16ENV10 MetroRADON

Deliverable 5

Report and Guideline on the definition, estimation and uncertainty of radon priority areas (RPA)

Lead organisation: BfS
Other involved partner organisations: AGES, BEV-PTB, IRSN, JRC, SUBG, UC, VINS

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1. Motivation

The purpose of the MetroRADON project, funded within the European Metrology Programme for Innovation and Research (EMPIR) is to develop reliable techniques and methodologies to enable SI traceable radon activity concentration measurements and calibrations at low radon concentrations. The need for this project has been largely motivated by the requirements of the implementation of the European Council Directive 2013/59/EURATOM (EU-BSS) (EC, 2013), one aim of which is to reduce the risk of lung cancer for European citizens due to high radon concentrations in indoor air. Furthermore, it is a goal of the project to enable uptake and exploitation of its results and experiences by all stakeholders concerned with radon, from regulators and policy makers, professionals in designing, performing, evaluating and interpreting radon surveys, radon instrument manufacturers to the end-users (e.g. companies providing radon measurement, construction industry) and the scientific community. More details about the MetroRADON project can be found at the project website (MetroRADON, 2020).

Article 103 of the EU–BSS requires that member states identify areas where the radon concentration in a significant number of buildings is expected to exceed the relevant national reference level – referred to as radon priority areas (RPAs) within the MetroRADON project and this report. The definition of RPAs will influence political and technical decisions, which in turn will have economic effects in these countries, such as mandatory radon measurements in workplaces in these areas according to Art. 54 EU-BSS, as well as mandatory preventive measures or priority of awareness programmes. As the definition of RPA in the EU-BSS allows a wide range of interpretation, different concepts and methodologies have been proposed and some already adopted.

Within the MetroRADON project a specific work package is included with the aim to analyze and develop methodologies for the identification of radon priority areas, to investigate the relationships between indoor radon concentrations and quantities including soil exhalation and to develop the concept of a "geogenic radon hazard index" (RHI) as a tool to help identify radon priority areas.

2. Introduction

This document ("*Report and Guidelines on the definition, estimation and uncertainty of radon priority areas (RPA*)) represents the deliverable D5 of the EURAMET 16ENV10 MetroRADON project MetroRADON project.

It reports the results of the activities developed in Work Package 4 – WP4: Radon priority areas (RPAs) and the development of the concept of a "geogenic radon hazard index" (RHI) regarding the definition, estimation and uncertainty of RPA (Task 4.1, 4.2, 4.4). The results of the new developments in estimation of radon priority areas (Task 4.3) are not part of this report, but discussed separately in the deliverable D6 of the MetroRADON project.

The report is structured as:

- Introduction to WP4
- Brief summary of Task 4.1 (detailed report in Annex 1)
- Brief summary of Task 4.2 (detailed report in Annex 2)
- Discussion of Task 4.4. activities (detailed report of 4.4.2 (mapping exercise) in Annex 4)
- Summary and Recommendations
- Annexes reporting the full results of Task 4.1, Task 4.2 and Activity 4.4.2

Work Package 4 – WP4

The aim of the WP is to analyse and develop methodologies for the identification of radon priority areas, to investigate the relationships between indoor radon concentrations and quantities, and to develop the concept of a “geogenic radon hazard index” (RHI) as a tool to help identify radon priority areas.

The aim of Task 4.1. is to review and evaluate the concepts which have already been proposed to define and to estimate RPAs. Therefore, information is collected and the methods for radon mapping and delineation of RPAs which are already being used in different countries and regions are discussed. It is evaluated what purpose they can be used for (e.g in workplaces, preventive measures, public radon exposure) and if and how certain methods, developed in one country for a specific purpose, could be used or adapted for other purposes or in other countries or regions. The work and results of Task 4.1 are briefly summarised in chapter 3 and a detailed report of all the work done and the discussion of results can be found in Annex 1.

The aim of Task 4.2. is to estimate the relationships between indoor radon or derived quantities such as the probability of exceeding a reference level within an area and quantities related to geogenic radon such as the radon potential or uranium concentration in the ground, as some concepts for mapping the geogenic Rn potential and RPA crucially depend on such relationships. Information about the approaches used to assess a “soil radon potential” are obtained and possible inconsistencies evaluated. The work and results of Task 4.2 are briefly summarised in chapter 4 and a detailed report of all the work done and the discussion of results can be found in Annex 2

The aim of Task 4.3. is to review and to propose new technical developments related to the RPA estimation, including the development of a methodology for a harmonised “Rn hazard index” (RHI) as a tool to visualise radon priority areas and to address uncertainty budgets and classification errors which emerge in this context. The work and results of Task 4.3 is discussed in detail in the deliverable D6 of MetroRADON project. An overview of the concept, history and experiences of the development of a geogenic radon hazard index is discussed in Bossew et al, 2020 (also attached in Annex 3).

The aim Task 4.4. is to develop a strategy to harmonise defined RPAs across borders. Differences between radon mapping and definitions of RPA across boundaries with accessible data are evaluated, a mapping exercise to test existing mapping methods with different accessible data sets is carried out and obstacles which currently exist with regard to harmonisation of RPA maps and data are investigated. The work and results of this task are discussed in chapter 5.

3. Evaluation of the concepts for the definitions of radon priority areas - Task 4.1

Delineation of Rn priority areas (RPAs) is generally considered an essential tool in the overall target of reducing the radon risk of the population. The definition of radon priority areas (RPA) in the European BSS allows a wide range of interpretation. In the past a number of different approaches has been brought forward, motivated by the availability of data for the predictor quantities (for various reasons different types of data sets are available in different countries) and by the purpose of RPAs which may also vary. In course of the European BSS process, concrete proposals have been made in some countries, and already implemented in a few cases.

The tasks reviews and evaluates concepts and definitions of RPAs, which have been proposed or already implemented in the past and the role of stakeholders in the implementation process of RPA. It is evaluated what purpose these approaches can be used for (e.g. in workplaces, preventive measures, public radon exposure) and if and how certain methods, developed in one country for a specific purpose, could be used or adapted for other purposes or in other countries or regions.

Particular RPA concepts are considered in detail from some countries and available documents are evaluated and experiences discussed between the partners, most of whom play an active role in assessment of RPAs. All results of the activity are discussed and summarised in this report.

In Annex 1 the detailed report of the task can be found. The report includes the legal background and concept of RPA, followed by a review about RPA concepts and definitions. The role of stakeholders in the selection and implementation process of RPA is an interesting topic, is discussed, considering all relevant stakeholders and summarises the practical experience in some countries (Austria, Germany, Serbia and Spain). In many cases RPA are delineated based on radon measurement data derived in dwellings, but the main implication of RPA are the mandatory radon measurements in workplaces in these areas according to Art. 54 EU-BSS (EC, 2013; EC, 2020). Therefore, one chapter of the report is dedicated to the comparability of RPA derived from dwellings vs. workplaces. As mentioned above, it is interesting if and how certain methods, developed in one country for a specific purpose, could be used or adapted for other purposes or in other countries or regions. One chapter focuses on this cross-usage of concepts according to the results of the study of workplaces vs. dwellings and also the results from MetroRADON activity 4.4.2 (report attached in Annex 4 of this deliverable). In addition some case studies of RPA concepts and delineation of RPA are presented. Finally, a brief summary and conclusions are reported.

Conclusions highlight that conceptual and theoretical work about RPAs is well advanced. This concerns understanding of the concept, definitions which serve to translate the concept into a workable subject and estimation methods. For the latter, quite a variety has been developed, depending on the data which are available for the purpose. Available data depend on national policies of surveying radon related variables, from indoor concentrations in dwellings to various geogenic quantities, which control geogenic and indoor radon to different extent.

An important result is the comparison of residential buildings and workplaces regarding their Rn characteristics. These were found to be different, in general. This is relevant, because RPAs are mostly estimated based on data of indoor radon concentration in dwellings, but legal consequences as stated in the BSS largely pertain to workplaces.

For evaluating the cross-usage of concepts, different mapping methods were compared and the agreement of the different methods was discussed by means of several parameters. Mapping methodologies are various and so are the definitions of RPAs. As a general conclusion about the cross-usage of concepts, it can be said that applying a mapping method using data sets, which were not designed for the specific requirements of the mapping method, is challenging.

Furthermore, the delineation of RPA by using different mapping methods often, but not always, delivers the same results in RPA classification, according to the definition of RPAs. Therefore, the definition of thresholds is a very important factor in the process of RPA delineation.

Details are discussed in the report in Annex 1, and some recommendations are given in chapter 6.

4. Relationship between indoor radon concentration and geogenic radon - Task 4.2

Aim and motivation of Task 4.2

The aim of this task is to estimate relationships between indoor Rn or derived quantities (e.g., the probability of exceeding a reference level within an area), and quantities related to geogenic Rn (e.g., Rn potential or uranium concentration in the ground) (see Task 3.2), as some concepts for mapping the geogenic Rn potential and RPA crucially depend on such relationships.

As RPAs are often estimated from quantities other than indoor Rn, such as geogenic Rn, the correlation and the statistical relationship between indoor Rn and the RPA predictor quantity (or quantities) needs to be established, because only indoor Rn is directly linked to reference values according to the EU-BSS. In most cases, the statistical relationships between indoor Rn and geogenic quantities are weak. These relationships have been studied for many years as regression and classification type approaches. The physical and statistical reasons for the weak relationships will be evaluated and explained, and their consequences assessed. In this task, existing models and methodologies will be reviewed and reported, in particular statistical procedures which have sometimes proved a weak point in such analyses in the past.

Structure of Task 4.2

In activity A4.2.1, the concept of radon potential (RP) is introduced. Various approaches are presented, in particular the "soil radon potential" or geogenic radon potential (GPR). The concepts are discussed and a literature review of the statistical relationships and correlation between indoor Rn and geogenic Rn has been performed. Sources of information include journals, reports and conference contributions. Based on this review, physical and statistical reasons of the weak relationships are evaluated and interpreted and a synopsis of the results is produced. Further, possible inconsistencies in the literature and their consequences are identified. Annex 5 is a table called <Lit_4_2_1_4-all-190424> which contains the detailed results of the literature survey.

Different methods have been developed, particularly in Europe, to assess the GRP that is then sometimes used for radon mapping and RPA definition. These approaches are based on different models (statistical, physical or empirical models) that use different input quantities, i.e., soil-gas radon concentration, radon exhalation rate at soil surface, soil permeability, soil Ra content, radon emanation factor etc. These parameters can be locally measured on the field or calculated. In A4.2.2, several existing approaches to assess a "soil radon potential" are reviewed, both from those identified in A4.2.1 and also others of which we know. Two case studies of GRP estimation are presented.

A report, Annex 2, which contains the detailed results of WP 4.2, outlines the current state of the art with regard to information about the relationship between indoor radon concentration and geogenic radon as well as the new results.

5. Harmonisation of radon priority areas across borders - Task 4.4

5.1 Introduction

The aim of this task is to develop a strategy to harmonise defined RPAs across borders and to incorporate it in a guideline.

Since RPAs are defined based on different Rn policies (related to different ways to interpret and to implement the European BSS) and the availability of data for the predictor quantities, RPAs defined by individual countries will in general not be consistent across borders. In this task, existing approaches to define RPAs are compared and tested using different datasets, possible causes of the inconsistencies are identified, existing obstacles that with regard to harmonisation of RPA maps are identified and ways of "top-down" harmonisation of RPAs are proposed. As an alternative approach, the concept of RHI is proposed in Task 4.3 which may "bypass" the lack of consistency in defining RPAs by creating a universally applicable index of geogenic Rn which does not compete with existing RPA concepts, but complements them. This is a particularly sensitive issue because harmonised approaches must not interfere with and jeopardise national approaches, and hence, appropriate communication and involvement of stakeholders is indispensable.

In Activity A4.4.1, differences between radon mapping and definition of RPAs across boundaries using accessible data are investigated. Information for specific cases of differences across boundaries is collected and possible causes of the inconsistencies are identified and examined (see chapter 5.2).

In Activity A4.4.2, existing mapping methods used in various countries (e.g., indoor radon, gamma dose rate, geology, soil gas radon) with different datasets accessible to JRC and BfS (e.g. national data from other countries, Austrian data set from extensive survey in 6 municipalities and the JRC database) are tested, and their comparability and their usability for other countries evaluated (see chapter 5.3 and Annex 4).

The obstacles that currently exist with regard to harmonisation of RPA maps and data are identified and possibilities to construct an RPA map on the European scale are investigated in Activity A4.4.3. In general, different countries use different methodologies to identify RPAs due to the different available input data. For this reason, it will be important to identify the "obstacles" (differences) and to find a way of reducing them through harmonisation (see chapter 5.4).

Given the political sensitivity of the subject, the potential proposals for harmonisation must be communicated properly, including - importantly – to NGOs, stakeholders and the media. A questionnaire is developed and sent to national authorities involved in radon mapping-communication to obtain information on their positions and views towards harmonisation. The responses are collected and analysed.

5.2. Consistency across borders - Activity 4.4.1

The definition of RPAs results from different Rn policies (related to different ways to interpret and to implement the EU-BSS) and different availability of data of predictor quantities. Therefore, RPAs defined by countries individually will not be consistent across borders, in general. This can lead to problems in communicating Rn issues and impair credibility.

In this task, existing approaches have been compared to identify the reasons for consistency/inconsistency between resulting maps, with some examples of existing maps at different borders. This state of art and discussion provide an interesting base to propose further studies.

5.2.1 Case studies and identification of reasons for inconsistency

For this study, it was decided to focus on some borders with France and Spain and for which data were available. The selected borders are France-Belgium, France-Switzerland, Spain-France and Spain-Portugal.

Methods

For the three borders with France, the map of the country was compared to three different maps on the French border side:

- The geogenic radon potential map: this mapping technique has been established by the IRSN (Ielsch et al. 2010, 2017) in order to characterize the capacity of the underlying rocks to generate radon at the surface on the French territory. It is only based on the characteristics of the geological formations (indoor radon measurement results are not considered). The two main used parameters are the uranium contents of the underlying rocks and the presence of factors that can facilitate the transport of radon towards the surface (faults, boreholes, mining works etc.). This map is based on data from the geological map of France at the scale of 1: 1,000,000.
- The classification of municipalities according to geogenic radon potential (www.irsn.fr/carte-radon): this classification is based on French geogenic radon potential map. Category 1 includes

municipalities located entirely on geological formations with low uranium contents and with no factors that may facilitate the transfer of radon to the surface. Category 2 includes municipalities also located on geological formations with low uranium contents, but a part of their territory is concerned by geological factors that can facilitate the transfer of radon to the surface. Category 3 includes municipalities which present, at least on a part of their territory, geological formations with uranium contents that are higher compared to the other formations. For this last category, the presence of radon at high concentrations in buildings is most likely. This map is currently used in policies for radon risk management in France.

- The average indoor radon concentration by municipality, calculated from radon measurements in dwellings, from the measurement campaign carried out over the period 1982-2002 by IRSN and the Ministry of Health (Demoury et al. 2013).

For the borders Spain-France and Spain-Portugal another method was also applied to compare the maps. In order to harmonise the radon measurements and the information, it has been established a unique reference system. The cells system 10 km x 10 km used by the European Commission is elaborated from the GISCO-LAEA projection. The Joint Research Centre (JRC) provides the coordinates of extreme points from which to build the cells system, Table 1.

Table 1: Reference system parameters defined by JRC

Projection:	Lambert_Azimuthal_ Equal_Area
False_Easting:	0,000000
False_Northing:	0,000000
Central_Meridian:	9,000000
Latitude_Of_Origin:	48,000000
Linear Unit:	Meter
GCS_ETRS_1989,	Datum: D_ETRS_1989

The analysis of the borders is done from the cells system considering the action area of 40 km from the border line. The selection criteria considered to include a cell to the Spanish territory must fulfil that is within it. Therefore, every complete or partially cell inside Spain is considered as Spanish and analysed as a whole. However, the cells which belongs to the border line and that are in both countries are analysed separately too.

Regarding to the Spain-Portugal and Spain-France boundaries the number of cells inside Spain, Portugal, France and exclusively in the border line in each case is presented in Table 2.

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Table 2: Number of cells exclusively in Spain, Portugal, France and in each boundary. In this case the border cells have not been associated with any country

	No. of cells
Spain (40 km from Portugal)	248
Portugal	227
Boundary Spain-Portugal	130
Spain (40 km from France)	157
France	127
Boundary Spain- France	75

In Table 2 and Table 3 the cells distribution on both sides of the Spanish border with Portugal and France is presented. They are the main data to analyse in order to find a harmonization of RPAs across borders. The number of radon measurements in air and the radon concentration average per cell in each case is shown.

Results and discussion

France-Belgium border

In Belgium, radon risk management is based on the map of probability of exceeding the value of 300 Bq/m³ per municipality. This map was directly made with the indoor radon concentration measurements in homes.

Figure 1 compares the Belgian map with the different types of French maps at the border. According to Belgian mapping, there is an area with a higher probability of exceeding the value of 300 Bq/m³ per municipality in the massif of the Ardennes. This radon priority area is not consistent with the French mapping based on geological data (Figures 1a and 1b). The Belgian priority zone corresponds more particularly to the Devonian outcrops (d1 and d2 in brown in Figure 2). Only few outcrops of these formations are observed on the French side of the border. On the French side, the available radon measurements in dwellings are very few compared to the number of data acquired in Belgium. These French results do not show higher values on these geological units, particularly.

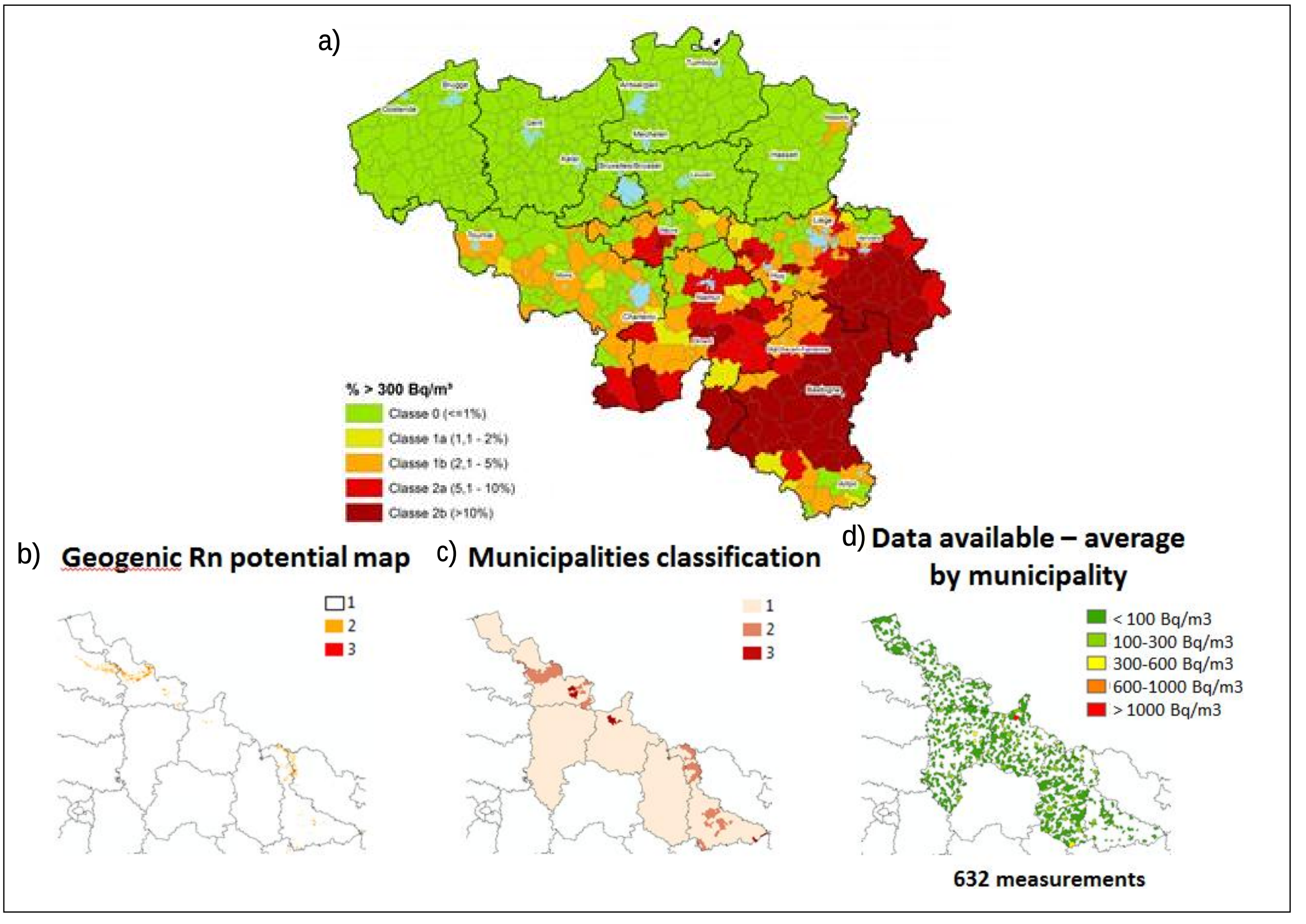


Figure 1: Comparison between the Belgian map of indoor radon exposure (a) and three French maps at the border: the French geogenic radon potential map (b), the French municipalities classification (c) and the mean indoor radon concentration by municipality (d)

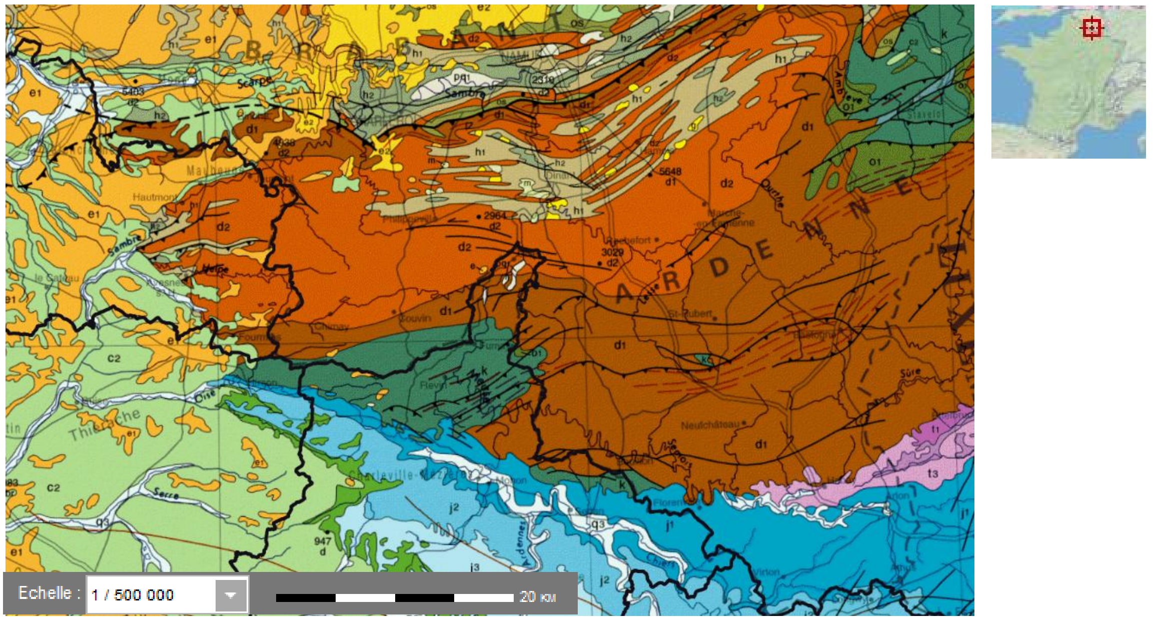


Figure 2: Extracted from the 1: 1,000,000 geological map at the France-Belgium border

France- Switzerland border

In Switzerland, the radon risk management is based on the map of probability of exceeding the value of 300 Bq/m³ in municipalities. This map was directly made with the indoor radon concentration measurements.

Figure 3 compares the Swiss map with the different types of French map at the border. According to Swiss mapping, there is an area with a high probability (>20%) of exceeding the reference value (300 Bq/m³) along the border, whereas the French mapping, based on geological data, shows a low geogenic potential. Moreover, the indoor radon measurements collected on the French side of the border show relatively high indoor radon concentration.

The Swiss “radon priority area” corresponds to the Jura karstic area which exists on both sides of the border. However, karstic systems are very complex and their impact on radon potential is not very well known. Indeed, the uranium content of karstic rocks (limestones) is very low but karsts are very permeable geological environments that can facilitate the radon accumulation and/or then the radon transport to the surface in their underground caves, fractures and other typical structures.

Last years, IRSN performed a study to enhance knowledge on the influence of karstic structures on the radon production and migration at a regional scale, in a karstic area located in the French Jura Mountains (Gréau et 2017, Mansouri et al. 2018). This study confirmed that karstic environments could be the source of locally high radon contents in the soil. The data analysis and the modelling show that the average levels of radon activity in soils are essentially the result of radium-226 emanation from the soil. Indeed, on the study area, a relative enrichment of radium-226 was observed in soils due to the important dissolution of limestones in the past (karst formation), and the soil radium-226 contents was quite similar to those observed in some granitic regions. However, the study is still ongoing in other karstic regions in France before to be able to transpose these conclusions to the French geogenic radon potential map.

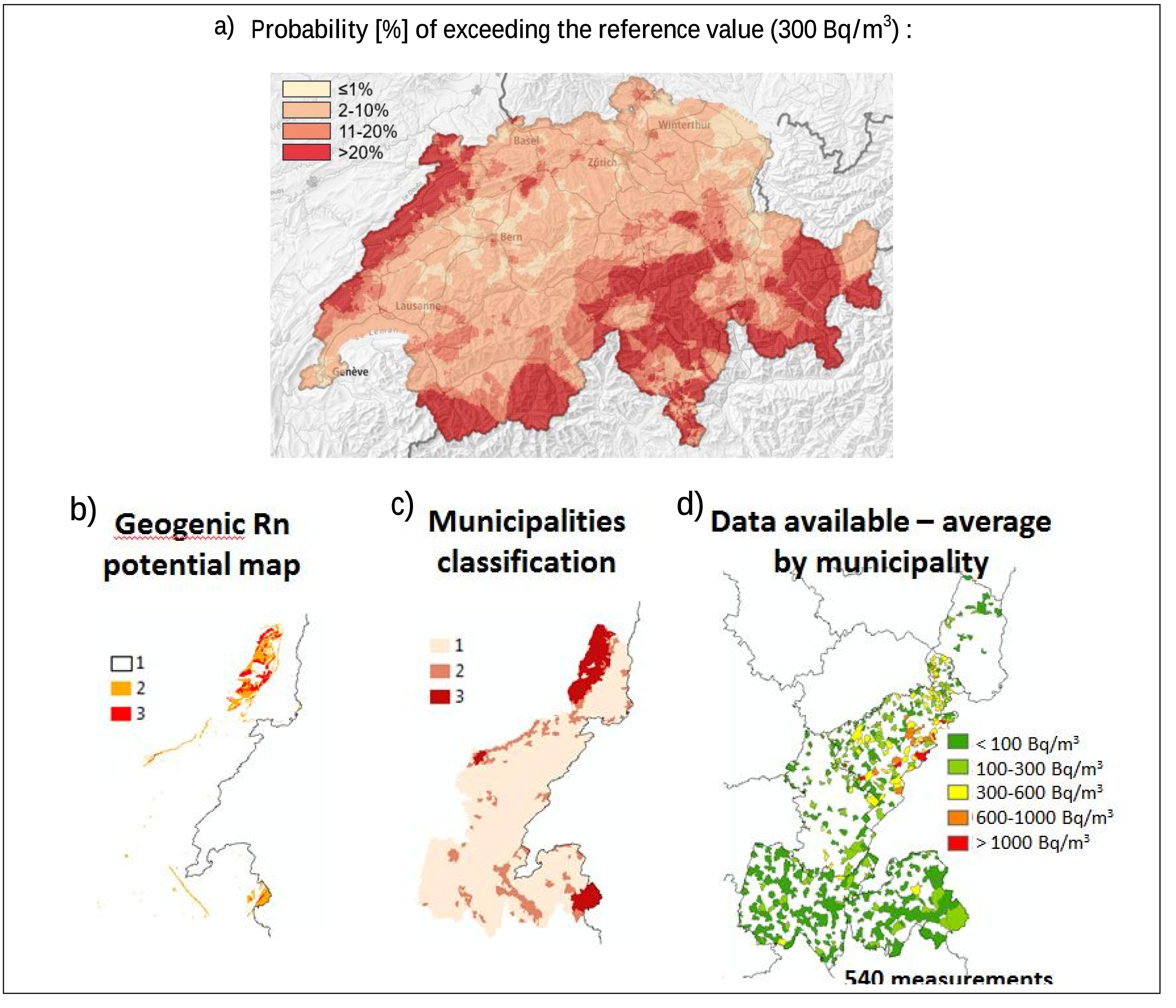


Figure 3: Comparison between the Swiss map of probability of exceeding the value of 300 Bq/m³ (a) and three French maps at the border: the French geogenic radon potential map (b), the French municipalities classification (c) and the mean indoor radon concentration by municipality (d)

France-Spain border

In Spain, the Spanish radon potential map provides the 90th percentile of exceeding the value of 300 Bq/m³ and is based on geological knowledge, on indoor radon measurements and on gamma exposure rate.

Figure 4 compares the Spanish map with the different types of French maps at the border. According to Spanish mapping, there is an area with higher indoor radon concentrations along the border (Figure 4d). The French maps show a higher geogenic radon potential also in this area (Figures 4a,b).

Therefore, the maps provide results that are relatively consistent on both sides of this border.

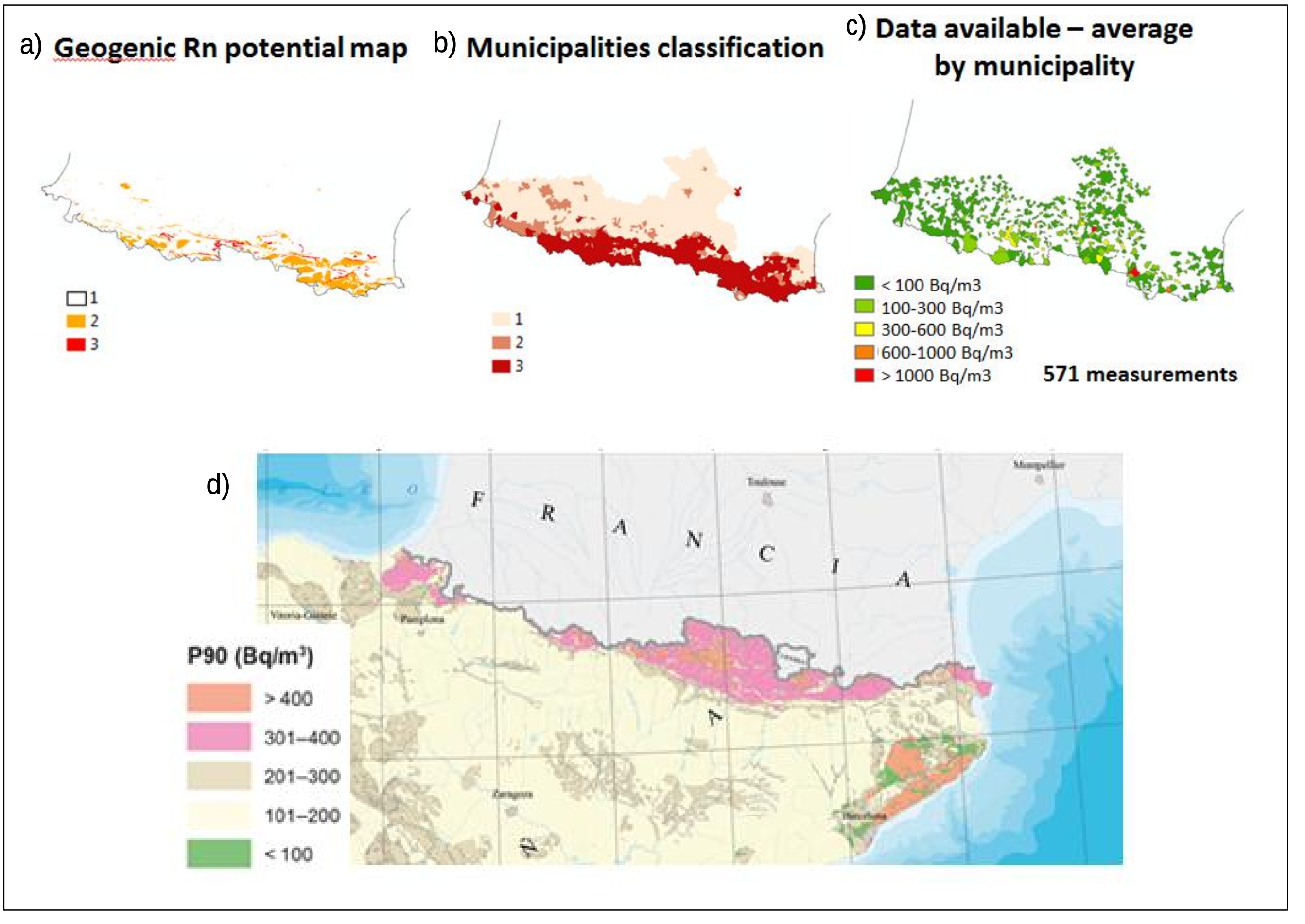


Figure 4: Comparison between the Spanish radon potential map (d) and three French maps at the border: the French geogenic radon potential map (a), the French municipalities classification (b) and the mean indoor radon concentration by municipality (c)

France-Spain border - Results of the second method

Table 3 shows the number of cells with radon concentration in the intervals <100, 101-200, 201-300, 301-400, >400 Bq/m³. Besides it is included the number cells for some number measurements interval.

Table 3: Number of Spanish cells with radon concentration in some intervals expressed in Bq/m³ and quantity of cells with a determinate number of measurements in the Spain-France boundary. It has been included the cells in the borderline.

Spanish cells in the Spain-France boundary		
	Number of cells	Percentage (%)
Total:	232	100
Without data:	114	49
In the Rn interval (Bq/m³)		
<100	90	39

101-200	23	10
201-300	3	1
301-400	1	0.4
>400	1	0.4
Number of measurements		
1	114	49
2	59	25
3 to 6	29	13
7 to 20	27	12
> 20	3	1

There is a high number of cells without measurements (49%). The main reason in that the studied area has a low population density. There are 75 cells in the borderline which are in both countries. Table 4 shows the number of cells in some radon concentration intervals and the number of data per cell.

Table 4: Number of Spanish cells with radon concentration in some intervals expressed in Bq/m³ and quantity of cells with a determinate number of measurements in the Spain-France border.

Cells in the Spain-France border		
	Number of cells	Percentage (%)
Total:	75	100
Without data:	57	76
In the Rn interval (Bq/m³)		
<100	9	12
101-200	6	8
201-300	2	3
301-400	1	1

>400	0	0
Number of measurements		
1	57	76
2	11	15
3 to 6	5	7
7 to 20	2	3
> 20	0	0

There is a high number of cells without measurements (76%). About 1% of cells have a mean radon concentration above 301 Bq/m³. It is significant that only the 3% of cells have more than 6 measurements.

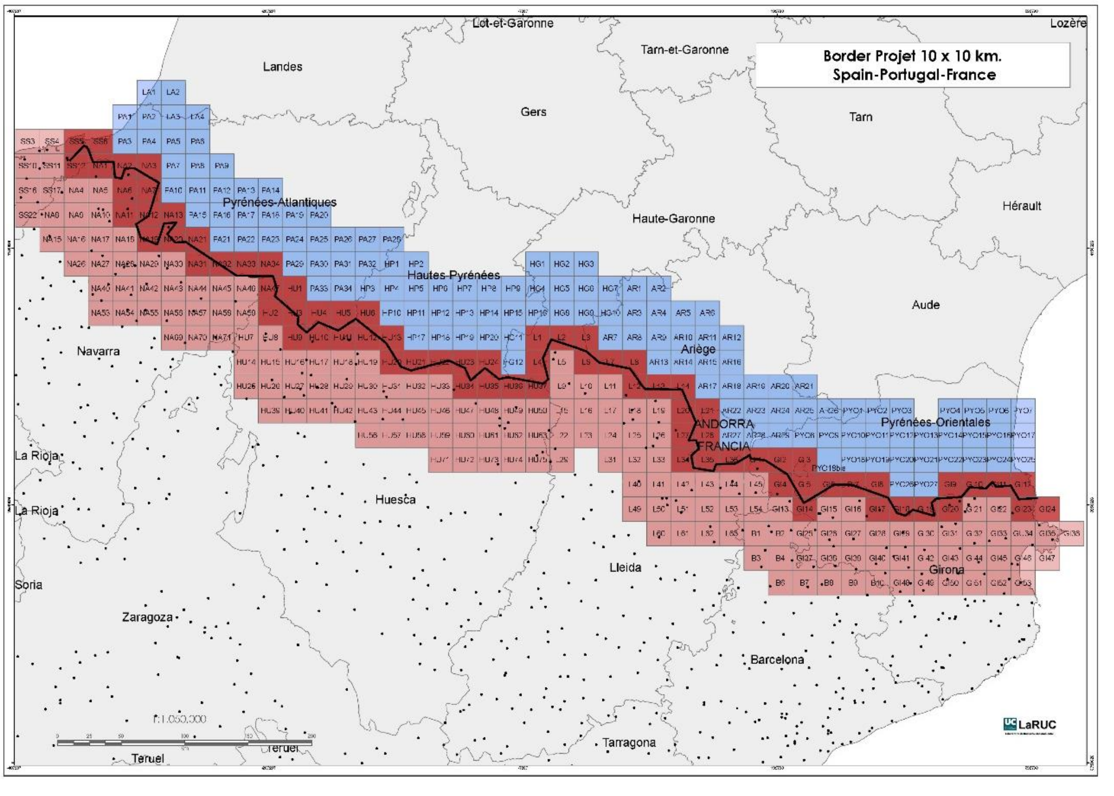


Figure 5: Cells at the Spain-France border. In this and the following maps, North is upwards in this and the following maps. For a high resolution version please see Annex 6.

