European Radon Week 2020

JRC Workshop

Methodology behind the first Pan-European Indoor Radon Map

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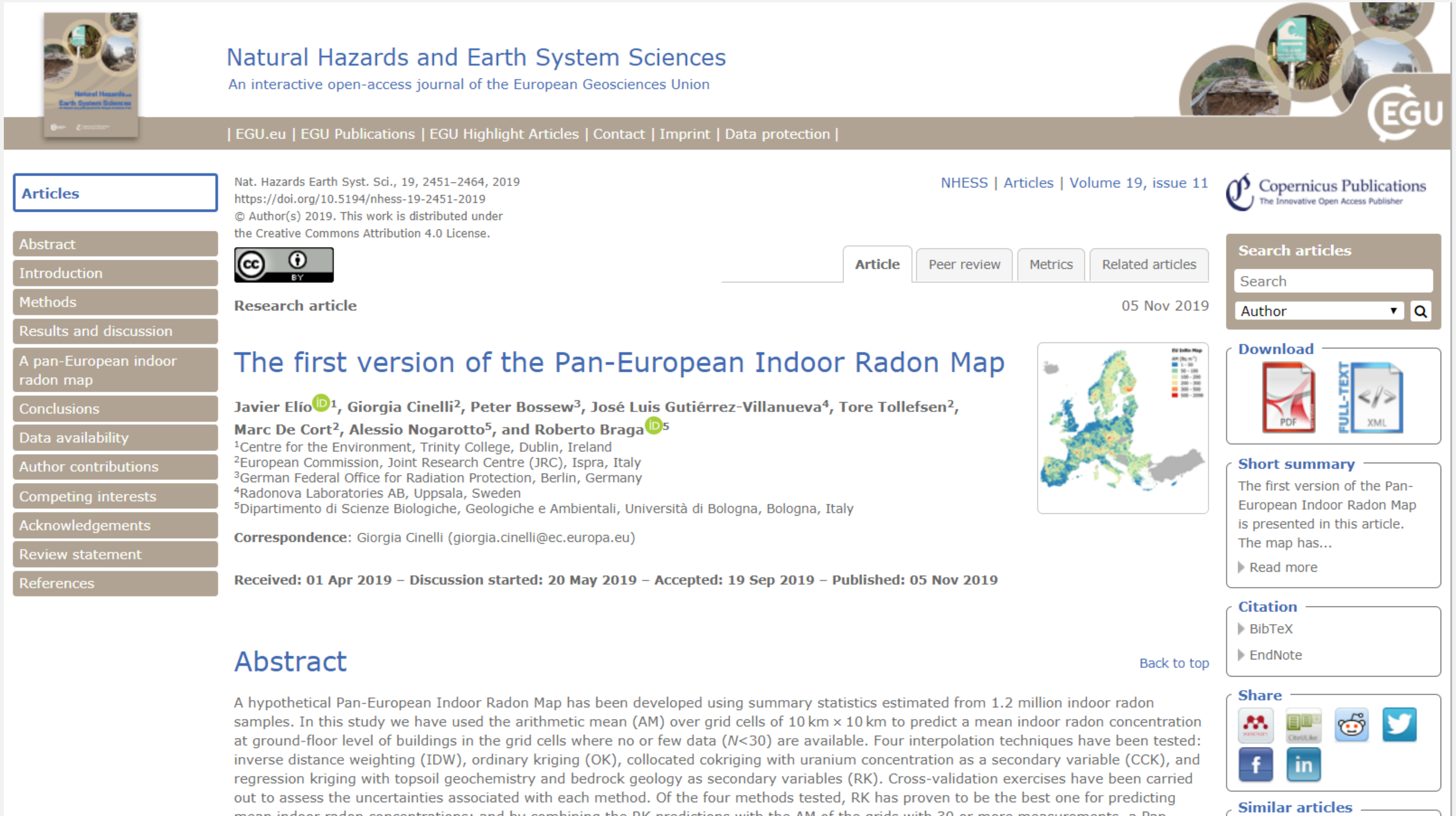

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Research article — 05 Nov 2019

The first version of the Pan-European Indoor Radon Map

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Short summary
The first version of the Pan-European Indoor Radon Map is presented in this article. The map has...
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Abstract

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A hypothetical Pan-European Indoor Radon Map has been developed using summary statistics estimated from 1.2 million indoor radon samples. In this study we have used the arithmetic mean (AM) over grid cells of 10 km × 10 km to predict a mean indoor radon concentration at ground-floor level of buildings in the grid cells where no or few data (N<30) are available. Four interpolation techniques have been tested: inverse distance weighting (IDW), ordinary kriging (OK), collocated cokriging with uranium concentration as a secondary variable (CCK), and regression kriging with topsoil geochemistry and bedrock geology as secondary variables (RK). Cross-validation exercises have been carried out to assess the uncertainties associated with each method. Of the four methods tested, RK has proven to be the best one for predicting

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Giorgia Iurlaro; *Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), Italy*

And all the people who have worked (and still work) on the map!!!

At the time of writing the article (end of 2018), 32 countries (EU and non-EU member states alike) contributed data, and information from almost 1.2 million dwellings were aggregated into 28 468 grid cells.

Motivation

Input data

Indoor radon

AM [Bq m^{-3}]

N ≥ 30

Geogenic factors

Geology (1:5M)

U (Topsoil)

K_2O (Topsoil)

Model 1

Cross-validation four interpolation techniques:

- IDW (AM)
- OK (AM)
- CoCK (AM + U)
- RK (AM + G + U + K_2O)

Output 1

Pan-European Indoor Radon Map: annual average indoor radon concentrations over grids of 10 km x 10 km (i.e. arithmetic mean, ground floor)

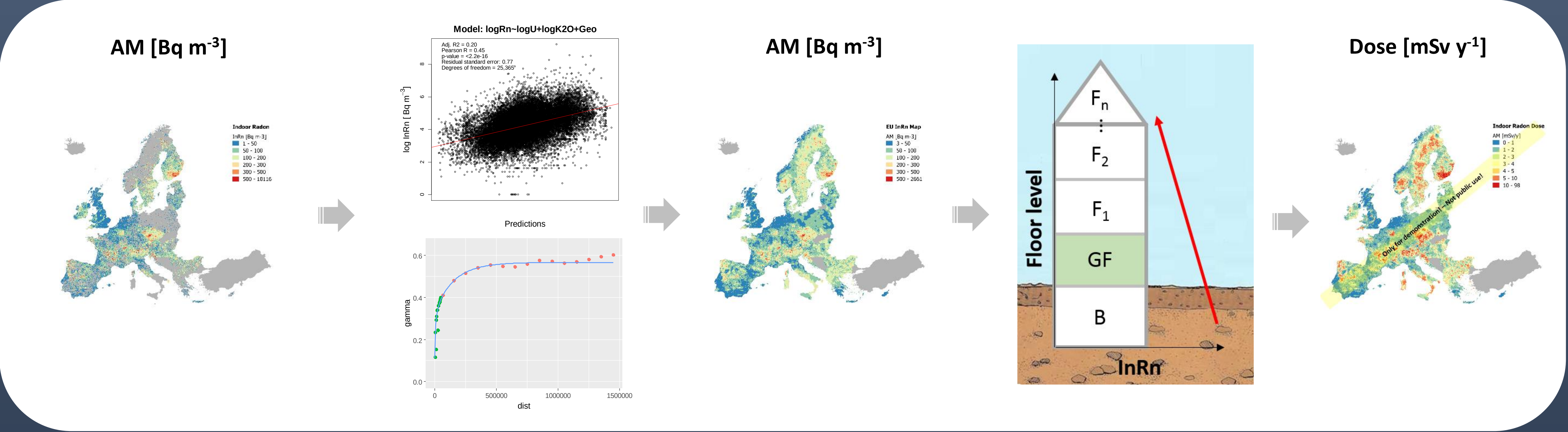
Model 2

a) **Floor correction model:** indoor radon map (all floors)

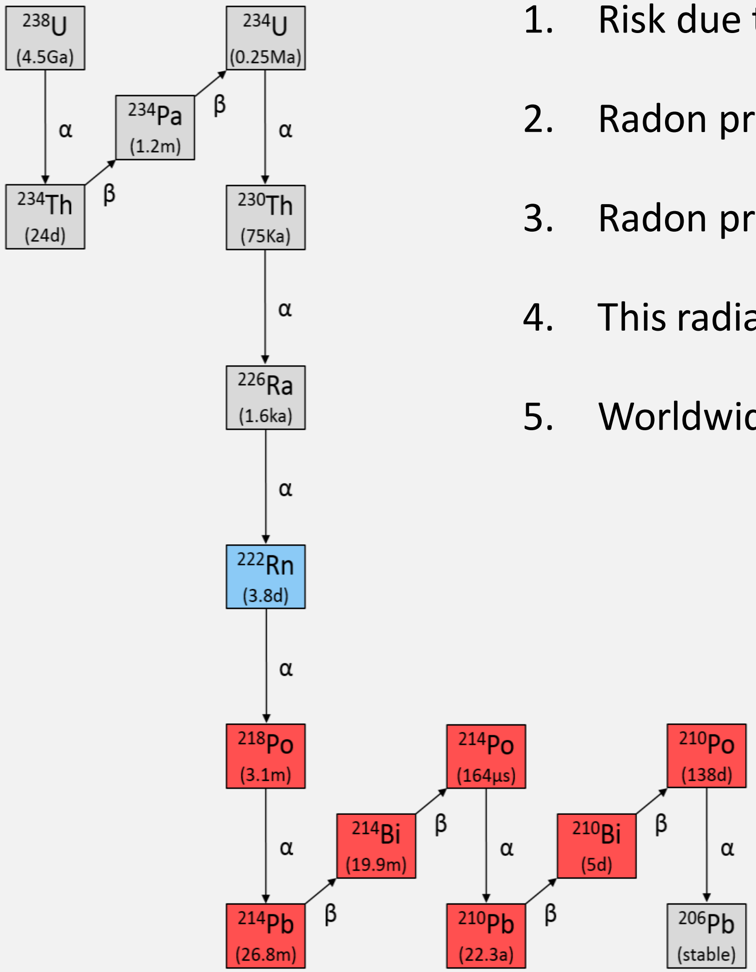
b) **Radon dose:** occupancy, equilibrium factor, dose conversion

Output 2

Pan-European Radon Dose Map: annual effective dose that a person may receive from radon indoor exposure with a resolution of 10 km x 10 km



Radon and lung cancer



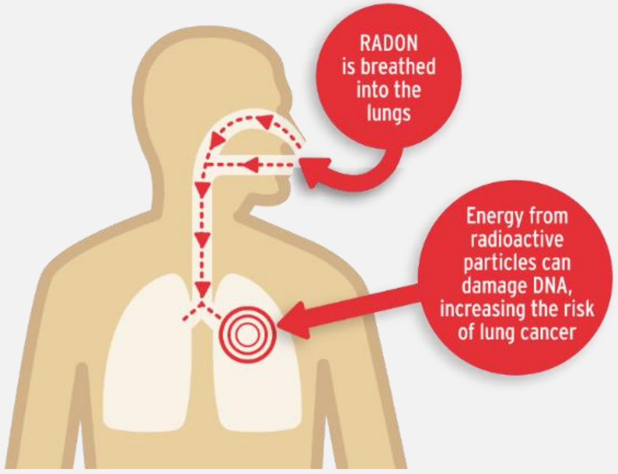
1. Risk due to the inhalation of existing radon (^{222}Rn) progeny attached to aerosols; i.e. suspended particles.

