Fruit basket, Giuseppe Arcimboldo
(ca. 1527–1593)

Thanks for the attention!!

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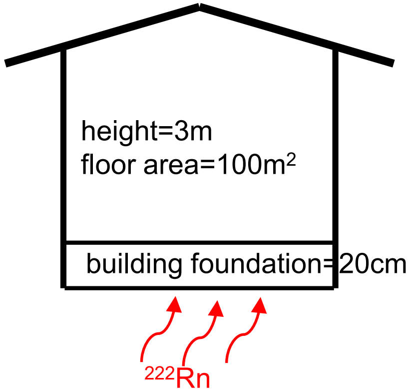
RESPIRE
Radon real time monitoring system

SIMULATION

«standard» dwelling

Building materials = concrete blocks



Geogenic Radon Potential	Calculated Indoor Rn
Low (≤50 kBq/m³)	<90 Bq/m³
Medium (50-100 kBq/m³)	90-180 Bq/m³
High (100-200 kBq/m³)	180-350 Bq/m³

Equation 1.

$$\boxed{RnIndoor_{calc} = J \cdot S \cdot TF}$$

J = radon flux (Bq/m²/s)
S = floor area of the room (m²)
TF = transfer factor

Equation 2.

$$\boxed{TF = \frac{e^{-\Delta_b \sqrt{\lambda_v - D_b}}}{V\lambda_v}}$$

λ_v = average air ventilation rate ($2.8 \cdot 10^{-5}$ s^{-1})
D_b = radon diffusion constant in the concrete blocks($1 \cdot 10^{-7}$ m²/s)
V = volume of the dwelling (m³)
Δ_b = thickness of the building foundation (m)

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