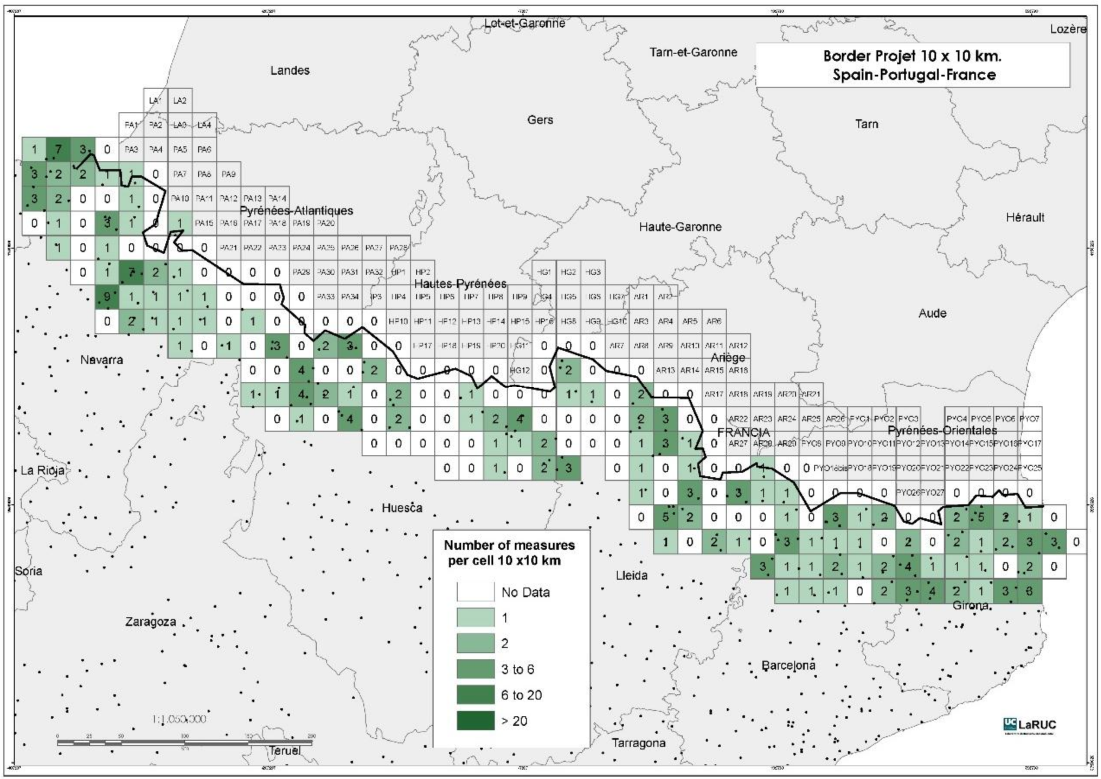


Figure 6: Number of radon measurements in air per cell at the Spain-France border. For a high resolution version please see Annex 6

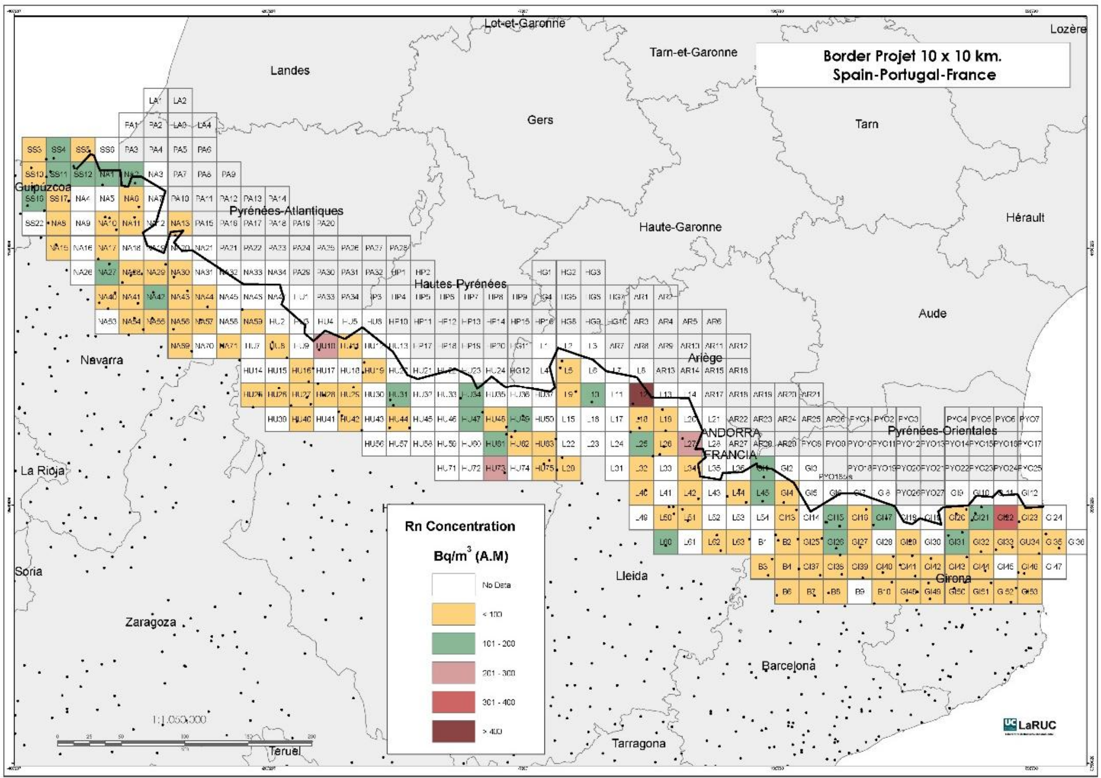


Figure 7. Mean radon concentration in air per cell at the Spain-France border. For a high resolution version please see Annex 6

Spain-Portugal border

Table 5 shows the number of cells with radon concentration in the intervals <100, 101-200, 201-300, 301-400, >400 expressed in Bq/m³. Besides it is included the number cells for some number measurements interval.

Table 5: Number of Spanish cells with radon concentration in some intervals expressed in Bq/m³ and quantity of cells with a determinate number of measurements in the Spain-Portugal boundary. It has been included the cells in the borderline.

Spanish cells in the Spain-Portugal boundary		
	Number of cells	Percentage (%)
Total:	378	100
Without data:	184	49
In the Rn interval (Bq/m³)		
<100	85	22
101-200	70	19
201-300	25	7
301-400	4	1
>400	10	3
Number of measurements		
1	62	16
2	26	7
3 to 6	61	16
7 to 20	42	11
> 20	3	1

There is a high number of cells without measurements (49%). The mainly reason in that the studied area has a low population density. The 4% of cells have a mean radon concentration above 301 Bq/m³. The 12% of cells 10x10 km have more than 6 measurements.

There are 130 cells in the border line which have area in both countries. In Table 6, the number of cells in some radon concentration intervals is shown and the number of data per cell.

Table 6: Number of Spanish cells with radon concentration in some intervals expressed in Bq/m³ and quantity of cells with a determinate number of measurements in the Spain-Portugal borderline.

Cells in the Spain-Portugal borderline		
	Number of cells	Percentage (%)
Total:	130	100
Without data:	88	68
In the Rn interval (Bq/m³)		
<100	13	10
101-200	15	12
201-300	8	6
301-400	2	2
>400	4	3
Number of measurements		
1	13	10
2	5	4
3 to 6	14	11
7 to 20	10	8
> 20	0	0

There is a high number of cells without measurements (68%). About the 5% of cells have a mean radon concentration above 301 Bq/m³. It is significative that the 8% of cells have more than 6 measurements.

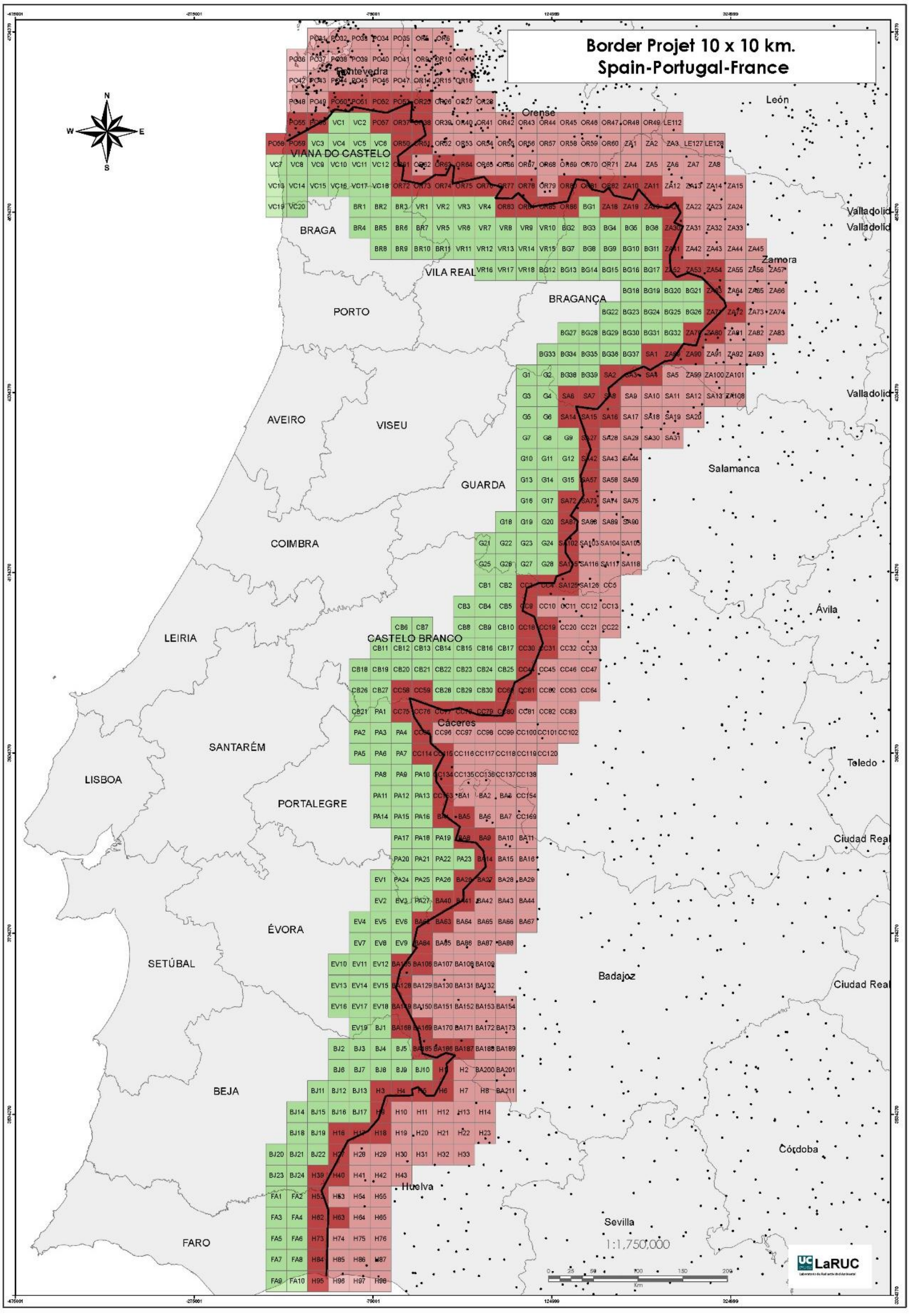


Figure 8: Cells at the Spain-Portugal border. For a high resolution version please see Annex 6

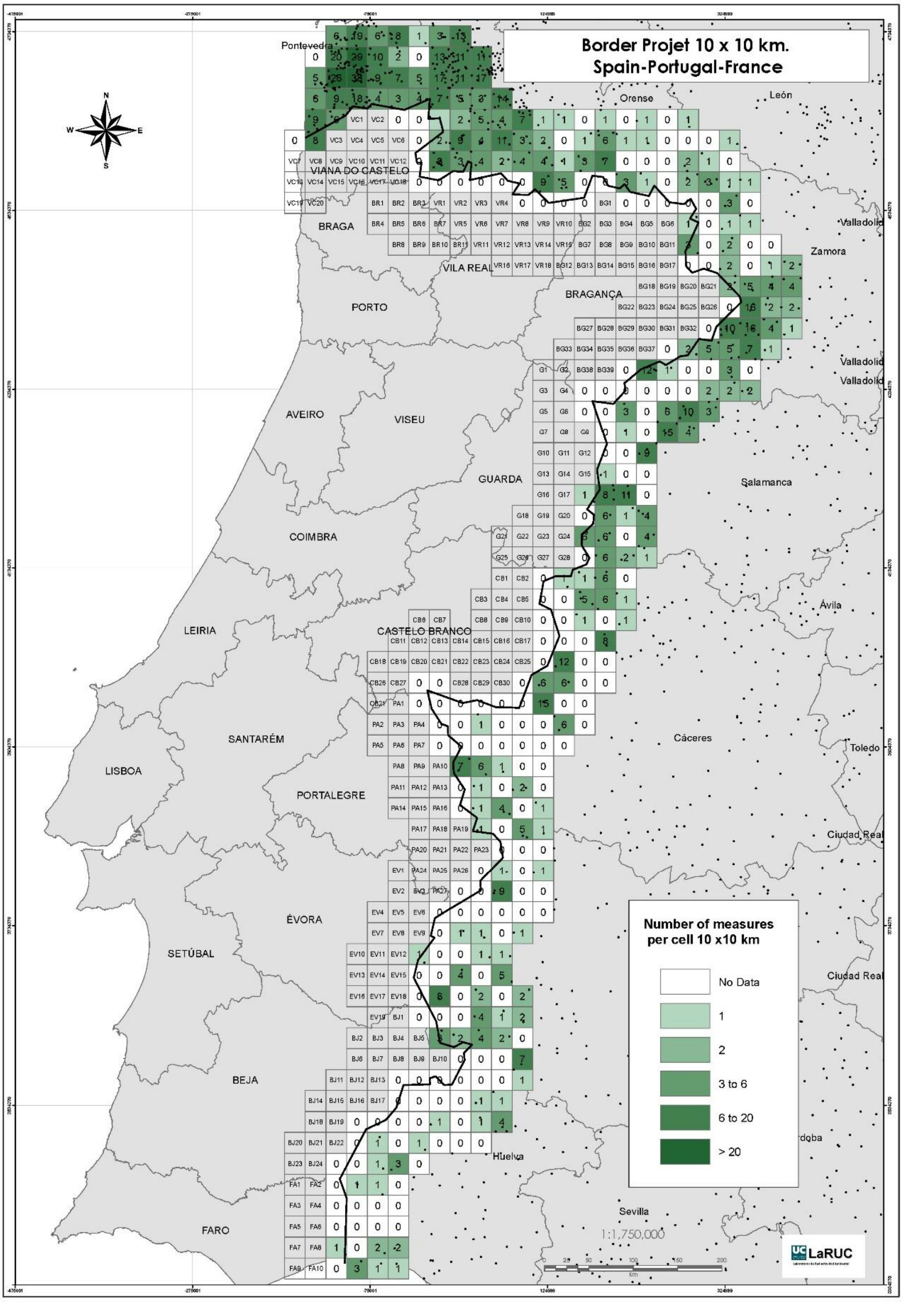


Figure 9: Number of radon measurements in air per cell at the Spain-Portugal border. For a high resolution version please see Annex 6

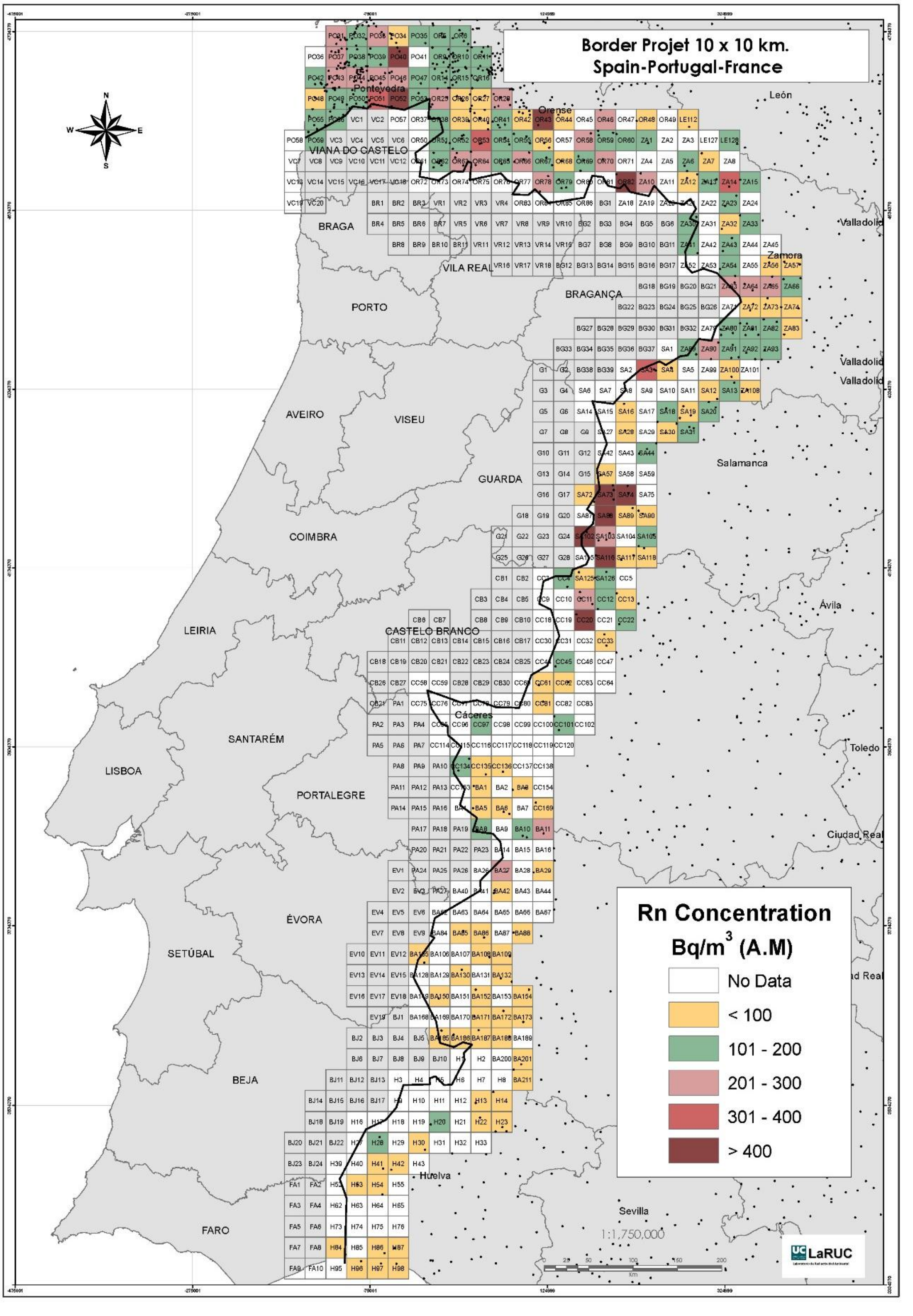


Figure 10: Mean radon concentration in air per cell at the Spain-Portugal border. For a high resolution version please see Annex 6

The possible influence of geological classification

There could be inconsistencies in RPAs due to the geological maps used for delineating those areas due to different mapping methods and/or criteria used by national authorities for mapping or grouping of lithostratigraphic units, and to the scale of the maps. For example, the cartography of the radon potential in Spain (P(90), in Figure 4) took into account the geological map of Spain at the scale of 1:200,000, whereas in Portugal, the only geological maps available for the entire country are the 1:500,000 and 1:1,000,000 maps. When comparing both maps in a small region located in northern Portugal, there is a clear mismatch between geological units across borders, as shown in Figure 11, which indicates that the units are defined differently.

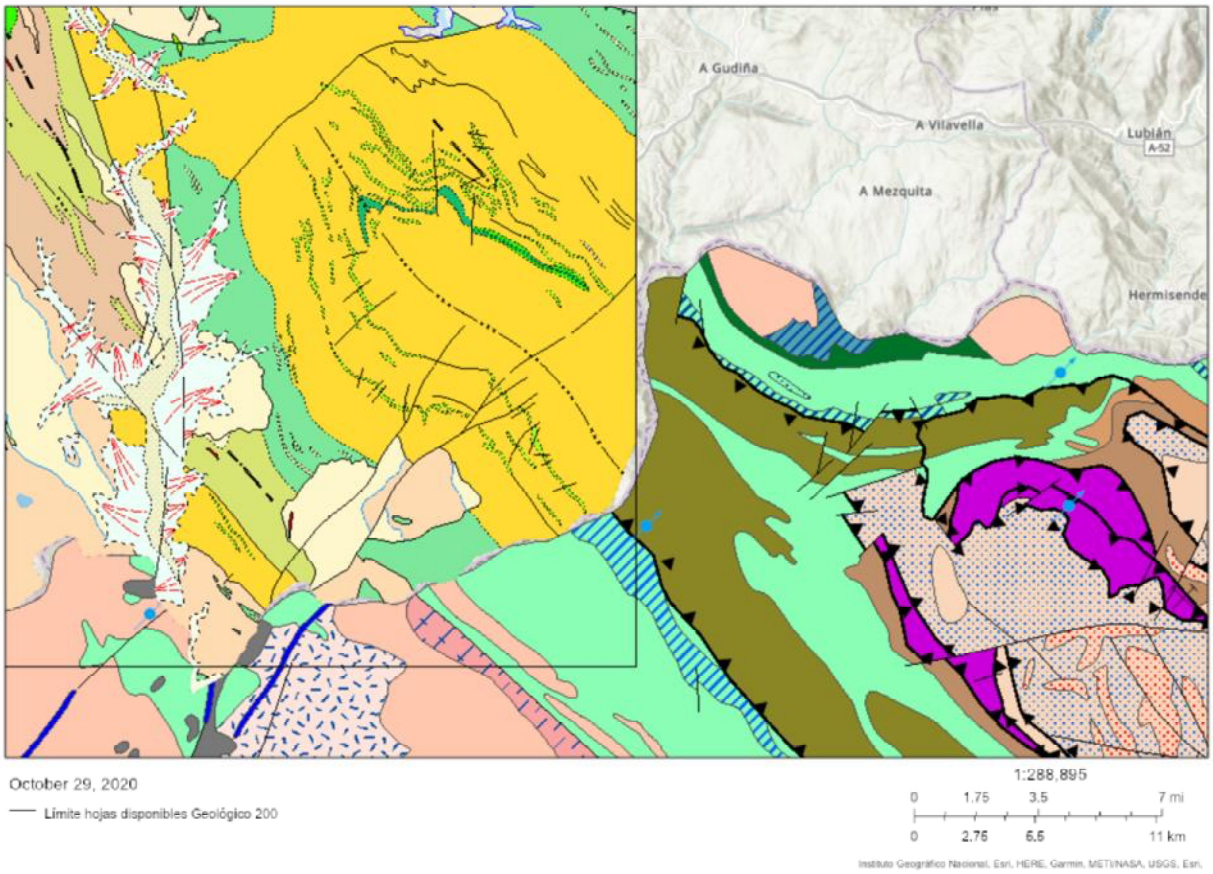


Figure 11: Extract from the geological map of Portugal at a scale of 1:500 000 (North sheet, source: https://geoportal.lneg.pt/mapa/#) and the geological map of Spain at the scale of 1:200 000 (2nd series, sheet number 17 – Ourense, source: http://info.igme.es/catalogo/resource.aspx?portal=1&catalog=3&ctt=1&lang=eng&dlang=eng&llt=dropdown&master=infoigme&shdt=false&shfo=false&resource=8409).

These differences can be due to different criteria for grouping the geological units as the authors can give a preference to lithology > age or conversely, age > lithology. For example, in the Geological map of Portugal at the scale of 1:500,000 there is a preference for grouping the Paleozoic units by age (ex. there is a unit for ordovician, silurian, devonian and carboniferous rocks, despite a significant variation in lithology in the geological record within these periods). In the Geological map of Spain at the scale of 1:200,000, the geological units are mapped based on both age and lithology, highlighting the lithological variation within each period compared to the geological map of Portugal. These issues could also explain the lack of consistency in the

French-Belgian border, where the definition of the Devonian units could be different among different countries.

It would be interesting to investigate possible inconsistencies in RPAs generated from geological maps due to these issues. It would also be important/easier for harmonization of RPA maps if the scale of the underlying information (ex. geological, soil and/or permeability maps) were similar, since grouping of units is generally carried out for the sake of representation.

5.2.2 Conclusion and perspectives for future studies

This first comparison of some examples of borders in Europe shows different mapping methods and different mapping results. If we compare those results, in a qualitative and relative way, the RPAs are generally consistent. The main inconsistencies that were identified at the studied borders are linked to the lack of data in some areas, for indoor radon measurements.

Further studies are still necessary in European Countries to provide the technical explanations of consistency or inconsistency between maps at borders and then communication elements for the Authorities and the public. These studies should include:

- investigation of the compatibility of the legends of geological or other scale-dependent categorical maps (soil properties, hydrology etc.), if these are used as predictors;
- criteria to increase the number of measurements per cell and to target regional surveys;
- type of measurements: for IRC: same exposure time in both side of the borders? Same number of detectors in every house? The same detector types? For example CR39, Makrofol, etc …; for soil radon: same sampling depth? etc.;
- Possible influence of climatic conditions in both sides of the borders at the times of respective measurements (in the case of grab sampling, which represent temporal snapshots).

Another important fact not considered is the final reference level that will be adopted by the countries after implementation of the BSS Directive in the national legislation. It might happen that the country A decides to go with 300 Bq m^{-3} and its neighbour, country B, adopts 200 Bq m^{-3}. How can this impact the evaluation of the RPA's across borders? The situation can be more complicated when considering which type of rooms and buildings to be included in RPA estimation: only dwellings? only workplaces? both? which mixture? (given that Rn characteristics of residential buildings and rooms and workplaces are different, in general). One more not satisfyingly resolved question is how to deal with seasonal corrections that are applied in some countries. An example is the border Ireland-UK: different seasonal corrections are used at both sides of the borders. Therefore, the radon concentrations can be different for the same objective radon exposure and the same exposure time. How will this affect the definition of the RPA's in the border?

Addressing, in particular, the first bullet in the above list, for future work we suggest closer investigation of the dependence of RPA estimates on scales and legends of categorical maps and their interpretation, such as geological maps, which may be used as predictors in the estimations. This may be an important issue in achieving harmonized maps across borders. It may also facilitate to explain and communicate inconsistencies between RPA delineation in neighbouring regions.

5.3 The radon mapping exercise - Activity 4.4.2

The aim of the task 4.4.2 was, to evaluate mapping methods and RPA definitions for their comparability and their usability for other countries. For this purpose, existing mapping methods used in different countries were applied using harmonised data sets of various variables (e.g. indoor radon, gamma dose rate, geology, soil gas radon). Afterwards the mapping and classification results for the provided data sets in the relevant areas were compared and the usability evaluated. The activity is referred to as “the radon mapping exercise” and is discussed in detail in the MetroRADON activity report 4.4.2, which can be found in Annex 4.

Two data sets were used for the exercise, different in geology, scale, co-variables, etc. to increase the scope and benefit of the exercise. One dataset is from an extensive survey in six municipalities in Austria, the second dataset is from Cantabria, Spain. The data include indoor radon measurements, building characteristics of measured dwellings, soil air radon activity concentration, permeability estimation, activity concentration of soil samples, ambient dose rate and maps of geogenic parameters derived from other sources (e.g. geology, soil type, airborne radiometry). The datasets differ in basic characteristics as size, sample density, data extent, quality and resolution. Methods to characterize radon priority areas for the two datasets may require different adequate data manipulations, but the comprehensive radon datasets provided in the exercise aim to be a solid basis for different strategies to identify RPAs.

Mapping methods used in the exercise were a generalized additive mixed model (GAMM), based on the methodology used in Austria for the delineation of radon areas, empirical Bayesian kriging regression (EBKR) prediction, ordinary kriging (OK) and Indicator kriging (IK) and the Belgian radon risk mapping method (BRRMS). All methods and the results of the methods applied to the data sets are discussed in detailed in the report in Annex 4.

The exercise showed that to apply the different mapping methods, the data sets may require adequate data manipulations and not all data is used for each mapping method, and also not every mapping method can be used for the dataset. In general, mapping methods are mostly specified to use either IRC as target variable (e.g., basic statistics methods, kriging IRC) or geogenic variables (EBK regression, kriging GRP). BRRMS combines IRC and geogenic variables, by taking into account geological units. The methods that use IRC with building characteristics could be only applied for the Austrian data sets, as no information about building characteristics is included in the Cantabrian data set. Only the GAMM method used all available variables as well for the Austria and the Cantabrian dataset. Except the basic statistic methods (IRC mean over threshold and probability of IRC over threshold per municipality or geological unit), all methods used interpolations to map the radon concentration or radon potential or radon risk. It can be summarised that in general, the selection of a mapping method for a certain area will highly depend on the available data sets. Not all mapping methods are applicable to all data and all areas, as depending on data quality, sample density, heterogeneity of the area, etc.

In the mapping exercise, it was also evaluated how the different results provided by different mapping methods would have an impact on the classification or delineation of RPAs. As a summary, the chosen threshold for the classification of RPAs has a major impact, depending on the level of radon concentration in the area. For Cantabria, which has a very low radon concentration, the differences in the results of the different methods do not impact the RPA classification. Whereas the Austrian municipalities show radon concentrations in the range of 150 - 400 Bq/m³, depending on municipality and mapping method. Therefore, the differences (even when small) in the radon concentration for the different methods for the same municipality can have an impact in RPA classification, when the threshold is chosen in the range of the variability of the results (e.g. 300 Bq/m³, the reference level, established in most of the member states). If the threshold is set with 100 Bq/m³ all six municipalities in Austria are classified the same, as this threshold does not lie within the range of the measurement/prediction results and therefore the variability of the results of the different methods do not have an impact on the classification of RPAs.

As said, the detailed report of the radon mapping exercise can be found in Annex 4 and some recommendations are included in chapter 6.

5.4 Obstacles against RPA harmonisations and possible way to overcome them - Activity 4.4.3

A prerequisite of harmonizing RPA maps is understanding the processes involved in the development of a RPA, from data collection to mapping procedures. For this purpose, radon maps and data in Europe have been analysed and we analysed the peculiarities of the processes and the differences between them and identify the challenges for harmonization.

The process to develop an RPA can be synthesized in the following steps (summarized in Figure 12):

a) *collection of radon data* (indoor, in soil gas or geogenic radon data) a*nd treatment of data: quality check, comparability* (in particular if data stem from different surveys), *statistical analysis*;

   Difference and comparability of radon data and their treatment have been analysed taking advantage of the results of the WP3 questionnaires on indoor and geogenic radon surveys (Annex 3 of Deliverable 3).

   Harmonization: to some extent possible (thanks to projects such as metroRADON, intercomparison exercises etc.)

b) *choose resolution and run a mapping method*.

   The resolution of the map depends on radon data density and scope of the map, some examples: Grid (100 m x 100 m, 1 km x1 km, 10 km x10 km), municipalities, postal code areas, geological unit, (lithology, stratigraphy or combinations, often simplified with respect to characteristics of Rn source and transport). The mapping method can be more or less complex, as examples:

   - Display observed (raw) data;
   - Simple statistics within units (e.g. AM);
   - Geostatistics: using nearby observations (and (optionally) limited number of co variables) to predict (e.g. kriging, IDW, moving average);
   - Machine Learning: Advanced regression, allowing many co variables. Does not necessarily consider an influence of nearby observations on the predicted value, as is typical for geostatistical methods.

Harmonization difficulties: As shown in the mapping exercise (chapter 5.3 and annex 4), different estimation / mapping methods can lead to different results even if based on the same data. Harmonization requires very good knowledge and understanding of the methods. However, except for certain cases, the impact of methodical variability, which contributes to the overall uncertainty budget of the output, seems lower than the one originating in certain type of data heterogeneity (in particular of "semantic" uncertainty, e.g. if input IRC data refer to ground floor rooms only in one dataset and rooms in any floor, in another) and the definition of RPA, see below. This latter component seems the most difficult to harmonize.

c) *output:* choose quantity appropriate for the objective of the map, for the representation of the indicator on the map.

Output quantities examples:

- Arithmetic mean (aggregation) or expectation (through geostatistics or ML) in cell
- % above reference level
- Geogenic radon potential
- Geogenic Radon Hazard Index GHRI
- Status RPA yes / undecided / no
- Moreover, all the above output quantities can be displayed using different levels- classes, both numerical (i.e. for % above the reference level: 5%, 10%, 15%) and categorical (i.e. for geogenic radon potential: Low, Medium, High). The way in which the classes are defined and displayed depends on the objective and cope of the map.

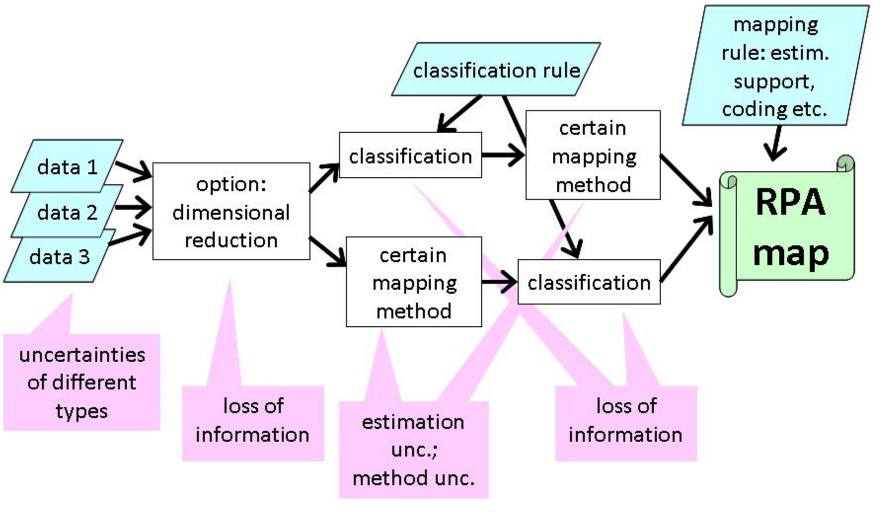


Figure 12: Schematic pathway leading to RPA maps. Blue: input (data and rules); pink: sources of uncertainty and loss of information. Note the bifurcation: according to the method chosen, classification may precede interpolation (mapping method), upper branch, or vice-versa, lower branch.

One of the main problems to define RPAs and harmonizing this areas in the Member States is related to the use of different methodologies to identify RPAs from one country to another. This fact is mainly attributable to the different input data that is available on each region. By listing the parameters involved in identifying RPAs, these areas could be more clearly defined. For this, national authorities, experts, researchers and in general all stakeholders interested in mapping could get involved in defining common approaches, including concepts and work methodology.

Once the parameters (reference levels, geological data used ...) and methods have been established, it should be necessary to define the type of cartography to be used in RPAs delineation. For this, the use of open accessible data to the European level and use the same base cartography all the states would be very interesting to delineate these areas.

Harmonization difficulties are twofold: (1) Conceptually, a level map, such as mean IRC or exceedance probability per estimation support unit (cell etc., see point b.) is different from a class map, as typical for RPA maps. The latter aggregate levels into 2 or more classes, hence information is lost compared to level maps. Therefore, while level map $\rightarrow$ class map is straight forward by indicator transform, the opposite is impossible. This means, that recovering level information (such as percentage above RL) from class information (such as RPA status = yes / no) is not possible. The radon hazard index (deliverable 6; annex 3 to deliverable 5) has been conceived as an alternative for generating harmonized maps; "bottom-up" and "top-down" variants are discussed, the former appearing more promising at current state of development; more details in Cinelli et al (2020) and Bossew et al. (2020).

(2) Harmonizing *level maps* is possible within limits. It may require modelling, e.g. transforming means into exceedance probabilities and vv. assuming a frequency distribution model and a dispersion parameter. This induces model uncertainty as another contribution to the uncertainty budget. Harmonizing *class maps* is even more difficult, because it requires the underlying level data, which can then be re-classified to a common standard. Theoretical studies about whether this can be avoided, and which uncertainty any possible re-classification model would induce, which does not rely on level data, is unknown and subject to further research. One family of methods may be fuzzy classification, but this has not yet been investigated for RPA standardization, to our knowledge.

Reasons for lack of harmony

Two sources of "disharmony" can be identified:

1. Data: in different countries, different quantities are available as datasets which can be used for RPA estimation. This has consequences for the choice of mapping methodology.
2. Political constraints: Countries define RPA definitions and estimation methods individually without coordination. Although warned beforehand and addressed in the Metro Radon draft, this will lead to a mostly incompatible patchwork of RPA maps. Consistency, harmonization and not least, communication problems can be the consequence.

A solution may consist in a European GRHI map (deliverable 6). However, foreseeable discrepancies between RPAs identified on European and on national scale may lead to discussions.

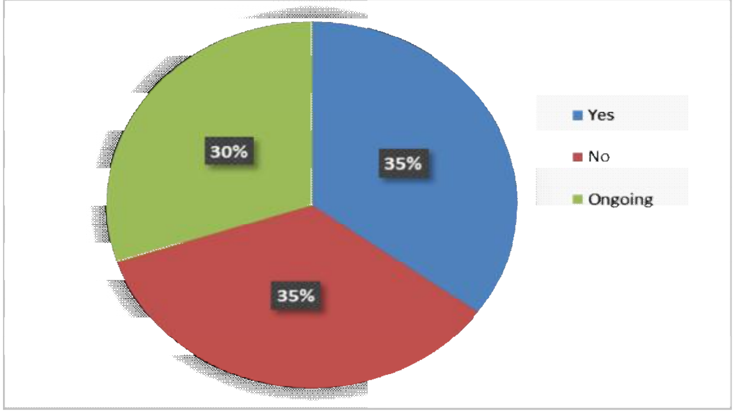
Conclusions: Harmonization of level maps is possible within limits, however requiring harmonization models and inducing an additional uncertainty component. Harmonization of class maps- in particular, and most importantly RPA maps -, still requires theoretical work. In addition, the political side of the problem will remain in discussion. Comparison exercises between different methodologies (such as the mapping exercise in Metro Radon) can help understanding the reasons of disharmony and inconsistence, and developing ways to overcome them.

Additional information

In the framework of MetroRadon project, a questionnaire for collecting information about indoor radon surveys has been prepared and addressed to all European institutions working in this field. The questionnaire forms have been collected between December 2017 and July 2018. A report on the results of the questionnaires is included in Annex 3 of Deliverable 3 of MetroRadon project. The focus of the questionnaire was on three main topics: characteristics of indoor radon survey – design; measurements methods; data management, statistical treatment, aggregate and mapping. Moreover, in section 5 "Policy on Indoor Radon", information has been collected about how EU Member States intend to transpose (or already have transposed) the latest Basic Safety Standards Directive into national law and hence about RPA. This session was addressed only to national authorities.

In details about RPA areas, the following questions has been asked, from the answers one can clearly recognize the heterogeneity of the approaches.

Have you identified radon priority areas (in the sense of art. 103 of the European Council Directive 2013/59/EURATOM)?



Data used to identify radon priority areas/classes?

For this question, the Institutions had multiple choices. All the received answers (16) contained "indoor radon data". In 8 cases they used only indoor radon data. In 3 cases they used also geology information and in the remaining cases they used also radon in soil gas, uranium concentration and gamma dose rate data.

How do you define a radon priority area/class?

Six Institutions reported that the RPAs have not been defined yet. Thirteen Institutions described briefly their definition of radon priority areas. Their answers are reported below:

- municipality where >5% of the dwellings > RL
- municipality, where the probability of exceeding RL in the workplace is higher than 30 %
- >10 % of IRC measurements above reference level
- The radon potential is estimated with a geostatistical procedure on a grid and linked to IRC by bivariate classification; RPA defined as 10% dwellings estimated above RL=300 Bq/m³ (Bossew and Hoffmann 2017)
- a significant percentage of dwellings exceed the reference level
- A 10 km grid square where 10% or more of homes are predicted to have radon levels above the 200 Bq/m^3 reference level
- 10% of all dwellings are above reference level
- area where more than 5% of the dwellings are above the reference level
- number of dwellings with concentrations higher then 200 Bq/m^3 exceeds 1%
- % probability of homes exceeding the Action Level of 200 Bq/m³
- Areas where concentrations of Rn-222 are likely to be higher than average
- NRPA define all of Norway to be a radon priority area
- not yet defined

- Municipalities at the radon priority areas are listed in legislation

Evidently, the most common choice (all except the last 4 answers) is based on percentages above RL.

Please briefly describe the classification criteria you used:

The classification criteria used have been reported by 9 Institutions.

- % of the dwellings > RL
- >10 % of measurements indicate levels above reference level
- 10 % excess probability of the reference level
- 10% of the dwellings above reference level
- Areas where 10% or more of homes have been found to have radon levels above 200 Bq/m3 in the 2002 National Radon Survey
- administrative regions
- geology (rock and soil type) in combination with radon concentration measurements
- >1% probability = radon Affected Area (AA)
- National Radon Survey

How do you apply the classification criteria to your data?

How the classification criteria have been applied, has been reported by 9 Institutions.

- Modelling
- mathematical model employing neuronal networks
- >10 % of measurements indicate levels above reference level
- "The federal states provide and publish lists with administrative areas on the basis of the estimate of the radon potential and own knowledge about local geological formations with high radon potential or other causes for enhanced radon concentrations in buildings (like mining)"
- an area is characterized as non-priority area if more than 90% of the measured dwellings have radon concentration lower than the reference level in 90% conf. level
- Data has been mapped to produce a radon predictive map
- Data has been mapped
- administrative regions
- High radium -226 content of rock and soil confirmed with average annual radon concentration over 300 Bq/m^3

In this case, the answers are partly little conclusive.

6. Recommendations and Guidelines

6.1 Task WP 4.1: Evaluation of the concepts for the definitions of radon priority area

The research on RPA concepts, definitions and development of RPA maps are in general performed by specialists/experts and researchers. Then, the regulators and decision makers have to take decisions that best fits to the country-region based on experts' proposals and advises. These decisions will then affect the population and workplaces. Therefore, it is fundamental that a good communication and trust will be established between the different actors: expert- regulator-population. A fundamental evaluation of all relevant stakeholders and their interests and concerns is very important in the process of implementation of EU-BSS and RPAs. Developing communication strategies adapted to the relevant stakeholder groups and the country specific needs are essential. International associations and co-operations like HERCA, SHARE, ERA and research programs (MetroRADON, RADONORM, etc.) and their recommendations, work and results are very helpful for efficient implementation of EU-BSS requirements, including delineation of RPA and stakeholder communication, in the member states.

RPA estimation methods, based on radon measurements in dwellings, can be sensitive but not specific from the distribution of radon in workplaces point of view, or vice versa. This suggests that each country should carefully consider also the distribution of indoor radon in workplaces and public buildings in its own territory, in general statically different from the one in dwellings.