2. Radon progeny may deposit in the respiratory tract.

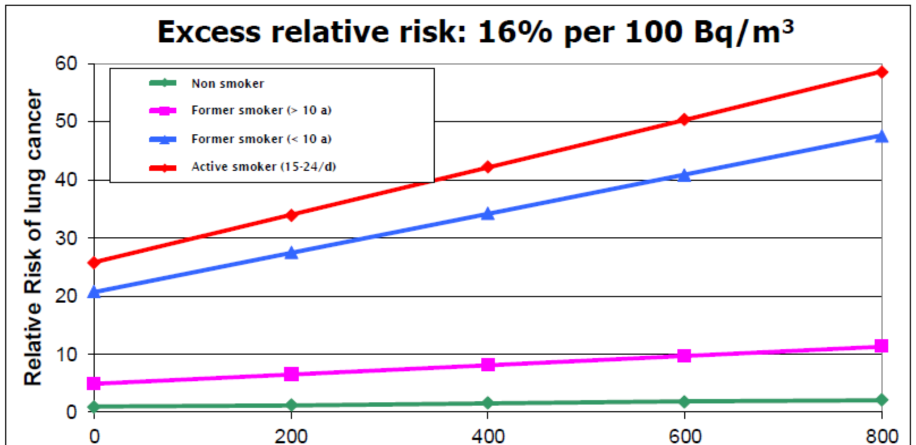
3. Radon progenies are also radioactive and emit alpha and beta particles.

4. This radiation can interact with lung tissue leading to DNA damage and development of lung cancer.

5. Worldwide radon exposure is linked to 222,000 of the 1.8 million annual lung cancer cases.

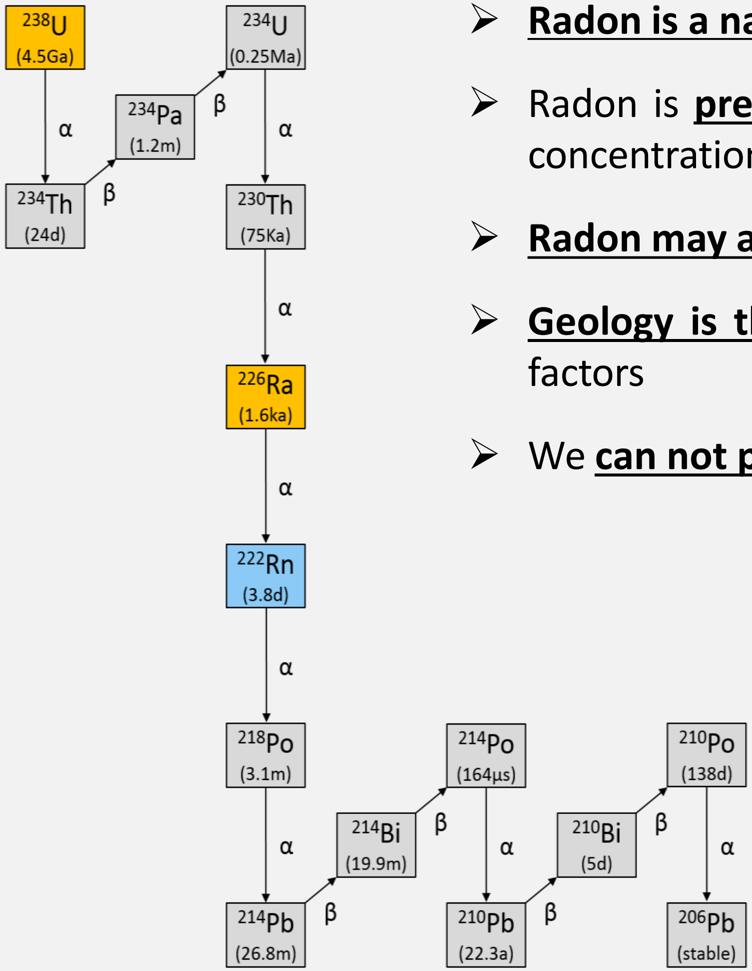


Source: EPA (Ireland): www.radon.ie

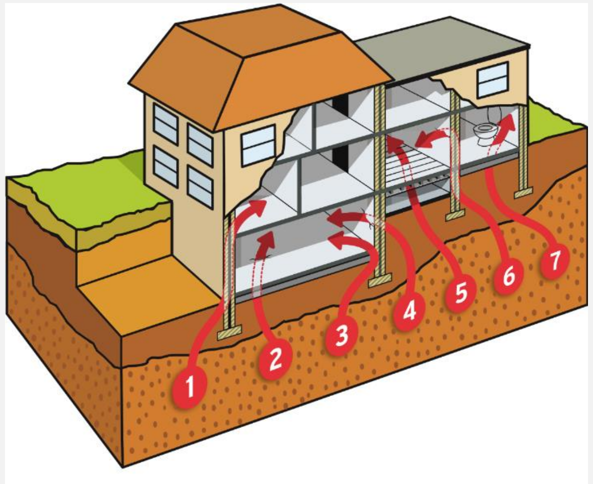


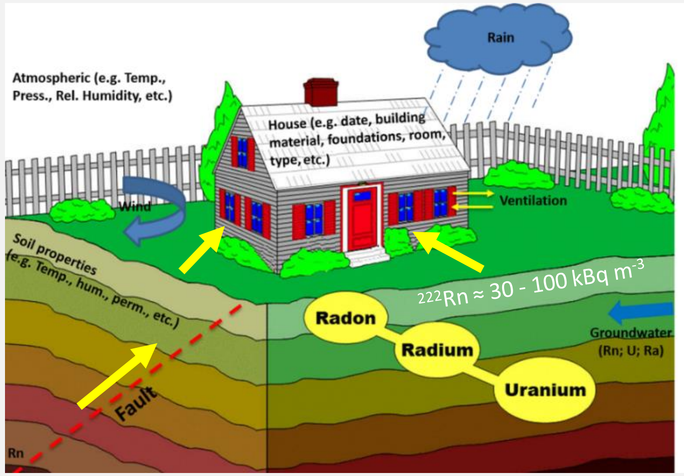
Source: W. Ringer 2016

Radon in dwellings



- **<u>Radon is a natural radioactive gas</u>** which forms as a decay product in the radioactive decay series of uranium.
- Radon is **<u>present in all soils</u>** at low levels, when radon reach the atmosphere it is diluted easily and outdoor concentration is normally low.
- **<u>Radon may accumulate in indoor air</u>** and reach high concentrations.
- **<u>Geology is the main factor</u>** controlling indoor radon concentration; however, it may be affected by multiple factors
- We **<u>can not predict</u>** the indoor radon concentration in a particular house!!





Legal background

Basic Safety Standards (BSS)

Council Directive 2013/59/Euratom laying down basic safety standards for protection against the dangers arising from exposure to ionizing radiation.
http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:L:2014:013:TOC (OJ L, 17.01.2014)

<u>Art. 103,3; Radon Priority Areas (RPA):</u>
"Member States shall identify areas where the radon concentration (as an annual average) in a significant number of buildings is expected to exceed the relevant national reference level."

Conceptual definition, which has to be translated into an *operable* definition.

<u>Art. 54, 74, annex XVIII; Radon Action Plan</u>:
In areas according Art.103,3: Buildings with public access and workplaces must be measured and if above RL, remediated. New buildings: particular Rn prevention. Strategy to reduce Rn in dwellings.

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Contents

II Non-legislative acts

DIRECTIVES

★ Council Directive 2013/59/Euratom of 5 December 2013 laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation, and repealing Directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom and 2003/122/Euratom 1

Price: EUR 4

EN

Acts whose titles are printed in light type are those relating to day-to-day management of agricultural matters, and are generally valid for a limited period.

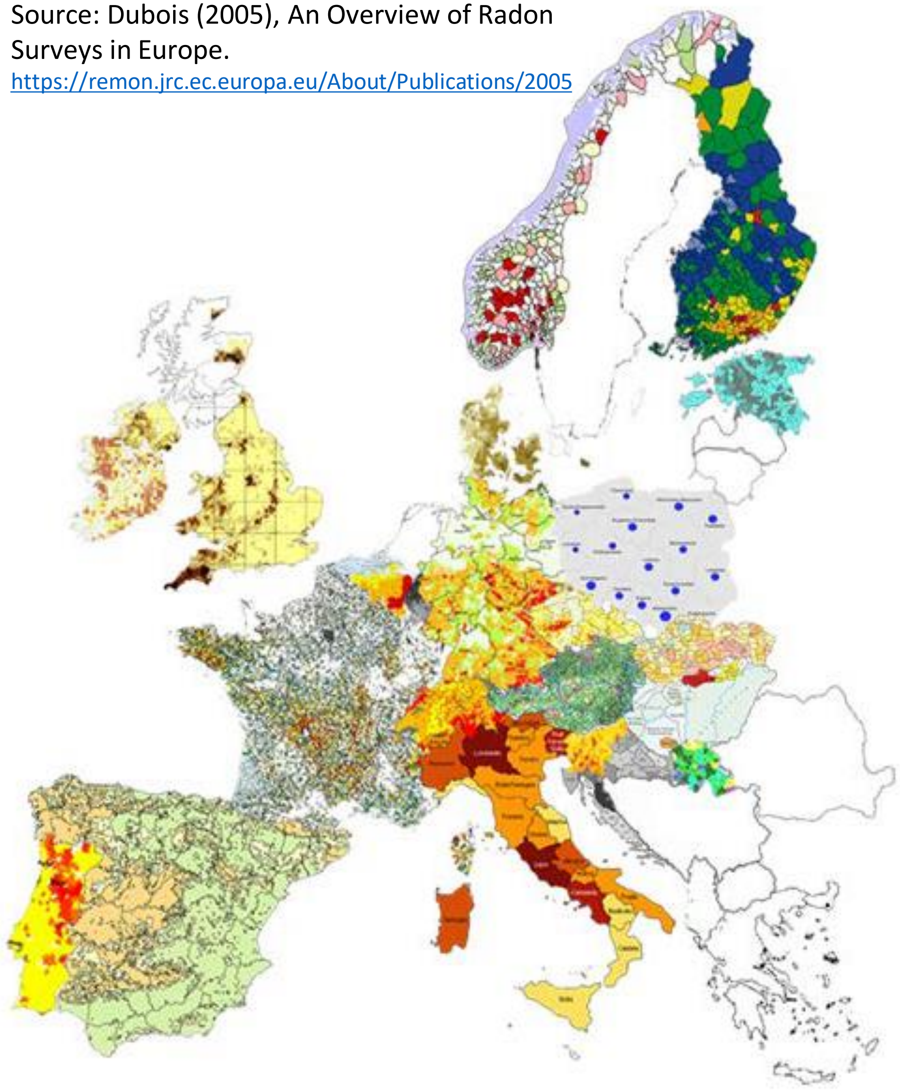
The titles of all other acts are printed in bold type and preceded by an asterisk.

Reference level (RL): must be ≤ 300 Bq/m³ (BSS Art 54,1 & 74,1)

These areas are called Radon Priority Areas (RPA) to indicate priority in taking action
(It does not mean "no action" in No-RPA).