In the MetroRADON project, statistical groundwork on this topic has been laid, but further elaboration is necessary. This concerns the fact that workplaces are no homogeneous statistical population, i.e. have different radon characteristics between their different types, and the regulatory consequences, which the finding may imply.

Within MetroRADON project, in the light of a cross-usage of concepts, different mapping methods were compared, and the agreement of the different methods was discussed by means of several parameters. As known and shown also within this exercise and this report, mapping methodologies are various and so are the definitions of RPAs. As a general conclusion about the cross-usage of concepts, it can be said, that applying a mapping method using data sets, which were not designed for the specific requirements of the mapping method, is challenging. Usually, data sets always have specific characteristics and are rarely comparable, even not for the same variable. Therefore, harmonisation is always a challenge.

In general, the selection of a mapping method for a certain area, will be highly depend on the available data sets. Not all mapping methods are applicable to all data and all areas as depending on data quality, sample density, heterogeneity of the area, etc. This information needs to be evaluated during the selection of a mapping method for a certain area or a certain available dataset. If a survey for delineation of RPA (as requested in the EU-BSS) is started from scratch, the mapping method and display/classification method for the map (e.g. % above RL in administrative area) should be decided at the beginning, so that the survey (measurement density, analysed parameters, etc.) can be optimised to these requirements. For harmonisation of mapping or delineation of areas (e.g. on a European basis) a method using less parameters might be preferable, as easier to apply to different data sets.

Usually the final goal of mapping is the delineation of RPA, as this is requested in the EU-BSS. It was shown, that independent of the applied method for large intervals of classification threshold the same RPA classification is predicted. Different methods often deliver the same results in RPA classification, depending on the definition of RPAs. So, the definition of thresholds is a very important factor in the process of delineation of RPA and might be as relevant as harmonising mapping methods.

The overall results put in evidence the role of the adopted method for the definition of RPA, the set criteria for the definition of RPA and also the radon risk/potential of the country. All those factors influence the reliability and comparability of the delineation of RPAs.

6.2 Task WP 4.2: Relationship between indoor radon concentration and geogenic radon

The idea of radon potential as a quantity which “subtracts” individual physical properties of buildings to indicate the natural conditions that control long-term mean indoor Rn concentration (IRC), has been around for more than 30 years. Concepts were reviewed in this action. One may distinguish between “top-down” approaches, whose initial variable is observed indoor Rn concentration, which is normalized with regard to house, room and usage properties, i.e. the anthropogenic factors which control IRC.

An alternative is the “bottom-up” approach, which starts from geogenic control quantities. The GRP is a particular kind of radon potential; it is defined physically from quantities which control Rn generation and transport in the ground. In this action, definitions are discussed as well as the geogenic quantities which are its input, and their measurement. Problems of representativeness of measured values for a measurement location are addressed, which are mainly owed to the temporal variability of some control quantities.

Regarding the used mapping process, the rationale of the RP in general, and the GRP in particular is that the geographic pattern of IRC mainly reflects the one of its geogenic controls. The reason is that the geographic dependence of anthropogenic factors is relatively lower if compared to the geogenic ones, at least on regional scale, i.e. anthropogenic factors appear as statistical noise on top of the geogenic pattern. In mathematical terms, the anthropogenic factor appears as a scalar factor relating IRC and its geogenic controls (or predictors) that has to be found by regression-type analysis.

Many regression studies have been performed for many years. In this task of Metro Radon, a literature review of relationships between geogenic quantities which control geogenic and indoor Rn concentration has been performed and the results interpreted. In particular, the often-poor correlation between IRC and geogenic quantities has been discussed. The main problem seems to be that models have been developed regionally, obviously considering only regionally variable controls, about constant ones regarded as fixed and entering regression coefficient. However, on larger scale, e.g. Europe, the latter controls are also geographically variable, if over larger distance compared to the regionally variable ones. Therefore, regionally developed models, though correct regionally, may not be applicable beyond the region in which they have been developed. This problem remains a challenge; first European-scale studies have been initiated only recently. Their further development and evaluation remain a task for the future.

The question is closely related to analysis of the spatial statistical properties of the anthropogenic factors, about which so far only very initial studies exist. These have not entered discussion in Metro Radon.

A further open problem, not addressed in Metro Radon, is the one of anthropogenically modified geogenic factors. This is typical for urban and built-up environments where geogenic controls - including geology itself - may not be equal to the one in its surroundings, i.e. open land, where data are usually being acquired in field studies (e.g. due to pavements, landscaping, landfills, historical construction activities etc.). The problem is important because most people live in strongly altered built-up environments. In particular in old European cities, this may challenge correct IRC estimation based on geogenic factors. It is recommended that the topic is addressed thoroughly in future investigations.

Methods to estimate the RP or GRP, respectively, have been addressed in this action. To illustrate it, case studies from two European countries are shown.

6.3 Task WP 4.4.1 and 4.4.3: Harmonisation of radon priority areas across borders

Consistency across borders can be jeopardized by differences semantics (e.g. legends) or scale of predictor quantities. This may be particularly relevant if geological maps are used as predictors, as geological legends mapping the same objective geological reality may differ between maps. Degree of detail depends on map resolution or scale, so that one measurement point may be assigned different geology if taken from geological maps of different scales, even if their legend is the same.

A further issue is the very definition of RPA. This usually has as main feature a threshold (or several thresholds, in case of multinomial classification) of the quantity that underlies RPA definition (e.g. probability that the IRC exceeds a RL), which defines the RPA status of a location or a map unit. If these are different between two neighbouring regions, so will be the RPA status in spite of objectively same natural conditions.

Harmonization of existing maps (i.e. top-down harmonization) remains a challenge, the bigger, the higher the aggregation level of the quantity displayed in the map. This is true in particular for RPA maps, whose aggregation chain may be intricate. Within Metro Radon, challenges were identified and direction of necessary further research indicated. One issue to be further discussed is that heterogeneity is owed to lack of coordination between European countries regarding definition and estimation of RPAs.

The harmonization of radon priority areas across borders could be improved through coordination between the actors involved in identifying RPAs. It might be considered that all countries work with the same type of cartography once the RPA identification parameters have been defined.

7. Summary of WP4: Open problems and recommendations for further work

During work on work package WP 4, a number of open problems were identified, whose investigation would improve estimation and mapping of radon priority areas. Solving the problems was not included in the work plan of Metro Radon, because they have been found and defined only during work.

- In many instances, available data of indoor radon concentration (IRC) are not sufficient for regionalized RPA estimation. Therefore, IRC predictor, controls and proxies are included in estimation. This leads to the necessity of regression models and geostatistics. Many regression studies have been performed on regional scale. It has turned out, however, that – while correct as such – they may not be extendable to other regions. The problem is discussed more technically in Annex 2. It is recommended that large-scale, i.e. European studies be performed which may lead to more universally applicable IRC prediction models.
- The matter is closely related to the one of spatial (geographical) properties of anthropogenic factors. To remind, IRC can be conceptualized as product of geogenic and anthropogenic factors. Its geographic pattern reflects the ones of the two groups of factors. While the one of geogenic factors has been relatively well explored, this is not the case for the anthropogenic factors.
- Most residential buildings and workplaces are on anthropogenically modified territory, i.e. altered by construction, land fill, historical activity etc. These geogenic conditions are different from the ones in open land, where in most cases geogenic variables that serve as IRC predictors have been measured in field studies. The effect of altered geogenic compartments (including “urban geology”) still remain to be studied.
- The geogenic radon potential (GRP) is composed of Rn source and Rn transport. Both can be measured in the field or estimated from other geogenic predictors. In some instances, notable for soil Rn

concentration (SRC) and gas permeability (k), this is done by grab sampling. The values reflect the condition at a certain time, which may be temporally variable to different extent. In the best case, the variability which results in uncertainty of estimated means of target quantities, enters as random noise; but not necessarily so: Depending on the design of sampling campaigns, it can lead to regional bias. Solutions have been proposed, some discussed in Metro Radon: (a) resort to long-term measurement; (b) replace by modelling based on temporally stable quantities. In the future, the options should be evaluated an compared more thoroughly.

- One alternative to the GRP is the radon hazard index RHI (its geogenic specification, GRHI). The concept and possible variants have been introduced in Metro Radon (deliverable 6). However, further development including estimation methods and evaluation of practical viability remain for future investigations.
- Rn quantities, notably IRC and GRP, tend to spatially and temporally extreme behaviour. This results in the occurrence of local anomalies. Including them in regression or geostatistical modelling is challenging, as such phenomena defy certain statistical preliminaries which are valid for "background" estimation. Initial investigations have been performed in Metro Radon. The question how to estimate and map anomalies adequately will remain an issue for same time, among other due to its statistical complication.
- An important issue consists in the fact that residential buildings and workplaces and public buildings have different physical characteristics, in general, in particular concerning their "response" to geogenic Rn. Studying systematic differences concerning their Rn behaviour between different types of buildings has been initiated in Metro Radon (Annex 1), but it turned out that the matter is complex and should be investigated further; in particular with respect to RPA estimation and definition.
- Harmonization of existing maps remains a challenge, the bigger, the higher the aggregation level of the quantity displayed in the map. In particular for RPA maps, whose aggregation chain may be intricate, harmonization is an open topic. Within Metro Radon, challenges were identified and direction of necessary further research indicated. A particular possible source of disharmony are differences of geological regarding legends or scales, if these are used as predictors of GRP or RPA. This issue may be serious and should be investigated in detail.
- Questions of more political nature pertain to stakeholder interests. These largely determine delineation of radon priority areas. The process of national transposition and implementation of the EURATOM BSS were underway during the Metro Radon project (discussion in Annex 1). Therefore, no final assessment is possible. However, it seems that it will result in a patchwork of RPA definitions across Europe which are not compatible across borders in spite of identical conditions that control IRC on either side. It will be interesting to follow this political process, to assess consistence of RPAs, or its lack, and in the future find ways to deal with the problem, which may be a challenge to Rn risk communication. Harmonization issues have been addressed in WP4, but the topic will remain on the agenda.
- More work is necessary to be done when it comes to the assessment of the dose due to radon exposure. It is common in some areas that workers commute between countries and work in different RPA's. Countries may have different criteria when it comes to dose evaluation.

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9. List of Annexes

- Annex 1: Report: *Review and Evaluation of the concepts of the definitions of radon priority areas*, P. Bossew, V.Gruber, R. Trevisi, F. Leonardi, G. Ielsch, G. Cinelli, C. Sainz, L. Quindos, G. Pantelic, I. Celikovic, M. Zivanovic, I. Vukanac, J.K. Nikolic, MetroRADON Activity Report 4.1.2

- Annex 2: Report: *Relationship between indoor radon concentration and geogenic radon,* P. Bossew, L. Szücs, G. Ielsch, C. Greau, G. Cinelli, C. Sainz, L. Quindos, J.L. Gutierrez-Villanueva, J. Nikolov, N. Todorovic, G. Pantelic, I. Celikovic, M. Zivanovic, I. Vukanac, J. K. Nikolic; MetroRADON Activity Report 4.2.3

- Annex 3: Paper: *Development of a Geogenic Radon Hazard Index - Concept, History, Experiences*, Bossew, P., Cinelli, C., Ciotoli, G., Crowley, Q.G., De Cort, M., Elio Medina, J., Gruber, V., Petermann, E., Tollefsen, T, Int. J. Environ. Res. Public Health *2020*, *17*(11), 4134

- Annex 4: Report: *Radon mapping exercise.* V. Gruber, S. Baumann, K.Himmelbauer, C. Laubichler, O.Alber, P. Bossew, E. Petermann, G. Ciotoli, A. Pereira, F. Domingos, F. Tondeur, G. Cinelli, C. Sainz, L. Qunidos-Poncela, A. Fernandez, J.L. Gutierrez Villanueva, MetroRADON Activity Report 4.4.2

- Annex 5: Table with results of literature survey in WP 4.2.1, <Lit-4_2_1_4--all-190424.xls>

- Annex 6: High-resolution versions of Figures 5 – 10.

- Annex 7: List of publications in context of WP4.

- Annex 8: Rationale and Summary of work package WP 4

16ENV10 MetroRADON

Activity 4.1.1/4.1.2

Review and Evaluation of the concepts of the definitions of radon priority areas

Lead organisation: BfS
Other involved organisations: AGES, INAIL, IRSN, JRC, UC, VINS

Authors:

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1. Motivation

The purpose of the MetroRADON project, funded within the European Metrology Programme for Innovation and Research (EMPIR) is to develop reliable techniques and methodologies to enable SI traceable radon activity concentration measurements and calibrations at low radon concentrations. The need for this project has been largely motivated by the requirements of the implementation of the European Council Directive 2013/59/EURATOM (EU-BSS) (EC, 2013), one aim of which is to reduce the risk of lung cancer for European citizens due to high radon concentrations in indoor air. Furthermore, it is a goal of the project to enable uptake and exploitation of its results and experiences by all stakeholders concerned with radon, from regulators and policy makers, professionals in designing, performing, evaluating and interpreting radon surveys, radon instrument manufacturers to the end-users (e.g. companies providing radon measurement, construction industry) and the scientific community. More details about the MetroRADON project can be found at the project website (MetroRADON, 2020).

Article 103 of the EU–BSS requires that member states identify areas where the radon concentration in a significant number of buildings is expected to exceed the relevant national reference level – referred to as radon priority areas (RPAs) within the MetroRADON project and this report. The definition of RPAs will influence political and technical decisions, which in turn will have economic effects in these countries, such as mandatory radon measurements in workplaces in these areas according to Art. 54 EU-BSS, as well as mandatory preventive measures or priority of awareness programmes. As the definition of RPA in the EU-BSS allows a wide range of interpretation, different concepts and methodologies have been proposed and some already adopted.

Within the MetroRADON project a specific work package is included with the aim to analyse and develop methodologies for the identification of radon priority areas, to investigate the relationships between indoor radon concentrations and quantities including soil exhalation and to develop the concept of a “geogenic radon hazard index” (RHI) as a tool to help identify radon priority areas. One specific task within this workpackage is dedicated to collect information and compare the methods for radon mapping and delineation of RPA which are already being used in different countries or regions.

2. Introduction

Delineation of radon priority areas (RPAs) is generally considered an essential tool in the overall target of reducing the radon risk of the population. The definition of radon priority areas (RPA) in the European BSS allows a wide range of interpretation. In the past a number of different approaches has been brought forward, motivated by the availability of data for the predictor quantities (for various reasons different types of data sets are available in different countries) and by the purpose of RPAs which may also vary. In course of the European BSS process, concrete proposals have been made in some countries, and already implemented in a few cases. These will be reviewed and compared in detail in this Task. Given the possible political and economic consequences of RPAs, stakeholders are keen to promote their interests in the discussions on defining RPAs.

The tasks reviews and evaluates concepts and definitions of RPAs, which have been proposed or already implemented in the past and the role of stakeholders in the implementation process of RPA. It is evaluated what purpose these approaches can be used for (e.g. in workplaces, preventive measures, public radon exposure) and if and how certain methods, developed in one country for a specific purpose, could be used or adapted for other purposes or in other countries or regions.

Particular RPA concepts are considered in detail from some countries and available documents are evaluated and experiences discussed between the partners, most of whom play an active role in assessment of RPAs. All results of the activity are discussed and summarised in this report.

The text for the specific activities and the involved partners are listed here:

Activity number	Activity description	Partners (Lead in bold)
A4.1.1	BfS, BFKH, AGES, IRSN, JRC and UC will review and evaluate the concepts and definitions of RPA which have been proposed or already implemented in the past and the role of stakeholders in the implementation process of RPA. It will be evaluated what purpose these approaches can be used for (e.g. in workplaces, preventive measures, public radon exposure) and if and how certain methods, developed in one country for a specific purpose, could be used or adapted for other purposes or in other countries or regions Particular RPA concepts that will be considered in detail are the ones from Spain (based on ambient gamma dose rate and geology), Germany (geogenic Rn potential and geology), Austria (standardised indoor concentration) and France (a multivariate scoring system). Available documents will be evaluated and experiences discussed between the partners, most of whom play an active role in assessment of RPAs. The consequences for developing a flexible multivariate RPA definition (to be carried out in A4.3.4) will be discussed.	**BfS**, BFKH, AGES, IRSN, JRC, UC
A4.1.2	Based on the results of A4.1.1, BfS and AGES will write a report which will be published that summarises and discusses RPA concepts existing and under discussion that will feed into D5, including information obtained from the stakeholder interest groups formed in A6.1.7, A6.1.8 and A6.1.9.	**BfS**, AGES

The report starts with an introduction to the legal background and concept (Chapter 3), followed by a review about RPA concepts and definitions (Chapter 4). The role of stakeholders in the selection and implementation process of RPA is an interesting topic, which is discussed in chapter 5, taking into account all relevant stakeholders and summarises the practical experience in some countries (Austria, Germany, Serbia and Spain). In many cases RPA are delineated based on radon measurement data derived in dwellings, but the main implication of RPA are the mandatory radon measurements in workplaces in these areas according to Art. 54 EU-BSS (EC, 2013; EC, 2020). So, chapter 6 is dedicated to the comparability of RPA derived from dwellings vs. workplaces. As written in the description of the activity, it is interesting if and how certain methods, developed in one country for a specific purpose, could be used or adapted for other purposes or in other countries or regions. Chapter 7 focus on this cross-usage of concepts, taking into account results from chapter 6 and MetroRADON activity 4.4.2. In addition some case studies of RPA concepts and delineation of RPA are presented in chapter 8. Finally, the report ends with a brief summary and conclusion in chapter 9 and references are listed in chapter 10.

Parts of the text of this report have been taken from Bossew (2018 a-d) and a contribution of the same author to the European Atlas of Natural Radiation.

3. Legal Background and concept

European Basic Safety Standards

On the one hand, radon exposure is ubiquitous, and contributes to total dose dominantly, also in low-radon regions, but on the other hand, technical possibilities and logistic and financial capacities to reduce it are limited. Thus, quite logically, the idea emerged that caring about the radon problem should start where it is most urgent. This logic led to the priority concept, as laid down in the EURATOM Basic Safety Standards (EC, 2014) which among regulating other sources and pathways of radiation exposure (e.g. medical and industrial exposure), also deals with indoor radon. The overall goal of the BSS concerning radon is sustainable reduction of the risk (in terms of lung cancer incidence and fatality) posed by indoor radon. This leads to the priority concept, as implicit in the notions of Reference Level (RL) and RPA. It implies that radon exposure should be reduced everywhere, if possibly with lower priority (given usually limited resources); after all, Ann. XVIII (13) states as part of the radon action plan: [Establish] "long-term goals in terms of reducing lung cancer risk attributable to radon exposure". Par. 6 of the same annex says, that a strategy for reducing radon exposure in dwellings should give priority to situations with potentially high radon exposure, which applies to the RPAs or other circumstances which may lead to high radon exposure.

As European law, the BSS have to be transposed into national law by EU Member States.

Reference Level

Main tools to this objective are concentration *reference levels* (RL) and *radon priority areas* (RPA). RL are set to maximum 300 Bq/m³ for dwellings and workplaces alike. However, a RL must not be confused with a limit or an action level.

BSS Art.4 (84) states,

> *"reference level" means in an emergency exposure situation or in an existing exposure situation, the level of effective dose or equivalent dose or activity concentration above which it is judged inappropriate to allow exposures to occur as a result of that exposure situation, even though it is not a limit that may not be exceeded.*

And Art.7 (1,2):

> *1. Member States shall ensure that reference levels are established for emergency and existing exposure situations. Optimisation of protection shall give priority to exposures above the reference level and shall continue to be implemented below the reference level. 2. The values chosen for reference levels shall depend upon the type of exposure situation. The choices of reference levels shall take into account both radiological protection requirements and societal criteria.*

Note that in par.1 the term *priority* appears. Put more colloquially, a RL could be understand as a guideline to assess the urgency of action or intervention. If exceeding a RL is deemed inevitable or reasonable, this has to be justified properly.

Radon priority area

The second tool is the *radon priority area*. This term does not occur in the BSS but has been coined later, about 2014, to underline the priority concept. Historically, the term *radon prone area* has been common. During discussions in the early 2010s that led to the BSS, this term has been rejected. In our opinion, although the forwarded arguments were without scientific rationale, this was still a good decision for conceptual reasons: the term radon prone area suggests that in areas which are not labelled so, radon exposure poses no risk, which is certainly incorrect. Instead, RPAs, how ever defined and estimated in practice, point to areas, in which prevention and remediation should be performed with priority; other areas are given lower priority with given resources, but certainly are NOT defined as "safe". Unfortunately, RPAs are often understood by administrations and the public in exactly that wrong way, thus foiling the underlying concept. Discussions are ongoing and hopefully the correct notion will eventually be accepted and prevail.

I should be noted that according BSS (Recital 22), *"Recent epidemiological findings from residential studies demonstrate a statistically significant increase of lung cancer risk from prolonged exposure to indoor radon at levels of the order of 100 Bq m³"*, hence, the RL and RPA rules cannot be misinterpreted for defining areas as "safe".

Some have concluded that graded approaches match the priority notion best; either by defining different RPA level classes requiring action of different severities or priorities, or by subsequent enlargement of RPAs according to completed tasks.

The philosophy of the priority concept has been well explained by Bochicchio et al. (2017).

The most serious consequences of an area labelled RPA concern workplaces and public buildings. According BSS Art. 54, in RPAs, workplaces in basements and ground floors have to be measured. No similarly strict rule has been foreseen for dwellings, except that in dwellings exceeding the RL, concentration-reducing measures shall be "encouraged" (Art. 74 (2)). Some countries, among them Germany, require that for new buildings, stricter construction norms apply for residential buildings (this mainly concerns insulation against the ground). As already quoted above, Ann. XVIII/6 says that in RPAs, strategies for reducing radon exposure should be developed as part of the National Radon Action Plan (required, Art. 103).

Since BSS implementation is still ongoing in many countries, no authoritative overview on radon regulation in detail (including technical specifications, mostly left to sub-legislation and ordinance) in European countries is available by mid 2020.

An important message is that there is no "natural" definition of RPA and consequently, no such thing as a "true RPA". Delineated RPAs always depend on their definition – resulting from political decisions, stakeholder interests, availability of resources and of databases – and to some degree also on estimation method. As results of statistical estimation, RPAs are uncertain objects (specific activity in MetroRADON, A 4.3.1, see deliverable D5). Communication of RPA uncertainty to the public and to decision makers is another challenge, not to be discussed here, but from experience known to be not easy.

4. Review of RPA concepts and definitions

Article 103 (3) of the BSS states,

> *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.*

The conceptual definition has to be transposed into an operational definition by the EU Member States. It is based on a radon measure, for example the mean over a geographical unit (grid cell, municipality etc.) or the probability that within the unit indoor radon exceeds a reference level.

Existing solutions are pragmatic in the sense that they have to rely on available data and on external "political" parameters such as reference levels, spatial units to which the term "area" refers and tolerable uncertainty.

RPA definitions differ by concept and by aspects of the practical implementability. While the target quantity is always - per BSS definition – the annual mean indoor radon concentration and its limiting value the RL, the meanings of "significant number", "area" and "exceed" are open to interpretation. Also "annual" is problematic, because it is known that annual radon concentrations in one room or building vary between years. The more appropriate term is therefore, “estimated long-term”.

(a) The simplest RPA definition may be, an area is called RPA if the mean radon concentration in buildings or rooms of certain type within an area (municipality, grid cell, etc.) exceeds the RL. Regarding room and building type, the definition can include the entire building stock, or filter for certain properties, such as dwellings only, ground floor rooms (frequent practice), buildings with basement, etc.

(b) Another definition may be based on exceedance probability: An area is labelled RPA, if the probability that a room or building has radon concentration above RL, exceeds a given probability threshold.

(c) Also, qualitative criteria may be used. A RPA is one, in which certain conditions are met, for example dominance of geology which is known for high GRP or prevalence of buildings without insulation against ground.

(d) Yet another definition, quite different from the above, and not applied by any European country so far, to our knowledge, could consist in calling RPA those geographical units (grid cells, municipalities) which represent an upper percentile of radon measures; for example, say, the 5% municipalities with the highest mean radon concentrations. Such strategy would also reflect the prioritization idea implicit in the BSS and limitation of resources: once radon problems have been largely tackled in the upper 5% of municipalities, one may start working the second highest 5%, and so on, as long as found reasonable and feasible.

(e) One can also argue that RPAs should not be defined based on radon concentration values in actual buildings, since these are subject to long-term variation. If an area has been labelled RPA, buildings will be remediated and new buildings better insulated against the ground, which results in lower radon concentration. After re-evaluation, the area could then be relabelled non-RPA, the radon protection rules removed and buildings return to higher radon concentration, which is obviously counter-intentional. Therefore, it has been proposed to base RPA definition on the non-remediated housing stock at a certain time (Belgian approach) or on geogenic quantities, which are not subject to change over geologic times, e.g. the GRP (German approach, Bossew 2015, 2018a). This is equivalent to arguing that not radon concentrations in actually existing buildings define RPAs, but concentrations that are expected to occur for geogenic reasons in a location, if a building of certain type was there, regardless of whether there is one (a concept analogous to the one of seismic vulnerability of a location).

(f) A different approach has been proposed by Elío et al. (2018). The authors argue that in order to reduce exposure, priority should be given to areas where most of *exposure* is located, opposed to the above approaches, which assign priority to areas where highest radon *concentration* occur. Indeed, highest concentrations may occur in little populated regions and thus do not contribute to total exposure, and hence to collective risk in terms of number of lung cancer cases. In most cases, approach (f) leads to assigning RPA status to densely populated areas such as cities, irrespective radon concentrations. In fact, one can argue that a small reduction of radon concentration in a densely populated area with low average radon concentration decreases exposure more than large reduction in an area with high concentration, but few buildings. Probably a radon strategy aimed towards statistically identifiable reduction of exposure will, at least to some degree, have to keep the Elío approach in its agenda.

(g) Yet another approach has been proposed recently, based on the frequency with which radon extremes occur in area, irrespective of the overall mean in that area. The idea is that anomalies (mainly of geological or tectonic nature) may occur also in otherwise “harmless” areas. The extremes may still not contribute significantly to the mean due to their small spatial extent. See Bossew (2018b) for initial considerations. The matter is illustrated in Figure 1, for an area in which the mean radon concentration equals 100 Bq/m³. The probabilities that 300 Bq/m³ are exceeded, depend on the dispersion, measured as GSD. High GSD is an indicator of the presence of anomalies.

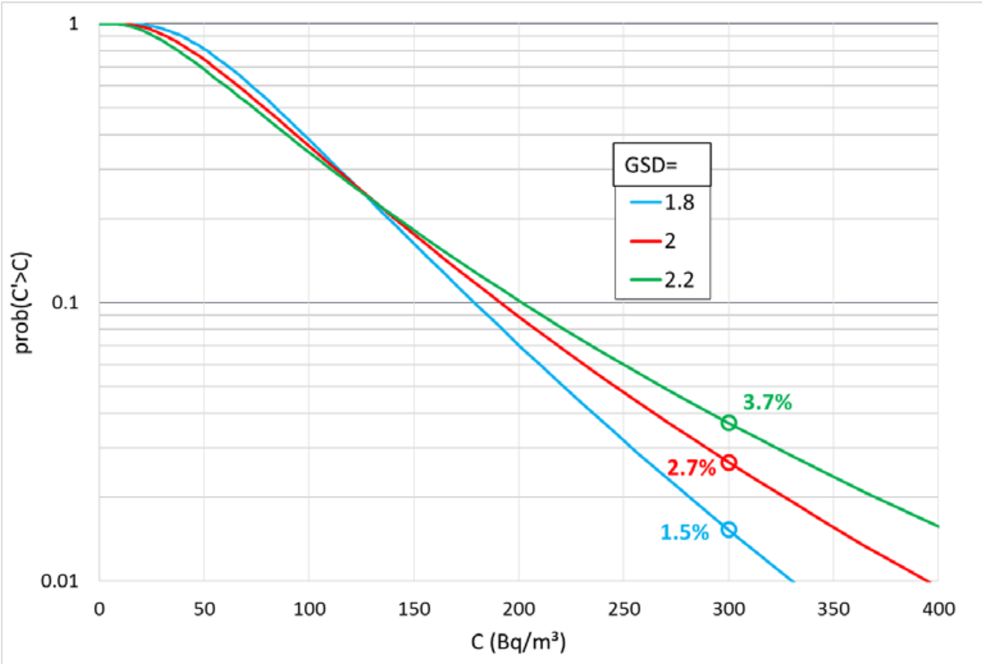

Figure 1: Probabilities that C Bq/m³ are exceeded in an area with arithmetic mean concentration AM(C)=100 Bq/m³, for different geometrical standard deviations GSD. For threshold C=300 the probability values are given.

The discussion is still ongoing. Radioprotection has two targets: minimizing overall risk, where reasonably feasible, and protecting individuals exposed to high dose, even if they contribute little to total exposure. Evidently, the approach (f) of Elío et al. concerns the first target while the more common approach based on reducing concentration, as well as the one based on extreme frequency, the second. Perhaps the solution is not to choose between approaches; but defining different preventive and remediation action in RPAs defined by different approaches.

To repeat, there is no “natural” definition of RPA! Therefore, there is also no “true” RPA. RPAs always depend on definition and to some extent, on estimation method. This is partly a political decision, partly a pragmatic one (i.e. availability of data).

One consequence is that RPAs delineated by individual countries may be inconsistent across borders, in general. This may create communication and credibility problems. This subject is evaluated further in MetroRADON task 4.4, “Harmonisation of radon priority areas across borders”, results are summarised in Deliverable D5 of MetroRADON project.

5. Role of stakeholders in the RPA selection and implementation process

Stakeholder definition

A *project stakeholder* is “an individual, group, or organization, who may affect, be affected by, or perceive itself to be affected by a decision, activity, or outcome of a project", Wikipedia, 2020a; original sources there).

This definition appears most appropriate in our context, supposing the term *project* for radon policy. Original usage of the term seems to have been *corporate stakeholder* (Wikipedia, 2020b) which to some degree can be understood as a subset of the former, as persons of groups which have an interest in the activity or in certain decisions or outcomes resulting from the activity.

Types of Stakeholders regarding radon policy

Usually, *primary stakeholders* are called those that are directly involved materially and economically in an activity; in our context this would be tax payers, those who decide about radon policy (parliament), who administrate it (government, ministry, regional administration), who design it (scientific institute, ministry).

Secondary stakeholders are those who are affected by decision of a project or an action. These cover a possibly wide range from citizens affected by high radon levels to construction industry, health business, media and NGOs.

Evidently, a clear distinction between primary and secondary stakeholders is impossible. In the following list of stakeholders, no distinction will therefore be made.

Risk, risk perception, interests and values

Tackling risks naturally implies costs in one or the other way, and hence conflicts of interests between different stakeholders, depending on the degree of benefitting of risk reduction or having to bear its costs. Below we shall give a list of stakeholders and their respective interests in the case of radon policy. Before this, we address the question of how interests in a matter translate into perceptions about that matter; in particular, we ask, how do interests related to either benefits or costs of radon-reduction-policy control perception of radon risk.

Objective vs. perceived risk has been discussed by a number of authors. For example according to Renn (2004), normative focus on technology-based risk model is not sufficient to achieve communication about risk, preventive and remediation measures, because it does not consider that risk perceptions are based on subjective issues, as values, for example. This leads to the question: How do these subjective values constitute? Understanding this is important to develop risk communication strategies, because, obviously, the balance which each stakeholder attributes to costs and benefits of risk reduction, depends on his preferences and values which are in turn controlled by his interests. This argument essentially follows classical Marxist sociology and its concept of material base and cultural superstructure ("Überbau") (Marx 2010).

Subjective values are based on different initial knowledge, different interests, expectations and desires. Actual creation of values depends on the interdependency of base and superstructure. Base denotes the group or society to which one belongs, economical relationships and material interests. Superstructure refers to the constitution of the nature of cognition according to the economic and social relations derived from the social group to which one belongs, which means knowledge, believes, ideology, mentality, cultural imprint and attitudes. The actual process of superstructure formation as function of these conditions is a matter of social psychological research.

Compromises which are built in a situation of conflicting interests bear the imprint of values which define the weights that are given to the interests. Dominant values are the ones defined by dominant interests. They can only prevail if they dominate the societal discourse. Therefore, the actual shape of a compromise always reflects hegemony in a discourse about values.

The purpose of this excursion is to show that for successful risk management it is not sufficient to address “objective” risks and the benefits and costs of their reduction, but account for risk perception by stakeholders, which leads to possibly controversial attitudes and approaches in dealing with the risk.

Stakeholder interests: its origin and its expression

Different stakeholders have different interests. In the following, we attempt to give a list of stakeholders affected by the radon risk, and involved in dealing with it. We try to identify, in terminology given above, their material base, i.e. their position in society, and their attitude towards radon risk management, i.e. the manifestation in the superstructure domain.

Stakeholders 1: Radon professionals

The radon professionals are an important category of stakeholders. They provide services to the citizens and employers to protect the workers. The main services in which they are involved are: radon measurements and radon remediation. Being involved in radon measurements, they are interested to have the techniques and methodologies available to enable SI traceable radon activity concentration measurements and calibrations at low radon concentrations. They are essential stakeholders, as they are covering the demands of radon measurements and remediation actions providing complementary services to the ones of the national authorities and strictly collaborating with the latter. They are directly affected by the implementation of EU-BSS in the definition and delineation of RPA in the countries, as this defines the amount of mandatory or necessary measurements and remediation, which influences the business of radon professionals. A quality control system (certification, accreditation) should be set up in the countries and radon professionals should be motivated, informed and trained to follow these standards to ensure sound radon measurements and remediation for workplaces and dwellings.

Stakeholders 2: Health professionals

Medical doctors, pharmacies and social workers are usually considered trustworthy persons by the public. In many cases, unfortunately, they are little informed about radon and natural radiation and it should be improved. It seems that so far they have been involved only marginally, but the existing examples show that their impact can be very high. A relevant issue could be, that the radon problem can not be solved by the health professionals themselves. So, they need to be informed and motivated to be an essential part in the overall radon protection system and should be involved more strongly in the radon debate.

Stakeholders 3: Constructions Corporations and Industries

Effective radon protection is mainly a civil engineering and architect task, either by including radon prevention measures in new buildings or remediate existing buildings with high radon levels.

Radon prevention measures (“radon proof” buildings) and radon remediation could create additional profit for construction industry. On the other hand, regulation has legal implications: compliance with strict laws could be costly because construction standards regarding radon must be assured because of liability. This implies additional quality assurance, including measuring building and construction materials.

An important point is the conflict between energy saving and radon protection. Conventional measures to reduce energy consumption make windows more air tight, which reduces air exchange and hence may increase indoor radon levels. In energy saving remediation measures, the radon issue needs to be taken into account, even if it might be more expensive. Good information and communication with the responsible stakeholders will be necessary for that purpose.

Stakeholder 4: Employers and Companies

In designated radon priority areas, regulation may imply measuring and possibly remediation in workplaces and if applicable implement additional radon protection measures (information of the employees, dose assessment etc.). This will be a cost factor for the company and an additional responsibility for the employer to provide a safe workplace and ensure occupational safety of his/her workers. Additionally, as a rather psychological effect, being labelled radon priority area may deter investors and costumers.

Workplaces with radon concentrations above the reference level shall undergo appropriate remedial actions. If, despite all actions to optimise, the radon concentration in a workplace remains above the national reference level, this workplace needs to be notified to the competent authority (according to Article 25 (2)) and the relevant occupational radiation protection requirements may apply (see Article 35(2) of the new Directive (EC, 2013). In this context is it worth noting that Article 31 paragraph 3c clearly recognises the responsibility of the employer or the undertaking for the protection of workers who are exposed to radon at work, in the situation specified in Article 54(3).

Stakeholders 5: Population and House owners

In general, all radon measures, radon regulation and radon work is to protect the population from radon. So, the population is an important stakeholder. The population can have all nuances of emotion and knowledge about radon - well informed, interested, indifferent, afraid, ignorant, sceptical, etc. about radon, depending on their knowledge, education, health interest, risk perception, social circumstances, economic environment, etc. Therefore, it is difficult to summarise the interest and their attitude towards radon, and therefore it is important to have very different strategies to address the population as a stakeholder. The population might also act different in their role as an employee, as a parent, as an individual, as a house owner, as a tenant etc. An employee or a tenant expects to be protected in his/her work place or in his/her dwelling. A parent wants to have his/her children protected in school or kindergarten. But they might have a different perception if they are responsible about the protection themselves. For house owners, radon can be a cost factor. Given possible remediation costs and maybe also possible legal consequences, they could be sceptic against radon regulation. Additionally, elevated radon levels in a house, or being located in a radon priority area, can decrease property value. People with health interest, want to have their dwelling as a safe place for themselves and their families, so they will be more receptive about radon risk communication and measure and remediate radon levels in their dwellings. House owners, who do not live in their houses themselves (landlords, investors) might have less interest in measuring and remediation of the houses, but should be sensitised to their responsibility for their tenants.

Stakeholders 6: Media

Media are important tools for informing and engaging the population on the radon issue. Media includes newspapers, TV and radio, social media etc and allow to reach a wide audience. Media are mostly enterprises acting on the market, or are in competition about quotas with such ones. Therefore, interest of the media mostly consists in quota, which generates their profit. This leads to a tendency to simplify topics or create lurid headlines. If a subject does not serve quota, it might be ignored by the media. So far, radon has drown little attention by the media. However, an information campaign on radon cannot avoid the use of media and it is important to increase the dialogue between the journalists, communication experts and radon experts to provide correct and catchy (attractive) information.

Stakeholders 7: Associations, unions

In some countries, Consumers' Associations inform the members about the radon problems providing them some tips and suggestions on how to perform measurements and remediation also indicating an average price for some services. So, they are relevant stakeholders for radon protection, as they are trusted by the consumers. In addition civil protection associations can play an essential role for the radon information of the public, as they are not seen to have a commercial interest and therefore are trusted in risk communication topics. These trusted associations should be addressed as information multipliers in the field.

In addition, occupational associations and unions are important stakeholders, as they have access to and impact on either the employers or employees. Both groups are relevant in radon protection (see stakeholders above) for effective information campaigns and support for the employers/companies (e.g. providing information material) for occupational safety. Occupational associations and unions should serve as a trusted information and communication channel for radon protection at the workplace.

ERA (European Radon Association) is a large and growing community in Europe of professionals such as scientists, technologists, public health officials and decision makers working in the radon field. Their areas of interest range from epidemiology, radiation dosimetry, instrument development and measurement protocols, remediation and prevention construction technologies to control strategies and regulation. In recognition of this, the European Radon Association (ERA) has been formed aimed at serving the interests of the European radon community and to assist in reducing the health burden of Radon Exposure in Europe (ERA, 2020a).

Stakeholders 8: Government, Administration

In Europe, in 2014, the latest Basic Safety Standards Directive – Directive 2013/59/Euratom laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation has been published (EC, 2013). The scope of the Directive has been extended to apply now to all human activities including those, which involve the presence of natural radiation sources and lead to a significant increase in the exposure of workers or members of the public. Based on this, the Directive introduces, for the first time, legally binding requirements on protection from exposure to radon.

As major provision with regard to the radon protection strategy, the new BSS Directive requires in Article 103 that Member States establish a national radon action plan addressing long-term risks from radon in dwellings, buildings with public access and workplaces for any source of radon ingress, whether from soil, building materials or water. Finally, Article 103 requires Member States to 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. For the annual average activity concentration in air, the reference level shall not be higher than 300 Bq m^{-3}. Moreover, the Directive requires the establishment of a national reference level for indoor radon concentration in workplaces. The reference level for the annual average activity concentration in air shall not be higher than 300 Bq m^{-3}, unless it is warranted by national prevailing circumstances. Member States are free to establish different reference levels for workplaces and for buildings, as long as they are not higher than 300 Bq m^{-3}. For further details, see chapter 3 - Legal Background and concept.

The government/administration in the countries are the ones who are responsible to transpose the EU-BSS directive in their national legislation. The national legislation need to fulfil the requirements of EU-BSS, but will be adapted to the country specific situation regarding e.g. radon levels and economic situation. The government is responsible to establish a radon protection legislation to protect the population in the best way, following the ALARA principle. Consultancy with all relevant experts (radiation protection, health) is therefore necessary for best possible implementation.

Stakeholders 9: Authorities and regulators

Member States need to ensure that the population is informed on a national level and even more on a local level in radon-priority areas, about indoor-radon exposure, the associated health risks, and the importance of performing radon measurements, as well as on the technical means available for reducing existing radon concentrations. Member States are also requested to establish programmes to carry out radon measurements in workplaces within the areas identified under the national radon action plan (see also Article 103(3)), and in specific types of workplaces also identified in the national action plan (see point 3 of Annex XVIII).

The Radiation Protection Authorities and regulators are directly involved on the implementation process of the Directive after the transposition phase. This process involves the technical aspects, i.e. metrology, standard, as well as the social aspects (inform the population). Practical and harmonized solutions to important regulatory issues to be implemented at the national level are also discussed at European level thanks to platforms as for example HERCA (Heads of the European Radiological Protection Competent Authorities).

Radon protection may also be under the responsibility of other authorities, which are usually not directly concerned with radiation protection, e.g. health, occupational safety, building sector. It is important to inform and motivate those authorities and regulators about the importance of radon protection, as they are often the ones who need to implement, evaluate and control the radon protection measures. Sufficient resources, information and training should be assigned to them to fulfil this task.

Communication to Stakeholders

Communication must be customized to the expectations, preferences and values of the stakeholders, as determined by their interests, and prior to any compromise, valuing them on an equal level, without ideological premise. Radon communication to stakeholders is not the scope of this report and activity, but some examples of initiative for improving communication are reported below.

The SHARE platform (https://www.ssh-share.eu/background/) aims to help society in its interaction with radiation risk by bringing together researchers from all relevant platforms, associations and projects related to ionising radiation.

The “Potsdam radon communication manifesto” was published (Bouder et al., 2019) as result of an international expert workshop of BfS in Potsdam, October 2019. The paper is addressed to governments, authorities and other stakeholders responsible for providing information on radon health risks and intend to help improve radon communication. The paper can be downloaded at the ERA website (ERA, 2020b).

The project RadoNorm (stated in September 2020) proposes a multidisciplinary and inclusive research project targeting all relevant steps of the radiation risk management cycle for radon and NORM exposure situations. One point of RadoNorm is the dissemination of the project achievements through targeted actions to the public, stakeholders and regulators by linking dissemination efforts directly to knowledge achievements and new recommendations.

Experiences and Case Studies

In the framework of MetroRadon project a questionnaire for collecting information about indoor radon surveys has been prepared and addressed to all European institutions working in this field. The questionnaire forms have been collected between December 2017 and July 2018. A report on the results of the questionnaires is included in Annex 3 of Deliverable 3 of MetroRadon project.

The focus of the questionnaire was on three main topics: characteristics of indoor radon survey – design; measurements methods; data management, statistical treatment, aggregate and mapping. Moreover, in section 5 "Policy on Indoor Radon", some information have been collected about how EU Member States intend to transpose (or have transposed) the latest Basic Safety Standards Directive into national law and hence about RPA. This session was addressed only to national authorities.

Figure 2 reports the role in the organization of the respondents to the questionnaire, in which multiple answers where possible. The majority of respondents are specialists/expert and researcher, only two covering policy function, while seven regulators. Therefore, it seems that in radon field the technical roles (Specialist/expert, researches) are separate from the policy function-regulator roles.

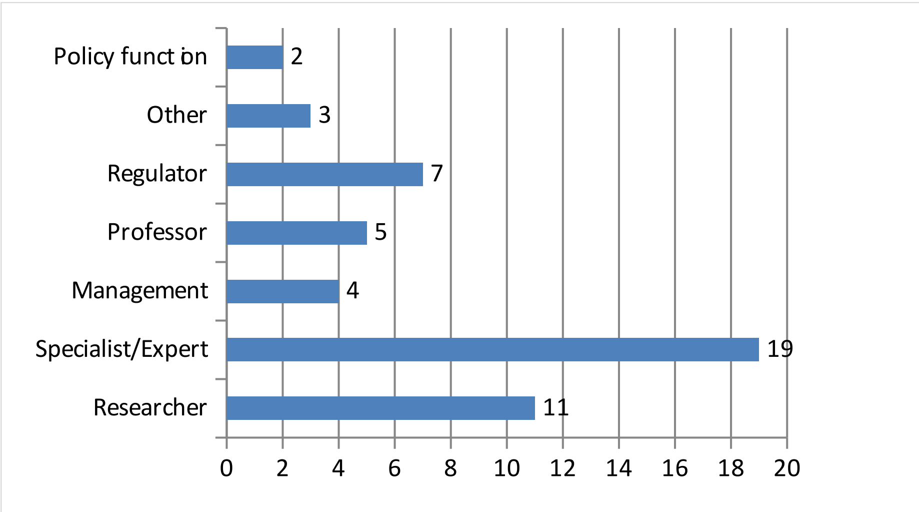

Figure 2: Role in the organization of the respondents to the MetroRadon questionnaire.

Austria

The requirements of the EU-BSS in the field of radon protection are transposed into Austrian legislation via a new radiation protection act (Republik Österreich, 2020) and a specific radon protection ordinance. The national authority responsible for radiation protection is the Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology (BMK, Status August 2020), which is the leading organisation to implement the EU-BSS into Austrian national legislation. Austria has nine federal states with federal governments and administrations and important parts within the field of radon protection are under the responsibilities of the federal states (buildings legislation, protection of workers). Therefore, the authorities of the federal states are important stakeholders and were involved in working groups in the process of the implementation of the EU-BSS. Building legislation is under the responsibility of the federal states, but the Austrian Institute of Construction Engineering (OIB) issues guidelines to harmonise the construction engineering regulations in Austria. Those guidelines are adopted by the federal states into their construction laws. Thus, the OIB is an important stakeholder in radon protection, and they included recommendations regarding radon protection in their guidelines.

The delineation of RPA was done on a national level, based on the measurement campaign and methodology described in chapter 8. The measurement campaign was financed by BMK and carried out by AGES in close cooperation with the federal states governments and the voluntary fire brigades. The methodology for the campaign and the delineation of RPA was proposed by the radon experts of AGES in cooperation with the BMK, and then discussed and agreed with the stakeholders in a working group (federal states, OIB, other ministries). As described in chapter 8, in Austria so called radon protection areas are established for the mandatory radon measurement in general workplaces (see Figure 5). In addition, a graded approach is planned for preventive measures in buildings, based on the type of area. The municipalities which are classified as radon protection areas or radon prevention areas are listed in the radon protection ordinance. The draft of the ordinance was sent to all stakeholders (federal states, building/construction sector, occupational safety sector, radiation protection institutes, relevant unions etc.) for review and comments in spring 2020.

The concerns about the new radon regulations of the stakeholders from the economic sector (Austrian Economic Chambers, Unions) were, that companies/employers will have a lot of extra costs, with the need to measure radon and remediate, in addition to so many other obligations they need to fulfil and especially in hard economic times, after Covid-19. The importance for radon protection for the health of the employees and the low cost of passive radon measurements and the already existing and tested efficient remediation methods were good arguments in these discussions. But it needs a lot of communication to transport these messages to the relevant stakeholders. As a next step, it will be important to communicate the obligatory radon measurements and the importance of radon protection to all the affected employers/companies. With the new regulation, that all workplaces in ground floor and basement in delineated areas, need to take action for radon protection, a lot of employers will for the first time be faced with radiation protection - e.g. offices, shops, hair dressers, crafts enterprises. To communicate this understandably and effective, will be a challenge. The involvement of stakeholders like the economic chambers and specific unions, which are trusted representatives for these groups, will be necessary.

One major point of criticism from the building sector and OIB within the process of the delineation of radon preventive areas is that it will increase the costs for new buildings, both private dwellings and workplaces. The counter-arguments are that if new buildings are built to the state of the art, there are in most of the cases no additional radon preventive measures necessary and if so, it is normally below 0.5 % of the total building costs. On the other hand, radon remediation and radon preventive measures could also be an additional market for the building industry and therefore a good impact for the economy. To have experts within the building sector for radon remediation and radon prevention a special training course was established by BMK and AGES, in cooperation with OIB and federal states and will be repeated in the next months.

The federal state governmental offices are the responsible authority for the control of radon protection at workplaces. Their major concern was a lot of additional work with the notification process, controlling and evaluation of measures of the radon workplaces without additional resources (staff, budget). In cooperation with the BMK and the federal states governmental offices electronic systems are being developed to simplify the notification process. In addition, the radon measurements and dose assessments in Austria need to be done by accredited laboratories according to standard protocols, to have unobjectionable results and easy control and evaluation by the authorities. Also the training of building professionals will ensure sufficient approved experts available, who provide sound, efficient and sustainable radon remediation.

The delineation of radon protection areas and radon preventive areas also concerns the municipalities. Their concern is that because of higher costs for workplaces (radon measurements, radon remediation) and new private houses they are less attractive. If communication about relatively low costs for workplaces and new buildings is done effectively (see above), then there should not be a relevant disadvantage for those municipalities. It is also important to have the municipalities well informed about radon protection, as the municipalities are the authority to grant permissions for new buildings. Training and information events for representatives of building authorities (local, regional) were organised in the last years in all federal states in cooperation of BMK, federal states and AGES.

In general, the implementation of the EU-BSS in Austria affects a lot of stakeholders and therefore the interest was quite high. It was tried to inform and involve them in an open way, via workgroups, information events, training, meetings and personal communication by BMK and radon experts of AGES. Of course, within that topic, very different roles, interests and views are present and it is not easy to satisfy every stakeholder and take everything into account. In the end, of course, the way of implementation of the EU-BSS is a political decision and always needs compromises between economic interests and optimum health protection, but nevertheless needs to follow the ALARA principle.

France

A local radon action was led by the French Institute for Radiological Protection and Nuclear Safety, in cooperation with 15 municipalities and the “Lycée des Métiers du Bâtiment” in Felletin , a college specialized in building works. This campaign was carried out in an area characterized by a high geogenic radon potential. It started in winter 2015/2016 for two years and was based on a voluntary and individual initiative. Firstly, 729 free radon measurement kits were distributed (10% of homes). The indoor radon concentration was above 300 $Bq.m^{-3}$ for around 70% of the measurements (main room), with 27% above 1000 $Bq.m^{-3}$. Then the participants were encouraged to find solutions and start mitigation actions to reduce the exposure to radon. Their initiatives were supported with small workshops and control measurements after mitigation were proposed. The final synthesis of this action provides a useful experience feedback for future similar actions in other territories.

Moreover, In the Region “Bourgogne-Franche-Comté” a regional pluralist project has been carried out since 2011, involving different local and national stakeholders (www.radon-qai-fcomte.fr/). The objectives of the project are to contribute to the information, training and support of different target audiences for the management of the radon risk: public, information relays such as doctors and teachers, health and building professionals as well as local decision makers. All the work of this program is carried out in a global perspective of "indoor air quality" and "energy saving" so that all the solutions proposed by the pluralist project are applicable and beneficial for the overall establishments open to the public and private housing. It is also part of public policies conducted at local, national and international level to benefit from synergies, resources and existing tools (example: Regional Health Environment Plan 3 Bourgogne - Franche-Comté, Local Health Contract of the Vosges Saônoises , Home energy renovation plan, etc.).

The different partners of this regional project continued to work together in the Interreg France-Switzerland project named JURAD-BAT (2016-2020) (www.jurad-bat.net). This European project aimed to improve the radon risk management in buildings in the Jura Mountains, at the border between France and Switzerland. The final objective was to develop a new online tool to provide information and propose courses/trainings on radon risk management for different targets audiences (public, building professionals/companies, experts, students, researchers etc.).

Serbia

The Article 106 of the EU-BSS says that “Member States shall bring into force the laws, regulations and administrative provisions necessary to comply with this Directive by 6 February 2018”.

The responsibility to establish a Radon Action Plan (RAP) in Serbia is on Serbian Radiation and Nuclear Safety and Security Directorate (SRBATOM). The first step within the RAP was to determine the radiological exposure risk to radon in residential areas and the national reference level for radon. For that purpose, SRBATOM has formed a “radon working group” consisting of academic experts in radon field from all relevant Institutes that will help manage the RAP. The members of Group helped SRBATOM in design and conduction of the first national indoor radon survey. Radon Reference Level (RRL) and RAP are a part of Exposure Situation Management Strategy document. SRBATOM is currently in the process of drafting the Strategy. Taking into account the regular process in Serbia for the adoption of legal documents such as the strategy, it is estimated that RRL and RAP will be implemented by the end of 2021.

Therefore, at this stage of establishing the RAP the stakeholders that are involved in its design are beside competent authority (SRNSSD), different institutions with their academic radon experts.

For the time being, definition of RPA in Serbia does not exist and therefore neither Republic not local authorities are responsible for areas that are at least by radon experts identified as a RPA. Although local authorities, as well as residents in dwellings where high indoor radon concentrations is found, are informed, they do not make any mitigation actions to reduce risk due to exposure to radon.

Full implementation of RAP will be extremely difficult, especially in areas (municipalities) that be delineated as a RPA.

Two examples are given:

1. Distinguished international radon experts have offered a free remediation to residents in certain dwelling, having annual average radon concentration >1.000 Bq/m³, yet it was refused out of fear and not due to financial reasons.
2. One tourist region in Serbia is known for high indoor radon concentrations. Since that gave bad publicity to the region and decrease of number of tourists (at least by interpretation of local authorities) some members of the local authorities have even asked one of the experts to give an interview stating that their area is not an area with high radon concentration.

It is also interesting to mention that some insurance and real estate companies ask about the radon level in the dwelling of interest, although it is not regulated by any regulations. Therefore, once the EU-BSS is transposed into Serbian law, it will influence a wide range of stakeholder, not only policy makers but a lot of different industrial stakeholders.

Having in mind that transposing EU-BSS into Serbian’s law is in progress, Serbia and its stakeholders (from authority to public) will gain a lot from the dissemination of knowledge from MetroRadon project aiming among others to develop strategy to harmonise methodologies and data and to reduce inconsistencies that will help to implement EU-BSS.

Spain

As is the case in different neighbouring countries, the degree of involvement of the stakeholders related with the radon issue has been very uneven in Spain during the last few years. The beginning of the radon activities in Spain dates back more than 30 years, having as main drivers for its development groups of researchers from different universities, among which the University of Cantabria, the University of Barcelona, and the Polytechnic University of Cataluna or the University of Santiago de Compostela had important role. Through research projects funded by the Nuclear Safety Council (CSN) and by European calls, it was possible to establish the fundamental background of the National Radon Plan, such as the elaboration of an indoor radon map in dwellings and the creation of a metrological control system of radon measurements. Along these main lines, very diverse training and dissemination activities were carried out, intercomparison exercises of radon measurement techniques, and specific research projects on radon remedial techniques and exposure in different workplaces such as spas, galleries, tourist caves or tunnels, among others.

Practically until 2001, in which the 1996 EURATOM Directive was implemented in Spain, including exposure to radiation of natural origin in the general framework of radiation protection in Europe, the role of other stakeholders was residual or directly non-existent. Few industries lend themselves to assessing the risks for workers as there was no solid normative basis in this regard during this period. Rarely the media echoed the problem of exposure to radon, resulting in news that was sometimes anecdotal and even imprecise. Likewise, the interest of administrations and governments, both national and local, was scarce, and in the field of construction corporations the problem of radon was not taken into account.

Obviously, the publication in 2013 of the EURATOM Directive has attracted the attention and interest of different stakeholders until today. The explicit definition of the different items that must constitute a National Radon Plan in all member countries has established a clear roadmap for many agents who were not previously involved in the issue. The number of professionals dedicated to radon measurement and mitigation has been increasing gradually, with the incorporation of foreign companies into the market and the creation of new national companies. On the other hand, the recent publication of the latest version of the Technical Building Code, which includes measures to prevent the entry of radon for new or renovated buildings, means that both construction and geotechnical companies are specializing specific radon departments, and even show bigger interest in participating in technological development projects.

It is becoming increasingly common to find news and reports in local and national media about the radon problem. The impact of these broadcasts continues to be uncertain, causing indifference in some cases, or excessive alarm in others. This highlights the need for continued efforts to improve the way we communicate the risk to the general population, and even to the authorities, who normally have never heard about radon.

Finally, it is important to indicate that the maximum responsibility for coordinating the development of the National Radon plan in Spain has been given to the Ministry of Health, which traditionally has not had any competence or experience in this field. Most of the actions contained in the Radon National Plan are supported by the regulatory body, the Nuclear Safety Council (CSN), and by the Ministry of Development. This latter body approved on December 27, 2019 the latest version of the Technical Building Code that contains, for the first time, protection requirements against radon in newly constructed and rehabilitated buildings. For its part, the CSN also approved in December 2019 the entire set of actions that correspond to it within the National Radon Plan.

Germany

Disclaimer:

The following text does not represent the position of the BfS, but the experiences and the state of knowledge and its interpretation by the author. Since German radon policy is still evolving, so is its perception, and quite naturally there is no static final position about is viability. The text is intended as a contribution to the discussion which goes along with that evolution.

Introduction

The German administration seminally engaged in shaping the EURATOM Basic Safety Standards (BSS) since its first drafts around 2010. After final publication (late 2013) and according obligation to transpose it into National Legislation, the new German Radioprotection Act was designed, including radon regulation, and issued 2017 [1]. Work on sub-legislation (ordinance level [2]) including radon Action Plan [3] was finished end

2018 (in compliance with the timeline specified by the EC), which was the point when the entire law came into force. Radon priority areas (RPA) shall be defined by the Federal States by end 2020.

Main stakeholders which actually engaged in the process were:

- Regulator, i.e. the German Federal Ministry of Environment, Nature Conservation, Building and Nuclear Safety;
- Its scientific office, the BfS
- Administrations that have to execute the radon Action Plan; i.e. mainly the Federal States (Bundesländer; FS), which by German constitution are the competent authorities in radioprotection that act on behalf of the State, Art 83-85 GG [4].
- Construction industry (to minor degree)

Stakeholders not really present were health industry (doctors, pharmacists), the radon measurement industry, radon science (universities etc.), media, NGOs and the public altogether, although participation was encouraged on different occasions. Some input came from experts about indoor air quality.

The entire process can be generalized by several phases: weakening initial proposals from the European Commission (about 2011-2013) to interpreting flexible and fuzzy regulations in a sense to render radon regulation as lean as possible (2014-2017): The BSS, which provides for minimum rules (preamble (5)) were mostly implemented in this minimum sense. However, finally a reverse tendency appeared to outweigh the former, which resulted in potentially efficient radon regulation and Radon Action Plan. During the legislative process, elements of the initial strict proposal re-entered. In particular, the Radon Action Plan appears promising from the perspective of radiation protection.

The federal structure of Germany

A key to understanding the complicated process is German federalism. It is deeply rooted in history (see e.g. Wikepedia, 2020c) and laid down in § 20/1 of the German constitution (Grundgesetz or Basic Law). § 30 says that legislative, executive and judiciary powers are with the FSs unless regulated otherwise by overruling State competences. (The relation is somewhat similar to the one between the EU and its Member States, which is characterized by primacy of European Law on the one hand, and subsidiarity on the other.)

Therefore, the representatives of the Länder have a strong say also in radon regulation. National laws and ordinances for radiation protection need the vote of the Bundesrat (the second chamber of the parliament with representatives from the Länder). The Bundesrat can enforce changes in the text or block the process for some time by calling the "conciliation committee" between the Bundesrat and the main parliament, the Bundestag. Regarding radon regulation, to avoid blockage, the Bundesländer were involved in a quite early stage of the political process. As a result of this early involvement, the German delegation at the Atomic Question Group meetings to transform the basic safety standards of the Article 31 Group of Experts (based on Arts. 30- 32 of the EURATOM Treaty, see references) to the draft council directive was required by the Bundesrat to avoid any binding regulation related to Radon at home and workplaces (Bundesrat 639/11, 25.11.2011). In the end, the German delegation was unable to impose this demand on its European partners. But it still succeeded in weakening the very strict first proposal by the European Commission, the be discussed in more detail in section in the next section.

The phase of BSS design, 2010 - 2013

The first proposal for the BSS was issued by the European Commission on 29 Sept 2011. Notable changes in the extant BSS (2013) are:

- Unification of Reference Levels (RL);
- removal of the term “radon prone area” (with the concept remaining, only without naming the areas);
- removal of the obligation to establish building codes for residential buildings in RPAs;
- removal of the obligation to notify the EC about RPAs.

The deletion of the term “radon prone areas” was first criticized by the radon community but then seen as a chance, and around 2012 the now common term “radon priority area” was coined to emphasize the priority concept that underlies these areas (Bochicchio et al. 2017). However, the new term did not enter the BSS text. Intense discussion between EU Member States (MSs) and EC dealt with RLs, their consequences, their relation to the 6 mSv rule, the concept and wording of then so called radon prone areas.

In a meeting between Ministry and FSs in September 2012, the participants agreed that the by then rejection of any radon Action Plans should be weakened since now the list of actions was indicative and not obligatory (and could be repudiated at all, as was added). The obligation to report delineated radon priority areas to the EC was rejected (still included in the BSS draft 15 May 2012, disappeared by 20 Dec 2012). Also, the obligation to define RPAs at all was rejected, including the term “Radon prone area” because of its inherent “stigmatization potential” (the term “particular concerned areas” was proposed instead). On the other hand, the usefulness of radon maps as tool to prioritize action was acknowledged at that point. It was found important that wording of the BSS was such that radon action would remain on a voluntary base. Obligation to remediate buildings in which the RL is exceeded, was rejected. It seems that these positions were fiercely defended in the non-public negotiations with the EC. According information from participants, the removal of the term “radon prone areas” in later versions of the BSS was indeed mainly owed to German pressure.

In the conference “Radon Fachgespräch” organized by BfS, 16 May 2013, the Ministry proudly boasted about its negotiation successes in the BSS preparatory group at the EC to avoid strict and obligatory rules in the articles concerning radon protection. (Although, according to our information, by March 2013 Germany already had withdrawn from some of her initially strict positions.) At the time, most concerned with radon on a technical expert level did not comprehend the rationale of the Ministry, while on its part, the Ministry appeared surprised of the by large sceptic reactions of the experts.

On the other hand, the German delegation reasonably proposed to modify article 103/3 about RPAs that action should be taken more generally in “situations with potentially high exposure to radon”, additionally to RPAs also if “other parameters” justify it (proposal 25 March 2013). This proposal has not been implemented in the final version of art. 103/3, but moved into annex XVIII (2).

As a summary, Germany (together with other MSs) succeeded to some extent to weaken the wording of the BSS, removing as much as possible any obligatory action. However finally, the content was largely saved, mainly owed to the linguistic skill of EC officials to rephrase paragraphs such as to please the advocates of weak regulation while preserving the substance. For example, the mandatory Radon Action Plan (art. 103) remained; the RPAs re-entered the article as par. 3 although removed in intermediary versions in 2012 (e.g. 11 Dec 2012), shifted to the indicative annex. This annex is now not any more labelled indicative, but its points “to be considered” (document 14 Feb 2013).

This tortuous process (mainly in 2013) may explain some awkward and overly diplomatic sounding formulation in the BSS. It seems that neither the process which led to the German positions nor the negotiations in the Article 31 group themselves included active consultation of and scrutiny by the public and stakeholders, although the formal possibility existed e.g. for NGOs, except federal and regional administration. The public was formally involved only in the legislative process, section 3. – Here is not the space for a detailed analysis of the history of the European BSS, which would however certainly be a rewarding endeavour. From today's perspective, some contributions had satirical potential.

National transposition and implementation phase 2014 - 2016

It seems that in the end the federal and regional administrations came to terms with the BSS although its radon regulations were stricter than deemed acceptable by them two years earlier. Energy now was shifted towards transposition into Law, and in particular, Radioprotection Ordinance, which contains the operable rules.

Suggestions of operable rules were prepared by the BfS and transmitted to the FSs by the Ministry. Main critical comments of the FSs were:

- RL=100 (BfS proposal) was rejected as too low, apparently mainly for economic reasons and because it was feared that regionally large fractions of buildings would be affected which would render implementation almost impossible;
- Proposed GRP and RPA maps were criticized because of unreliable or un-representative input data (regarding sampling design and methodology; the arguments are partly correct, but there was little choice but to work with factually available data);
- Methodology (geostatistics and cross-classification to link GRP to IRC) was met sceptically by some. Some doubted the suitability of the GRP as IRC predictor. Partly in response to the critique, partly following scientific progress in the field, methodology continues to be further developed by the BfS.
- Some doubted the practical value of radon maps, because they might led to misinterpretation; they would suggest false safety and not address scale issues. These are indeed serious issues, which deserve further discussion the future.

On the other hand, two FSs claimed underlining the priority aspect in defining RPAs, very much in line with the position of the BfS. This did not enter the next stage of discussion (see also below), but seems to have reappeared about 2018.

Many laid quite some effort onto interpreting the BSS in the weakest possible sense. Apart from usual populism – which is always at hand since EU bashing is a common diversion strategy; however unlikely in this case because the BSS never became a case of public dispute - as reasons one may see scepticism against rampant over-regulation (which is indeed a EU problem, or at least has been one in the past) and secondly, related to it, an attempt to fight the unpopular home-made "Regelungsflut", i.e. the perceived tsunami of norms for each and everything, by trying to abolish one regulation for every new one enacted.

The legislative process was public, as proposals were submitted to a public hearing. Unfortunately, the civil society did not recognize the relevance of the new radioprotection legislation and its bearing to future radon protection policy. (An exception was the "Bund für Umwelt und Naturschutz Deutschland (BUND; Friends of the Earth Germany), which called for an IRC maximum permissible value (instead of RL) of 50 Bq/m^3 which is clearly unrealistic; in fact also counterproductive because this way they practically disqualified in the discussions.)

In the perspective of 2020, German radon policy is certainly not to be called courageous or innovative, but certainly much better than what had to be feared in the earlier phase, as can be concluded from available documents about the decision-making process between administrations and authorities.

Implementation

Reference level

Given the constitutional power of the Federal States and political respects, the Federal Ministry was strongly driven by the interests of the FSs. In the absence of public pressure, the main interest of most FSs (with notable exceptions) consisted in avoiding any radon action to utmost degree. The BfS, on the other hand, tried to defend the interests of radiation protection, which led to frictions with the Ministry, whose subordinate the BfS is. For example, the BfS opted for a reference level (RL) 100 Bq/m² and still considers it scientifically sounder than the RL 300 Bq/m³, which was finally adopted in the radiation protection law ([1] §§ 124, 126) on pressure of administrations. 300 Bq/m³ is the highest allowable choice according to the European BSS (Art. 54/1, 74/1). It corresponds to up to some 15 mSv/a, depending on the dose conversion factor chosen. Indeed, also the very EU-BSS state (preamble (22)), that "a statistically significant increase of lung cancer risk from prolonged exposure to indoor radon at levels of the order of 100 Bq/m³" has been demonstrated. Recently, the BfS seems to adapt its position in reaction to now existing regulation ([1,2,3]).

The hitherto RL=100 Bq/m³ position of the BfS is supported by the WHO (Radon Handbook, section 6.3, p.90, WHO, 2009)). The German Committee on Indoor Guide Values (Ausschuss für Innenraumrichtwerte, AIR, 2020) recommended a RL=100 Bq/m³ in its session 4/5 November 2014 (AIR 2014; agenda 3.2). The policy of the AIR is to set the concentration RL for carcinogens corresponding to a maximal lifetime risk 10^{-6}. For IRC, this would correspond to unachievably low radon concentration in the order of Bq/m³, i.e. equal or lower than typical outdoor radon concentration. In such case, the 95% percentile of the actual frequency distribution is proposed, which is about 100 Bq/m³ in Germany and thus happens to coincide with the WHO RL. However, since this corresponds to risk 1.7 10^{-4}, i.e. far above the target 10^{-6}, according to the AIR, optimization should be attempted also below 100, as far as feasible, and robust data about the statistical distribution of IRC in Germany should be generated.

In the Radioprotection Act ([1], §5 (29)) the definition of RL is weaker than in the BSS. The Act states: A RL is a value which serves as reference for checking whether a measure is appropriate. In the BSS (Art. 4 (84)): the RL is the level, "above which it is judged inappropriate to allow exposures to occur as a result of that exposure situation".

Radon priority areas and priority aspect

Priority concept

The main question of conflict was, and continues to be by mid 2020, delineation of radon priority areas. In the new German radioprotection law, the priority aspect (e.g., BSS art. 7/1, Annex XVIII (6), implicitly preamble (36) about "graded approaches" and definition of RL, art. 4, definition (84) as, while exposure above RL is "inappropriate", it does not say that exposure below RL be "appropriate", and Bochicchio et al. 2017) was practically ignored in the paragraphs about RPA, although this appears quite fundamental in the BSS, as it is in radioprotection altogether (a consequence of the ALARA principle). In an earlier draft (shown in a presentation in a meeting June 2013), Annex XVIII (then still XVI) (2) still explicitly used the term "priority", but this has disappeared later (We can at the moment not say on whose initiative this happened). In the Radioprotection Act ([1] § 121) RPAs have no particular name, but are unofficially termed radon prevention (provision, precaution) areas (approximate translation of German "Radonvorsorgegebiet"). Some interpret this term as an implicit reference to the priority concept.

In consequence, RPA thresholds were practically understood by both Ministry and administrations (but not by the BfS, and although not stated in the Radioprotection ordinance, [2]§ 153, nor in the Radon Action Plan brochure [3], p. 9, which explicitly mentions the priority aspect) as a kind of delineation between "risk" and "no risk", which is in stark contrast to reality and to the concept of RPA. *Practical* means that, although of course known that RPA zones represent regions of different degree of risk or hazard (potential risk), "green" areas were understood as ones which would not require any action. In contrast, the RPA concept consists in defining areas which for pragmatic reasons (i.e. limited resources, such as measurement and remediation capacities) should be considered first; one natural choice is areas, in which the frequency of high-radon dwellings is increased; hence the conceptual RPA definition of the BSS (article 103/3).

Similar to the Radon Action Plan brochure, in October 2020, a presentation by the Ministry at a regional radon meeting (BMU 2020b) summarized the strategy to RPA delineation, as laid down in the radiation protection Act [1], the Ordinance [2] and the Action Plan [3], i.e. the strategy to ensuring compliance with BSS Art. 103 (3) and Annex XVIII (2). In this document, the term prioritization reappears explicitly, additionally stating that this means that RPA status indicates particular need for action.

Proposals for RPA definition

The further consequence of the wrong understanding of the RPA concept was that administrations bargained for as small as possible RPAs. This led to a proposal of the Ministry (elaborated by the BfS, fig.3, upper left), defining RPAs as areas, in which with 90% confidence, dwellings would have frequency RL>300 of 10%. Non-RPAs were areas in which with 90% confidence, the same frequency would be <10%. The undecided area between the two (yellow in the figure) was meant to be left for further investigation. The proposal was meant to serve for planning but not for public risk communication. Classification with more than two levels (RPA / non-RPA) was not wanted from the beginning, probably for the sake of clarity, although in principle possible in the BSS.

Even this very un-conservative approach was not accepted. It is un-conservative, because a probability 90% to see an effect (RPA status=yes) means, in statistical terms, that the first kind error chance (i.e. labelling an area RPA although it is not) is at most 10%. This implies, on the other hand, that the second kind error chance is high, almost 60% in this case, that is, with 60% probability a true RPA may not be recognized as such. The suggestion led to an RPA map, Figure 7 in section 8 (Case studies; Germany) and Figure 3, upper-left.

The idea of basing limits of RPA on misclassification probabilities was skipped early 2019, as it became clear that some FSs would not accept it. Instead, the Ordinance ([2]§ 153 (2)) now says: The competent authority can assume that the annual mean IRC in living spaces (includes dwellings) and workplaces exceeds the RL in a significant number of buildings (i.e., that it is RPA), if based on a scientifically founded prediction, in at least 75% of the territory of an administrative unit (municipality or district, to be defined by the FSs) one can expect that in at least 10% of buildings of the RL is exceeded.

How this is determined is left to the FSs which are the competent authorities; the GRP prediction map (generated by the BfS) serves as guidance. Also, how it is decided whether the RL is exceeded in 10% of buildings, or likewise, how large the exceedance probability is in a given administrative unit, is not ordained, except that it be based on a scientific method ([2] § 153 (1)).

Methodology is however crucial if the RPAs are defined based on the GRP. It remains to be seen how the FSs will implement this paragraph of the Ordinance; there is chance that it leads to RPAs which are actually more conservative than the ones of the first proposal; first promising attempts have been shown (Heinrich et al. 2010; Sachsen 2020). The 75% rule has no scientific base and is not supported by the BfS. During discussions some FSs asked for a more conservative rule (e.g. 50% instead of 75%). Instead, the BfS proposed that regional authorities consider local circumstances that are only assessable locally, such as, which part of a municipality or district is actually built-up area, or presence of local peculiarities like mines, tunnels, small-scale geological features etc.

Summing up, the latest, but perhaps not last state of the RPA discussion is that Federal States themselves decide about the criteria on how to define RPAs, guided by a national GRP map issued by the BfS. Probably this will lead to a patchwork of RPA definitions. This procedure is scantily supported by radioprotection considerations and has little scientific base. Rather, it appears to be the outcome of political haggling. The final decision should be published end-2020, following the Radioprotection Act ([1] § 121 (1)) which says that the RPAs shall be defined before 2 years after publication of the Radioprotection Ordinance [2].

At the time of writing (September-October 2020), in spite of the reluctance, not to say resistance, of the FSs in previous phases, their contributions became increasingly constructive and cooperative for about 2-3 years, so that currently slight optimism prevails about their role in achieving an efficient radon mitigation policy. On the other hand, the in tendency misunderstanding of the RPA concepts seems to persist and negotiation about every m² labelled RPA - or rather not - has sometimes absurd traits.

Individual and collective protection

Implementation of the BSS in the legislation mainly considers protection of individuals by caring for high individual exposures (through establishing a RL and obligatory measures in RPAs), but less so for collective exposure which causes an overwhelming fraction of risk attributable to radon, although called for by BSS article 5b and in spite of annex XVIII (13), saying that the long-term goal of radon action is reducing lung cancer risk, and in spite of section 122 (1) and (4) of German Radioprotection Act [1].

This objective is also addressed directly in the title of the radon Action Plan brochure [3], "for the sustainable reduction of radon exposure" and later (p.7f.) "The measures presented below are intended to sustainably reduce the number of lung cancer cases caused by exposure to radon..." (cf. BSS Annex XVIII (13)); also indirectly, in that the population has to be informed about radon risk and mitigation possibilities, hoping that this would eventually lead to reduction of collective exposure. Also including the building industry in the implementation process is expected to serve this end.

Applying the priority principle to protection of the public and taking the goal seriously to reduce health impact would lead to priority action in areas with high collective exposure per unit area, i.e. basically, where the product of RL exceedance probability and population density is high (This RPA concept has first been proposed by Elío et al. 2018). Examples of tentative maps of PPAs according these considerations are shown in Figure 3. The Radon Action Plan brochure [3] responds to the call to reduce mean exposure only by announcing information of the public, and that radon protection "should become an aspect to be considered in quality assurance and financial support measures for construction projects" (following BSS Annex XVIII (12)). (pp. 8, further expounded p. 18).

Radon Action Plan

It was attempted to include the topics of the list "to be considered" of BSS Annex XVIII into Radiation protection Act and Ordinance. This is explained in a brochure issued by the Ministry in 2019 [3], further discussed in section 6. Some interpret this strategy as potentially even stronger than the BSS (which, ironically, years ago Germany attempted to weaken).

On the other hand, measures and targets sometimes appear vague and rather calling for good will than for legally founded action. For example, it says (p.7) that “it should be sought to keep exposure as low as reasonably achievable, also below the reference level” (which correctly addresses the topic of collective exposure). It is true, however, that linking targets and measures which are by nature political, such as public information and support of further research, to quantitative margins is difficult. Referring to the above example, defining quantitative, legally based action which would reduce collective exposure and risk for a certain percentage, is impossible with today’s knowledge, and probably also legally difficult as it would imply encroaching upon many different areas of law. Still, one may have slight doubts about the efficiency of measures which largely rely on voluntary action or information, given that radon prevention, and even more so, mitigation and prevention costs money. However, the possibility of financial support for such action is under “review” ([3] p. 18).

Again on the other hand, evaluation of the law is obligatory which some interpret in the sense that the legislator understands that final wisdom on radon policy has not yet been found.

Regarding evaluation, the BfS has been commissioned to provide quantitative metrics for assessing the efficiency of radon action.

Political constraints

The political respects mentioned above are the following:

- Being labelled RPA might lead to an area being less attractive for investment, tourism and property value. In the discussions, the term “stigmatization” has been used recurrently. (This is due to bad experiences which have been made with sensationalist media coverage of legacy contaminated sites mainly in former East Germany.)
- Radon action which is obligatory in an area labelled RPA costs money (measurement in work places and public buildings, possibly remediation (BSS article 54/2, annex XVIII (7), preamble (25)).
- “encouraging“ (BSS wording) radon prevention and remediation in dwellings in general (art. 74/2, annex XVIII (8)) and with priority in RPAs (annex XVIII (6)); in practice this means (although not said explicitly in the extant BSS, in contrast to the first proposal of 2011) implementing construction codes also for residential buildings. This may have effects which represent partly competing, partly coinciding stakeholder interests: (1) additional costs reduce profits of property investors; (2) they increase costs for tenants. Both is politically undesired, if for different motives. Disentangling them is difficult (not only) in this particular case.

It is true that according the BSS (preamble (42), article 5, annex XVIII (14)), in designing the Radon Action Plan (BSS preamble (23), article 103), radioprotection concerns should be deliberated against societal aspects. This also corresponds to the ALARA principle. Naturally, every decision represents a compromise between stakeholder interests; however, the deliberation which leads to the compromise has never been demonstrated by administrations.

Since there is no public pressure on the administrations, the impression remains that they decided to rate economic and political arguments above health arguments, in general. In other words, there seems to be a certain under-explained asymmetry between stakeholder interests. Future discussion will tell whether or to which degree this impression is correct, and how administrations will defend their decisions in the case of the public or NGOs eventually waking up on the radon issue.

Communication

Responding to Annex XVIII (10), a brochure has been issued in 2019 in which the Radon Action Plan is presented and explained [3] (see also above).

- Reference level: 100 Bq/m³, as also favoured by the BfS in accordance with WHO (see above) is said not to be feasible "due to specific national circumstances" (p. 7), without naming them. The choice 300 Bq/m³ is not further explained.
- Radon priority areas: The actual definition and methods of their determination is not included, probably because this was still under discussion at the time of publication. Assessment shall be reviewed every 10 years and / or (not clear) if the database has improved (p. 15, further p. 24; [1] § 121 (1)). Ironically, in the English version of the brochure the term "radon prone area" reappears, whose purging from the BSS was a non-negotiable condition of Germany few years ago. Additional measurements of ground and indoor radon have already be performed during 2019-20 and entered the new GRP map proposed by the BfS in autumn 2020 (unpublished as yet, Oct. 2020). Further quite large measurement campaigns are ongoing or planned for the next years, including creation of a nationally representative IRC database that shall serve as reference to validate the effect of radon action.
- The Plan includes a quite extensive list of measures for radon prevention (new buildings) and mitigation (existing buildings). The measures are sound; see however in the radon action plan section on considerations about their efficiency.

Altogether, this brochure is well done. Its structure essentially follows the issues of BSS Annex XVIII. It also contains a timeline for the implementation of measures (a kind of to-do list) which follow the requirements of the Plan (p. 14 and p. 26ff.). On the other hand, critical and potentially controversial topics are not discussed, i.e. choice of RL, definition of RPAs, deliberation of radioprotection against economic (and other societal) factors (this point is not addressed at all).

As another element of information to the public, a folder has been released, BMU 2020a. In several FSs, radon information brochures have been published for some years.

Summary and outlook

Evidently, radon policy is a long-term endeavour. Hence only an interim conclusion is possible by autumn 2020. In this contribution, we described an about 10 year's journey from almost fundamentalist refusal of mandatory radon policy over partly controversial discussions between German administration and the EU and between stakeholders within Germany to a respectable albeit not overly courageous result. However, its efficiency in meeting the overall target of the BSS, namely reduction of radon risk, remains to be seen in the future. It will certainly not least depend on the participation of stakeholders, in particular of the general public and the civil society.