Radon mapping

- Detect Radon Priority Areas:
  - There is **not a "natural" definition**, and different criteria may be applied. For example:
    a. AM in the area > Threshold;
    b. Prob[InRn > Reference Level] > Threshold;
    c. AM of the area represents the upper X% (e.g. 90^{th} Percentile);
    d. Collective exposure (AM x Population) is among the upper X%.
  - **Political decision** (and data availability)
- Accurate mapping is important:
  - To increase public awareness of radioactive environment.
  - To target homeowners so remediation work can be carried out.
  - As it may affect building regulations; e.g. all new homes in "Radon Priority Areas" must be build with a radon barrier.
- Two types of maps depending on the datasets used:
  - Indoor Radon Maps: based on indoor radon measurements.
  - Geogenic Radon Maps: based on geological information.



Source: Dubois (2005), An Overview of Radon Surveys in Europe. https://remon.jrc.ec.europa.eu/About/Publications/2005

European Atlas of Natural Radiation

- The Atlas **started in 2006** with indoor radon measurements.
- The **objective of the Atlas** are:
  - Increase public knowledge of natural ionizing radiation;
  - Analyse the level of natural radioactivity caused by different sources;
  - Produce a better estimate of the annual dose to which the general population is exposed;
  - Compare natural and artificial sources.
- For more than ten years, the JRC has been developing the **European Atlas of Natural Radiation**. It includes maps of the natural radioactive levels of:
  - Annual cosmic-ray dose;
  - Indoor radon concentration;
  - Uranium, thorium and potassium concentration in soil and in bedrock;
  - Terrestrial gamma dose rate;
  - Soil permeability.
- Digital versions of these maps are available on the JRC website (https://remon.jrc.ec.europa.eu/About/Atlas-of-Natural-Radiation)

EU Indoor Radon Map

- The European Indoor Rn Map (EIRM) currently shown in the European Atlas of Natural Radiation (EANR) is **regionally incomplete**. Data generation is slow: coordination of national, regional, and local authorities (difficult).

- **Only ground floor** measurements, although most people live in higher floors. When started in 2006, it was concluded (Prague conference) that if at all, only for ground floor rooms ± representative data would be available. It seems that this argument is still valid.

- **Exposure** requires input of **demographic and sociological** knowledge:
  - Time spent indoors (home and workplace)
  - How much time spent at either?
  - They are usually located in some distance

- Physics inputs:
  - **Equilibrium factors, unattached fraction**? Reasonable to use default values?
  - Rn characteristic of **workplaces**! Data only for homes; workplaces probably different.

Input data

Indoor radon

Geology

Uranium concentration in topsoil

Potassium concentration in topsoil

Indoor radon

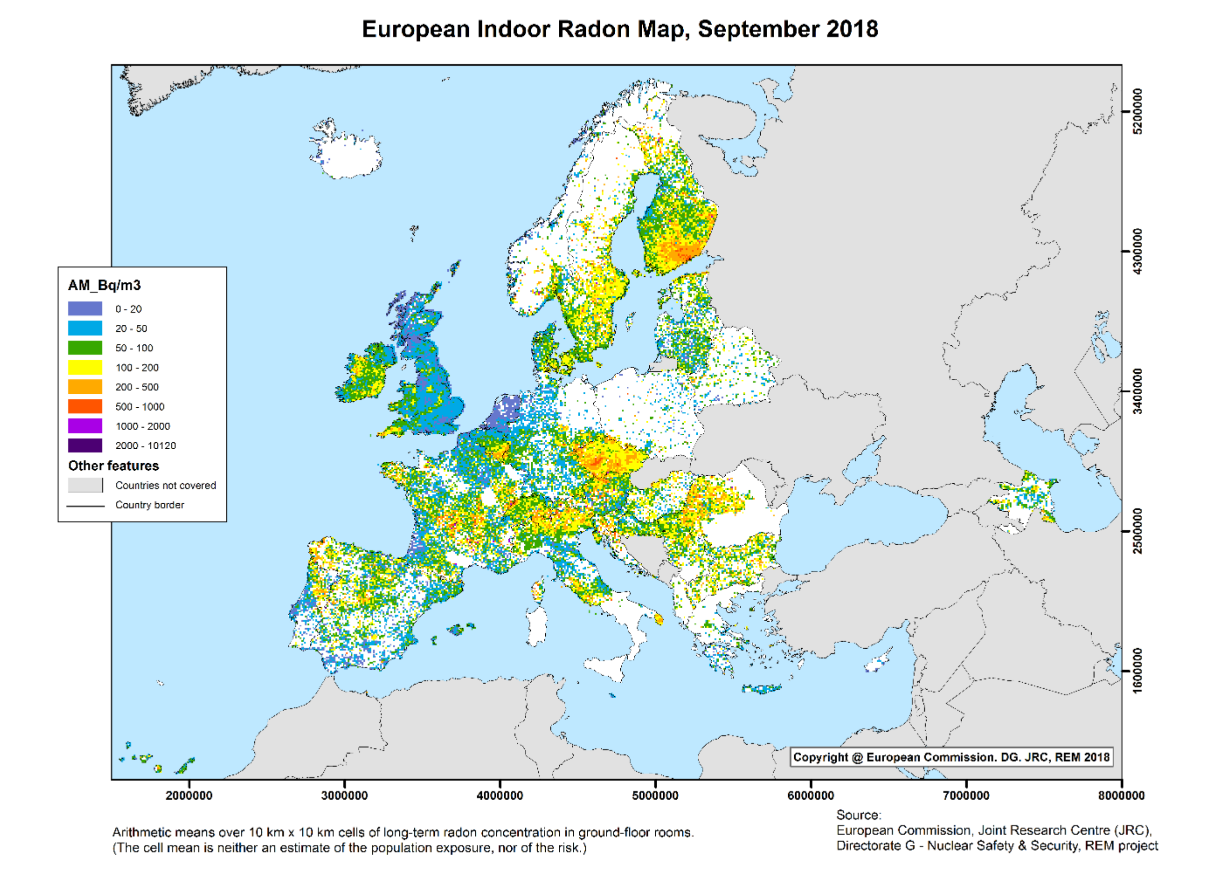
Data: annual average indoor radon concentration measured on ground floor of residential dwellings

Participating countries provide summary statistics estimated over 10 km x 10 km grid cells without communicating the original data to guarantee confidentiality (Original data remain with suppliers!)

In each cell, statistics are calculated:

- Number of measurements
- Arithmetic mean (AM)
- Standard deviation (SD)
- AM(ln data) $\rightarrow$ GM = exp(AM ln)
- SD(ln data) $\rightarrow$ GSD = exp(SD ln)
- Median
- Minimum
- Maximum

JRC: plausibility checks, statistics over cells, map



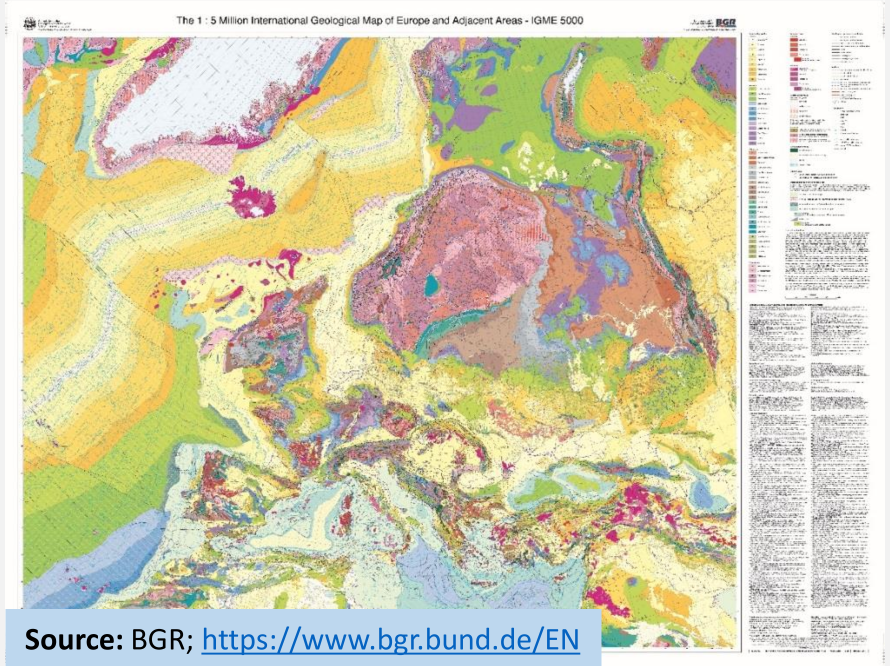
Source:
https://remon.jrc.ec.europa.eu/About/Atlas-of-Natural-Radiation

Geology

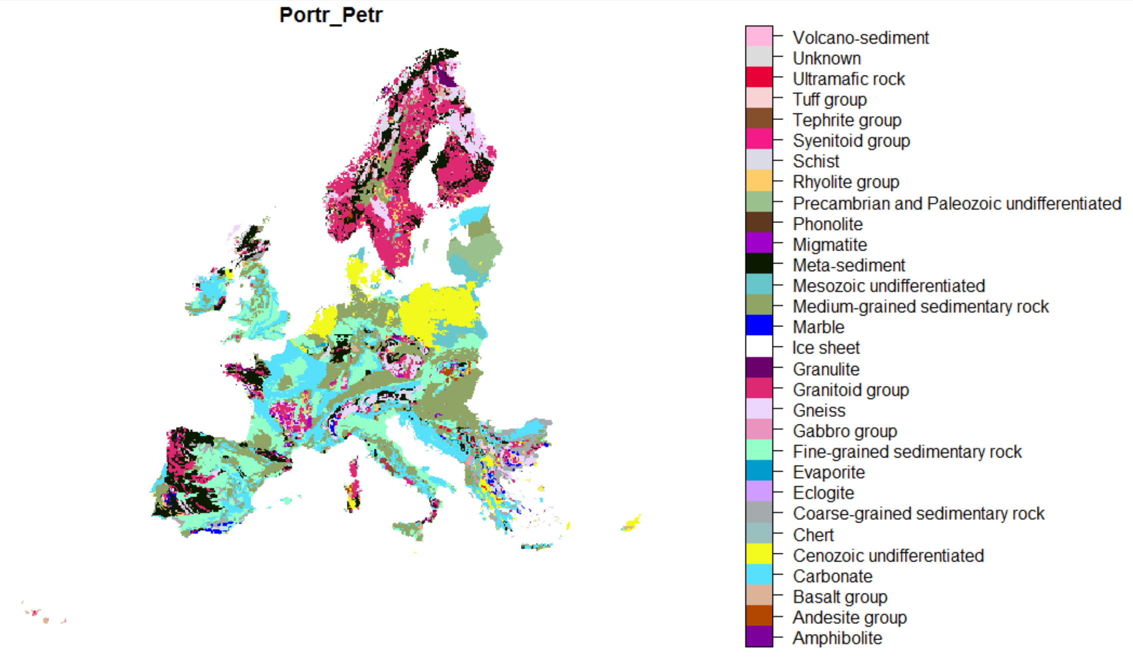
Geological map: 1:5 Million International Geological Map of Europe – IGME 5000 (Asch, 2003)

Simplification: The original IGME map presents 178 lithostratigraphic units that were reduced to 28 lithological units based on ANOVA tests ran on an extensive Italian geological database (Nogarotto et al. 2018).