The first draft of the BSS seems to be from 24 February 2010. The documents are found in https://ec.europa.eu/energy/topics/nuclear-energy/radiation-protection/scientific-seminars-and-publications/group-experts_en. The first version which resembles the final version seems to be from September 2011. It is found in https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2011:0593:FIN:EN:PDF

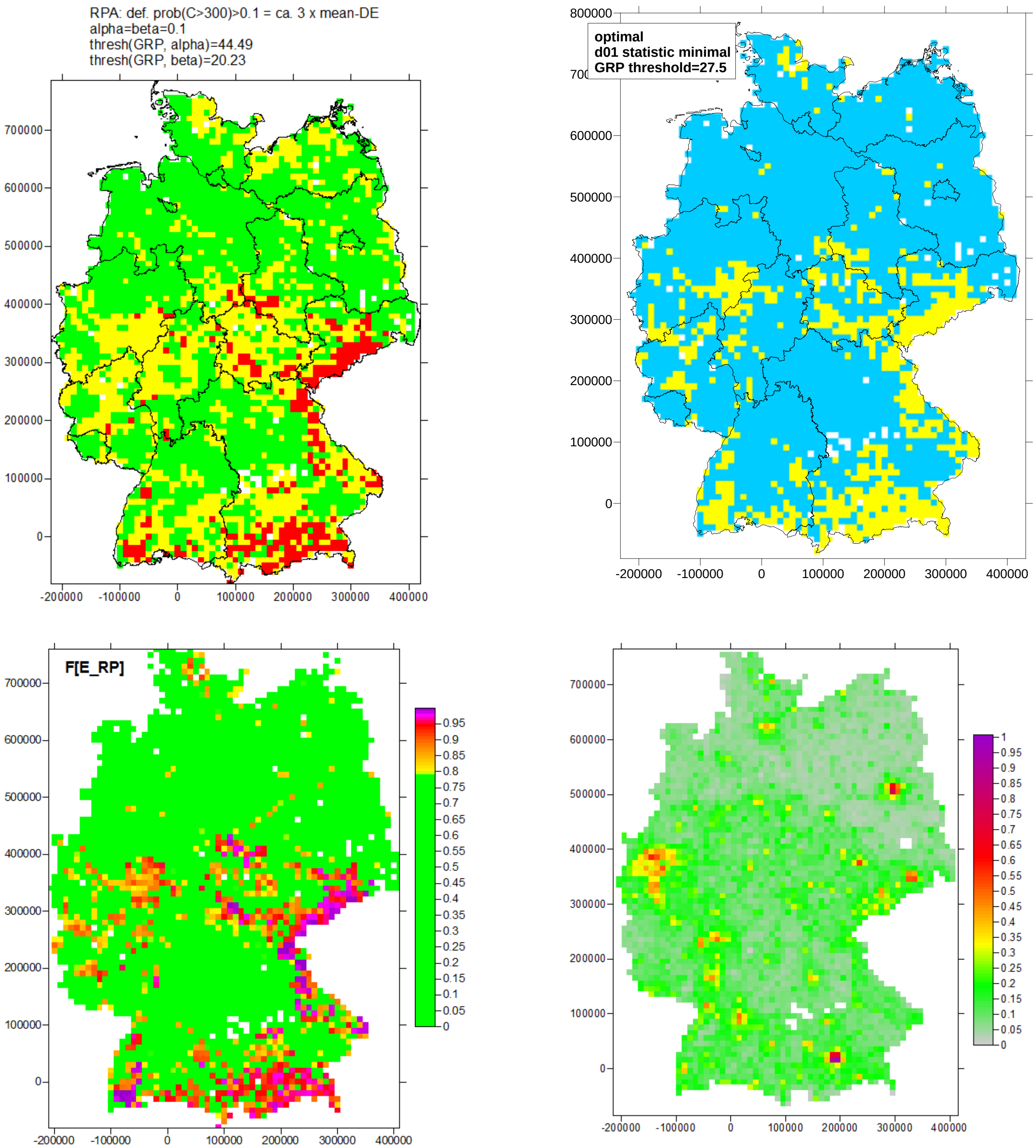

Figure 3: Upper left: BfS proposal for RPA, 2016 (see also section 8, case study Germany); Upper right: Classification RPA (yellow) optimal according d01 minimization in ROC space; Lower left: percentiles of the GRP; Lower right: distribution of the collective exposure (scaled to unity). (All based on the GRP map 2013; 10 km × 10 km cells; white cells: not assigned; axis units: m. The GRP map based on data available mid-2020 looks slightly different.)

References to German legal and government documents:

[1] https://www.gesetze-im-internet.de/strlschg/ ; Concerning radon: part 4, chapter 2, paragraphs 121 - 132; issued 27 June 2017, latest amendment 19 June 2020; English translation: https://www.bmu.de/fileadmin/Daten_BMU/Download_PDF/Gesetze/strlschg_en_bf.pdf

[2] http://www.gesetze-im-internet.de/strlschv_2018/ , Concerning radon: Part 4, chapter 1, sections 1 and 2, paragraphs 153 – 158; issued 31 December 2018, latest amendment 27 March 2020; English translation: https://www.bmu.de/fileadmin/Daten_BMU/Download_PDF/Gesetze/strlschv_en_bf.pdf

[3] Radon action plan for the sustainable reduction of radon exposure. Published by Federal Ministry for the Environment, Conservation and Nuclear Safety (BMU), Division for Public Relations, Online Communication and Social Media, 2019. www.bmu.de/publikation/radon-action-plan/

[4] German Grundgesetz (de facto constitution): Basic Law for the Federal Republic of Germany, English version: https://www.gesetze-im-internet.de/englisch_gg/index.html

6. RPA derived from dwellings vs. workplaces

Motivation

A particular problem consists in the fact that the legal and administrative consequences of having an area declared RPA concern workplaces and public buildings in the first place (BSS Art. 54). On the other hand, RPAs are, in most cases as far as known, defined per indoor concentration in dwelling and estimated from indoor data in dwellings. The reason is that most data are available for dwellings. So far, radon data for workplaces (except schools) and public buildings are scarce.

Apart from this practical reason, there are many different types of workplaces and public buildings. Even hypothetically located on the same site and thus subject to the same geogenic radon influence, their "building physics" concerning air circulation and radon accumulation and dilution, is very different among them, and from the one of residential buildings, and consequently their indoor radon concentrations. It is evident that, say, schools, shops, police stations, ancient castles, workshops, metro stations, industrial production halls, museums, etc. etc., have different physical characteristics and have little in common, apart from being workplaces. A typology of workplaces regarding radon is still missing. It is therefore not clear, how correct or adequate RPAs derived from residential buildings and dwellings are with respect to the RPA definition applied to workplaces altogether or to a certain type of workplace. Also in this case discussion is ongoing. Among literature comparing workplaces and dwellings is Bucci (2011) and Žunić et al. (2017) and references there.

Methodology

In order to compare radon levels in dwellings and in workplaces in a given area and to evaluate if they have different distributions and different mean levels an international pilot study has been initiated in 2018. An expert group under JRC umbrella is working on data (radon annual activity concentrations in dwellings and workplaces) provided by Austria, Italy, Germany and Finland.

The discussion among experts is ongoing with the aim to identify a suitable methodology and the national available datasets are adequate for statistical analysis, the coverage of territory (national, regional) and the measurement methodology (e.g. measurement duration). Nationally, available data sets consisted in radon annual activity concentrations in dwellings and radon annual activity concentrations in general workplaces (Italy and Finland) or in particular kind of workplaces, such as administrative buildings, schools and kindergartens (Austria and Germany). Moreover, in case of Finland and Italy database covered the entire national territory, while in case of Austria and Germany the available data were on regional scale (Upper Austria and Saxony).

Another question regarded the influence of inhomogeneous methodological aspects: for example, the duration of sampling and period of sampling (season) and the order of magnitude of available data (sample size). In Table 1 a summary of the main characteristics of national datasets is given.

Table 1: Summary of the main characteristics of the national radon datasets

	Italy	Finland	Germany	Austria
Duration of measurements/ dwellings	12 months	60-70 days	4 – 12 months	6 months (*half winter half summer*)
Duration of measurements/ workplaces	12 months	60-70 days	12 months	3 months for schools 6 months (*half winter half summer*) for administrative buildings
Workplaces included in the dataset	General workplaces (*including administrative buildings, schools, kindergartens)*	General workplaces (*including administrative buildings, schools, kindergartens)*	Public buildings (*administrative buildings, schools, kindergartens*)	Public buildings (*administrative buildings, schools, kindergartens*)
Sample size (dwellings/workplaces)	15.000/9.500	200.000/6.000	1.700/300	7.000/2.000

Workplace data have been aggregated in the same grid as already done on data related to dwellings to update of the European Indoor Radon Map (EC, 2019), based on 10 km × 10 km grid cells. The same statistics were collected, viz. AM, SD, AML, SDL, Median, Min, Max and number of data n (AML(x)=AM(ln x)=ln(GM x), SDL(x)=SD(ln x)=ln(GSD x)).

In this way, two structurally equal datasets were generated, which can then be compared statistically.

Results

Analysing national datasets, dwelling and workplace datasets have a different frequency distribution of sample size (dwelling and workplaces) in cells (see Figure 4): typically, dwelling datasets have a higher number of radon measurements in cells; the range of frequency classes is very wide (from some tens to several hundreds of samples in a cell). Conversely, in workplace datasets radon measurements are few compared to dwellings and the size is generally 20 up to 80 samples within a cell.

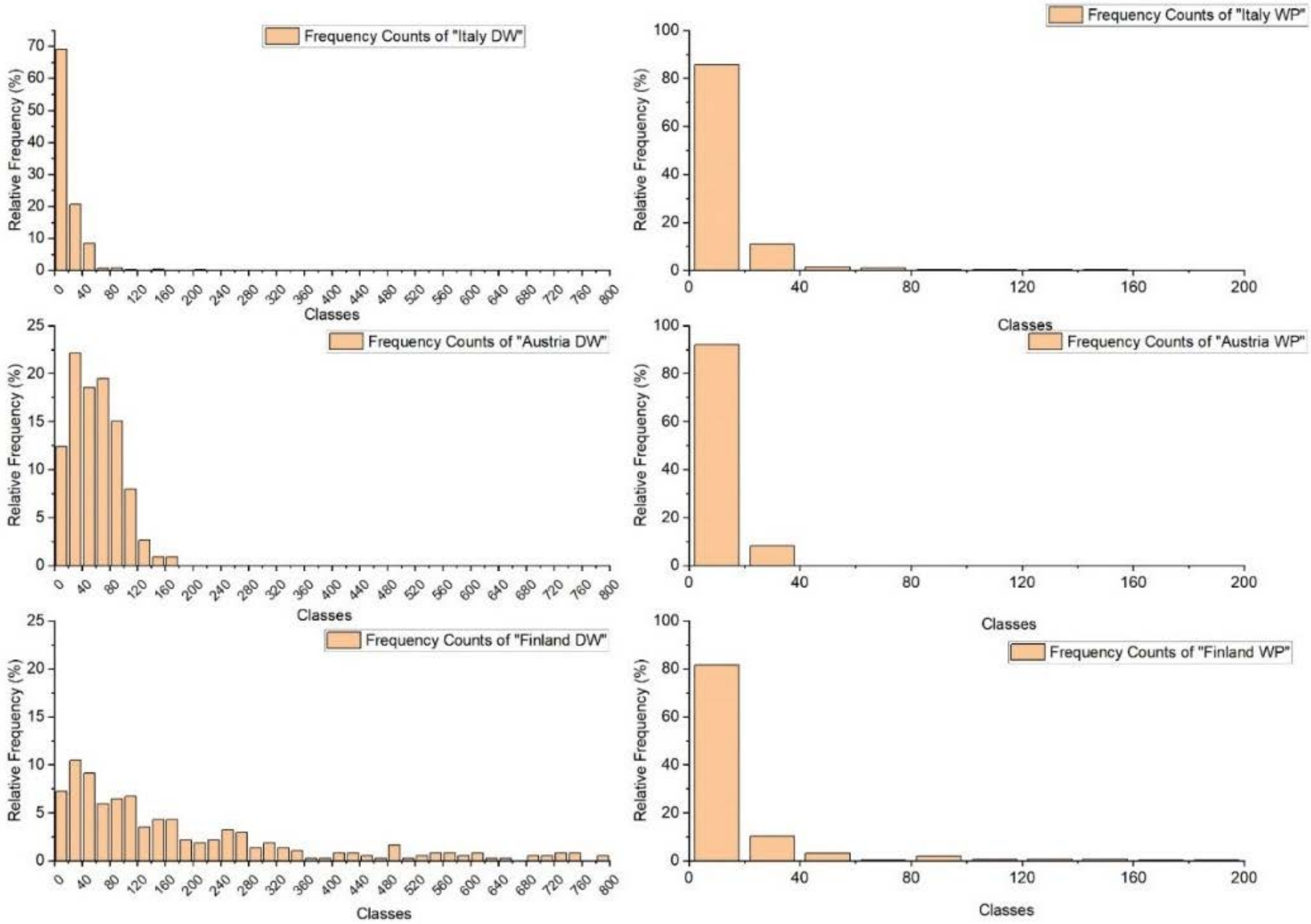

Figure 4: Frequency distribution of sample size in cells in each national dwelling and workplaces dataset (Italy, Austria and Finland)

Among statistical parameters, the AM(ln) and SD(ln) are good parameters for statistical analysis, when there is no information about the distribution of data (radon annual average concentration) within cells. On national final datasets, the dwelling and workplace data were compared - as paired observations - by using statistical tests (Student's t-test, in case of normal distribution of parameters, or Mann-Withney's non parametric test).

First results put in evidence that radon levels in workplaces and dwellings are statistically different: as considering the effect of geology (comparison of data referred to the same grid cell) [paired test], as considering the effect of sample sizes [test on data weighted on sample size].

Moreover, respect to dwellings, in “general” workplaces radon levels are significant lower and more variable, in terms of a wider distribution and greater standard deviation: in Figure 5, as example, the box plot of Finnish AM(ln)s related to dwellings and “general” workplaces (DW/WP)is given. Comparing dwellings and schools, radon levels do not statically differ, even if mean radon levels in dwellings tend to be less scattered than in schools.

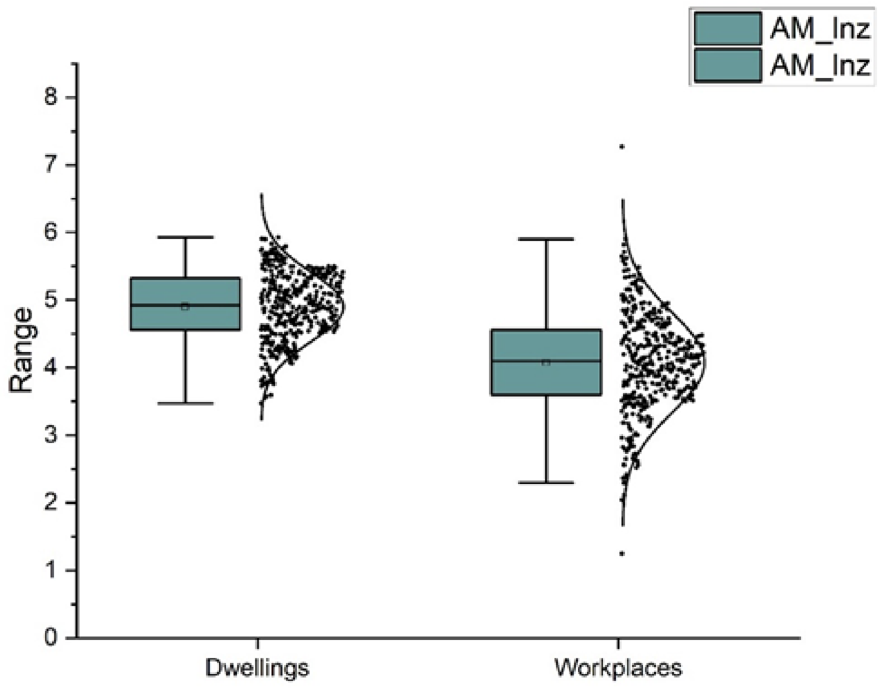

Figure 5: Box Plot of AM(ln)s related to dwellings and "general" workplaces (DW/WP): Finnish data

Hence, dwellings seem more suitable than workplaces to represent radon distribution (less internal variability, less CV, etc.) in a territory (mapping).

Three different linear regression models were tested: the simple regression, the orthogonal (or Deming) regression and the Passing-Bablok regression. Best results were achieved with the application of a linear regression (linear model), in which the radon level in workplaces is a dependent variable while the radon level in dwellings is independent. This analysis confirmed that dwelling sample size and workplaces sample size are independent variables: in all countries, participating to the pilot project (Austria, Finland, Germany and Italy), radon levels in dwellings and in workplaces seem have a statistically significant positive correlation. It means that when the radon levels in dwellings increase, radon levels in workplaces increase, too.

In conclusion, the international pilot project, still ongoing, showed that in the same area the distributions of radon in workplaces and dwellings are statistically different and positive correlated: this phenomenon has to be taken into account in the RPA identification since it introduces legal and administrative obligations in workplaces and public buildings located in areas declared RPAs. Further details about the "cross-usage of concepts" are discussed in chapter 7.

7. Cross-usage of concepts

As discussed in the previous chapters, different concepts and definitions of RPA and methods to delineate RPA exist and are used and implemented in Europe. The purpose of this activity was to evaluate and review the different approaches. But also to evaluate, if and how certain methods, developed in one country for a specific purpose, could be used or adapted for other purposes or in other countries or regions. This is discussed in this chapter, based on the results from chapter 6 and MetroRADON activity 4.4.2, where different mapping methods were applied to the same data and the results were compared.

Cross-usage of concepts - workplaces vs. dwellings

As first example of a cross-usage of concepts, the cross-usage of workplace and dwelling radon data has been tested with the aim to evaluate if different mapping methods deliver similar RPAs.

In particular, in the framework of the pilot project described in chapter 5, national data about radon in dwellings and workplaces were used to run an exercise focusing on one possible definition of RPA (i.e. 10% above 300 Bq/m3): results were evaluated „consistent“ or not by means several parameters. The exercise involved data from Austria, Finland, Germany and Italy: a summary of main results is in .

In , it can be observed that Finnish and Austrian results show a similar trend, as well as Italian and German ones. For Finland and Austria, the proportion of positive cases (TPR= True Positive Rate, in other words, is when an area is defined RPA as from workplaces as from dwelling data) is very high (>80%): this is a measure of the *sensitivity* of the RPA estimation method; however, the proportion of negative cases (TNR= True Negative Rate, that is when an area is non-RPA from workplaces and non-RPA from dwellings) is in the range 30-40%: this means that at the same time the method is not very *specific*.

In case of Italy and Germany, the trend is opposite. Indeed, the proportion of positive cases (TPR) is around 45% and the proportion of negative cases (TNR) is very high (near 90%): in these cases, the RPA estimation method is not very sensitive but highly specific.

Logically, where the estimation method is very *sensitive*, the percentage false negative case (estimated by FNR - False Negative Rate, that is the proportion of positive cases - RPA from workplaces - are wrongly predicted negative or predicted non-RPA from dwellings), is low and viceversa.

Analogously, if the method is very *specific*, the number or percentage of false positive case is high: it is expressed by the FPR values, (FPR= False Positive Rate, the proportion of negative cases - non-RPA from workplaces - which are wrongly predicted positive - RPA from dwellings-).

In all countries the „*precision*“ of the RPA estimation method, expressed by PPV (PPV= Positive Predicted Value, that is the proportion of positively predicted cases on the base of dwelling data, which is confirmed by workplace data) is in the range 40-60% and the accuracy (ACC), which accounts for true positive and the true negative cases, ranges between 55% and 78%.

Running the same excercise with other two different criteria (5% and 15% above 300 Bq/m3), it is possible to observe the robustness of the RPA estimation methods. A synthesis is given in Table 3. In the table only the main parameters are shown (TPR, TNR, PPV, ACC).

Typically, different criteria influence all parameters (sensitivity, specificity, precision and accuracy) but do not change the order of magnitude of each single parameters: in general, the trends observed by using the first criterion (10%) is confirmed with few exceptions.

Table 2: Results of a cross-usage of dwelling and workplace radon data to estimate RPAs. TPR: True Positive Rate; FNR: False Negative Rate; TNR: True Negative Rate; FPR: False Positive Rate; PPV: Positive Predicted Value; FDR: false discovery rate ; ACC: accuracy; FOR: False omission rate.

	sensitivity		**specificity**		**precision**		**accuracy**	
	TPR	**FNR**	**TNR**	**FPR**	**PPV**	**FDR**	**ACC**	**FOR**
FINLAND	87%	13%	40%	60%	51%	49%	59%	19%
AUSTRIA	81%	19%	35%	65%	42%	52%	55%	28%
ITALY	45%	55%	89%	11%	58%	42%	78%	29%
GERMANY	44%	56%	86%	14%	67%	33%	70%	17%

Table 3: Comparison of a cross-usage of dwelling and workplace radon data to estimate RPAs with different criteria of identification of RPAs (5%, 10% and 15% above 300 Bq/m3; respectively). TPR: True Positive Rate; TNR: True Negative Rate; PPV: Positive Predicted Value; ACC: accuracy.

	sensitivity			***specificity***			***precision***			***accuracy***		
	TPR			**TNR**			**PPV**			**ACC**		
	0.05	**0.1**	**0.15**	**0.05**	**0.1**	**0.15**	**0.05**	**0.1**	**0.15**	**0.05**	**0.1**	**0.15**
FINLAND	94%	87%	81%	32%	40%	47%	50%	36%	23%	65%	59%	57%
AUSTRIA	94%	81%	71%	18%	35%	55%	51%	35%	24%	59%	55%	60%
ITALY	65%	54%	50%	77%	84%	88%	27%	16%	9%	72%	75%	78%
GERMANY	46%	44%	35%	81%	86%	90%	26%	17%	13%	62%	70%	70%

This exercise is an interesting example of a "cross-usage of concepts": a cross-usage between workplace and dwelling radon data has been tested by using data provided by some countries. The overall results have been analysed and discussed by means of many parameters. They highlighted that RPA estimation methods, based on radon measurements in dwellings, can lead to sensitive but not specific estimation of areas, in terms of RPA, also from a workplaces point of view and vice versa. This experience suggest that each country should carefully consider the distribution of indoor radon in workplaces and public buildings in its own territory, often statistically different from the one in dwelling. This is important, because the definition of RPAs influence further political and technical decisions, such as mandatory radon measurements in workplaces in these areas.

Cross usage of concepts - different mapping methods and RPA definitions

Within the MetroRADON project one task was, to evaluate mapping methods and RPA definitions for their comparability and their usability for other countries, which is another example for the “cross usage of concepts”. For this purpose existing mapping methods used in different countries were applied using harmonised data sets of various variables (e.g. indoor radon, gamma dose rate, geology, soil gas radon). Afterwards the mapping and classification results for the provided data sets in the relevant areas were compared and the usability evaluated. The activity is referred to as “the radon mapping exercise” and is discussed in detail in the MetroRADON activity report 4.4.2, which is also part of the Deliverable D5.

Two data sets were used for the exercise, different in geology, scale, co-variables, etc. to increase the scope and benefit of the exercise. One data set is from an extensive survey in six municipalities in Austria, the second data set is from Cantabria, Spain. The data include indoor radon measurements, building characteristics of measured dwellings, soil air radon activity concentration, permeability estimation, activity concentration of soil samples, ambient dose rate and maps of geogenic parameters derived from other sources (e.g. geology, soil type, airborne radiometry). The data sets differ in basic characteristics as size, sample density, data extent, quality and resolution. Methods to characterize radon priority areas for the two data sets may require adequate data manipulations for different methods. But the comprehensive radon data sets provided in the exercise aim to be a solid basis for different strategies to identify RPAs.

Different mapping methods were applied to the data sets in the exercise. The basic analysis based on indoor radon data showed, that the indoor radon concentration (IRC) distributions differ in the regions of the exercise data sets and the concentrations are considerable higher in Austria than Cantabria. This is of course also true for the aggregates of the distributions that might be used for basic radon risk prediction. Other methods used were a generalized additive mixed model (GAMM), based on the methodology used in Austria for the delineation of radon areas. The idea is to identify relevant explanatory variables to predict the expected indoor radon concentration for a specified grid. Another method was the empirical Bayesian kriging (EBK) regression prediction, which is a geostatistical interpolation with known explanatory variable rasters to affect the value of the data that should be interpolated. Also ordinary kriging (OK) and Indicator Kriging (IK) was used to predict the indoor radon concentrations in areas. The last method which was applied was based on the Belgian radon risk mapping method (BRRMS), which map the variations of the radon risk within geological units with the moving average method, while geological units with significantly different levels of risk are considered separately.

To apply the different mapping methods the data sets may require adequate data manipulations and not all data is used for each mapping method, and also not every mapping method can be used for the data set. In general, mapping methods are mostly specified to use either IRC as target variable (e.g. basic statistics methods, Kriging IRC) or geogenic variables (EBK regression, Kriging GRP). BRRMS, the Belgium mapping method, combines IRC and geogenic variables, by taking into account geological units. The methods using IRC with building characteristics could be only applied for the Austrian data sets, as no information about building characteristics is included in the Cantabrian data set. Only the GAMM method used all available variables as well for the Austria and the Cantabrian data set. Except the basic statistic methods (IRC mean over threshold and probability of IRC over threshold per municipality or geological unit) all methods used interpolations to map the radon concentration or radon potential or radon risk.

It can be summarised that in general, the selection of a mapping method for a certain area, will be highly depend on the available data sets. Not all mapping methods are applicable to all data and all areas as depending on data quality, sample density, heterogeneity of the area, etc. In our example, the methods using building characteristics for the prediction of IRC were not possible to use for the Cantabrian data set, where this information was not available. On the other hand, methodologies based on differences between geogenic factors (e.g. EBK regression) could not be adapted to the very small, quite geogenic homogeneous areas of Austria. Also for the BRRMS, taking into account information of geological units, had problems within the Austrian area with only very few geological areas. All this information needs to be evaluated and taken into account when choosing a mapping method for a certain area or a certain available data set. If a survey for delineation of RPA (as requested in the EU-BSS) is started from scratch, the mapping method and display/classification method for the map (e.g. % above RL in administrative area) should be decided at the beginning, so that the survey (measurement density, analysed parameters, etc.) can be optimised to these requirements. For harmonisation of mapping or delineation of areas (e.g. on a European basis) a method using less parameters might be preferable, as easier to apply to different data sets.

The delineation of radon priority areas is a multiple-step process – collecting and preparing the available data or in practice, performing the measurement campaign to get the data, selecting or developing the best mapping method for the situation and applying it to the data, and classifying the results according to the definition of RPA. As discussed earlier, different definitions of RPA concepts are adapted in the individual countries.

In the mapping exercise it was also evaluated how the different results provided by different mapping methods would have an impact on the classification or delineation of RPAs. As a summary, the chosen threshold for the classification of RPA has a major impact, depending on the level of radon concentration in the area. For Cantabria, which has a very low radon concentration, the differences in the results of the different methods do not impact the RPA classification. Whereas the Austrian municipalities show radon concentrations in the range about 150 to 400 Bq/m³, depending on municipality and mapping method. Therefore, the differences (even when small) in the radon concentration for the different methods for the same municipality can have an impact in RPA classification, when the threshold is chosen in the range of the variability of the results (e.g. 300 Bq/m³, the reference level, established in most of the member states). If the threshold is set with 100 Bq/m³ all six municipalities in Austria are classified the same, as this threshold does not lie within the range of the measurement/prediction results and therefore the variability of the results of the different methods do not have an impact on the classification of RPAs.

Final conclusions about the cross-usage of concepts are made in chapter 9.

8. Case Studies

Austria

In Austria, a radon potential map exists already since the early 2000s, based on radon measurements in dwellings in the Austrian national radon programme (OENRAP, 1992-2001, Friedmann, 2005). The radon potential was defined as an expected radon concentration in a standard situation and characterises the radon risk from ground with the influences of different living situations eliminated. Information about specific construction features, building materials and living style was collected via questionnaires and a standard living situation was defined. A mean radon potential was then computed for every municipality based on the standard situation and the results were displayed as a map with three classes (0-200 Bq/m³, 200 - 400 Bq/m³, > 400 Bq/m³). This radon potential map, only updated with new data over the years, was used for communication and a graded approach for radon protection measures in Austria until present.

The radon map of Austria reflected the geogenic radon potential because of the innovative method of normalising the measurement data to a standard situation. The measurement data on the other hand have the potential for improvement, as different measurement methods were used, including short-term measurements and only few dwellings per municipality were tested.

In the framework of the implementation of the EU-BSS regarding RPA in Austria, it was decided to carry out a new national indoor radon survey, as basis for the reliable delineation of RPA. The survey was carried out between 2014 and 2019 with indoor radon measurements in selected private dwellings of members of the voluntary fire brigades. The voluntary fire brigade in Austria has a lot of members (4 % of the Austrian population) and is well organised, so a nationwide efficient sampling was provided. The dwellings were selected based on the coordinates of the dwellings, according to defined criteria to assure a uniform distributed, area-wide sampling. The main criteria were at least 12 dwellings per municipality and at least 1-3 dwellings per 2x2 km grid cell, dependent on the diversity of the geology. Two measurements were carried out per dwelling in the most used rooms with track-etch detectors for 6 months, half winter and half summer time to represent the annual mean radon concentration. Information about building characteristics was collected via a questionnaire. In total, measurements in about 28,000 dwellings were carried out (about 1% of the dwellings in Austria).

For mapping the radon potential the radon influencing factors (building characteristics, measurement duration, geology) needed to be taken into account. The used approach to generate normalized indoor radon concentrations was outlined by Borgoni et al. (2014) and was applied already in the past in a similar form for the Austrian radon potential map (Friedmann, 2005). A generalized additive mixed model (GAMM) was applied, using the measured indoor radon concentrations and factors as building characteristics and geology. With the model, the radon concentration can be predicted for a selected house type for every location in Austria. For the delineation of RPA a representative standard house was selected and the radon concentration was predicted for each inhabitated 250 x 250 m grid cell. The arithmetic mean of the predicted radon concentration of all grid cells within a municipality is set as the predicted radon concentration for each municipality.

Following the example of the radon potential map of Austria, which has been used for 20 years, the idea is to continue the graded approach for radon protection measures based on the classification of municipalities. The EU-BSS require the delineation of RPA, where measurements in workplaces in the basement and groundfloor are mandatory. In Austria these areas are named "radon protection areas", and cover all municipalities with a predicted radon concentration above the Austrian reference level of 300 Bq/m³ (Figure 6). 104 municipalities (approximately 5% of all municipalities) are classified as "radon protection area". In addition, radon preventive measures in new buildings should follow a graded approach, so it is planned to classify the municipalities according to their predicted radon concentration in more detail for different recommended preventive measures.

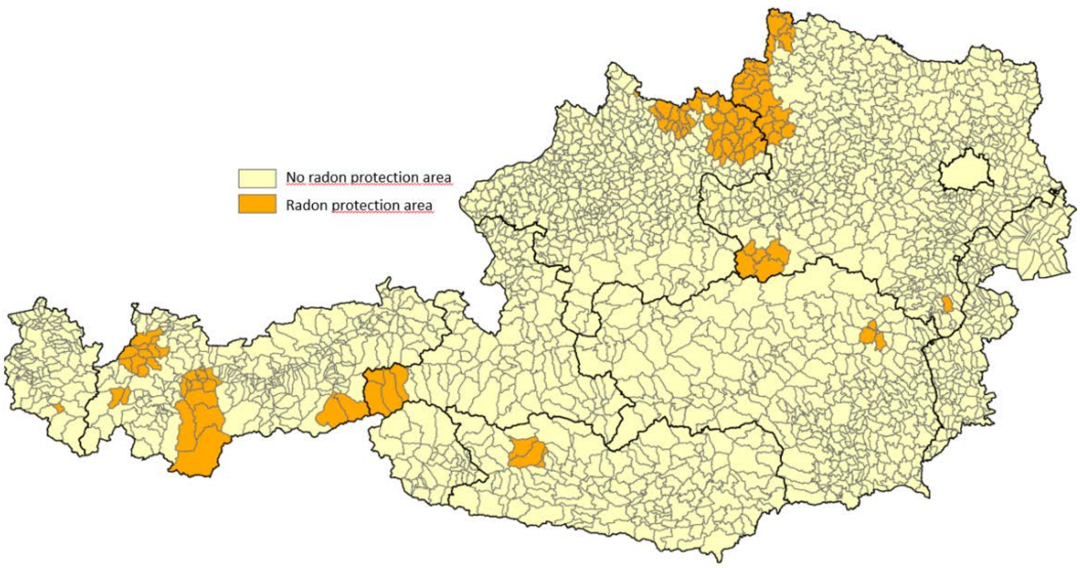

Figure 6: „Radon protection areas" in Austria (orange), Status September 2020

Germany

The basic definition of RPA in Germany is: an area is labelled RPA, if prob(C>RL)>γ p_1 otherwise, non-RPA, i.e. a binomial scheme was chosen. C – long-term mean indoor concentration in ground floor dwellings of houses with basement, RL – reference level; p_1 – the same probability estimated for the entire territory of Germany. RL has been set 300 Bq/m³, the multiplier γ = 3, and $p_1 \approx$3%. The definition is in approximate accordance with the one applied by other countries, prob(C>300)>10%. Since the German indoor radon database is fragmentary and insufficient for direct RPA estimation from indoor radon data, the geogenic radon potential (GRP) is used as secondary variable, because a dataset (about 4,500 locations) covering the territory about representatively is available. (This approach has also a conceptual advantage, see above). The task consists in finding a derived or secondary threshold for the GRP, so that classification according this threshold conforms with the (hypothetical) one according the primary RPA definition.

However, the federalist structure of Germany has it that the last word is with the Federal States (Bundesländer). The procedure is laid down in an ordinance which states that the RPAs have to be delineated until end-2020. Therefore, at the time of writing (finalization early 2020) no final answer can be given.

One approach for a gross RPA map on federal level has been proposed between 2016 and 2017 in several stages and is presented in the following. (In this reasoning, the final legally binding RPAs shall be defined on district or municipality level or even below, taking advantage of locally available knowledge about geology and settlement patterns, which central planning on federal level cannot deliver. In the non-assigned areas (yellow in Figure 7), further measurements shall clarify the situation.) For the state of RPA definition in Germany by Sept. 2020, see section 5, case report Germany.

Estimation support is a grid of 10 km × 10 km cells (identical to the grid of the European Atlas of Natural Radiation). The task of finding a secondary threshold of the RPA has been achieved by cross-tabulation, based on for which indoor radon data are available. The GRP has been estimated by geostatistical means including geology as categorical deterministic trend predictor, Bossew (2015).

Additionally, a constraint on estimation confidence has been imposed: first and second-kind classification error rates shall be below 10%. Practical implementation was via a ROC-type procedure on the 2×2 truth table (more details see in D5). The result is factually a trinomial classification, as apart from cells assigned RPA (red) and non-RPA (green) with 90% confidence, some cells remain un-classified, shown in yellow, because confidence is not sufficient.

Being estimates (and hence the RPA being “random objects”, see more details in D5), the class limits have uncertainty. By bootstrapping one finds that the 90% confidence limits for the upper limit are (41.2, 48.0) and for the lower limit, (14.3, 23.5).

An open question consists in the fact that also in non-RPAs a certain risk of indoor concentration above RL is present that would go undetected since in these areas no action is envisaged.

Currently (early 2020), a more refined approach to generating a federal-level RPA map is under way. It is based on machine learning, more specifically by application of the random forest technique. A greater number of geogenic covariates is included, exceeding what is possible with traditional geostatistical means. Higher resolution (1 km × 1 km grid) seems possible. Here, coupling between indoor and geogenic radon is done by logistic regression.

Further, several Federal States have initiated sampling campaigns to fill gaps in soil radon data. These will be integrated into new federal-level maps later in 2020. The results can therefore not be reported here.

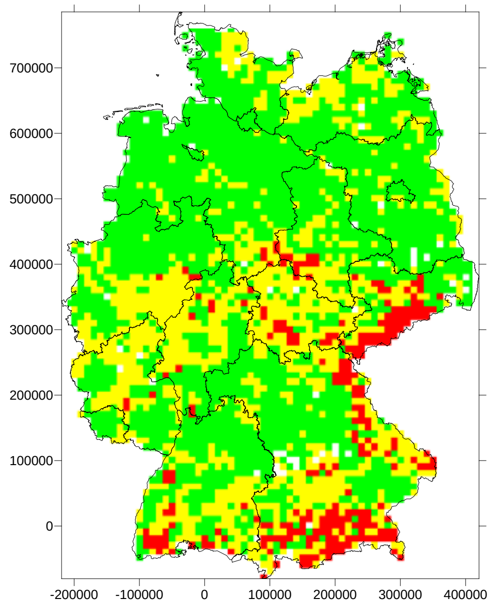

Figure 7: Radon priority areas in Germany (red), defined by GRP>44.5. Green: non-RPA, GRP<20.2. Yellow: undecided.

France

In France, the first maps produced were based on measurements of indoor radon concentration. A national radon survey, beginning in the nineteen-eighties and consisting in more than 10,000 measurements of indoor radon concentration in dwellings, was conducted by the Institute for Radiological Protection and Nuclear Safety (IRSN) in collaboration with the French Ministry of Health. Housing characteristics and information on the lifestyle of the dwelling residents were also collected during the survey. National and regional maps of indoor radon concentration (Gambard at al., 2000) were realized on the basis of this data. The Authorities defined priority areas for radon risk management from the national map of the arithmetic mean of indoor radon concentrations by “department” (district). However, radon mapping based solely on indoor measurements requires a large number of data. In France, some limitations of the above-mentioned national map were discussed (e.g. representativeness of the data, lack of data in several areas/district) and different needs (better precision of the map for local risk management, complementary data) were identified.

For more than 15 years, different studies and research programs have also been realized by the IRSN on the different parameters influencing the radon emanation and transport in the geosphere, as well as on modeling of radon transport in rocks, soils and buildings (Ferry at al. 2001, 2002, Richon et al., 2007, Ielsch et al., 2001, 2002). The results of those studies allowed assisting the Authorities by proposing a complementary method, geologically based, for radon mapping at a national scale. This deterministic and indirect approach was harmonized over the whole French territories and aimed to estimate a geogenic radon potential of the ground. It consisted of determining the capacity of the geological units to produce radon and to facilitate its transfer to the atmosphere, based on the interpretation of existing geological data (uranium content, lithology, petrography, main parameters which control the preferential pathways of radon through the ground as faults, cavities and thermal sources). This methodology has been applied to France (Ielsch et al., 2010) (Figure 8) and to all French Overseas Territories (Ielsch et al., 2014). This mapping supplied of further information in the radon map based solely on indoor measurements. The maps allow defining areas at the scale of the “commune” corresponding to the smallest French administrative unit. They were used to re-define the list of priority areas for radon risk management, by defining a classification of the municipalities according to the radon geogenic potential. This classification is currently used in the French regulation (www.irsn.fr/carte-radon) (Figure 9).

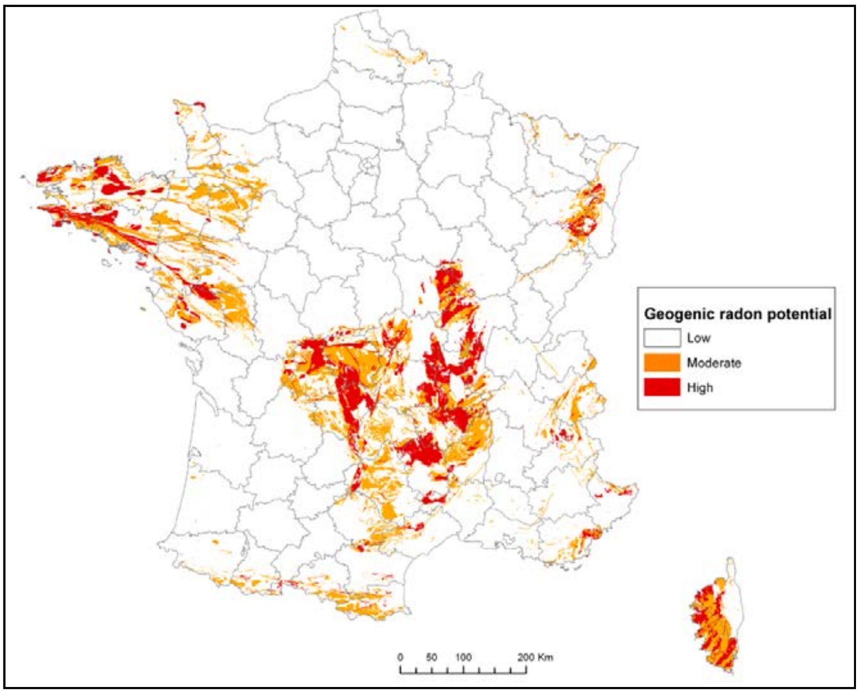

Figure 8: Geogenic radon potential map of France (source: IRSN)

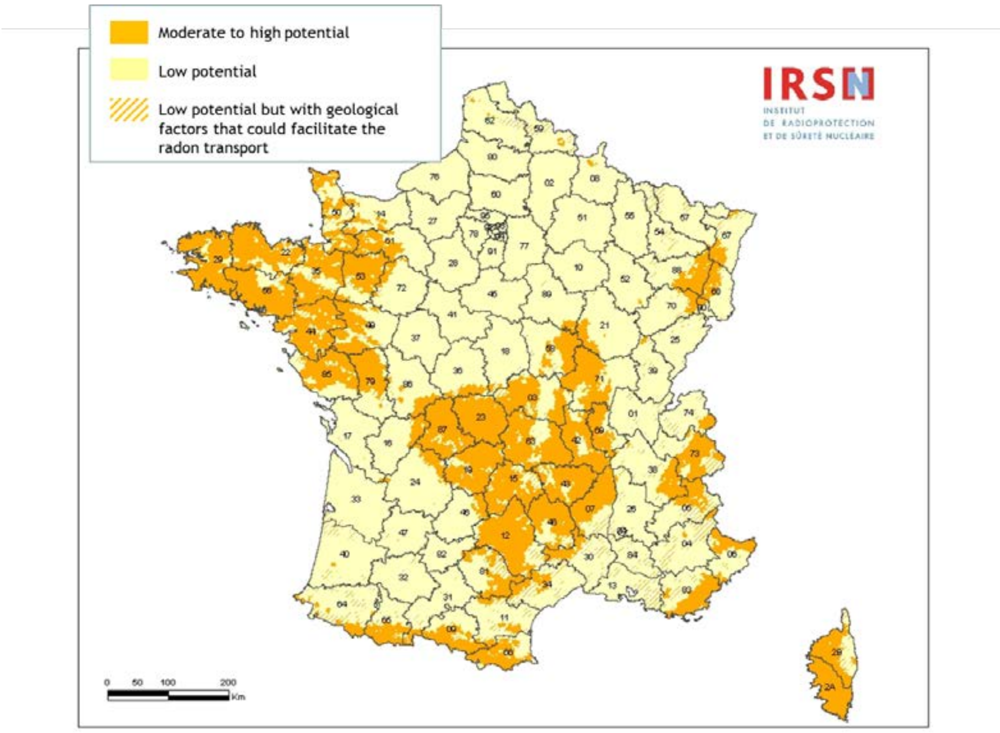

Figure 9: Classification of the municipalities of France according to the geogenic radon potential. (source: IRSN - www.irsn.fr/carte-radon)

More recent studies carried out by the IRSN aimed to combine both datasets, indoor radon measurements from the national survey and geogenic radon potential, by using statistical and geostatistical modeling.

A study notably investigated the factors influencing indoor radon concentrations (geogenic radon potential, house-specific factors and lifestyle characteristics) using statistical modeling (Demoury et al., 2013). The geogenic radon potential was found to have the most significant influence on indoor radon concentrations. The prevalence of exposure to radon above specific thresholds and the average exposures to radon clearly increased with increasing classes of geogenic radon potential. Housing/lifestyle characteristics explained only 7.9% of radon concentration variability. When geological information was added, 20% was explained. The objective of the study was also to determine the optimum use of the information on geogenic radon potential that showed the best statistical association with indoor radon concentration. Combining the datasets enabled improved assessment of radon exposure in a given area in France.

Different geostatistical models (kriging, co-kriging, kriging with external drift) were also tested to obtain more precise estimates of the spatial variability of indoor radon concentration in France and produce maps of probability to exceed different thresholds (100, 300, 400 $Bq.m^{-3}$) (Ielsch et al., 2015). The results also provided useful data for recent or current epidemiological investigations in France related to radon and gamma radiation exposure, such as lung cancer and other cancers which have been studied more recently (radon and childhood cancers, childhood leukemia, quantitative risk assessment, radon and lung cancer in never smokers) (Ajrouche et al., 2018, Demoury et al. 2013, 2014, Laurent et al., 2013). The data were also used to estimate the exposure of the population to natural radioactivity in France (IRSN Report 2015).

Complementary research program is currently in progress at IRSN to improve the national geogenic map in some particular areas. A regional study is carried out on the impact of karstic areas on the geogenic radon potential. This study combines field investigations and modeling of radon transport by using TOUGH2-Rn code (Saadi et al., 2014, 2015, 2017), from the karstic caves and structures to the soil surface (Greau et al., 2017, Mansouri et al. 2018). Moreover, another study was launched in 2019 in order to determine more precisely the areas that could be concerned by very high radon levels by using statistical and geostatistical tools, indoor radon measurements and geogenic data.

Spain

The Nuclear Safety Council (CSN) is the competent body in Spain in terms of nuclear safety and radiation protection. Its mission is to protect workers, the population and the environment from the harmful effects of ionizing radiation.

The CSN has developed the Radon Potential Map of Spain from the use of the 90th percentile (P90) of estimated radon concentration (CSN, 2017a; 2017b). Each area is grouped according to its P90, given a radon concentration level this means that the 90% of the radon distribution would be below that level and the 10% would be above it. Therefore the Radon Priority Area (RPA) is obtained directly from the Radon Potential Map for the P90 of a radon level of 300 Bq/m^3 established as reference level in the European Council Directive 2013/59/EURATOM.

The Spanish Radon Potential Map has been obtained from three parameters: radon in air measurements in dwellings, the Lithostratigraphic units and the gamma exposure rate map.

Radon in air Spanish database: The database used has 12,000 radon in air measurements in dwellings done in the ground floor. In case of uninhabited house the measurements were carried out in the first floor. In general, the associated risk increases in basements and it decrease about a 20% every floor in flats. Most of measurements were done using passive detectors CR-39 among the period 1991-2016.

Geology: The Lithostratigraphic and hydrogeology Spanish map has included the permeability in order to group the lithostratigraphic units in a homogeneous way, categorizing such units with similar permeability. Lithostratigraphic, permeability and hydrogeological map of Spain developed by the Spanish Geological Survey (IGME) is available at a scale of 1: 200,000 (IGME, 2009).

Gamma exposure rate: The Spanish gamma exposure rate map provides information about the gamma exposure rate expressed in µR/h at 1 meter high from the soil in scale 1:1,000,000 (CSN, 2001). It was elaborated from the correlation between field and aerial measurements within the MARNA project (CSN, 2000). It was used about 250,000 gamma exposure rate measurements from uranium prospecting campaigns among 30 years carried out by the Spanish National Uranium Company ENUSA.

The CSN combined and took into account the three variables presented above to obtain the Spanish Radon Potential Map (Figure 10). Accordingly to the P90, it was established 5 categories: P90 > 400 Bq/m³; P90 (301-400 Bq/m³); P90 (201-300 Bq/m³); P90 (101-200 Bq/m³) and P90 < 100 Bq/m³. Accordingly to this, there are two categories considered as RPA in Spain, where P90 > 300 Bq/m³.

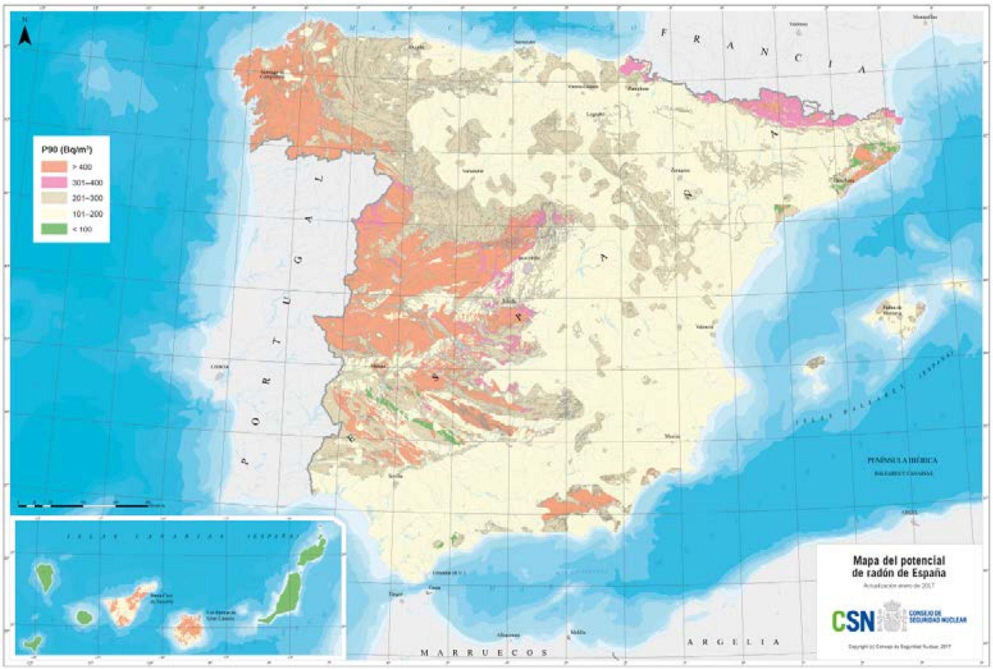

Figure 10. Spanish Radon Potential Map (CSN, 2017a).

Implementation on European level

Earlier knowledge

Discussions about RPA definition and estimation methods are still ongoing in many European countries. Therefore, we cannot give an authoritative overview about this matter. It seems, however, that the most popular definition is of the probabilistic type (b), RPA: prob(C>RL)>p_0 (see chapter 4).

Examples of (b) are Finland, Germany, Greece, Montenegro (also some non-EU members adopted the BSS) and Spain which chose RL=300 Bq/m³ and p_0=10% (for Germany, derived from ground-floor rooms in buildings with basement only; for Spain, from ground or first floor rooms only). Ireland has chosen RL=200 Bq/m³, p_0=10%.

Belgium and Luxemburg chose RL=300, but 3 priority levels, p_0^{I}: prob<1%; p_0^{II}: prob between 1 and 5%; p_0^{III}: prob>5%. Note that this information reflects discussions from 2018 and final legal decisions may turn out different.

Alternatively, some chose definitions of the type (a), i.e., an area is labelled RPA, if the mean indoor concentration in it exceeds the RL. Example is Switzerland, which opted for two priority levels with thresholds 100 and 200 Bq/m³. For comparison, assuming log-normal distribution with GSD=2 within a 10 km × 10 km cell (about realistic by experience), AM(C)=300 corresponds to prob(C>300)=36%. The earlier state of discussion of about mid-2017 has been summarized in Bossew (2017a).

Knowledge acquired in the present project

Evaluation of a questionnaire in the context of the MetroRADON project (more details in chapter 6) (Activity 3.1.2, Annex 3 in Deliverable 3) sent to the competent authorities of all European countries. A short discussion on the replies given to the questions about RPA is reported below.

It reflexes discussions or decisions by about mid-2018. Missing countries: no response, or matter is under discussion. Varying or missing response should certainly not be understood as negligence, but as indication that the subject is considered serious and sensitive, requiring careful deliberation and discussion.

Figure 11 shows the results of the MetroRADON project questionnaire - Question 5.8 *"Have you identified radon priority areas (in the sense of art. 103 of the European Council Directive 2013/59/EURATOM)?"*

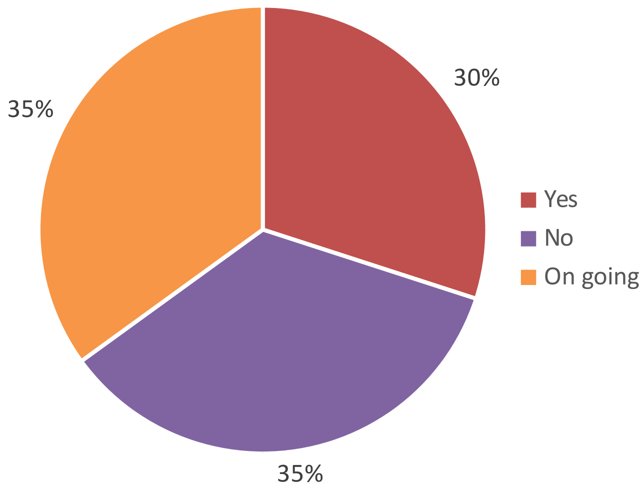

Figure 3: Answers to the question 5.8. of the MetroRADON questionnaire: „ *Have you identified radon priority areas (in the sense of art. 103 of the European Council Directive 2013/59/EURATOM)*

For Question 5.9 *"Which input data have you used to identify radon priority areas/classes?"* the institutions could select select multiple choices between the list:

- Indoor radon data
- Geology
- Radon in soil gas
- Soil permeability
- Gamma dose rate

- Uranium concentration
- Other

All the received answers (16) contained “indoor radon data”. In eight cases they used only indoor radon data. In three cases they used also geology information and in the remaining cases they used also radon in soil gas and gamma data.

To the Question 5.10 *“How do you define a radon priority area/class?”* six Institutions reported that the radon priority areas have not been defined yet. 13 Institution described briefly their definition of radon priority area:

- Municipalities, where >5% of the dwellings > RL
- Areas where concentrations of Rn-222 are likely to be higher than average
- Municipalites, where the probability of exceeding RL in the workplace is higher than 30 %
- >10 % of measurements indicate levels above reference level
- The radon potential is estimated with a geostatistical procedure in a grid
- Significant percentage of dwellings exceed the reference level
- 10 km grid square where 10% or more of homes are predicted to have radon levels above the 200 Bq/m3 reference level
- 10 % of all dwellings are above reference level
- Area where more than 5% of the dwellings are above the reference level
- Number of dwellings with concentrations higher than 200 Bq/m^3 exceeds 1%
- NRPA define all of Norway to be a radon priority area
- Municipalities at the radon priority areas are listed in legislation
- % probability of homes exceeding the Action Level of 200 Bq/m^3

Eight institutions answered to Question 5.11 *“Please briefly describe the classification criteria you used”* and their answers are:

- % of the dwellings > RL
- >10 % of measurements indicate levels above reference level
- 10 % excess probability of the reference level
- 10 % of the dwellings above reference level
- Areas where 10% or more of homes have been found to have radon levels above 200 Bq/m3 in the 2002 National Radon Survey
- Administrative regions
- Geology (rock and soil type) in combination with radon concentration measurements
- >1% probability = radon Affected Area (AA)

Nine institutions answered to the Question 5.12 *"How do you apply the classification criteria to your data?"* and reported their applied classification criteria:

- Modelling
- Mathematical model employing neuronal networks
- >10 % of measurements indicate levels above reference level
- The federal states provide and publish lists with administrative areas on the basis of the estimate of the radon potential and own knowledge about local geological formations with high radon potential or other causes for enhanced radon concentrations in buildings (like mining)
- An area is characterized as non-priority area if more than 90% of the measured dwellings have radon concentration lower than the reference level in 90% conf. level
- Data has been mapped to produce a radon predictive map
- Administrative regions
- High Radium-226 content of rock and soil confirmed with average annual radon concentration over 300 Bq/m^3
- Address data is linked to AA probability banding. Information is supplied by address search (on-line by payment) or linked to highest for each 1 km square using GIS (online free of charge or downloadable as a dataset

In Question 5.13 it was asked "*Which action will be/have been taken in radon priority areas?*" The actions that have to be take (or have been taken) in radon priority areas are described by 11 Institutions. Their answers are reported below:

- Preventive measures for new buildings; obligatory measurements in general workplaces in ground floor and basement
- Measurements in workplaces, protection of new buildings
- Obligatory measurement at workplaces on the first floor and in the basement
- At work places, measurements are obligatory
- Obligatory measurements at workplaces in radon areas in cellars and in the ground floor, information of owners and inhabitants of dwellings, building industry, architects and regional and local authorities, to encourage to take measurements
- Public awareness
- Building regulations requiring radon preventive measures in place since July 1998
- Preparation of additional Radon Action Plan for the identified radon priority areas
- Information campaigns
- Communication to increase public awareness, information to local decision makers, additional measurements financed by competent authority, guidance on methods of remedial measures
- Targeted advice and surveys including as part of the buying and selling process. Installation of radon protective measures in new buildings and conversions - as part of the Building Regulations

Tabelle 4: Definition of RPA and support unit in different countries (status mid-2018, basis: questionnaire of MetroRADON activity 3.1.2)

country	RL	support	definition
AT	300	municipality	modelled AM>RL
BE	300	municipality	prob(C>RL)>5%
CY		"area"	AM(C)>national average
CZ	300	municipality	prob(C>RL)>30%
DE	300	"area"	prob(C>RL)>10% with 90% confidence; non-RPA: prob(C>RL)<10% with 90% conf. Remaining: undecided status
FI	200 (dwellings), 300 (workplaces)		prob(C>RL)>10%
GR	300	"area"	prob(C>RL)>10%; non-RPA: prob(C<RL)>90% with 90% confidence
IE	200	10 km x 10 km cell	prob(C>RL)>10%
LT	300	"administrative region"	prob(C>RL)>10%
LU	300	"area"	prob(C>RL)>5%
MT	200		prob(C>RL)>1%
NO			all NO declared RPA
UK	200	"Rn affected area"	prob(C>RL)>1%

A very enlightening analysis of the influence of choice of support (the area unit which is labelled RPA or assigned a certain priority level) has been shown by Fojtiková et al. (2017), on the example of the Czech Republic.

9. Summary and Conclusion

Within this task of the MetroRADON project the motivation and legal background of RPA delineation was reviewed, as well as RPA concepts and definitions. Concepts were illustrated with several national examples. The role of stakeholders, in particular of authorities in RPA definition was addressed and illustrated with several national examples.

As conclusion, it appears that conceptual and theoretical work about RPAs is well advanced. This concerns understanding of the concept, definitions which serve to translate the concept into a workable subject and estimation methods. For the latter, quite a variety has been developed, depending on the data which are available for the purpose. Available data depend on national policies of surveying radon related variables, from indoor concentrations in dwellings to various geogenic quantities, which control geogenic and indoor radon to different extent. Several of these details are extensively discussed in other parts of MetroRADON.

The research on RPA concepts, definitions and development of RPA maps are in general performed by specialists/experts and researchers. Then, the regulators and decision makers have to take decisions that best fits to the country-region based on experts' proposals and advises. These decisions will then affect the population and workplaces. Therefore, it is fundamental that a good communication and trust will be established between the different actors: expert- regulator-population. A fundamental evaluation of all relevant stakeholders and their interests and concerns is very important in the process of implementation of EU-BSS and RPAs. Developing communication strategies adapted to the relevant stakeholder groups and the country specific needs are essential. International associations and co-operations like HERCA, SHARE, ERA and research programs (MetroRADON, RADONORM, etc.) and their recommendations, work and results are very helpful for efficient implementation of EU-BSS requirements, including delineation of RPA and stakeholder communication, in the member states.

An important result is the comparison of residential buildings and workplaces regarding their radon characteristics. These were found to be different, in general. This is relevant, because RPAs are mostly estimated based on data of indoor radon concentration in dwellings, but legal consequences as stated in the BSS largely pertain to workplaces.

RPA estimation methods, based on radon measurements in dwellings, can be sensitive but not specific from the distribution of radon in workplaces point of view, or vice versa. This suggests that each country should carefully consider also the distribution of indoor radon in workplaces and public buildings in its own territory, in general statically different from the one in dwellings.

In the MetroRADON project, statistical groundwork on this topic has been laid, but further elaboration is necessary. This concerns the fact that workplaces are no homogeneous statistical population, i.e. have different radon characteristics between their different types, and the regulatory consequences, which the finding may imply.

Within this task of the MetroRADON project, in the light of a cross-usage of concepts, different mapping methods were compared and the agreement of the different methods was discussed by means of several parameters. As known and shown also within this exercise and this report, mapping methodologies are various and so are the definitions of RPAs. As a general conclusion about the cross-usage of concepts, it can be said, that applying a mapping method using data sets, which were not designed for the specific requirements of the mapping method, is challenging. Usually, data sets always have specific characteristics and are rarely comparable, even not for the same variable. Therefore, harmonisation is always a challenge. In general, the selection of a mapping method for a certain area will be highly depend on the available data sets. Not all mapping methods are usable for all data sets or areas, depending especially on data quality, sampling density, or heterogeneity of the mapping area. For harmonisation of mapping (e.g. on a European basis) a method using less parameters might be preferable, as it would be easier to apply to different data sets.

Usually the final goal of mapping is the delineation of RPA, as this is requested in the EU-BSS. It was discussed, that independent of the applied method for large intervals of classification threshold the same RPA classification is predicted. Different methods often deliver the same results in RPA classification, depending on the definition of RPAs. So, the definition of thresholds is a very important factor in the process of delineation of RPA and might be as relevant as harmonising mapping methods.

The overall results put in evidence the role of the adopted method for the definition of RPA, the set criteria for the definition of RPA and also the radon risk/potential of the country. All those factors influence the reliability and comparability of the delineation of RPAs.

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16ENV10 MetroRADON

Activity 4.2.1 and 4.2.2

Relationship between indoor radon concentration and geogenic radon

Lead organisation: BfS
Other involved organisations: BFKH, IRSN, JRC, UC, UNSPMF, VINS

Authors:

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1. Motivation

The purpose of the MetroRADON project, funded within the European Metrology Programme for Innovation and Research (EMPIR) is to develop reliable techniques and methodologies to enable SI traceable radon activity concentration measurements and calibrations at low radon concentrations. The need for this project has been largely motivated by the requirements of the implementation of the European Council Directive 2013/59/EURATOM (EU-BSS) (EC, 2013), one aim of which is to reduce the risk of lung cancer for European citizens due to high radon concentrations in indoor air. Furthermore, it is a goal of the project to enable uptake and exploitation of its results and experiences by all stakeholders concerned with radon, from regulators and policy makers, professionals in designing, performing, evaluating and interpreting radon surveys, radon instrument manufacturers to the end-users (e.g. companies providing radon measurement, construction industry) and the scientific community. More details about the MetroRADON project can be found at the project website (MetroRADON, 2020).

Article 103 of the EU–BSS requires that member states identify areas where the radon concentration in a significant number of buildings is expected to exceed the relevant national reference level – referred to as radon priority areas (RPAs) within the MetroRADON project and this report. The definition of RPAs will influence political and technical decisions, which in turn will have economic effects in these countries, such as mandatory radon measurements in workplaces in these areas according to Art. 54 EU-BSS, as well as mandatory preventive measures or priority of awareness programmes. As the definition of RPA in the EU-BSS allows a wide range of interpretation, different concepts and methodologies have been proposed and some already adopted.

Within the MetroRADON project a specific work package (WP 4) is included with the aim to analyse and develop methodologies for the identification of radon priority areas, to investigate the relationships between indoor radon concentrations and quantities including soil exhalation and to develop the concept of a “geogenic radon hazard index” (GRHI) as a tool to help identify radon priority areas. One specific task (WP 4.2) within this workpackage is dedicated to analyse the relationship between indoor radon concentration and geogenic quantities.

2. Introduction

2.1 Aim and motivation of Task WP 4.2

The aim of this task is to estimate relationships between indoor Rn or derived quantities such as the probability of exceeding a reference level within an area, and quantities related to geogenic Rn such as the Rn potential or uranium concentration in the ground (see Task WP 3.2, deliverable 3), as some concepts for mapping the geogenic Rn potential and RPA crucially depend on such relationships.

As RPAs are often estimated from quantities other than indoor Rn, such as geogenic Rn, the correlation and a statistical relationship between indoor Rn and the RPA predictor quantity (or quantities) therefore needs to be established, because only indoor Rn is directly linked to reference values according to the EU-BSS. In most cases, the statistical relationships between indoor Rn and geogenic quantities are weak. These relationships have been studied for many years as regression and classification type approaches. The physical and statistical reasons for the weak relationships will be evaluated and explained and their consequences assessed. In this task, existing models and methodologies will be reviewed and reported, in particular statistical procedures which have sometimes proved a weak point in such analyses in the past.

2.2 Structure of Task 4.2

In activity A4.2.1, the concept of radon potential (RP) is introduced. Various approaches are presented, in particular the "soil radon potential" or geogenic radon potential (GPR) (chapters 3 and 5). The concepts are discussed and a literature review of the statistical relationships and correlation between indoor Rn and geogenic Rn has been performed (chapter 4). Sources of information include journals, reports and conference contributions. Based on the review, physical and statistical reasons for the weak relationships are evaluated and interpreted and a synopsis of the results is produced. Further, possible inconsistencies in the literature and assess their consequences are identified.

Different methods have been developed, particularly in Europe, to assess the GRP that is then sometimes used for radon mapping (chapters 4 and 6) and radon priority area definition (deliverable 5, chapter 3). Those approaches are based on different models (statistical, physical or empirical models) that use different input quantities such as soil-gas radon concentration, radon exhalation rate at soil surface, soil permeability, soil Ra content, radon emanation factor etc. These parameters can be locally measured on the field or calculated. In A4.2.2, several existing approaches to assess a "soil radon potential" are reviewed, both from those identified in A4.2.1 and also others of which we know. In chapter 7, two case studies of GRP estimation are presented.

All results of the activity are discussed and summarised in this report.

The text for the specific activities and the involved partners are listed here in the following table. Additional institutions that joined this task later are VINS (Vinca institute) and UNSPMF (University Novi Sad).

Activity number	Activity description	Partners (Lead in bold)
A4.2.1	BfS, JRC and UC will obtain information about the approaches used to assess a "soil radon potential" and will undertake a literature review of the statistical relationships and correlation between indoor Rn and geogenic Rn. Sources of information will include journals, reports and conference contributions. Based on this review BfS, JRC and UC will evaluate and explain the physical and statistical reasons for the weak relationships and will produce a synopsis of the results. BfS, JRC and UC will then identify possible inconsistencies in the literature and assess their consequences.	**BfS**, JRC, UC

A4.2.2	Different methods have been developed, particularly in Europe, to assess a "soil radon potential" that is then sometimes used for radon mapping and radon priority area definition. Those approaches are based on different models (statistical, physical or empirical models) that use different parameters such as soil-gas radon concentration, radon exhalation rate at soil surface, soil permeability, soil Ra content, radon emanation factor etc. These parameters can be locally measured on the field or calculated. Certain methods also include a parameter that represents the capacity of soils to favour the radon entry in a house after building. IRSN and BfS will review at least 5 existing approaches to assess a "soil radon potential", both from those identified in A4.2.1 and also others of which they have knowledge. IRSN will then compare selected approaches using experimental data from France that IRSN has access to by applying the data to mathematical models and will draw conclusions regarding the applicability of the selected approaches.	**IRSN**, BfS
A4.2.3	Based on the results from A4.2.1 and A4.2.2, BfS, IRSN, JRC and UC will write a report outlining the current state of the art with regard to information about the relationship between indoor radon concentration and geogenic radon as well as the new results. These results will also be published in scientific journal articles and presented at conferences. The report will feed into D5 and D6.	**BfS,** IRSN, JRC, UC

3. The radon potential RP

3.1 Introduction: Motivation and purpose of RP

Two factors contribute to indoor radon concentration: 1, radon sources and conditions which control Rn transport in the subsoil, summarized as geogenic factor, and 2, building properties and usage, summarized as anthropogenic factor. Sources include geogenic radon which infiltrates from the ground, outdoor radon, and radon from tap water (Jobbágy et al. 2017 for a recent overview) and natural gas as used for heating and cooking (Neznal et al. 1996). Building materials are another source, which can be included among the anthropogenic factors. However, the most important source is geogenic radon, followed by Rn exhalation from building materials. Outdoor Rn, tap water and natural gas play a minor role in most cases, as far as this has been investigated. Anthropogenic factors, except building materials, include building construction, which determines Rn infiltration from the ground and exchange with the atmosphere, and building usage, i.e. ventilation habits.

For decades, there have been attempts to define a quantity called *radon potential* or RP, intended to "factorize out" the anthropogenic contributions. The RP is supposed to be a standardized quantity in which the anthropogenic factors play no role. It shall measure the availability of radon, originated from natural (geogenic) sources, to exhale from the ground into the atmosphere, or to infiltrate a building. It has, therefore, been said more colloquially, that the RP measures "what Earth delivers in terms of radon".

Basically, two types of approaches have been proposed in the past. They are discussed in the following sections. The particular concept of the geogenic radon potential, GRP, is discussed in more detail in section 4.2.2.

3.2 Concepts of RP in general and GRP in particular

a) Standardized indoor concentration

Suppose that at a site, there was a room within a building with both having defined standardized properties instead of the actual room and building. These properties concern those which affect Rn concentration most strongly: presence of basement, type of interface between ground and building, floor level of the room, type of windows (which determines the ventilation rate). The ideal building would, for example, be one with basement with concrete slab floor, the room would be on ground floor and have double glass windows. These are called the standard conditions. The deviations between the actual and ideal rooms and buildings are quantified by multipliers. Applying them on the observed Rn concentration would yield the one in an ideal room and house, i.e. according to standard conditions, on the same site. This approach underlies the so-called Friedmann radon potential, developed by H. Friedmann around 1990 duringthe first national Austrian radon survey (1992-2001) (Friedmann 1995, 2005). To some extent, also the European Indoor Radon Map (EIRM) has been guided by this idea, as it maps Rn in ground floor rooms only. The resulting map is shown in Figure 1. A newer version is shown in https://geogis.ages.at/GEOGIS_RADON.html .

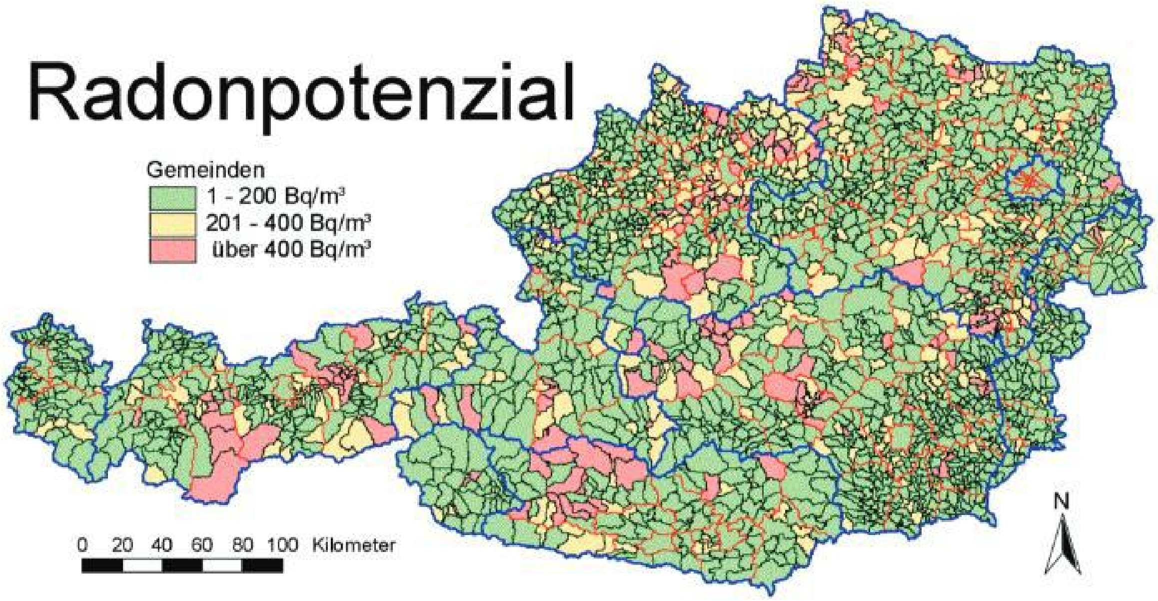

Figure 1: Austrian RP map, based on the first Austrian survey (Friedmann 2005).

Among problems of this approach are the following.

(1) The standardization factors or multipliers are found by statistical analysis of actual buildings, in which together with Rn concentration measurements, building, room and usage information has been acquired by questionnaires. This is a common practice with radon surveys. However, usually it is not known, to which degree the information is correct and accurate. Sometime important information is simply not known (e.g. floor of the basement), ambiguous (e.g. building along a slope, in which the same room may be a ground floor room upslope and a first-floor room down slope), insulation capacity of windows (double windows may be poorly insulating if the window frame is degraded), etc. It has turned out, however, that certain relevant information can be summarized in proxy quantities. For example, the age of a building, although itself is not a physical control variable, is a good indicator of its insulation against the ground. As another example, in Germany it has been found that whether a building is located in former East or West Germany is a useful proxy factor, since the building stock in former East Germany is older and physically less radon tight, on average,

than in former West Germany. Put together, selection of appropriate standardization factors requires sophisticated analyses.

(2) The factors, although carefully selected, are inevitably fuzzy factors, to different degree, since they rely on qualitative assessment, as explained above. These factors, as independent variables in a regression or ANOVA logic, are affected by uncertainty which is difficult to quantify. Furthermore, the set of factors can never be complete, because certain factors (e.g., frequency of opening windows) can hardly be quantified. (In the quoted Austrian survey, it has been found that the number of children in a family is a proxy of the ventilation rate.) Therefore, standardization multipliers, or standardization model parameters, are subject to uncertainty, which carries through to the resulting standardized Rn concentration. This means that local variability between Rn concentrations, due to different anthropogenic factors, is partly counterbalanced by model-induced uncertainty of the standardized RP value. If done statistically correctly, one can assume that the errors cancel on regional (e.g., municipality) average, although one cannot assume that a local RP (at one particular location) equals exactly the hypothetical Rn concentration in a standard room in a standard house at that very location. Obviously, it is also impossible to verify if it is.

(3) Certain factors are ignored in this reasoning, namely outdoor Rn, exhalation from building materials or tap water and natural gas contributions.

As a result, the RP based on standardization of measured indoor Rn concentration is only an approximation of the site-specific Rn situation, controlled by geogenic Rn, with anthropogenic factors removed only approximately. Still, it has been found that the Friedmann-RP reflects geological reality (which in turn controls geogenic Rn) rather well (e.g., Bossew et al. 2008). The EIRM, although filtering only for one factor, namely floor level, also leads to a representation of European geology in terms of the regional distribution of Rn concentration.

b) Other definitions

There is no unanimous definition of the RP, as this has evolved as a working concept over time, in different contexts. Another definition, quite different from the above, shall be mentioned. In the UK and Ireland, RP denotes the exceedance probability of indoor Rn concentration over a reference level, within an area, $RP:=prob(C>RL)$.

Tanner (1988) proposed the radon availability number (RAN) defined as source times migration distance of Rn in the ground under standard pressure difference. Alonso et al. (2010) proposed using Ra concentration times emanation power, because it can quantify the “potential radiological hazard” of a porous material.

Among schemes based on combined scoring of factors, there is:

The one introduced by the U.S. EPA (Schumann 1993): classes of indoor Rn concentration, eU, geology, soil permeability, prevalent basement type;

The approach proposed in Kemski et al. (2001, 2009) and similarly, the Czech Radon Index (Neznal et al. 2004), are based on joint classification of soil Rn concentration classes and permeability classes;

Wiegand (2001, 2005) suggested a “10-point system” based on scoring categorical variables such as lithology, topography and land cover. Used in Tung et al. (2013).

In Sweden, schemes for regional classifications and for characterisation of building sites based on lithology, permeability, texture, Ra and soil Rn concentration has been introduced (Ek in Long Way 2011, sec. 5.3.9);

Guida et al. (2010): combined scoring of permeability, geology, Ra conc., vegetation cover, morphology, tectonics and karst features;

Ielsch et al. (2010): aggregation of classes of Rn source potential, factors which enhance transport, “aggravating” factors.

Details can also be found in the Long Way (2011) document, chapters 5.2 and 5.3.

When using the term radon potential, one must therefore always add to which definition it refers.

For further discussion see section 4.3.4 about the Geogenic Radon Hazard Index and Bossew et al. 2020 (Annex 3).

c) Case study: Spain

The Spanish approach to assess the soil radon potential was born from a specific research project funded by the Nuclear Safety Council (CSN) developed during the years 2015-2017. The work teams were formed by the Autonomous University of Barcelona, University of Cantabria, University of Las Palmas de Gran Canaria and The Polytechnic University of Catalunya. Moreover, the company Geomnia collaborated in the geological part of the project.

The methodology recommended in Spain to determine the radon risk in a terrain on which it is intended to build is based on the Czech method (Neznal et al., 2004). From the measurements of radon concentration in the soil and the intrinsic permeability it is obtained the radon index (RI) or radon potential (RP). According to this approach, the radon index provides a level of risk for a terrain that can be expressed numerically from the radon potential of the terrain. The radon index can be determined from a non-numerical estimate of the air permeability of the soil and the radon concentration measured. Fixed the permeability in three classes (high, medium and low), the radon index can be obtained from Table 1.

Table 1: Radon index classification based on radon activity concentration C (kBq/m³) measured in soil and estimated gas permeability.

Radon index	Low	$C < 30$	$C < 20$	$C < 10$
	Medium	$30 \leq C < 100$	$20 \leq C < 70$	$10 \leq C < 30$
	High	$C \geq 100$	$C \geq 70$	$C \geq 30$
		Low	Medium	High
		Permeability		

It is established that for terrain of an area equal to or less than 800 m², at least 15 radon measuring points are required to characterize them. For an area of greater extension, 10 m x 10 m grids should be established. In areas with high radon concentrations a 5 m x 5 m sampling grid is recommended. The classification is based on the evaluation of the measured radon concentration values and their distribution. For each terrain a unique radon value of the soil must be obtained, assigned from the third quartile (75% of the data set).

The soil gas permeability limits established in the Czech method are shown in Table 2.

Table 2: Gas permeability in soil classification (Neznal, 2005).

Class	Permeability k (m²)
High	$k > 4.0\ 10^{-12}$
Medium	$4.0\ 10^{-12} \geq k \geq 4.0\ 10^{-13}$
Low	$k < 4.0\ 10^{-13}$

If the gas permeability of the soil value is available, it is possible to obtain the RP from the next equation:

$$RP = \frac{C - 1}{-\log k - 10}$$

where C is the radon concentration in soil expressed in kBq/m^3 and k is the permeability (m^2).

Therefore, the relationship between the Radon index and the radon potential can be obtained from Table 3 or the graphical representation of Figure 2.

Table 3: Radon Potential and Radon Index classification.

Radon Potential(RP)	Radon Index(RI)
< 10	Low
$10 \leq RP < 35$	Medium
$35 \leq RP$	High

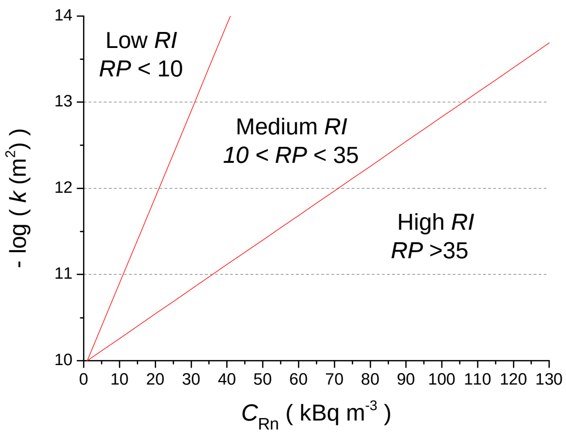

Figure 2: Graphical representation of Radon Potential and Radon Index classification.

The considerations of the use of the Czech method as a standard for the determination of the radon risk in a terrain discussed in the mentioned project are divided in advantages and disadvantages as following:

<u>Advantages</u>

1. Radon concentration and permeability of soil are two parameters that should reasonably be good indicators of the potential risk of a terrain. However, the relative importance of diffusion as an entry mechanism in homes will increase as the reference levels decrease.

2. The radon concentration measurement in the soil, following the standard procedure, does not show major problems and it is usually consistent regardless of the type of instrument used.

3. The radon average value in a terrain is usually representative if sufficient measurements are carried out.

<u>Disadvantages</u>

1. The most important inconvenience is the difficulty to obtain a representative permeability value of the terrain. It is necessary to establish which methodology should be used to obtain an intrinsic permeability value representative of the site.

2. The radon concentration measurements in the soil are affected by the different soil layers. Therefore, it is difficult to apply depth correction and it makes useless the radon measurement at the 80 cm level from the surface. One way to avoid this effect is to make the measurements from the foundation level, but this also indicates that the characterization that has been made of the locations does not have to be correct.

3. The seasonal variations observed in the different locations where the project was developed have not generally affected the risk classification. However, there are studies in the literature that show large fluctuations in radon levels in the soil, especially in fractured soils. No site with large fractures in the project was studied.

4. As far as the group of experts involved in the project knows, this strategy has not been validated experimentally.

5. In Spain there are regions where the Czech method cannot be applied because it is not possible to measure the radon in the soil.