Grid cells of 10x10 km: The prevalence unit in each grid of 10 km x 10 km is assigned to be compare with the indoor radon concentration (AM)



Source: BGR; https://www.bgr.bund.de/EN



Uranium

- The European uranium concentration in soil map displays the estimated concentration of uranium in soil over 10 km x 10 km grid cells.

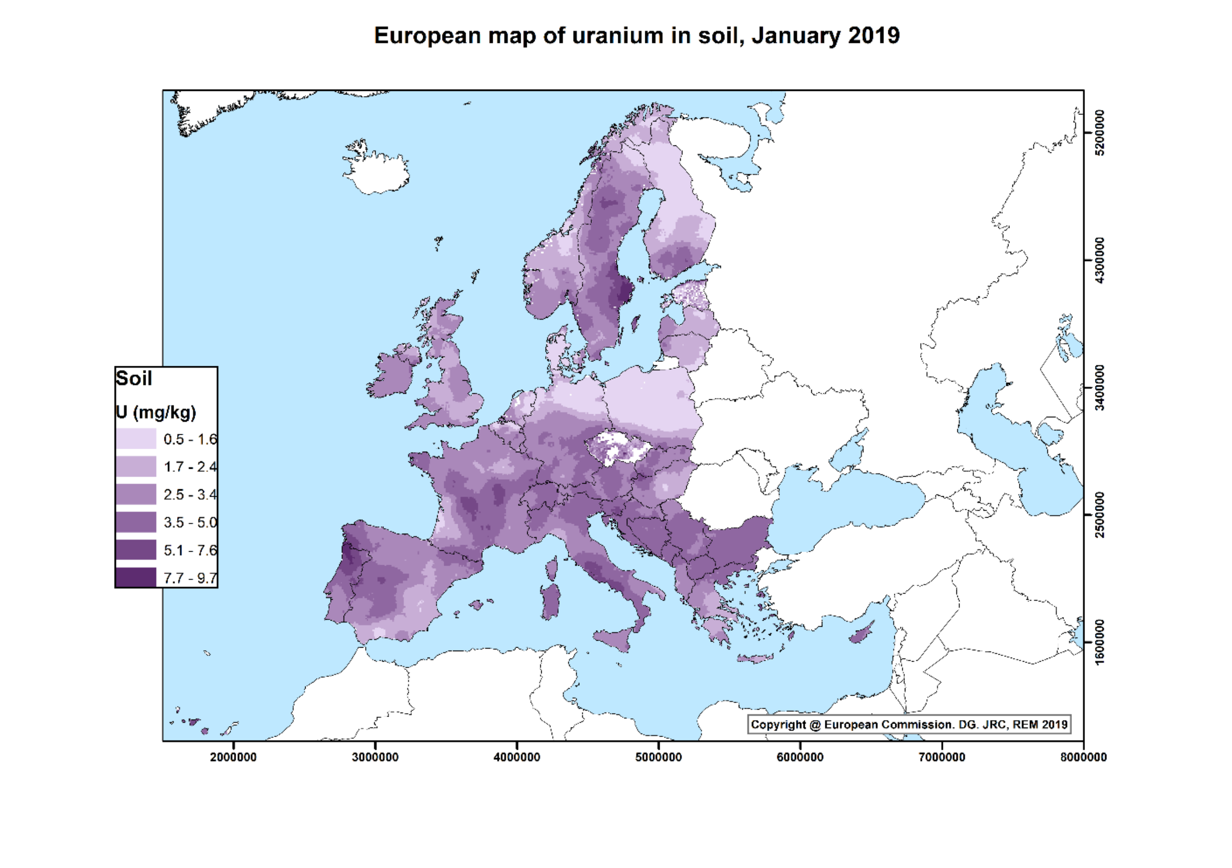
- The map has been created using approximately 5,000 data from topsoil samples belonging to two European databases:

  a) The Geochemical Atlas of Europe developed by the Forum of European Geological Surveys - FOREGS (http://weppi.gtk.fi/publ/foregsatlas/index.php);

  b) The Geochemical Mapping of Agricultural and Grazing Land soil in Europe – GEMAS (http://gemas.geolba.ac.at/).

- The data were interpolated using ordinary kriging.

- For Belgium, the Czech Republic and Estonia, data from their national databases have been used.



Source: https://remon.jrc.ec.europa.eu/About/Atlas-of-Natural-Radiation

Potassium

- The European uranium concentration in soil map displays the estimated concentration of uranium in soil over 10 km x 10 km grid cells.
- The map has been created using approximately 5,000 data from topsoil samples belonging to two European databases:
  a) The Geochemical Atlas of Europe developed by the Forum of European Geological Surveys - FOREGS (http://weppi.gtk.fi/publ/foregsatlas/index.php);
  b) The Geochemical Mapping of Agricultural and Grazing Land soil in Europe – GEMAS (http://gemas.geolba.ac.at/).
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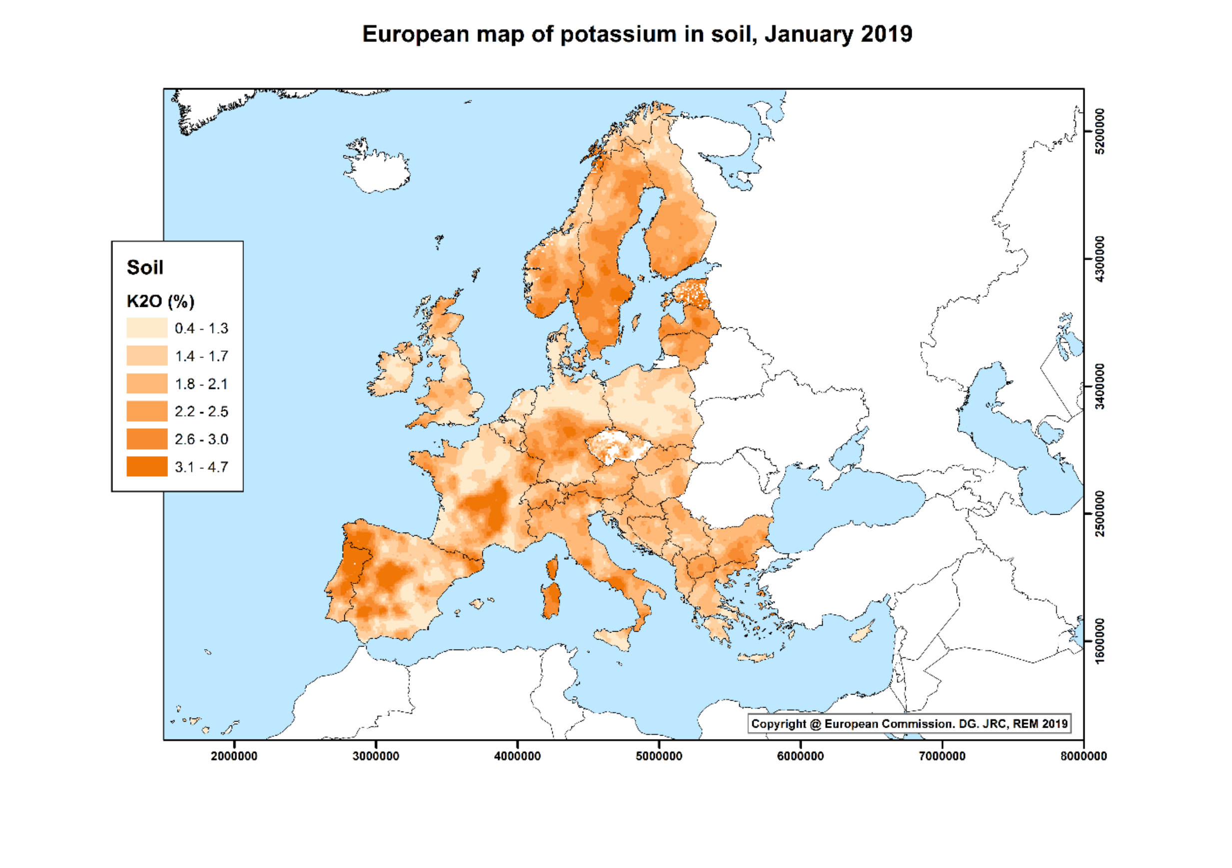


Source: https://remon.jrc.ec.europa.eu/About/Atlas-of-Natural-Radiation

Indoor radon vs. Geogenic factors

The total indoor radon variance explained by U, K_2O, and Geology is about 20%

	df	Sum sq.	Mean sq.	F value	Pr (>F)
Log(U)	1	1457.8	1457.77	2461.303	$<2.2 \times 10^{-6}$
Log(K_2O)	1	1483.6	1483.58	2504.891	$<2.2 \times 10^{-6}$
Sim. Geology	27	868.1	32.15	54.228	$<2.2 \times 10^{-6}$

- **Uranium (7,75%)** is a source of radon in soil, and thus a positive association with indoor radon is expected. The Pearson's correlation coefficient between indoor radon and uranium concentration in topsoil is however relatively low (r = 0.2783), which implies that estimations with U as secondary variable are still mainly based on the primary variable (i.e. AM).

- **Geology (4.61%)** is associated with both uranium and radon sources, and with physical properties which permit the release of radon from the soil matrix and its transport in the environment (e.g. mineralogy, porosity, permeability).

- **Potassium (7.88%).** The positive correlation between indoor radon and potassium is, however, not evident. K_2O may be related to clay content in soils, and although the permeability of wet clays is low, it may increase when soils are dried as a consequence of building a house.

Model 1: Indoor radon predictions

Inverse Distance Weighted (IDW)

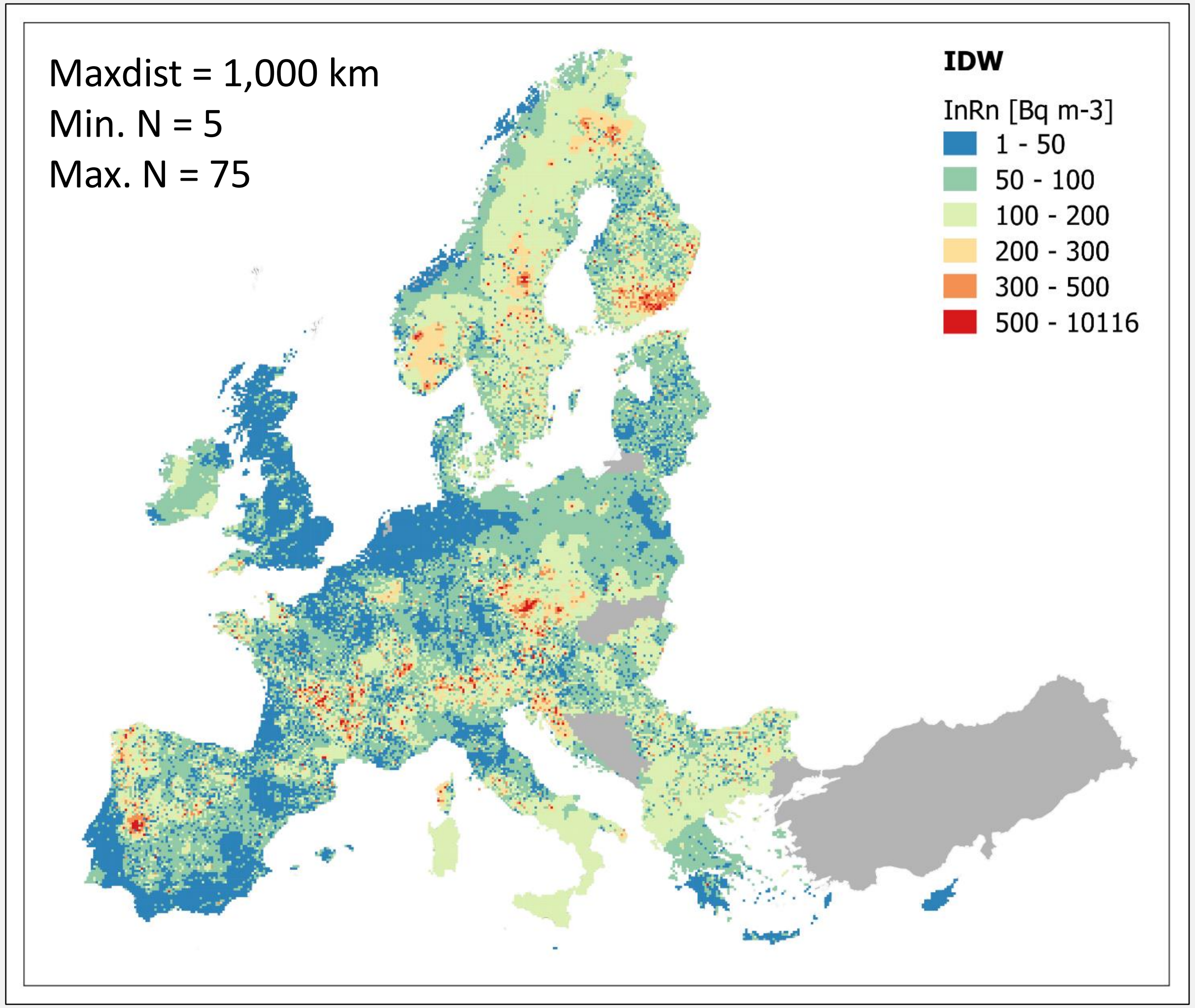
Ordinary Kriging (OK)

Collocated CoKriging (CoCK)

Regression Kriging (RK)

Cross-validation

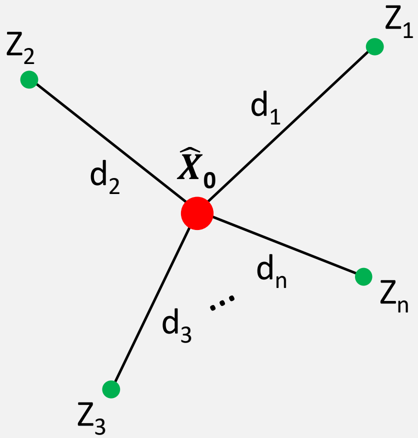
Inverse Distance Weighted



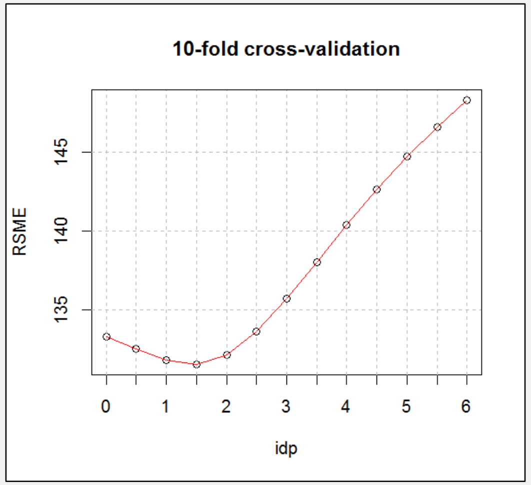
Predictions:

$$\hat{Z}_0 = \frac{\sum_{i=1}^{n} \frac{1}{d_i^p} Z_i}{\sum_{i=1}^{n} \frac{1}{d_i^p}} \qquad \text{if di} > 0$$

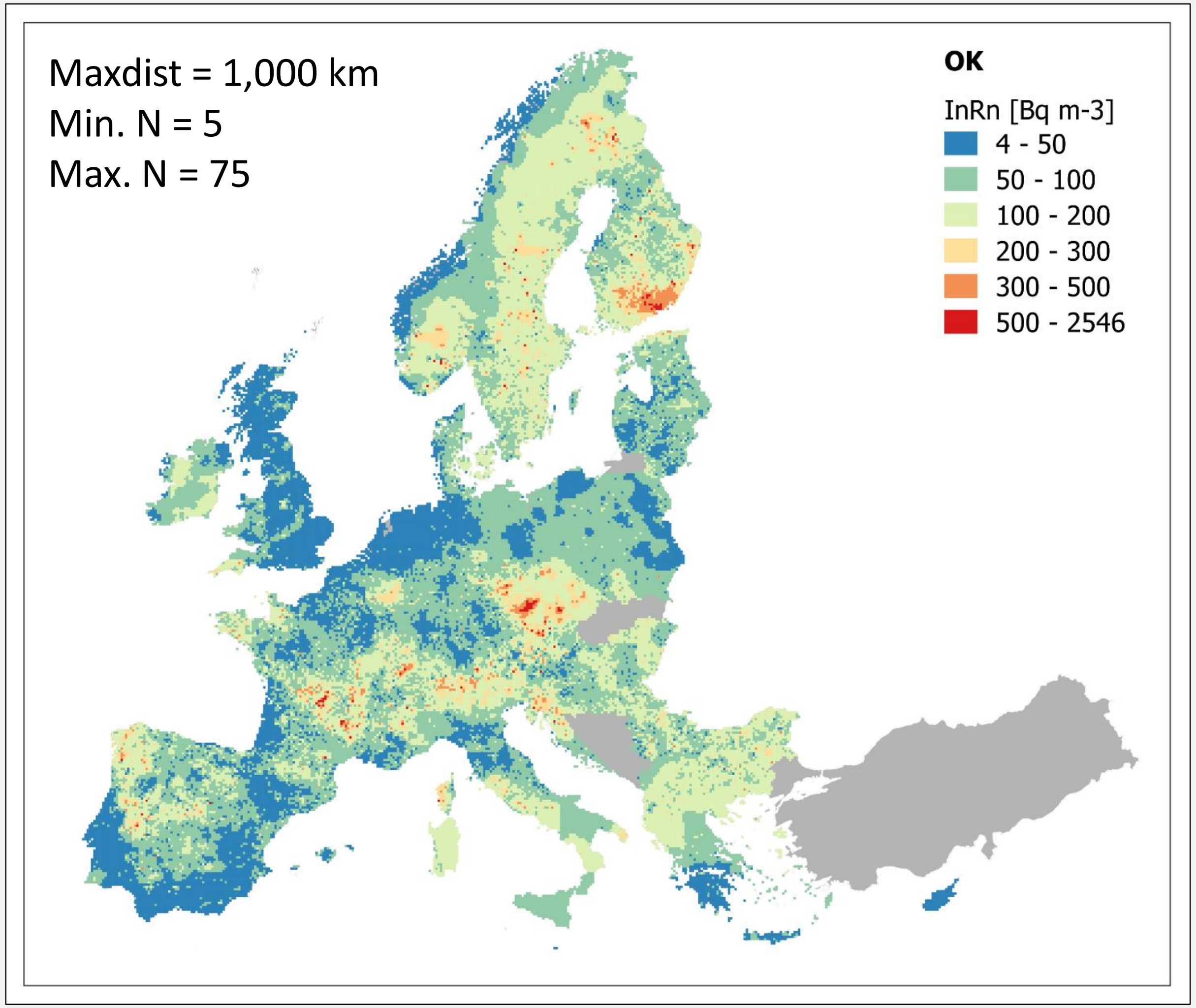
$$\hat{Z}_0 = Z_i \qquad \text{if di} = 0$$



Optimal p: value which minimizes RMSE (p = 1.5)



Ordinary Kriging

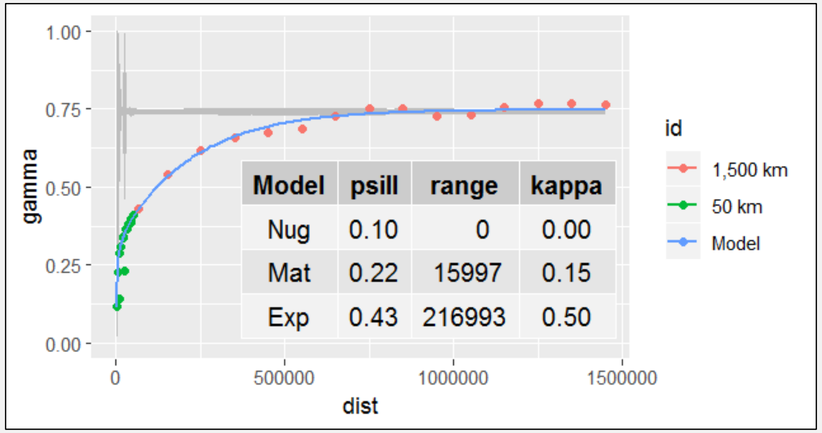


Trans-Gaussian kriging using Box-Cox transforms:

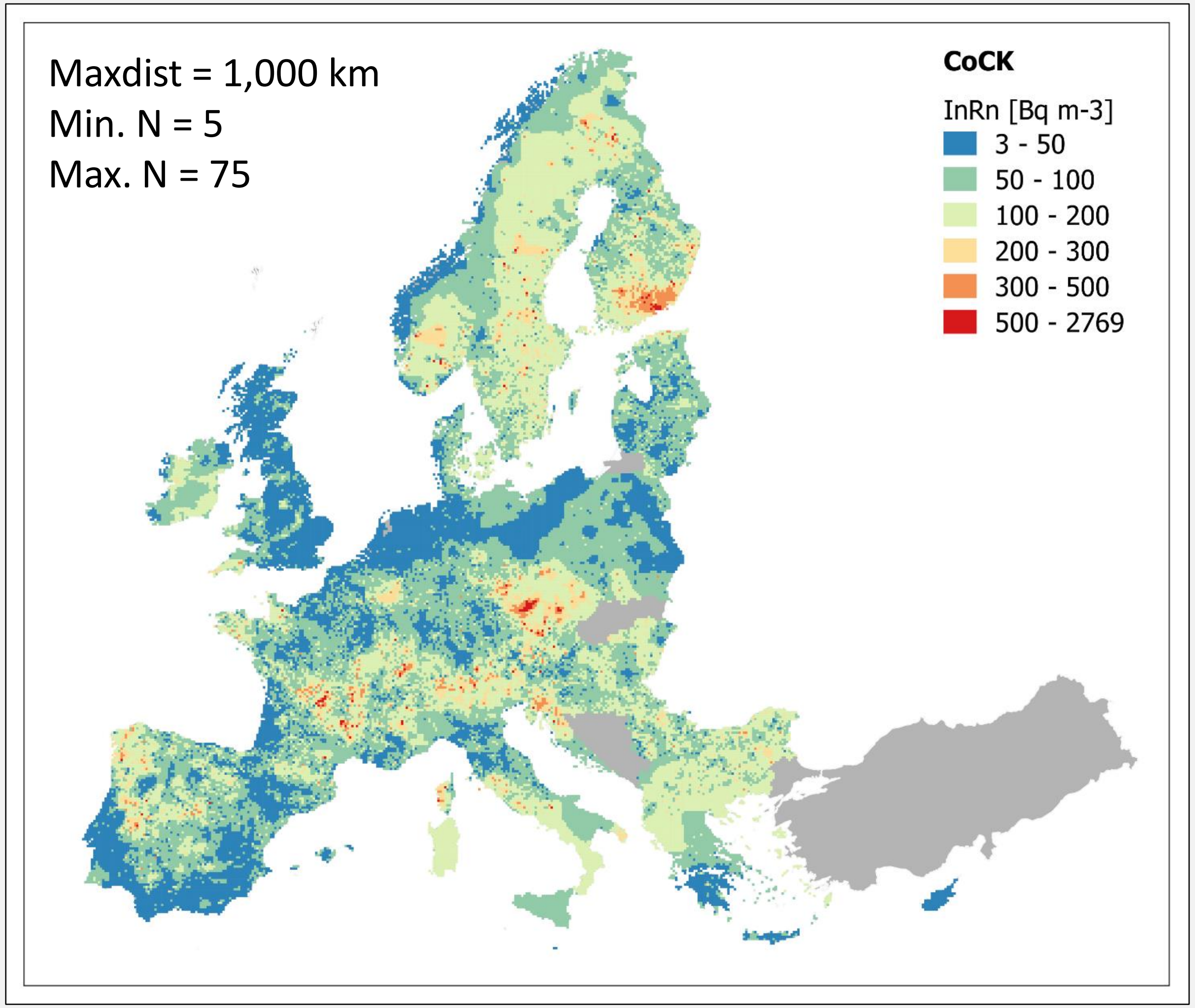
Predictions are carried out over the transformed data, and then unbiased back-transformed to the original scale using the Lagrange multiplier (function krigeTg in R software, "gstat" and "MASS").