The study of possible alternative methods for estimating the radon concentration in soil did not provide satisfactory results, and this is a further inconvenience to establish a standard method.

Radon levels in houses depend on multiple factors, with entry through the ground by advection being very important, but the other factors cannot be neglected.

The best tool for determining the radon risk in an area is the radon map of dwellings with a good resolution as a result of including a large number of measurements. The radon level maps in homes integrate all the factors: the soil potential, the typical construction characteristics of the area, the habits of the population, and the climate of the place. For this reason, the best way to know if a region should be a priority action is to look at a map of housing levels, what percentage of homes have levels above the established reference level. Only in the case of start an urban development in a large uninhabited region would it make sense to carry out a study of characterization of the land. Nowadays in Spain, the official national radon map, which takes into account data from indoor radon measurements and other information (geological, lithostatrigraphical, etc…), is the Radon Potential Map created by the Spanish Nuclear Safety Council (CSN, 2017a; 2017b; 2019).

General Recommendations for new buildings construction

In the opinion of the group of experts involved in the project, the best strategy for radon protection in new buildings includes the following actions:

1. Establish a basic level of protection for the entry of radon in all homes, similar to what has been done in Ireland, and increase it according to the estimated potential risk.

2. Determine the potential risk of each terrain from the potential Spanish radon map and also use the Czech method if it is possible. For risk characterization in large uninhabited areas, use the Czech method.

3. Promote campaigns to measure radon in air in dwellings. The best tool for determining the potential risk in a newly constructed area is to use of a map of radon levels in homes.

4. Establish a mechanism to improve the scale of the potential radon map and to incorporate the new radon level data in houses to the map.

5. Validate the methodology implemented by measuring radon levels in newly built housing, or by designing statistically significant measurement campaigns after a period of a few years to check if radon levels decrease. This validation is the most important task in the coming years from the point of view of the National Radon Protection Plan.

4. Estimation and mapping methods

Several steps lead from the data to a map (Figure 3). As a first step, data of input quantities, from Rn concentration in the ground and permeability to other predictors such as geological factors or geochemical concentrations, or also indoor Rn concentration in the case of the 4.2.1.2a (standardized indoor concentration), must be acquired. This is done by measuring or taking from existing databases, such as geological maps.

Sometimes, relevant target quantities must be calculated from others through models (section 4.2.1.4), which are established and calibrated through special studies.

Target quantities, whether measured of predicted, are aggregated into spatial units which are the basis of the maps, such as grid cells or administrative units. These units constitute the wanted map.

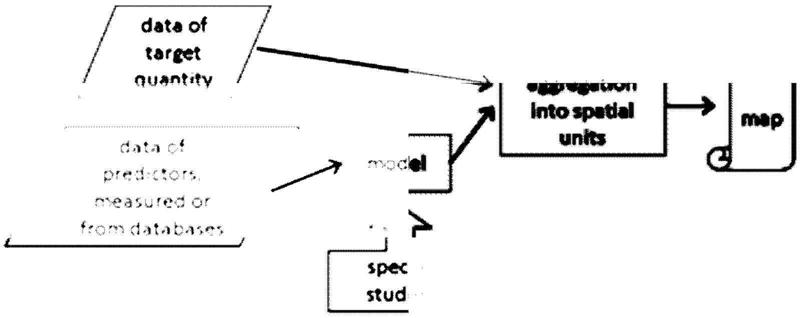

Figure 3: Flow scheme: from data to map

The subject is further discussed in sections 5.2 (measurement of input quantities) and 6 (estimation and mapping).

4.1 Relationships between indoor and geogenic Rn, and predictors and proxies – literature review

(For the terminology of "predictor" and "proxy", see section 4.2a.)

Relationships between geogenic quantities and indoor radon must be known in order to use the former for predicting the latter. In this subsection, literature will be reviewed in this respect, while in the subsequent section, the physical background is discussed.

a) structure of the literature database

For comparability, a set of criteria has been defined along which literature has been evaluated. The result is given as table <Lit-4_2_1_4--all-190424.xls>, to be found as annex.

The columns of the table are:

1. identifier;
2. motivation, objective, purpose of the study;
3. target variable, i.e. the quantity which shall be estimated, modelled or predicted;
4. predictor quantities;
5. sampling method;
6. sampling design;
7. temporal aspect, if applicable;
8. sample size;

9. region in which the study has been performed, and from where the conclusions have been derived;
10. physical characteristic of the region;
11. size of the region;
12. method of statistical analysis;
13. main results;
14. correlations identified;
15. residuals (indication of heterogeneity of population, missing predictors, adequacy of model);
16. are the results likely transferable to other regions?, can they be generalized?;
17. Comments.

b) Summary evaluation

47 papers found in literature were evaluated. The evaluated papers were written between the early 1990s and 2018, mostly from European research institutions.

The papers have the following motivations:

- Predict indoor radon concentration (IRC) and GRP from geogenic quantities;
- Investigate how much of geographical IRC variability can be traced to the ones of its geogenic controls;
- Improve spatial IRC estimation including RPA maps by using covariates as additional predictors.
- Soil gas Rn as tracer of environmental processes.

In most studies, the target variable is IRC; a few are focused on soil gas radon concentration (SRC), outdoor Rn concentration and Rn exhalation from the ground. In some cases, the target variables are derived quantities which are not directly observable, such as IRC exceedance probability, GRP, indices or hazard classes.

The predictors used are of two different types: radiological quantities and non- radiological quantities. Radiological quantities are U, Ra, Th, K, SRC, radon in indoor air, radon emanation coefficient, GDR. The non-radiological quantities are geochemical concentration in soil and rock other than U, Th, K; geological and tectonic variables (geological units, fault density etc.) and soil type. Among anthropogenic predictors are building types and characteristics.

Predictors and response variables can be ordinal (continuous numbers, typically: concentrations or ordered classes: “low, medium, high”) or nominal-categorical (geology, i.e. without intrinsic ordering). Different types of variables imply different analytical treatment.

Differences between measurement methods are especially relevant for Rn measurement. IRC was measured with passive integrating monitors in all but one paper (continuous time-resolved monitoring). However, also different passive measurement methods exist, concerning detector material, sensitivity against Tn, exposure time, placement of monitor. In none of the studies evaluated here, measurement method is used as additional predictor or confounding variable; apparently mostly due to the fact that only one technique was used in a study. Further investigation of possible impact of methodology on the result remains on the agenda.

Data sources of the studies are either surveys or sampling campaigns specifically performed for the study, or existing data which were re-used for the specific objective (or both, if necessary). Using modelled or aggregated data as input involves an additional uncertainty component, namely modelling uncertainty, which is often difficult to assess.

The situation is different with regard to spatial and temporal sampling design:

- Spatial sampling designs follow sophisticated schemes, in many cases. This shows awareness towards the problem of representativeness, which is difficult to solve in particular for IRC surveys. However, if the purpose is a survey which should serve for further decision making in the framework of Rn policy, this is crucial.
- Temporal design: The period of measurements varies among the countries too. This is due to the fact that some countries have strict protocols that indicate when radon measurements must be performed. This is the case of Finland and Norway when measurements have to be done in the winter season (assumed to yield conservative results). But which months are considered to be winter varies between these two countries. In other countries, such as the UK, it can be measured any time of the year and the result is seasonally adjusted. (The problem is minor for 1-year measurements, because annual cycles are averaged out, although the problem of long-term variability between years remains.)

Regarding the method used in the analysis and the results, all papers have used different types of regression analysis, however differently advanced, from conventional simple and multiple regression to machine learning (ML). Traditional geostatistical tools are applied by some researchers if the objective is mapping. Including categorical predictors is traditionally done by ANOVA or by ML in more advanced approaches.

c) Transferability of results

An important, but complicated issue is to see to which extent the *results* of the publications in terms e.g. of regression coefficients, can be transferred to other countries or regions rather different from the study areas.

As expounded before and in the next section, Rn quantities (most importantly IRC) result from a complex pathway, or rather network, “from rock to risk”. Therefore, results of analyses of response of e.g. the IRC to one or several predictors depend on controls not accounted for in a study; these may indeed be irrelevant in a given study situation, because they can be assumed about constant over the domain of that study. A typical case is climate which may be irrelevant in a regionally confined study. However, the results may not be comparable with ones of a study performed in a region with different climate, in which this factor is different, but also not accounted for. Another example is correlation between IRC and ambient dose rate (ADR): the strength of the association depends on the presence of confounding covariates (e.g. Th concentration in the ground). If they are not accounted for, correlations of the two quantities cannot be reasonably compared between studies.

Even if a number of studies do apply advanced regression models that account, to different degree, for the complex and partly nested interaction structure between predictors, a “large-scale” regression study – or meta-study – which spans the variabilities of all potential controls, is still missing. Its objective would be to model, or “explain” IRC (or other Rn quantities) as response to all predictors that vary across Europe. Notably this concerns climate, building styles and living habits (partly functions of climate) which are variables that exhibit large-scale variability, which may be irrelevant, and therefore (rightly) ignored in regional studies.

At present, it seems impossible to “distil” existing regression and modelling studies, as evaluated in this section, to achieve the objective of a large-scale model in the above sense. This severely limits the more universal usability of most studies, without restricting to the specific situations that underlie them.

On the other hand, the *methods* used by some of the studies seem to be universally applicable. This is to say that the lack of transferability of results is owed to the predictor data, which are regionally specific, but not to methodology.

d) Conclusions

(1) As first conclusion, a number of studies prove the association between Rn quantities and geogenic quantities. However, this is not unexpected. But even assuming that the individual studies are correct for their respective (regionally specific) boundary conditions, quantitative results are difficult to generalize beyond the regional conditions, in most cases.

(2) Methodology has become quite developed for the last 20 years or so. Therefore, potential new studies whose objective is to extend applicability, should take advantage from existing ones. In certain regards there is however still space for further development. This concerns more rigid treatment of geochemical quantities as (in a mathematically sense) compositional and closed variables, for which the CODA (compositional data analysis) approach should be further exploited; 2 studies evaluated here have already done so. Further, it seems that the convoluted dependence structure of Rn quantities on different types of environmental controls and proxies limits the applicability of traditional regression models; at current state of knowledge, ML approaches seem to be most suitable to deal with such situation. However, questions, among other, related to interpretation of component effects and uncertainty budgets require further investigation.

4.2 Relationships between indoor and geogenic Rn, and predictors and proxies – physical causes and their statistical manifestations

a) General

The physical relationship between quantities which are related to Rn concentrations in different media is very complex, even in a simplified visualization (Figure 4). Even if the nature of the physical processes which generate the relationships is not very complicated – radioactive decay, diffusion, advection, dissolution – the intricate interaction generates the complex behaviour of the system.

Therefore, the statistical relationship between quantities is often weak although they are physically related. This reduces the potential of proxy quantities to Rn concentration to substitute it in cases where no Rn values are available, schematically shown in Figure .

Conceptually, one distinguishes between proxies (or surrogates) and physical predictors, Figure 6. The latter are ones that are in a causal relationship with the target variable, e.g., uranium concentration in the ground as a physical direct predictor of soil Rn concentration. Proxies are ones that are statistically related to the target, but not directly linked by physical causality. An example is terrestrial gamma dose rate component (TGDR) of ADR as Z_1 in the figure, which is statistically related to IRC (=Z_2) because both share the same predictor, namely the uranium content in the ground (Z_0). However, both ADR and IRC are also influenced by other variables, e.g., ^{137}Cs fallout and Th concentration in soil (Z_0”’ and Z_0”) influencing dose rate and ground permeability (Z_0′), the IRC; therefore, their correlation is weak. In this example, Z_0’, Z_0” and Z_0”’ act as confounders.

For further illustration of the concept, examples of proxies from other fields are shown in a table, taken from the Minitab blog (link not existing any more):

Examples of proxy variables

Intended variable	Proxy variable
Historical environmental conditions	Widths of tree rings
Quality of life	Per-capita GDP
True body fat percentage	Body Mass Index (BMI)
Cognitive ability	Years of education and/or GPA
Depth that light penetrates into the ocean over large areas	Satellite images of ocean surface color
Hormone levels in blood	Changes in height over a fixed time

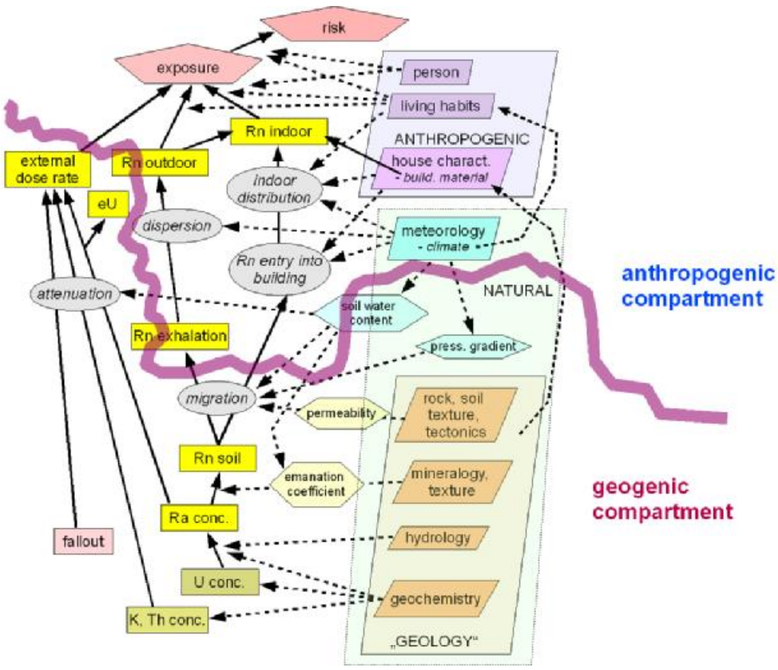

Figure 4: "From rock to risk" – Simplified visualization of the complex relationships between quantities that control Rn concentrations in various media.

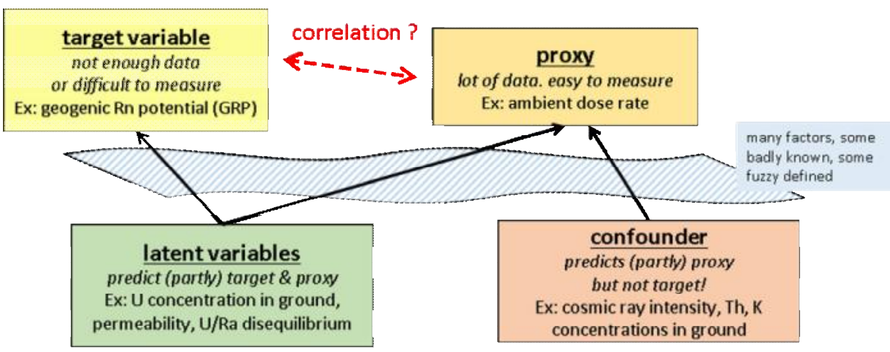

Figure 5: Correlation between target variable and proxy obscured by interaction of confounders and intermediate influencing factors.

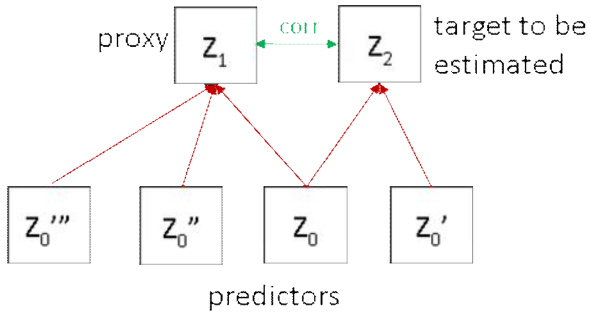

Figure 6: Physical predictors, proxy and target variable.

To sum up, the influences of “confounding” quantities reduces, or even may obscure the statistical association between target quantity (e.g. indoor Rn concentration) and proxies (ADR), predictors (U concentration in the ground) and between Rn quantities (Rn concentration indoors and in the ground).

b) Specific: Radon

Specifically, for indoor radon concentration (IRC), the physical phenomena to be considered are Rn generation by radioactive decay of Ra, emanation into pore space and transport in rock, soil and ground water to the surface; subsequently, infiltration into buildings.

^{226}Ra concentration (immediate parent nuclide of ^{222}Rn) may be in equilibrium with ^{238}U in geological media or not, depending on the chemical environment. Ecological process may separate the two because of their different chemical properties which determine sorption on environmental matrices.

Emanation of Rn from grains into the pore space depends on mineralogy of the grains and water content. Transport in the medium is controlled by porosity (available pore space) and tortuosity (connectedness of pores), both dependent on humidity in rather complicated manner. Diffusive transport depends on temperature, advective transport on pressure gradients and permeability, in turn a function of the above factors.

The transition from the geogenic to the anthropogenic compartment, i.e. the indoor atmosphere, depends on building properties and usage of the building. For the former, the tightness of the building shell against the ground (factors: diffusivity and advection pathways) and advective “suction” (driven by thermal stack effect or wind) of the indoor against geogenic compartment. The latter are usage type (residential, workplace of some type) and usage habits (dependent on cultural and climatic factors – so far little understood!).

The anthropogenic factors translate the geogenic radon potential GRP (“what Earth delivers”) into the observed IRC. The ratio between IRC and GRP is very variable on every spatial scale due to the variability of building types and usage patterns. However, as found in many studies (among them some quoted in section 4.1), the spatial pattern of IRC largely reproduces the one of the GRP, while the variability of anthropogenic factors appears as spatial “noise”. The reason is that on local and regional scale, the anthropogenic factors have little spatial trend, as opposed to the geogenic factors (mainly controlled by geology and soil properties whose variabilities are obviously subject to trend).

However, the spatial correlation properties of anthropogenic factors have so far been little investigated. It can be expected that over larger scale climatic trend is present which is a main control of these factors. But to some degree, this is likely also the case in regional scale, subject to geography (lowland / mountains) and degree of urbanisation. Investigation of this subject remains on the agenda.

As a conclusion, in any case, it is evident that the variability of factors blurs the dependency between source (^{238}U) and IRC, or even worse, between proxy such as ADR and IRC.

(For thoron, i.e. ^{220}Rn, the situation is partly more complicated because the decay chain between ^{232}Th and Tn contains several longer-lived radionuclides, which can render ecological fractionation more complex. On the other hand, the short half life of Tn (56 s) compared to the one of Rn (3.7 d) allows only short migration distances, along which less variability of controlling factors may be expected.)

4.3 Correlation and concordance concepts

The strength of the association between variables can be quantified in different ways. A very common indicator is the *Pearson correlation coefficient* which can be applied for numerical variables and measured their linear association. It is defined as $r(X,Y) := cov(X,Y)/(\sigma(x)\ \sigma(Y))$. The sample r is only asymptotically unbiased with sample size. For small samples, approximate bias correction is available. The Pearson correlation coefficient is not robust against outliers. For X,Y bivariate normal, exact significance tests are available, and approximate ones otherwise.

If X and Y are not linearly, but still monotonically related, often the *Spearman rank correlation coefficient* is used. This is the Pearson coefficient applied to rank-transformed data. It is also less sensitive against outliers. Significance can be tested.

Also the *Kendall correlation coefficient* is a rank coefficient. All pairs of a joint sample of X and Y, (x_i, y_i), are screened whether they are concordant, that is, if $x_i > x_j$ then $y_i>y_j$ or if $x_i<x_j$ then $y_i<y_j$, otherwise discordant. From the number of concordant and discordant pairs a coefficient is defined. Variants for ties are available. A significant test also exists.

The association between nominal data is investigated via contingency tables. It is measured by statistics derived from χ^2 statistics, typically the *contingency coefficient* CC. In particular for binary data, 2 × 2 tables are quantified by the *Matthews correlation coefficient* MCC or statistics derived from the odds ratio, such as the *Yule coefficient of colligation*. For details, see the statistics sub-section of section 4.1.1.2, which deals with association of radon priority areas estimated from dwellings and workplaces.

The *intraclass correlation coefficient* (ICC) for grouped data measures the performance of the grouping scheme, or how similar data are which belong to a particular group.

4.4 Synopsis of literature results, assessment of consistency, consequence for RPA estimation and for construction of RHI

Interpretation of literature results has been given in section 4.2, physical interpretation of apparent lack of consistency in section 4.3.

The mostly regional nature of studies and their results, which is the source of apparent inconsistency has consequences for RPA estimation and GRHI construction.

a) RPA

RPA estimates that rely on transfer models (mathematically, regression analysis between IRC and controls or proxies) will reflect the regional conditions which underlie the models. For example, if ADR is used as proxy predictor, its classification power as well as the actual classifications will be different in parts of Europe with different environments, because of the large-scale regional cofactors which contribute.

Indeed, this effect is desirable as delineated RPAs should naturally reflect regional conditions. On the other hand, it means that regionally adapted models must be developed for RPA estimation in a particular region, and ones suited for other regions with different border conditions must be used very cautiously, if at all. This may be remediated if “grand” models are available which account for the complete variability of relevant controls over a domain, say Europe (with regard to which regional results are special cases).

b) GRHI

Due to lack of experience, the impact of inconsistency between dependence models on the GRHI is so far unclear. In current understanding, potentially most affected seem “local” versions of the GRHI which are based on collations of regional models (see discussion in the GRHI section). However, it seems that the dominant source of inconsistency across borders between regions, along which the GRHI estimates are collated or “sewn”, is uncertainty that is due to its estimation from different sets of predictors between regions, but less so owed to predictors that vary between regions – but this would have to be investigated in detail.

For the “global” GRHI version, based on datasets common to entire Europe, the problem does not appear by definition. (In fact, the “global” GRHI version has been developed to avoid inter-regional inconsistency problems, in spite of disadvantages; see the GRHI section.)

5. Geogenic radon potential GRP

This section is based on text submitted to the European Atlas of Natural Radiation and a report by BFKH.

5.1 Concepts of geogenic RP

While the approach to define the RP by standardizing indoor Rn concentration (“Friedmann RP”, see section 3.2) can be called a top-down approach, as the value from which it starts, i.e. indoor Rn concentration, lies very high up in the “rock to risk” scheme. In contrast, the GRP is a bottom-up approach, since it starts from geogenic quantities, which measure geogenic radon source and transport in the ground. Remember that Rn availability on the surface, or its availability for infiltration into a building, depends on both factors.

The main physical mechanism for infiltration into a building is advection through the interface of the building with the ground, possibly to cracks or fissures if there is a slab type foundation. Diffusion may play a role if there is no constructed barrier, as in earth basements of old buildings.

Advective flux is proportional to the pressure gradient across the interface times source strength. Proportionality factors are permeability in the ground and resistance of the interface. Rn availability, normalized against anthropogenic factors (pressure gradient, which depends on air circulation physics of the building, and type of the interface), is therefore proportional to source strength times permeability (k) of the ground, GRP $\propto$ source $\times$ k.

The matter is more complicated if diffusive transport is considered too. Diffusive flux depends on concentration gradient and resistance again diffusion, quantified by diffusion coefficients of the ground and of the barrier of which the interface ground-building consists (if any). Diffusive transport is independent of pressure gradients. Therefore, diffusive flux cannot be integrated into the GRP defined as flux normalized by pressure gradient. Diffusive flux through the soil surface $\propto$ source × $\sqrt{D}$, D – the effective diffusion constant in the soil. For a recent reference on Rn transport in soil, Chakraverty et al. (2018).

Several operational definitions of the GRP have been proposed. Currently most used seems to be version (1), a combination of Rn concentration in soil under equilibrium, C_∞, de facto in 70 to 100 cm depth (Czech and German definition, respectively). As a formula, the so-called Neznal-GRP is most popular,

$GRP := (C_\infty - C_0)/(-10-{}_{10}\log k)$ (Neznal et al. 2004)

C in kBq/m³, k in m². For mean to high permeability (k = 10^{-11} to 10^{-12} m²), this is approximately proportional to the advective flux, normalized by pressure gradient. Very low and high permeability result in higher and lower GRP than expected by k C_∞. The formula has been found semi-empirically, as combination that allows optimal prediction of indoor Rn concentration. C_0 is a very small concentration, set to zero by most users of that approach. In the original publication, C_0=1 kBq/m³. The formula is not applicable for very high permeability, about $5 \cdot 10^{11}$ m².The relationships of permeability k, the transformed 1/(-10-lg k), migration length and influencing factors is shown in Figure 4.

(2) As alternative, the source term has been proposed to estimate C_∞ as proportional to mean U or Ra concentration down to about 1 m in the ground, times emanation power. (Also porosity and water content has to be considered.) This approach has been developed and used in Estonia, Petersell et al. (2017)(map 6.1 f, theory and references p. 27). U or Ra concentration is usually determined from soil samples in the laboratory, as are emanation power and other soil specific parameters. For Ra concentration, a possible alternative is airborne gamma-ray spectrometry. The European U map of this Atlas could be an input database for the source term required for calculating the GRP.

k [m²]	10^{12} k	1/(-10-lg k)	texture	transport	influence of humidity	migration length
>>	>>	-	karst		low	some km
10^{9}	1000	-	coarse gravel			some 100 m
10^{10}	100	∞	gravel	advective		some 10 m
$8{\cdot}10^{11}$	80	5				
$5{\cdot}10^{11}$	50	3	coarse sand			up to 10 m
10^{11}	10	1	sand			few m
10^{12}	1	1/2	silt – sand			< 1 m
10^{13}	1/10	1/3	silt			50 cm
10^{14}	1/100	1/4	silt – clay			10 cm
10^{15}	1/1000	1/5	clay	diffusive		cm
10^{16}	1/10,000	1/6	fine clay		high	mm

Figure 4: Relationship between permeability and influencing factors (adapted from Kemski et al. 2012). lg = $_{10}$log.

Version (1) requires measuring soil gas radon concentration C_∞. Soil gas samples are collected using a stainless-steel probe pounded in the ground with a co-axial hammer to a depth of about 70–100 cm to avoid the influence of atmospheric air. Gas is extracted by purging the probe with a plastic syringe (50 cm³), or by an automatic pump connecting the probe directly to the measuring device. This can be done in situ rather quickly and cheaply. The practice has been used, among other, in CZ, DE, AT, BE and IT. It requires careful probing in order to avoid "clean air contamination" of the sample, i.e. intrusion of atmospheric air which dilutes the Rn concentration in the sample.

The main problem is that soil gas Rn concentration, even at 1 m depth, is not constant in time, but subject to seasonal and daily cycles related to temperature and mean soil humidity, and possibly also fluctuating ground water table. Their amplitude depends on soil type and can represent a variability of up to 50% under unfortunate conditions. To minimize the effect, sampling is recommended by practitioners to be performed avoiding certain conditions (frost, saturated soil after rain, untypically dry soil). For these reasons, soil gas survey should be conducted during low-precipitation seasons (typically summer to early fall) to minimise any variations induced by different sampling periods. As such it is believed that all the surveys represent the same populations and that they can be combined for statistical and geo-spatial analysis.

To remediate this problem, it has been proposed to measure soil Rn with passive detectors buried in the ground, such as CR-39 or polycarbonate based monitors (Turek et al. 1997, 2004; Conrady et al. 2011). The method has been used in Israel (Shirav-Schwartz et al. 1997) and in Kosovo (Kikaj et al. 2016) as well as in a soil Rn survey in Rhineland-Palatinate (Germany) (results unpublished). It has been shown that also polycarbonate based material as used for CDs/DVDs can be used for the purpose (Pressyanov et al. 2010, 2014, Mitev et al. 2018). The subject is discussed in detail in section 4.3.2. Integration periods can be between days and possibly years, depending on Rn concentration and detector type. Measuring for days to weeks (apparently the usual period with CR-39) does not solve the problem posed by seasonal variability, though (Kikaj et al. 2016). Polycarbonate is less sensitive and therefore allows longer collecting times, mitigating the problem of temporal variability (Shirav-Schwartz et al. 1997). Pressyanov et al. 2015, 2018 report usability of the CD/DVD method between exposures of 10 and 10^6 kBq h/m³, allowing very long exposure. The method is logistically more complicated than grab sampling, as sites have to be visited twice and the burying and recovery procedure is more labour intensive. Additionally, influence of soil humidity on track-etch monitors is not quite clear, and thoron may interfere substantially. (The latter problem seems to have been solved by installing appropriate diffusion barriers for the buried-TE method and for the CD/DVD method by particular etching procedures, Pressyanov et al. 2003.) A comparative assessment of grab sampling and passive methods has been given in Kemski et al. (2012).

The same problem of temporal dependence applies for point measurement of permeability. A possible alternative is using model based, i.e. calculated, instead of measured permeability. Theoretically, one should be able to estimate permeability from soil parameters like grain size distribution (texture), porosity, humidity and others. Databases of these quantities are available Europe wide. Investigation of whether calculated permeability can or shall substitute the measured one is currently (late 2018) under way in Germany (Petermann et al. 2018); preliminary results are however little encouraging, as it was so far not possible to establish a model that could explain measured permeability values with satisfactory precision. The problem is currently unresolved.

On problems of soil permeability determination in general, Neznal et al. 2005.

In the future, a European GRP map could be based on the U map and soil databases, for example the European LUCAS database (https://esdac.jrc.ec.europa.eu/projects/lucas; Orgiazzi et al. 2018). There is little chance that a GRP map based on method (1) could be accomplished in foreseeable future, because many countries do not plan soil gas Rn surveys (as performed in CZ, DE and IT), and if they do, completion may take long time. (However, it should be said that soil gas Rn and geochemical surveys are logistically much easier than indoor Rn surveys, concerning issues of representativeness and data protection.)

A different way of defining radon potential is based on multivariate cross-tabulation. This method results in an index with a categorical-ordinal quantity, the results are given in classes such as (I, II, III, IV) or (low, medium, high). Classes are assigned based on scores either assigned to a combination of input quantities or calculated as the sum of points delegated to the input quantities. The second type allows for the consideration of multiple factors. Available quantities are soil gas radon, permeability, standardised indoor concentration, equivalent uranium concentration or other geochemical quantities, external terrestrial gamma dose rate, geological categories, quantities related to tectonics, and the presence of 'special features' like mines, caves, water bodies and other extraordinary conditions, which are coded binary (yes, no) (Gruber et al. 2013).

A similar approach has been applied in France, Ielsch et al. (2010), Figure 5. In a study in Bourgogne region, the following set of geogenic variables has been used as constituents to create a classified GRP: geology, lithology, U content, fracturing (presence of faults), underground mines, and thermo-mineral sources as quantitative parameters. This was made necessary by the relative sparseness of the soil-gas data in France. The data was provided by previous geological and geochemical surveys, studies and databases, to compile the map they selected a 1.5 km² sized minimal object size and calculated the mean U content of the geological units based on the geological map of France (1:1,000,000, digital map). Then the authorsconsidered the various artefacts (mines, geological fractures, etc.) inside the geological units and constructed a map by compiling all considered layers together. For classifying the geogenic radon potential they used two quantitative scales, a more detailed 5 step and a more easily interpretable three step scale. The French approach is discussed in more detail in section 4.2.2.4b.

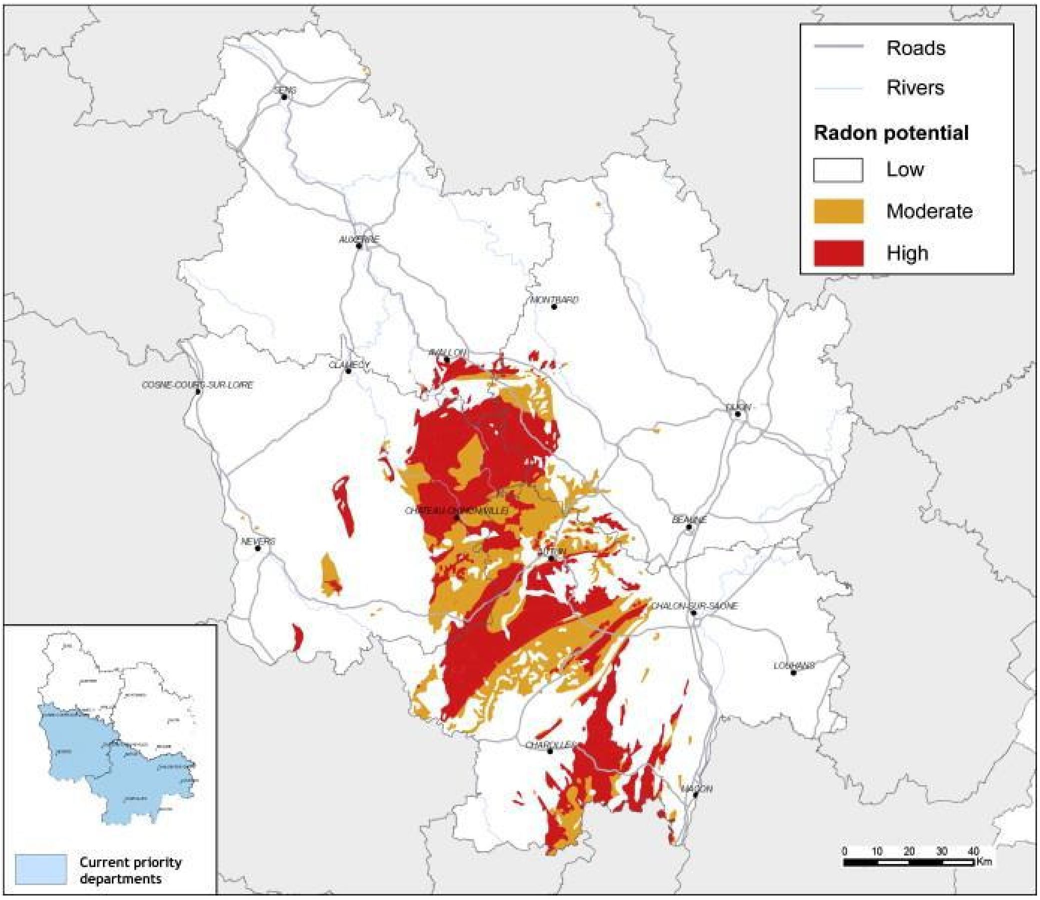

Figure 5: The geogenic radon potential map of Bourgogne (Ielsch et al. 2010).

5.2 Input quantities: Measurement

Physical controls of the GRP are Rn source and Rn transport in the ground. These can be captured in different ways for defining a GRP quantity, e.g. the popular Neznal-GRP. Input quantities are Rn concentration in the ground and permeability.

Measurement techniques:

Uranium concentration in the ground: ICP-MS, X-ray fluorescence are most common, gamma spectrometry of ^{234}Th and ^{234}Pa lines is possible with care.

Radium concentration in the ground: Usually determined by gamma spectrometry of progenies ^{214}Pb and ^{214}Bi. The samples have to be sealed for (optimally) one month before measurement in order to have equilibrium between ^{226}Ra and its progenies.

Radon concentration in the ground: Different techniques are available: Grab sampling, continuous sampling and passive exposure. Grab sampling can be taken using different options available in the market such as Neznal probes (www.radon-vos.cz/?lang=en&lmenu=en_measuring&page=en_measuring_rm2) or MARKUS system (https://radoninstrument.com/en/product/markus/). These instruments are ionization chambers (Neznal probes) or silicon detectors (MARKUS). In both cases it is necessary to make a hole in the soil 0.7 to 1 m deep. Then, the measurement system sucks an air sample. After several minutes the instrument gives a reading of the radon concentration in the soil gas where the sample was taken. Although these systems are widely used, other methods such as passive detectors can be used too. They are CR39 detectors specially designed to operate under the conditions of 0.7 – 1m deep and the typical exposure time ranges from 1 to 15 days. Finally, continuous devices such as Alphaguard have systems to measure radon in soil gas too. Further information abut this can be found in the ISO standard 11665-11:2016 "Measurement of radioactivity in the environment — Air: radon-222 — Part 11: Test method for soil gas with sampling at depth".

Permeability: The measurement of permeability in the soil can be done by active methods such as the one proposed by Neznal "Radon Jok" that allows the measurement of this parameter in situ. The system applies negative pressure to suck air from the soil using the device and calculate the permeability using the known air flow through the probe. The system allows to measure a range of permeabilities from $k = 10^{-11}$ m^2 to 10^{-14} m^2. Further information can be found in the website www.radon.eu/jok.html .

Permeability can be estimated as the weight percentage of fine fraction (<63 μm): high permeable soil have the weight percentage of the fine fraction <15 %, medium permeable soil have weight percentage between 15–65 % and low permeable soil have weight percentage of fine fraction above 65 %.

There is also possibility of getting values of soil permeability in some of the existing databases of soil characteristics. One example is the European map of soil permeability that can be found here: https://data.europa.eu/euodp/en/data/dataset/jrc-eanr-11_soil-permeability .

Porosity: The porosity of the soil can be determined experimentally in the laboratory by taking soil samples and applied standard analytical methods.

Emanation power: There are two ways to estimate the radon emanation coefficient from the soil: gamma spectrometry and measurements of radon and radium. The gamma spectrometry technique consists on measuring the peaks of ^{214}Pb and ^{214}Bi several times in conditions of equilibrium and lack of equilibrium. It is important to guarantee that the soil sample has no radon in the soil pores before the measurement starts. The other way of determining the emanation coefficient is enclosing the soil sample and waiting for secular equilibrium between radium and radon. Then the radon concentration must be measured by active or passive methods as well as the effective volume of the sampling device and the weight. Further information about these methods and the mathematical expressions to calculate the emanation coefficient can be found here: www-pub.iaea.org/MTCD/Publications/PDF/trs474_webfile.pdf (IAEA Technical report series No. 474 "Measurement and calculation of radon releases from NORM residues, IAEA 2013").

6. Geogenic radon potential (GRP): Estimation and mapping

If input quantities, such as C and k values for the Neznal-GRP, are not available, then the radon potential is usually estimated from proxies or surrogates. Such proxies are the standardised indoor radon concentration (measured in defined standard conditions such as ground floor rooms, presence of a basement, etc. to 'factorise out' anthropogenic factors) The standardised indoor radon concentration is correlated to the GRP, with inaccuracies caused by remaining unaccounted for or poorly assessed factors. Other quantities such as equivalent uranium (eU) or dose rate have similarly describable relations to the GRP, however these relations can be locally different, according to the regional predominance of some factors. The controlling factors have to be considered when using substitutes for the soil radon in the formula (Gruber et al. 2013).

Several options exist for compiling maps. The target variable has to be matched to spatial units (area), which will serve as the basis of the map. These spatial units can take various shapes and forms such as administrative or geological units or a grid cell. Geographical units might be a practical choice for the radon potential, and if desired those units can be decompiled into a grid system. The spatial units are then assigned a value derived from the measured target variables inside (arithmetic mean, geometric mean, median, etc.) (Gruber et al. 2013). The technique requires availability of sufficient data. Various estimation or interpolation techniques (local regression methods, different versions of kriging, Bayesian inference or extensive Monte Carlo simulations) can be implemented during the construction of such maps. However, it should be kept in mind that the interpolated concentration is only an estimate, not the true radon concentration, even though it can be useful for the visualisation of the data and in defining areas with higher risk probability (Cafaro et al. 2014). The different spatial units offer different advantages and disadvantages. Administrative boundaries make administrative action easier, but disregard the relation between the radon potential and the geology and soil properties. Grids makes mapping independent from other variables, but ignores variation within the grid cells. Geological boundaries are much more closely related to the radon potential but still there can be variations in the radon potential inside the geological units (Ielsch et al. 2010). In case of sufficient data density maps can be made by displaying each point of data, without interpolation for the areas between the data points, which would still give an instinctive grasp of the overall situation (McKinley 2015).

Multivariate estimation

Estimation from possibly several predictors additional to, or instead of GRP data, one has to rely on association between target variable (GRP in this case) and predictors. The subject is discussed in detail in section 4.2.1.4. Two examples are quoted here:

In case of the multivariate cross-tabulation, values can be assigned to the various parameters or qualitative categories can be set up. For example, in case of a study on Bourgogne, a five-step qualitative scale was used to define radon source potential based on lithology and uranium content. For the geogenic radon potential map the authors narrowed down the number of categories to three and included the various artefacts such as mines and hot springs into the analyses (Ielsch et al. 2010).

In case of the geogenic radon potential formula reliant on soil gas and soil permeability measurements, there are some methods correlating various other parameters if the input is not directly available. Appleton and Miles performed least squares (LS) regression analysis to establish empirical relationships between estimated uranium in the <2mm fraction of topsoils derived from airborne gamma spectrometry data, U measured in the <2mm fraction of topsoil geochemical samples soil gas radon and indoor radon concentrations based on observations in the United Kingdom (Appleton and Miles 2010). The linear relationships were compared to those described for other countries. The described relationships are dependent on the underlying geological units. Similar relationships were described by other authors for Germany, Croatia and the Czech Republic (Appleton and Miles 2010).