$$\phi_{\lambda}^{-1} = \begin{cases} \dfrac{X^{\lambda} - 1}{\lambda} \\ \log(X) \end{cases} \qquad \phi(x) = \begin{cases} (x \cdot \lambda)^{\frac{1}{\lambda}} \\ e^{x} \end{cases} \qquad \phi''(x) = \begin{cases} (1-\lambda)(x \cdot \lambda + 1)^{\frac{1}{\lambda}-2} & \lambda \neq 0 \\ e^{x} & \lambda = 0 \end{cases}$$

$$\hat{Z}(S_o) = \phi\left(\hat{Y}_{OK}(S_0)\right) + \phi''(\hat{\mu})\left(\frac{\sigma_{OK}^{2}(S_0)}{2} - \mathbf{m}\right)$$



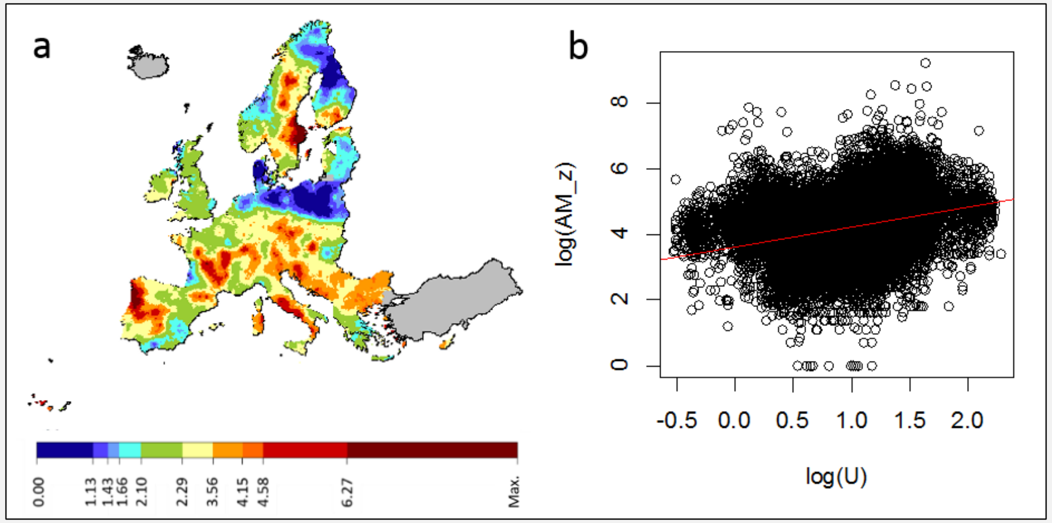
Collocated CoKriging



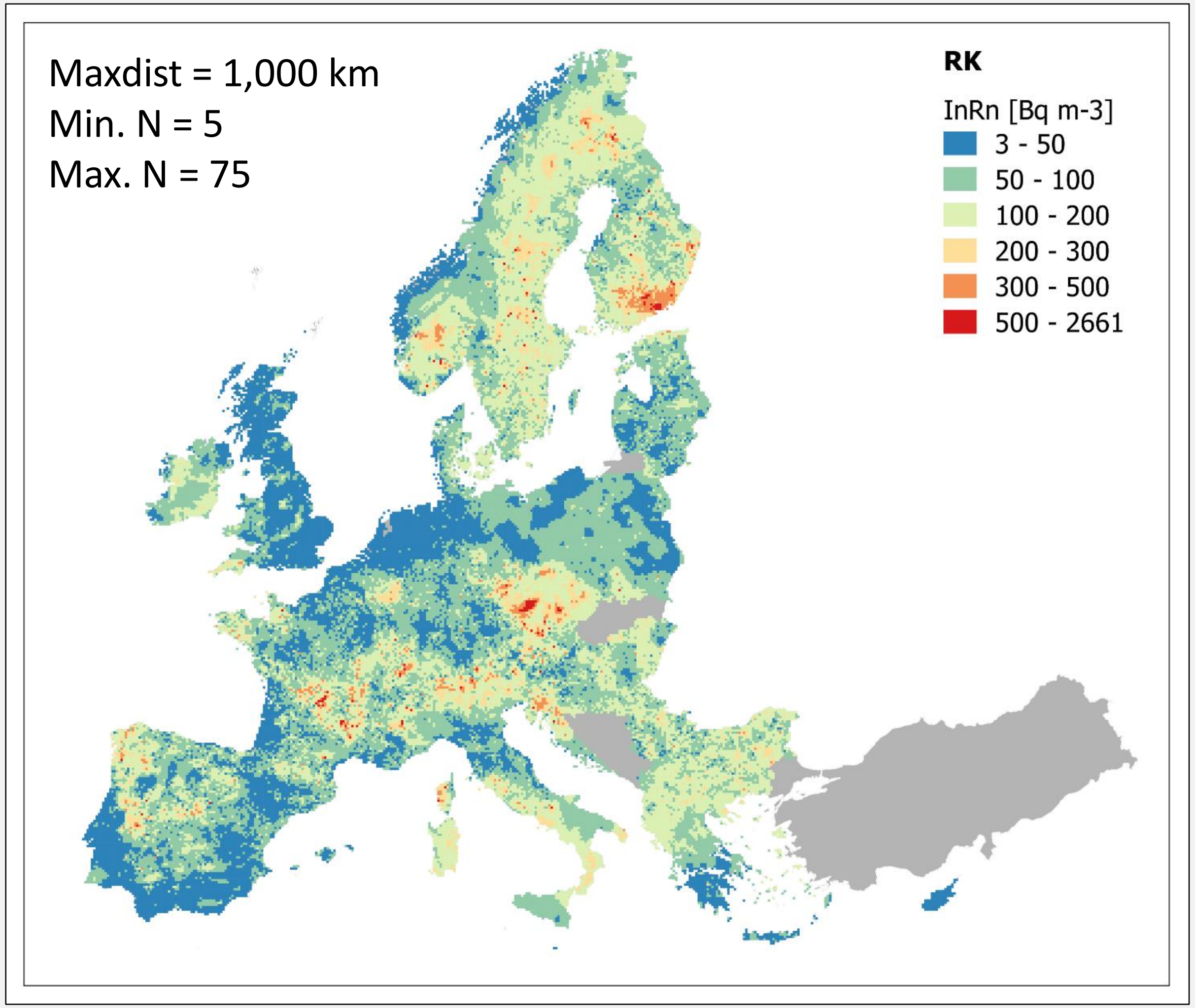
Predictions:

Special case of cokriging where only the direct correlation between the primary (e.g. AM_z) and the secondary variables (e.g. U) is used, ignoring the direct variogram of the secondary variable and the cross variograms. It simplified the cokriging equations although the secondary variable must be sampled at all prediction points

$$\mathbf{E}[X] = e^{\left(\mu + \frac{\sigma^2}{2}\right)} \qquad \mathbf{var}[\mathbf{X}] = \mathbf{e}^{(2\mu + \sigma^2)} \cdot \left(\mathbf{e}^{\sigma^2} - \mathbf{1}\right)$$



Regression Kriging



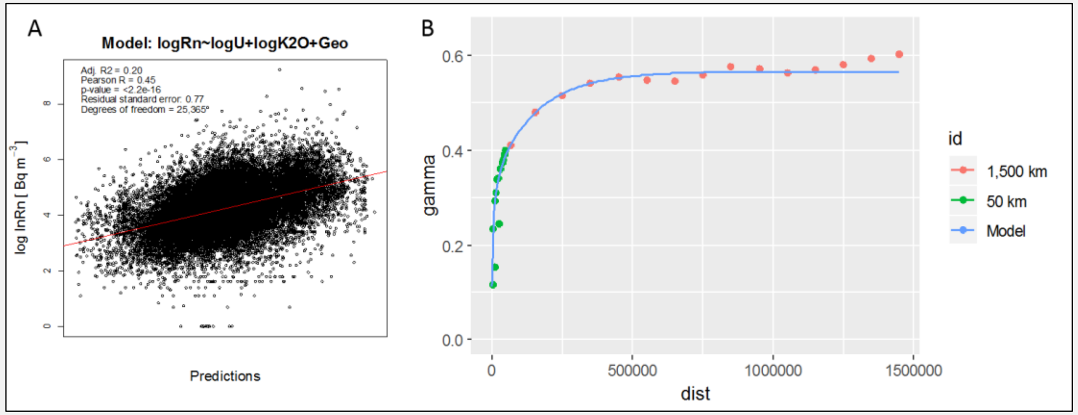
Predictions (two-steps):

1. **Regression estimation** of the dependent variable (e.g. AM_z) based on secondary variables (e.g. geogenic factors: Geology, U, K_2O).

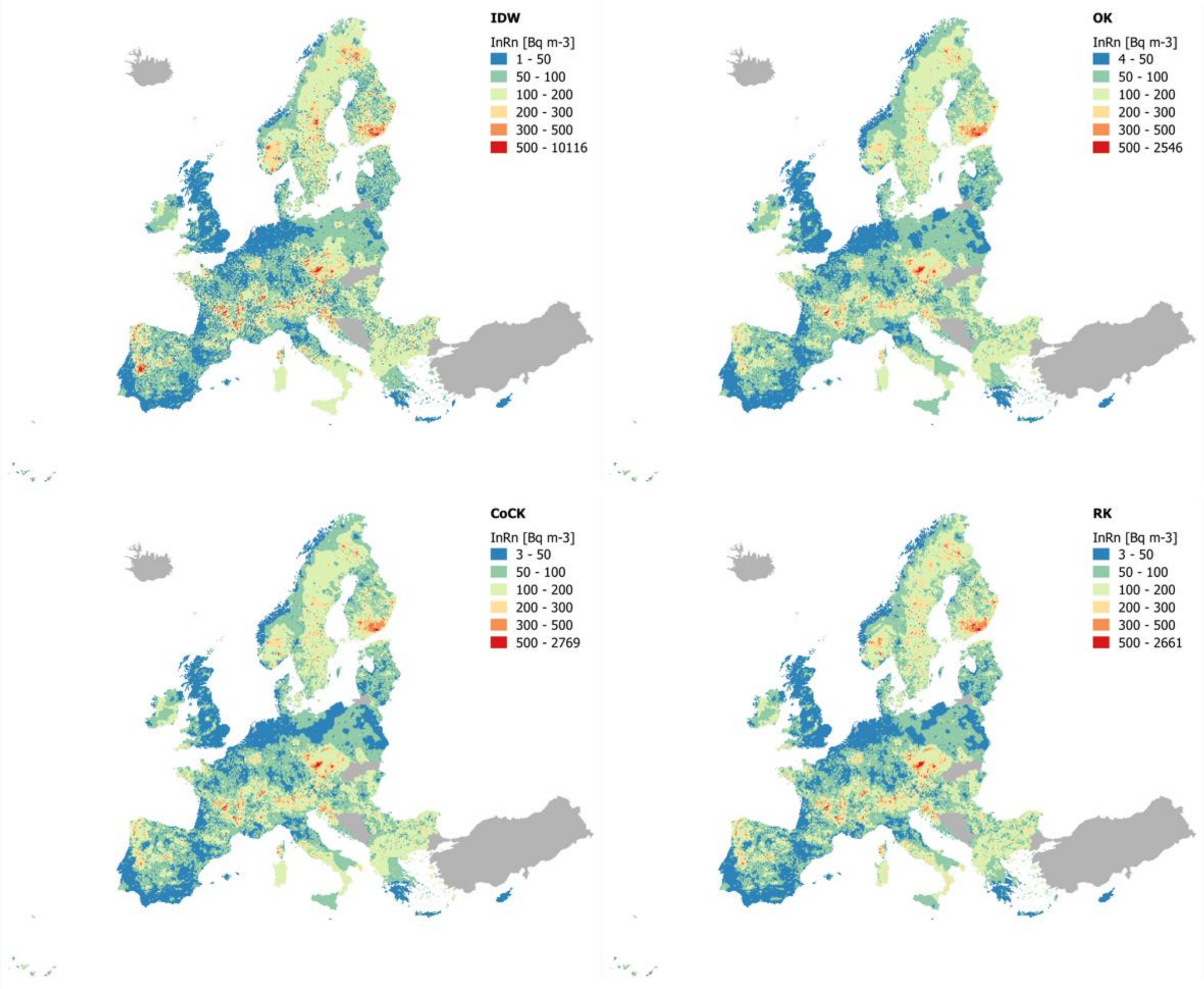
2. **Spatial distribution of the residual** (Ordinary Kriging)

Final estimates are the sums of the regression estimates and the ordinary kriging estimates.

$$\mathbf{E}[X] = e^{\left(\mu + \frac{\sigma^2}{2}\right)} \qquad \mathbf{var}[\mathbf{X}] = \mathbf{e}^{\left(2\mu + \sigma^2\right)} \cdot \left(\mathbf{e}^{\sigma^2} - \mathbf{1}\right)$$



Predictions



Limitations

- Input data are actually grid cells means treated as point samples.
- Reliability of data because of different numbers of measurements is a problem.
- Small differences may be appreciated in the predictions of the different interpolation techniques
  - IDW and OK are weak in areas with no conditioning data.
  - CoK and RK are more reasonable in the physical sense but they are analytically more complicated
- Back-transforming predictions to the original scale.
- Variogram parameters must be estimated very carefully, ill assessment of the kriging SD leads to large errors in E[X] and Var[X] due to exponentiation.
- Deviations from stationarity.
- The map appears “noisy” to varying degrees between different regions.

5 x 10-Fold Cross-validation

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|Z_i - X_i|$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Z_i - X_i)^2}$$

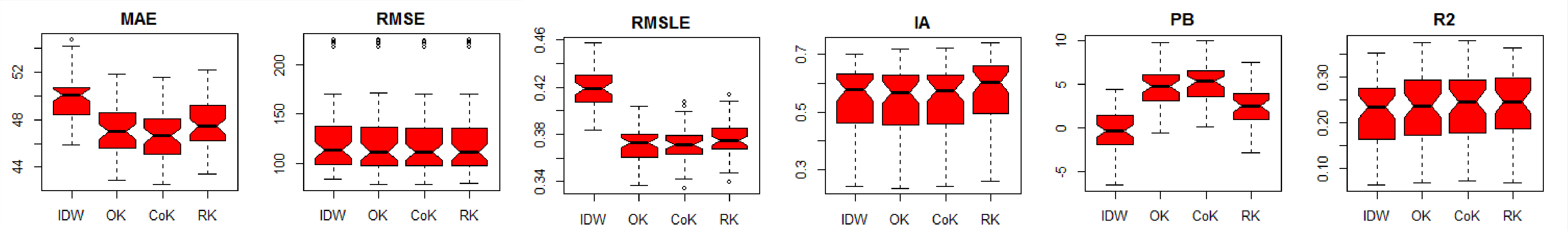
$$RMSLE = \frac{1}{n}\sum_{i=1}^{n}(\log(Z_i + 1) - \log(X_i + 1))^2$$

$$IA = 1 - \frac{\sum_{i=1}^{n}(Z_i - X_i)^2}{\sum_{i=1}^{n}(|X_i - \bar{X}| - |Z_i - \bar{X}|)^2}$$

$$PB = 100\,\frac{\sum_{i=1}^{n}(Z_i - X_i)}{\sum_{i=1}^{n} X_i}$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(Z_i - X_i)^2}{\sum_{i=1}^{n}(X_i - \bar{X})^2}$$

Method	MAE	RMSE	RMSLE	IA	PB	R2
IDW	50.07	113.44	0.4189	0.5755	-0.346	0.2352
OK	46.98	112.10	0.3728	0.5680	4.785	0.2377
CoCK	46.62	111.64	0.3711	0.5741	5.326	0.2460
RK	47.41	111.73	0.3744	0.6014	2.513	0.2462



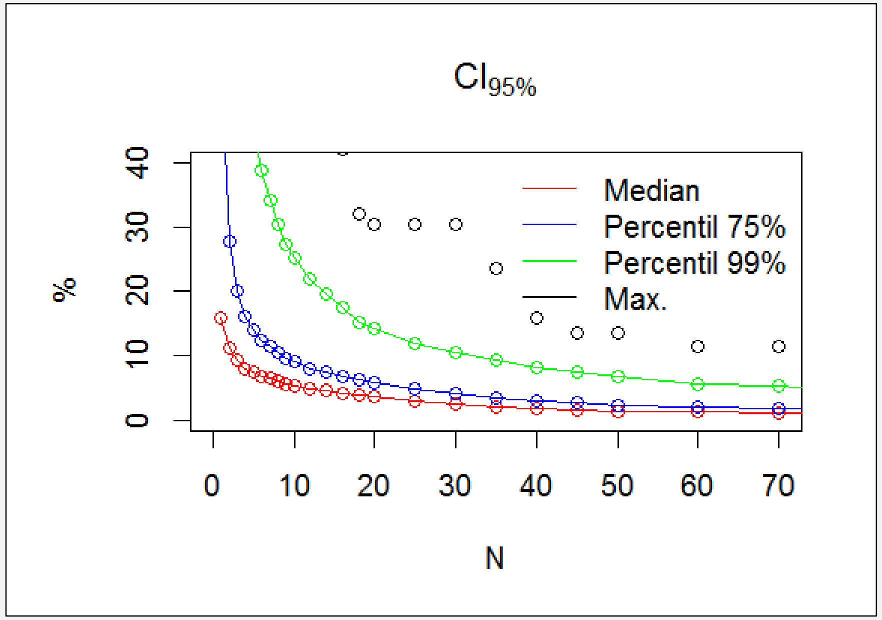
MAE and **RMSE** may be influenced by outliers. **RMSLE** is less sensitive to outliers and preferable when there is a large range in the values. These parameters are positive values and the closer they are to 0, the better is the model fit. **IA** is a standardized measure of the degree of model prediction error; it varies from 0 (no agreement at all) to 1 (perfect match). **PB** (%) measures the average tendency of having larger/smaller predicted values than the observed ones. The optimal value is 0, and positive/negative values indicate over/under-estimation bias. **R^2** is a measure of how well the model fits a data set; a perfect model has $R^2 = 1$.

Output: Pan-European Indoor Rn Map

Objective: produce an All-European Indoor Radon Map by minimising data processing, and therefore we prefer to estimate the radon average directly by indoor radon measurements carried out at each grid (i.e. AM_z).

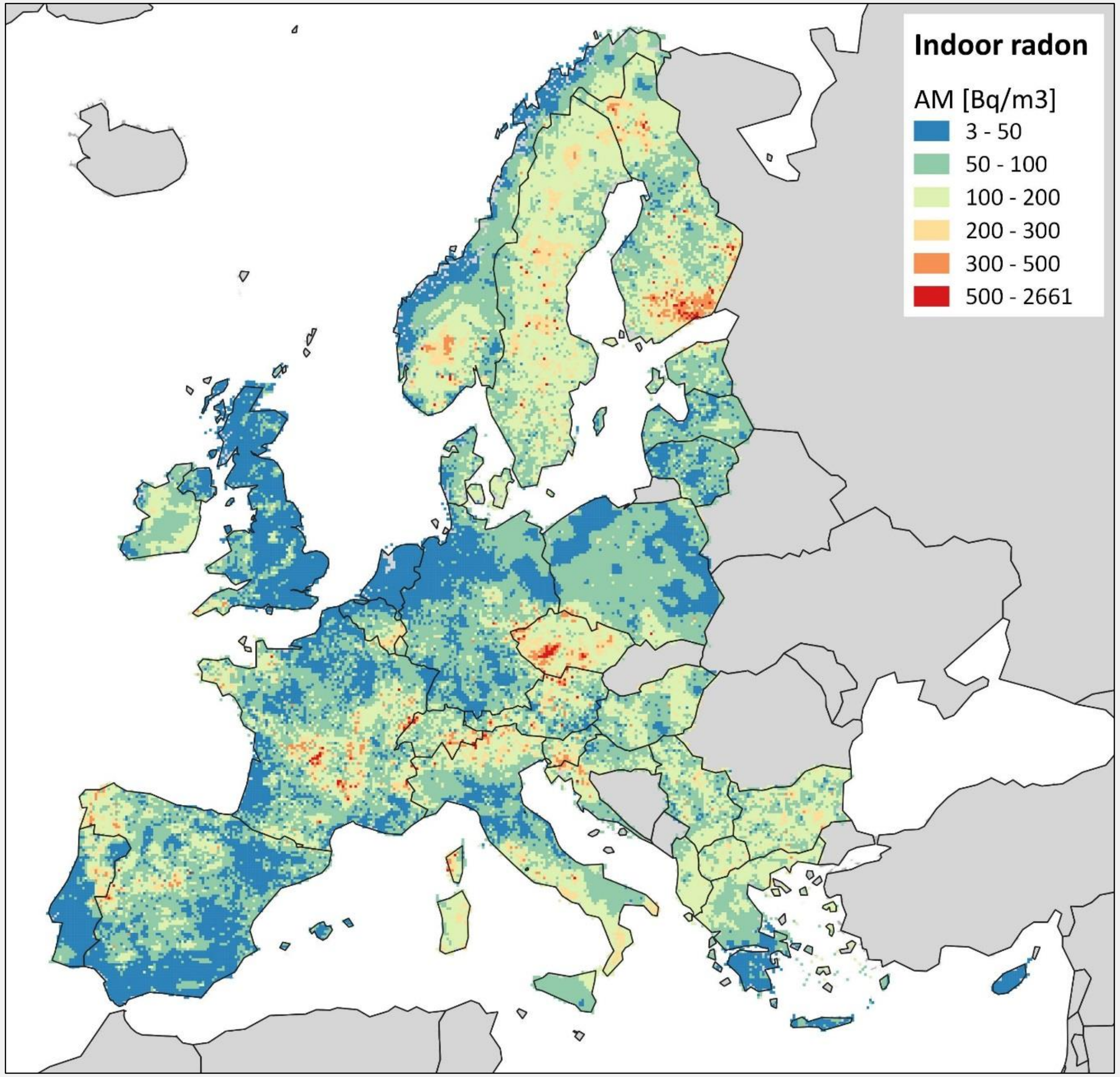
Mean value and the confidence interval:

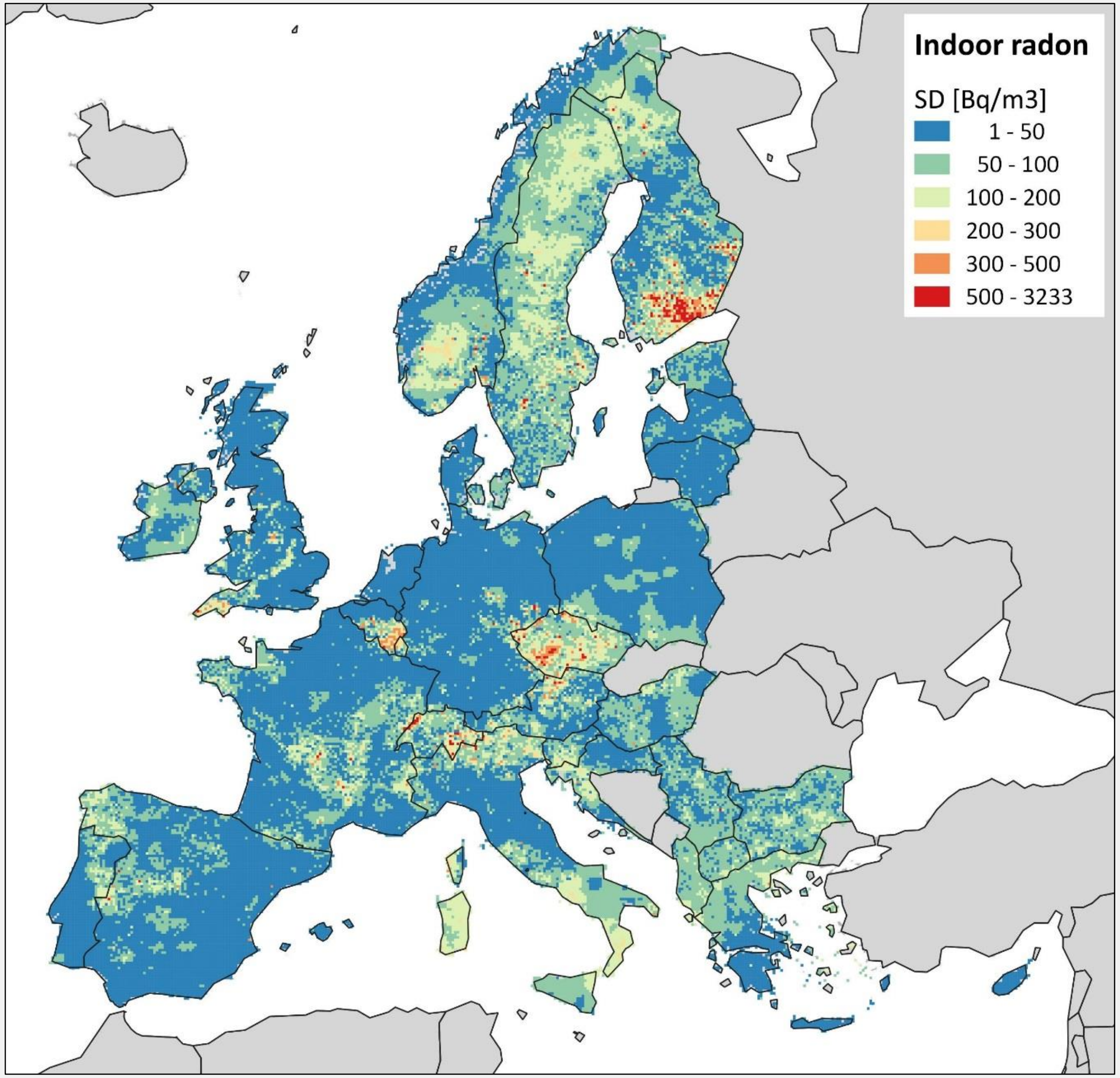
$$\bar{x} = \frac{1}{n}\sum_{i}^{n} x_i \pm t_{\left(1-\frac{\alpha}{2},n-1\right)} \frac{s}{\sqrt{n}}$$



- The **confidence interval** decreases when the sample size increases. In our cases, the <u>$CI_{95\%}$ (α = 0.05) for sample size of about 30-40 data is around ±5%,</u> and generally lower than 15 - 30%.
- **30 measurements seems reasonable for obtaining a good estimation of the radon exposure in a specific grid** although the assumption of data independence is not valid (i.e. there is spatial correlation between indoor radon measurements which can be modelled by the variogram).
- For the final **All-European Indoor radon map** we use therefore the <u>AM of the grids with 30 or more measurements, and the value predicted by RK</u> in the grids with less than 30 measurements.

Output: Pan-European Indoor Rn Map



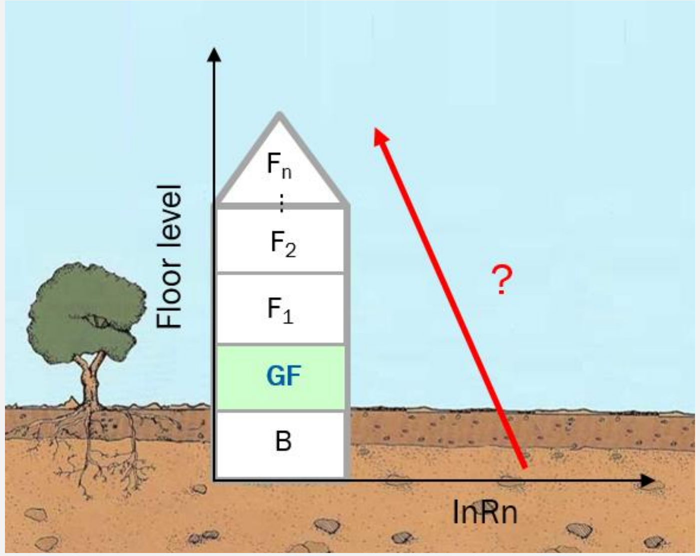


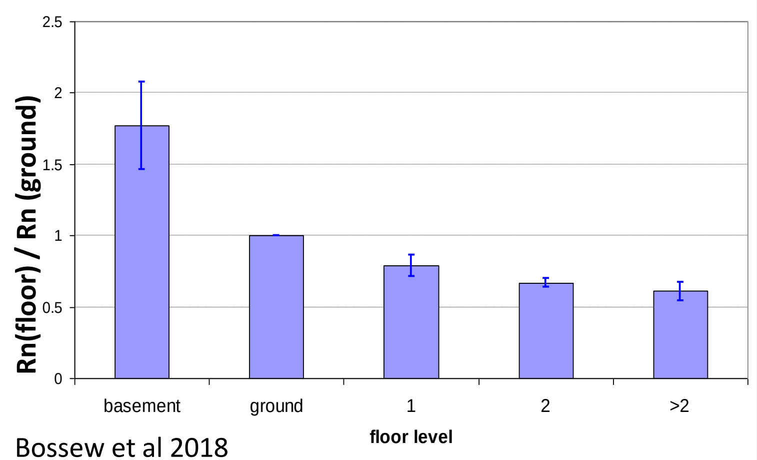
Model 2: Pan-European Radon Dose Map

Floor correction

Dose conversion

Floor correction





Bossew et al 2018

- The **Pan-European indoor radon map** represents the average value of <u>indoor radon concentration in ground floor</u>
- It is **not representative of the radon exposure** to European citizens since most people do not leave on ground floor.
- It may **overestimate the radon exposure** since for most residential buildings Rn decreases with floor level
- A **floor correction model** must be developed – **to be further investigated**
- Maybe regional trend? (due to regionally different building styles? climate?) – **to be further investigated**
- At a location (grid cell), which is the **fraction of rooms** in basement, ground, 1., 2.,… floor? Link with population density? – **to be further investigated**

Dose conversion

$$\textbf{Annual dose: } \mathrm{D}\left[\mathrm{mSv}\ y^{-1}\right] = C_{Rn} \cdot F_E \cdot \mathrm{T} \cdot F_O \cdot F_D$$

Challenges (to be further investigated):

1. **Annual indoor radon concentration (C_{Rn}):**
   a) **Predictions** over grid cells of 10 x 10 km (this presentation). Can we improve predictions? New statistical models (e.g. ML)? Other secondary variables (e.g. soil permeability)?.
   b) **Floor correction** model.
2. **Equilibrium factor (F_E):** convert C_{Rn} to the Equivalent Equilibrium Concentration (EEC) of radon daughters. Take default values (e.g. 0.4 UNSCEAR)? Regional trends? Dependence of usage?
3. **Time expend indoors?** (Occupancy factor - F_o). UNSCEAR recommend a value of 0.8. Can we use it for all Europe? Differences between rural vs. urban areas?
4. **Time spend at home vs. workplaces?** Rn characteristic of workplaces in general different from dwellings. Can we model this?
5. **Commuting patters.** Workplace in most cases not at same location as home. Sometimes quite far away… people commute 100 km. How to model such effect?
6. **Dose conversion factor (F_D):** dose coefficient applied to the EEC. International recommendation $9 \cdot 10^{-6}$ mSv per Bq m^{-3} h (under discussion).

Output 2: Pan-European Rn Dose Map

Annual dose: $\mathbf{D}\left[\mathbf{mSv}\ y^{-1}\right] = C_{Rn} \cdot F_E \cdot \mathbf{T} \cdot F_O \cdot F_D$

FIRST TRY:

- Indoor radon concentration at ground floor level and standard dose conversion factors.
- Uncertainty analysis by Monte Carlo simulation:
  (Elío et al, Environnent International 114: 69–76, 2018)

  Nsim = 100

  C_{Rn} ~ N(AM_z, SD_z) [truncated InRn > 0]

  F_D ~ N($9 \cdot 10^{-6}$; $1.5 \cdot 10^{-6}$)

  F_O ~ N(0.8, 0.03)

  F_E ~ LN(0.4, 1.15)

- Map the AM and SD of the simulated values

Note: It is a sensitive issue. Whether and how it can be published must be decided by the JRC

European Radon Week 2020

JRC Workshop

Methodology behind the first Pan-European Indoor Radon Map

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