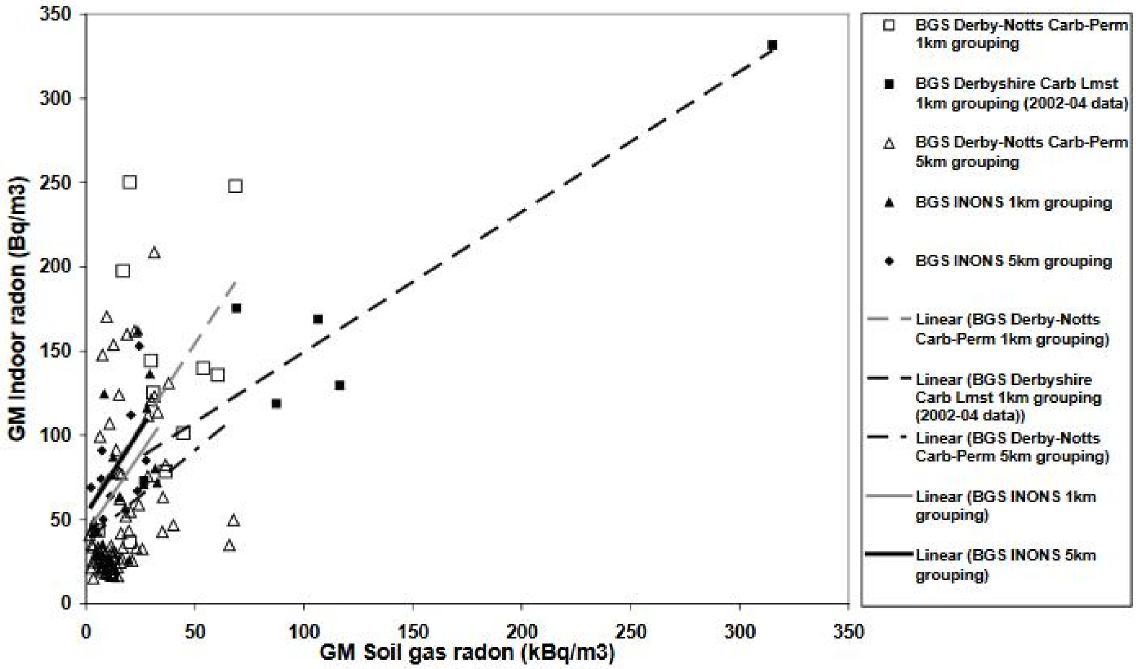

Figure 6: The relationship between indoor radon concentration and soil gas radon by least square regression analysis (Appleton and Miles 2010).

Various log - ratio transformation methods (pairwise, additive, isometric, etc.) have been also used for the eliminating the constant sum closure effects caused by the relative nature of geochemical data (McKinley 2015). Yet another method is using correlation coefficient matrices either on the original data or if lognormal distribution is assumed then the logarithms of the data (Pereira et al. 2017). In some cases, (for example the Portugal C2-type granites) the correlation might not be made between the desired parameters due to the high variability of the data. Some other examples are the Global Ordinary Least Squared and the Geographically Weighted Regression, the latter being suggested favourable due to the inclusion of local geographical parameters (De Novelis et al. 2014, Ciotoli et al. 2017).

7. Case studies

7.1 Germany

In Germany, several versions of GRP map evolved over time. In the 1990s, Kemski et al. (2001) proposed a map of soil Rn concentration (SRC) in 1 m depth, aggregated into a 3 km × 3 km grid. Interpolation is by inverse square distance weighting within geological units. A simplified litho-stratigraphic geological classification was designed such as to classify geological units according their GRP. The resulting map is published on the home page of the BfS, www.bfs.de/DE/themen/ion/umwelt/radon/karten/boden.html , shown in Figure 7.

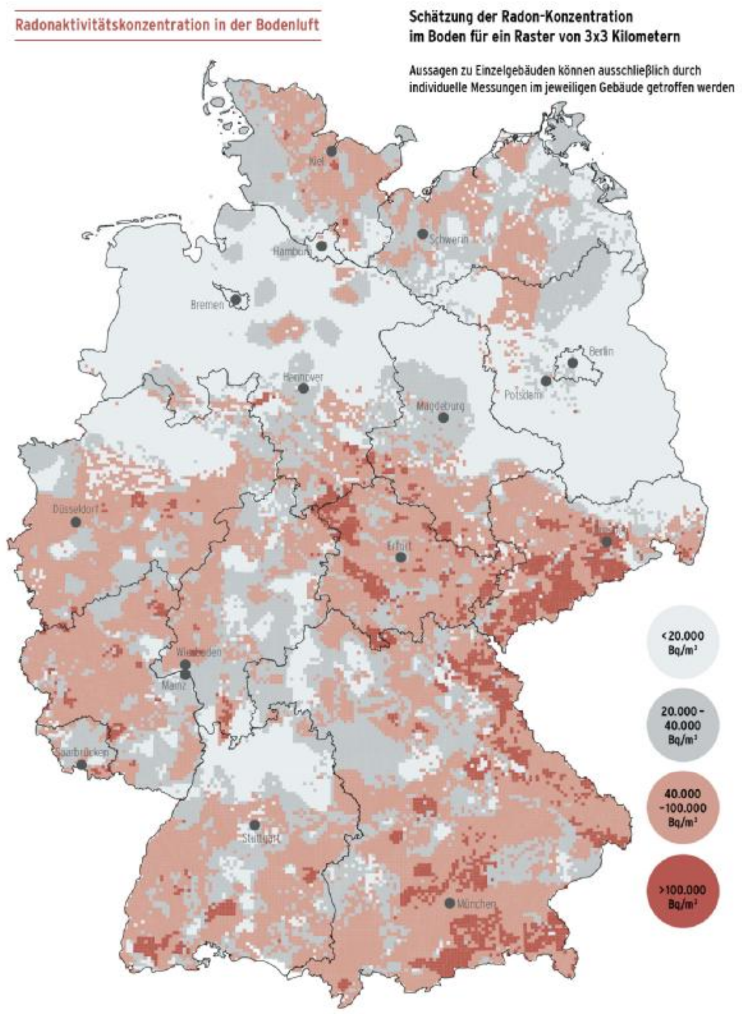

Figure 7: Map of Rn concentration in soil, Germany.

In 2012, a map of the Neznal-GRP was proposed, Bossew (2013, 2015). At each measurement point, the GRP was calculated from measured SRC (data mostly the same as above) and permeability. These were normalized to geology by dividing by the GM(GRP) per geological unit. A simplified geological classification scheme as above was applied. The ln-transformed normalized values were subjected to sequential Gaussian simulation (SGS). The 100 realizations were back-transformed and statistics computed. The estimation units were 10 km × 10 km grid cells.

In Figure 8, the mean over realizations (so-called E-type map) is shown on the left. The right map shows the relative dispersion between realizations, defined as Qdev90 := (Q95 – Q05)/(Q95 + Q05), Q the quantiles to percentiles 5 and 95. The dispersion essentially reflects density of input data.

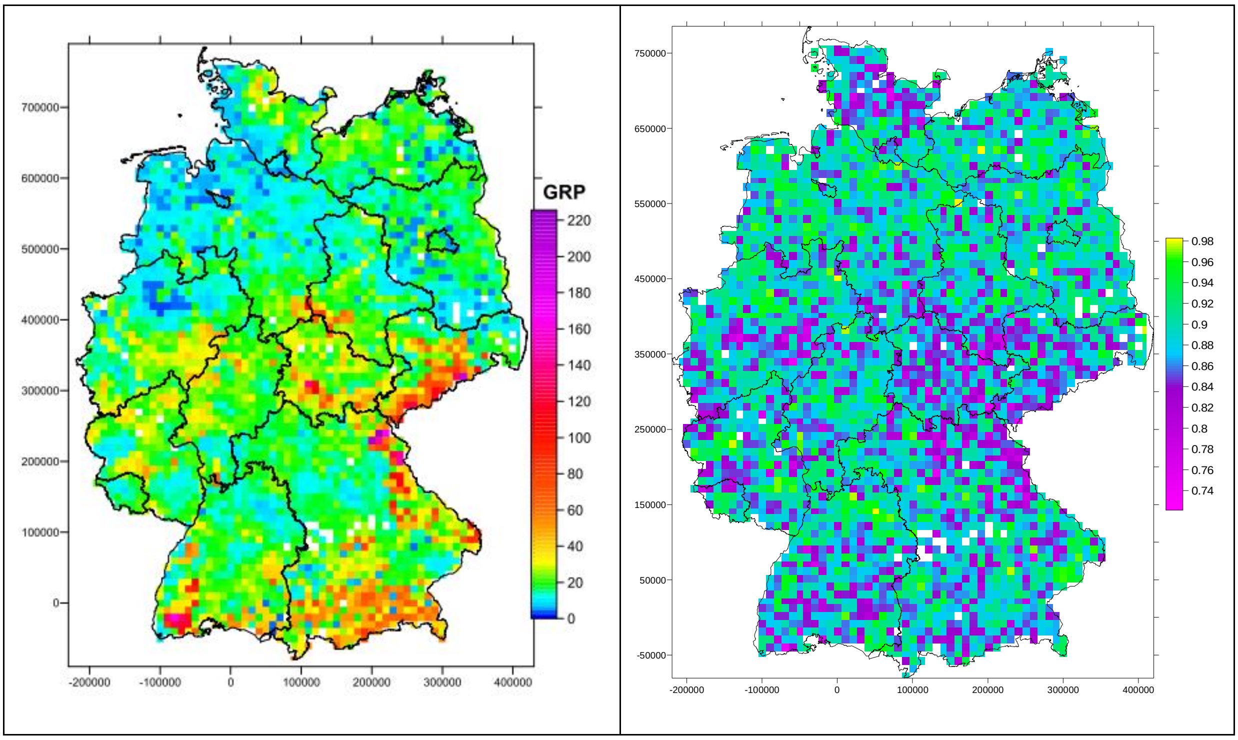

Figure 8: GRP map of Germany based on GSG. Left: Expectation, Right: Relative dispersion between realizations.

The latest version is based on machine learning. Random forest turned out the optimal method according to various performance scores. Predictors are related to geology, hydrology, soil properties, meteorology and geochemical concentrations. The result has been published, Petermann et al. (2020).

7.2 France

A map of the radon potential of the geological formations has been established by the IRSN (Ielsch et al. 2017b; Ielsch et al. 2010) in order to characterize the capacity of the underlying rocks to generate radon at the surface on the French territory. This mapping is based on the characteristics of the geological formations. The main parameters considered are the uranium contents of the underlying rocks and factors that can facilitate the transport of radon to the surface (faults, underground mining works, thermal springs...). This map is based on data from the geological map of France at the scale of 1: 1,000.000.

Moreover, a measurement campaign of the radon in dwellings was carried out over the period 1982-2002 by IRSN and the Ministry of Health (Demoury al. 2013). During this campaign, 12,940 measurements were collected over the French territory. In complement, measurements of indoor radon concentration in public buildings were also used for this study (database of the French Ministry of Heath). They represent 8,253 results acquired between 2014 and 2018. At last, 2,305 measurements acquired from local measurement campaigns in homes were also collected for this study (databases of the French local Health Authorities).

Thus, a totality of 23,499 indoor radon measurement results in 9,967 different municipalities spread over French territory have been used. Table 4 provides the statistics associated calculated from this dataset. Once should note that these measurements overestimate indoor radon concentrations because measurements in public buildings and local measurements campaigns in homes were rather carried out in high radon potential areas.

All the data could not be located precisely with coordinates. For half of the data, the name of the municipality was available and not the exact location. (A new problem has been caused by the European General Data Protection Directive GDPR (2016), as reporting exact geolocation data is not allowed and aggregation of data (or some similar process) should be used).

Table 4: Statistics of indoor radon concentrations available for the whole French territory. A.M – arithmetic mean, S.D – standard deviation of the sample

	Number of data	Radon concentration ($Bq.m^{-3}$)						
		Min	Max	Average (A.M)	S.D	1st quartile	Median	3rd quartile
Dataset	23,499	1	28,553	219	571	40	84	202
National campaign in dwellings	12,940	1	4,382	89	159	28	49	93

<u>Relation between indoor Radon concentration and geogenic Radon at the national scale</u>

At first, all measurement results were directly compared to the map of the geogenic radon potential in 3 classes. For each municipality, we first calculated the percentage of the surface covered by the “low” category of the geogenic radon potential map. The arithmetic mean of indoor radon concentrations was then calculated for each concerned municipality (Figure 9c). Thus, the mean radon concentration in municipalities with 100% of their surface concerned by a “low” category is 78 Bq/m^3 while that of municipalities with 0% of their surface in a “low” category is 322 Bq/m^3.

The same method was then applied considering the percentage of “high” radon potential area (Figure 9d).

In both cases, the results obtained show a good consistency between the geogenic radon potential map and the results of indoor radon measurements in dwellings and public buildings.

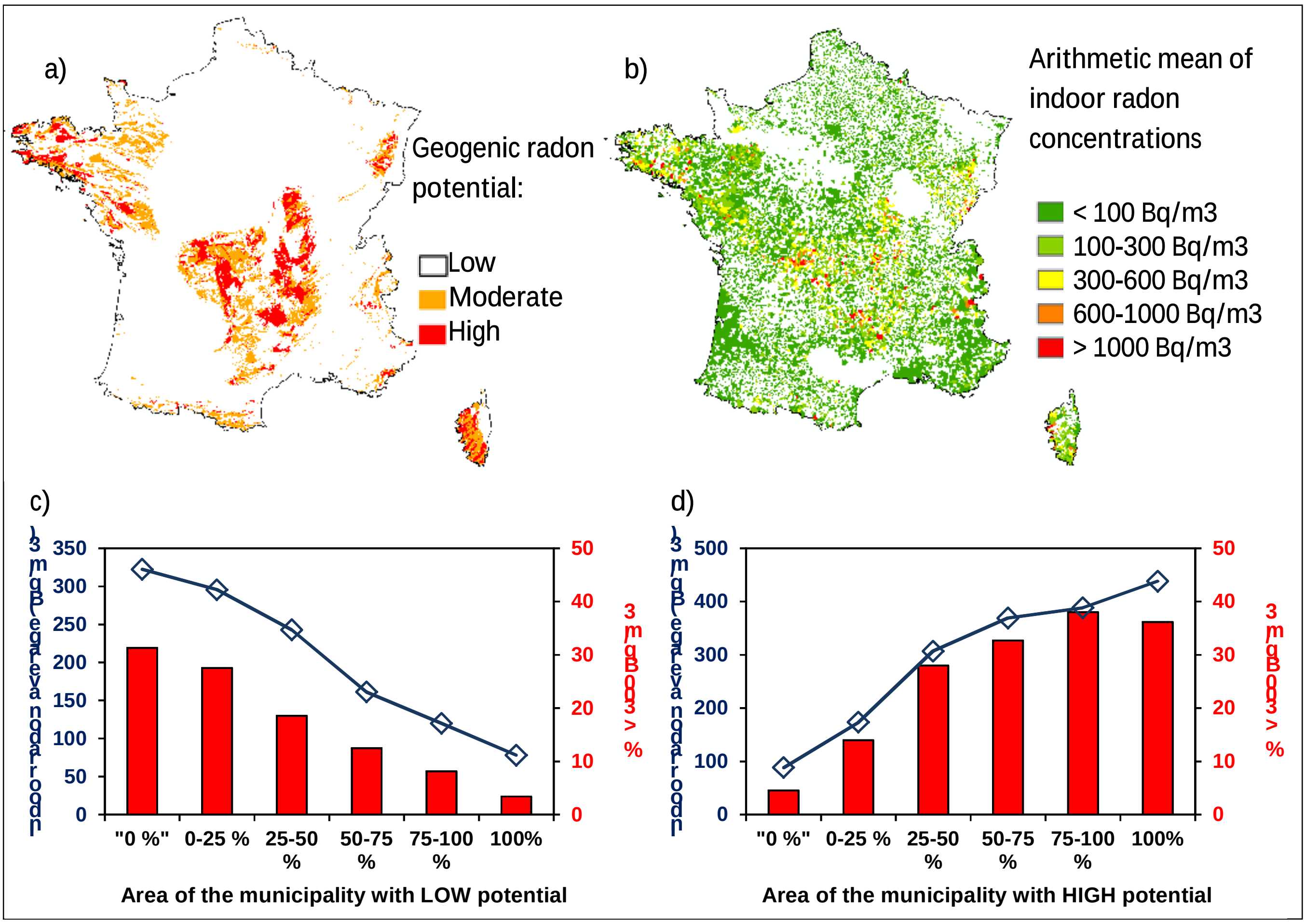

Figure 9: Comparison between the French geogenic radon potential map (a) and the mean radon concentration by municipality based on 23,498 indoor measurements (b) considering the surface of the municipality (%) covered by a low geogenic radon potential (c) or a high geogenic radon potential (d).

Moreover, from the French geogenic radon potential map, the municipalities have been classified in three categories of radon potential:

- Category 1 municipalities are those located entirely on geological formations with low uranium contents and with no factors that may facilitate the transfer of radon to the surface
- Category 2 municipalities are also located on geological formations with low uranium contents, but a part of their surface is concerned by geological factors that can facilitate the transfer of radon to the surface
- Category 3 municipalities are the municipalities which present geological formations whose uranium contents are estimated higher compared to the other formations, at least on a part of their surface. For this category, the presence of radon at high concentrations in buildings is most likely.

This classification of municipalities into three categories is currently used in the French regulation with an obligation of radon measurement in certain public buildings in the municipalities of category 3.

Figure 10 shows the relation between the percentage of indoor radon concentrations exceeding of the values of 100, 300, 600 and 1000 Bq/m³ and the category of the municipality. A good correlation is observed between the municipality categories and the probability of exceeding these values.

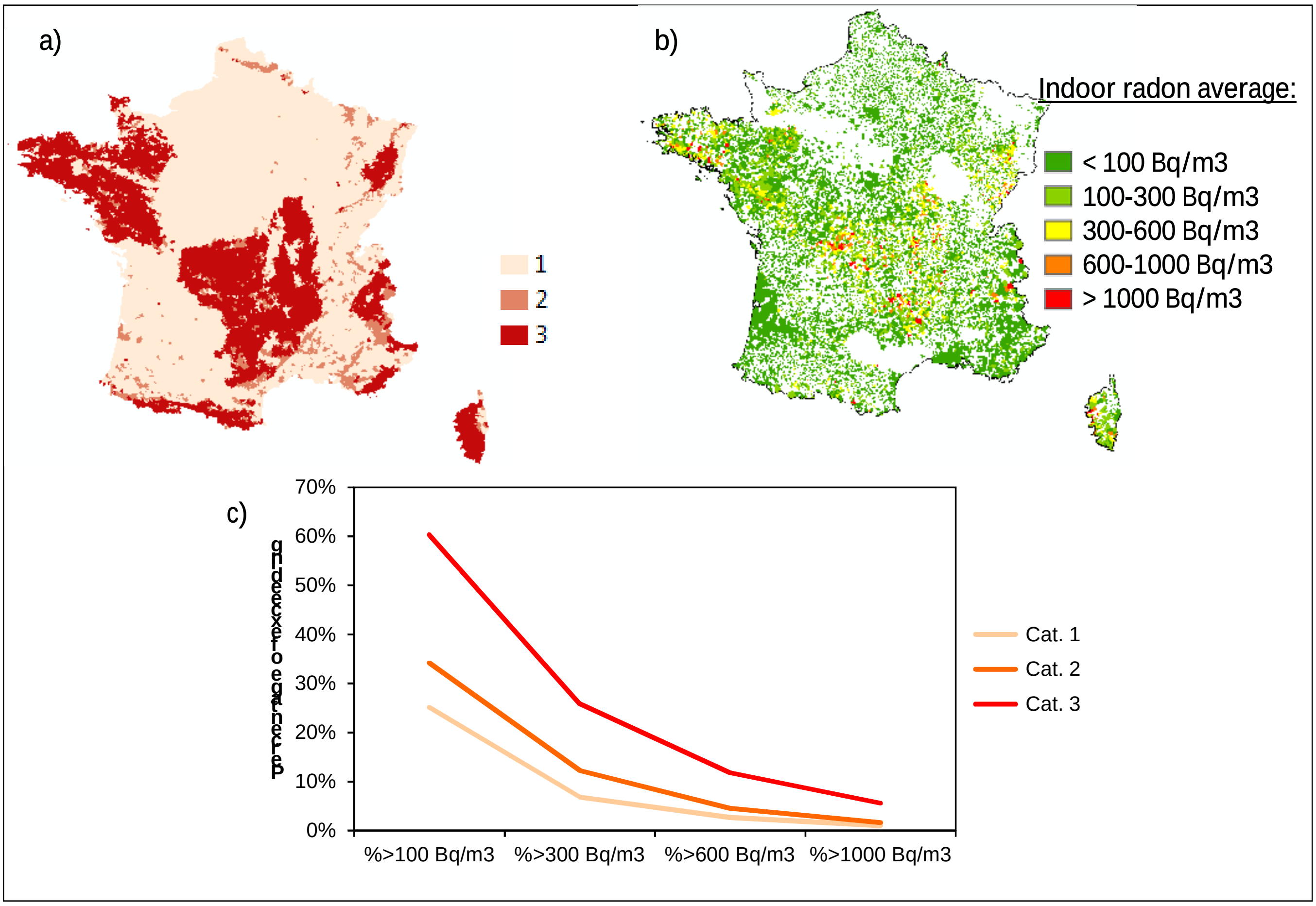

Figure 10: Comparison between the French municipalities radon classification (a) and the mean indoor radon concentration by municipalities based on 23,498 indoor measurements (b) considering the percentage of exceeding different values by municipality (c)

<u>Relation between indoor Radon concentration and geogenic Radon at the regional scale</u>

The comparison of the means by municipality with the percentage of the surface of each municipality with a “Low” or a “High” geogenic radon potential was also carried out at the scale of a smaller territory. For this, data analysis was restricted to the Haute-Vienne *“département”* (French district), a territory characterized by high radon concentrations in dwellings. In this area, 1,132 measurement results are available and distributed in 112 different municipalities. Table 5 provides the statistics calculated from this data.

Table 5: Statistics of indoor radon concentrations available in Haute-Vienne “département”. *A.M – arithmetic mean, S.D – standard deviation of the sample.*

Number of data	Radon concentration (Bq.m^{-3})						
	Min	Max	Average (A.M)	S.D	1st quartile	Median	3rd quartile
1,132	7	16,928	746	1,270	177	382	774

Figure 11c shows the relation between the arithmetic mean of indoor radon concentrations (Figure 11b) and the percentage of surface concerned with a “low” geogenic radon potential for the municipalities in Haute-Vienne *“département”*. A very good correlation is observed between these two parameters. Figure 11d shows the same analysis with the surface of municipalities concerned by a “high” geogenic radon potential. A good correlation is also observed.

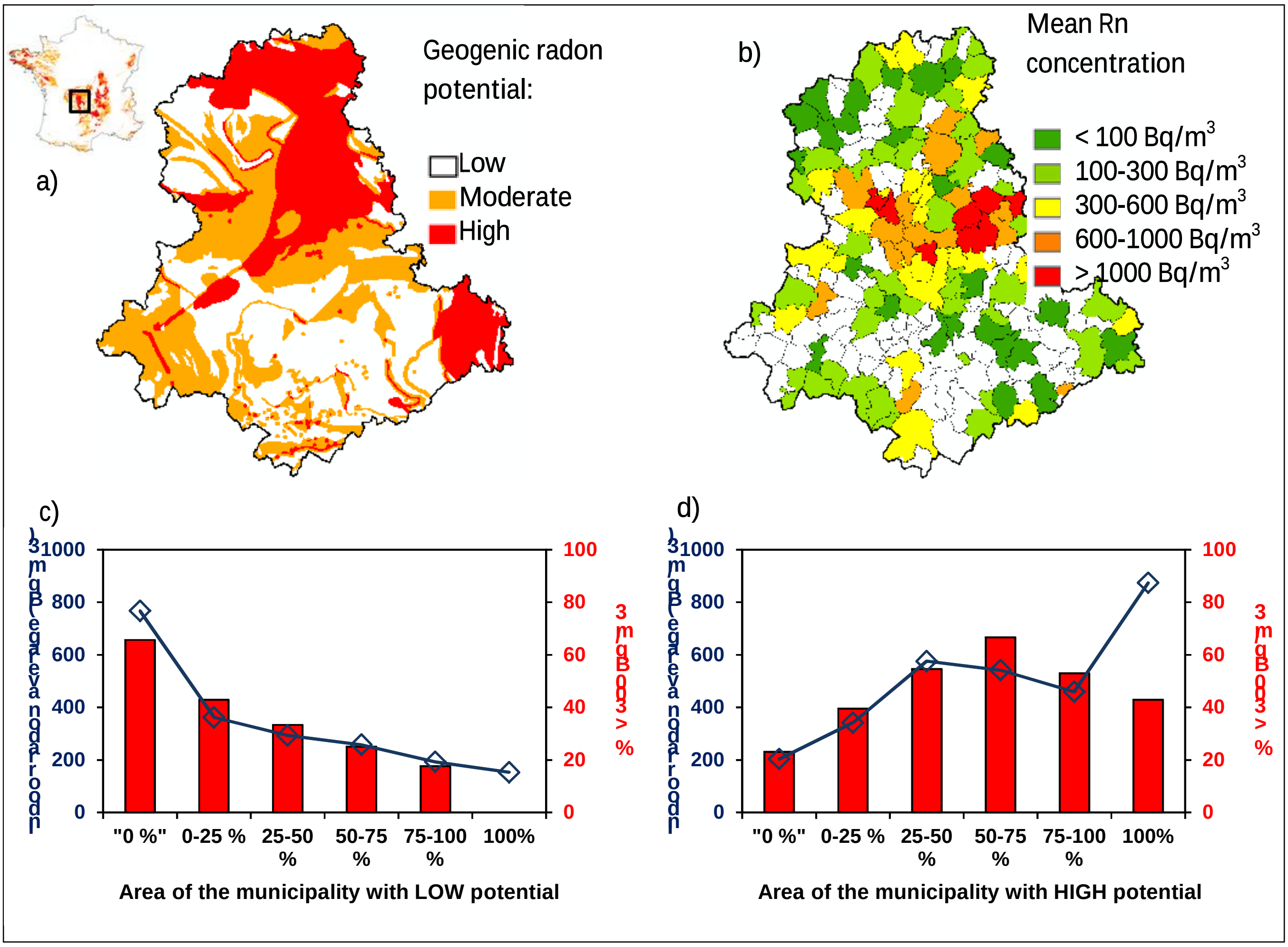

Figure 11: Comparison between the geogenic radon potential map for Haute-Vienne territory (a) and the average by municipalities based on 1 132 indoor radon measurements over this local territory (b) considering the surface of the municipalities covered by a low radon potential (c) and a high radon potential (d)

Relation between indoor Radon concentration and geogenic Radon at a local scale

Finally, an analysis was made on a restricted area of the Haute Vienne *"département"*, with a surface of 50 km x 25 km. This sector, comprising 15 municipalities, is an area with a high radon potential already identified (presence of old uranium mines). During the winter of 2015/16, a measurement campaign was initiated by IRSN to raise awareness of the radon issue and to inform the public on remediation techniques (Ielsch et al. 2017a). 706 indoor radon measurements were made in dwellings during this campaign. Table 6 presents the statistical summary of the data acquired. All these data could be geolocated precisely (with coordinates).

Table 6: Statistics of indoor radon concentration data acquired on a small area with a high radon potential. A.M –arithmetic mean, S.D – standard deviation of the sample.

Number of data	Radon concentration (Bq.m^{-3})						
	Min	Max	Average (A.M)	S.D	1st quartile	Median	3rd quartile
707	7	16,928	985	1,474	272	575	1,050

Fehler! Verweisquelle konnte nicht gefunden werden.a shows the precise location of the measurement points on the geogenic radon potential map in 3 classes. Fehler! Verweisquelle konnte nicht gefunden werden.b shows the relation between the geogenic radon potential class on which the dwelling is located and the indoor radon concentration. A very good correlation is observed for these two parameters.

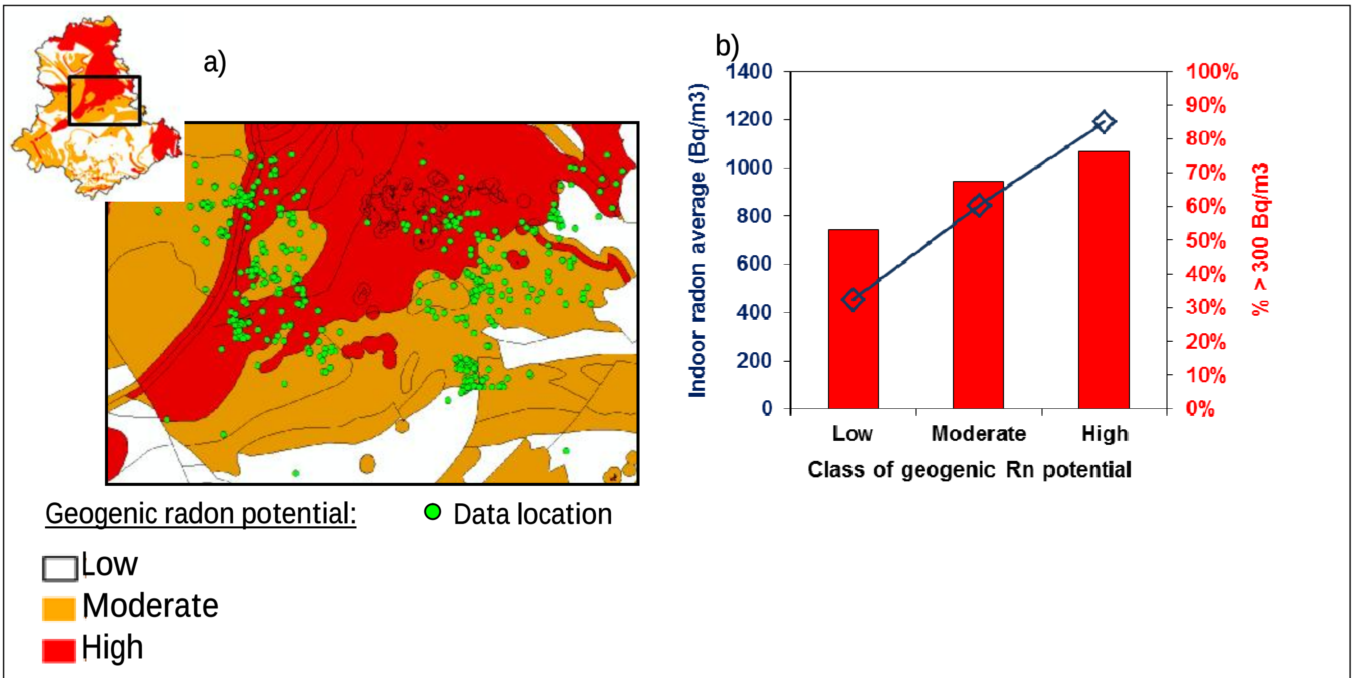

Figure 12: Comparison between the local geogenic radon potential map (a) and the geolocated indoor radon measurements (b)

7.3 European level

Generation of a European map of geogenic radon is an ongoing project of the JRC as part of the European Atlas of Natural Radiation (Cinelli et al. 2018). A first trial version has been proposed by Gruber et al. (2012). Units of the OneGeology map (http://www.onegeology.org/) were assigned values of the GRP and classified according two schemes: frequency of resulting GRP values and correlation with indoor Rn. For the trial maps, the geological units were calibrated with German GRP data (because of otherwise limited availability). While the EGRM presents a unified picture of the collected data, the trial version was calibrated using German geotypes, so for other countries analogies were used. The result is shown in Figure 13.

Further problems are due to some countries missing in OneGeology, partly insufficient classification depth of OneGeology (which was not made for Rn mapping) and inconsistencies in its legend at that time.

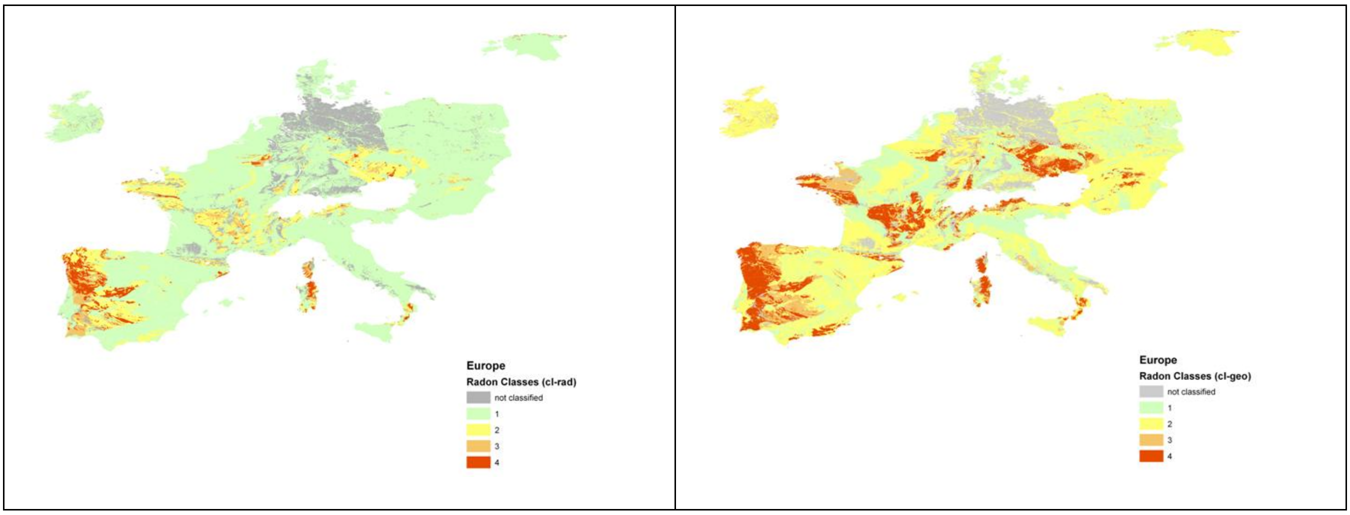

Figure 13: Trial versions of the European Geogenic Radon Map (EGRM) with „radiological" (left) and "geological" radon classes (Gruber et al. 2012)

Calibration on German data only appeared problematic because nominally same geologically units can still be different with respect to Rn. Some regions are covered by geology which does not occur in Germany and could therefore not be included. As an example, the mismatch between the European trial maps and the correct Czech geogenic radon maps is shown in Figure 14.

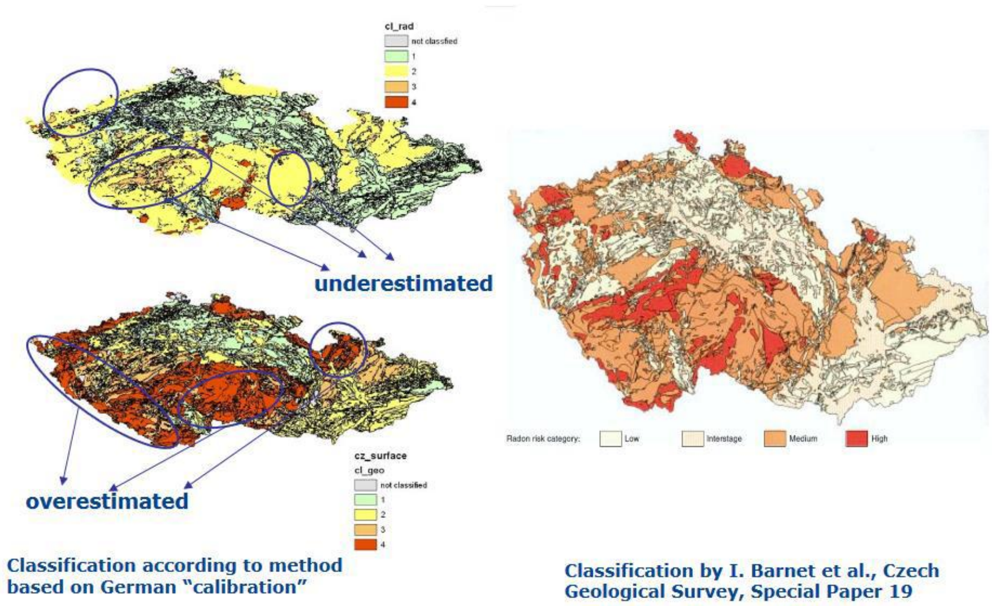

Figure 14: Mismatch between the trial version of the European and the Czech geogenic radon maps.

8. Summary, conclusions and open problems

The idea of radon potential as a quantity which "subtracts" individual physical properties of buildings to indicate the natural conditions that control long-term mean indoor Rn concentration (IRC), has been around for more than 30 years. Concepts were reviewed in this task. One may distinguish between "top-down" approaches, whose initial variable is observed indoor Rn concentration, which is normalized with regard to house, room and usage properties, i.e. the anthropogenic factors which control IRC.

An alternative is the "bottom-up" approach, which starts from geogenic control quantities. The GRP is a particular kind of radon potential; it is defined physically from quantities which control Rn generation and transport in the ground. In this action, definitions are discussed as well as the geogenic quantities which are its input, and their measurement. Problems of representativeness of measured values for a measurement location are addressed, which are mainly owed to the temporal variability of some control quantities.

Regarding mapping, the rationale of the RP in general, and the GRP in particular is that the geographic pattern of IRC mainly reflects the one of its geogenic controls. The reason is that the geographic dependence of anthropogenic factors is relatively minor compared to the geogenic ones, at least on regional scale, i.e. anthropogenic ones appear as statistical noise on top of the geogenic pattern. In mathematical terms, the anthropogenic factor appears as a scalar factor relating IRC and its geogenic controls (or predictors) that has to be found by regression-type analysis.

Many regression studies have been performed for many years. In this task of Metro Radon, a literature review of relationships between geogenic quantities which control geogenic and indoor Rn concentration has been performed and the results interpreted. In particular, the correlation between IRC and geogenic quantities, which is poor in many cases, has been discussed. The main problem seems to be that models have been developed regionally, obviously considering only regionally variable controls, about constant ones regarded as fixed and entering regression coefficient. However, on larger scale, e.g. Europe, the latter controls are also geographically variable, if over larger distance compared to the regionally variable ones. Therefore, regionally developed models, though correct regionally, may not be applicable beyond the region in which they have been developed. This problem remains a challenge; first European-scale studies have been initiated only recently. Their further development and evaluation remain a task for the future.

The question is closely related to analysis of the spatial statistical properties of the anthropogenic factors, about which so far only very initial studies exist. These have not entered discussion in Metro Radon.

A further open problem, not addressed in Metro Radon, is the one of anthropogenically modified geogenic factors. This is typical for urban and built-up environments where geogenic controls - including geology itself - may not be equal to the one in its surroundings, i.e. open land, where data are usually being acquired in field studies (e.g. due to pavements, landscaping, landfills, historical construction activities etc.). The problem is important because most people live in strongly altered built-up environments. In particular in old European cities, this may challenge correct IRC estimation based on geogenic factors. It is recommended that the topic is addressed thoroughly in future investigations.

Methods to estimate the RP or GRP, respectively, have been addressed in this action. To illustrate it, case studies from two European countries are shown.

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Review

Development of a Geogenic Radon Hazard Index—Concept, History, Experiences

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Abstract: Exposure to indoor radon at home and in workplaces constitutes a serious public health risk and is the second most prevalent cause of lung cancer after tobacco smoking. Indoor radon concentration is to a large extent controlled by so-called geogenic radon, which is radon generated in the ground. While indoor radon has been mapped in many parts of Europe, this is not the case for its geogenic control, which has been surveyed exhaustively in only a few countries or regions. Since geogenic radon is an important predictor of indoor radon, knowing the local potential of geogenic radon can assist radon mitigation policy in allocating resources and tuning regulations to focus on where it needs to be prioritized. The contribution of geogenic to indoor radon can be quantified in different ways: the geogenic radon potential (GRP) and the geogenic radon hazard index (GRHI). Both are constructed from geogenic quantities, with their differences tending to be, but not always, their type of geographical support and optimality as indoor radon predictors. An important feature of the GRHI is consistency across borders between regions with different data availability and Rn survey policies, which has so far impeded the creation of a European map of geogenic radon. The GRHI can be understood as a generalization or extension of the GRP. In this paper, the concepts of GRP and GRHI are discussed and a review of previous GRHI approaches is presented, including methods of GRHI estimation and some preliminary results. A methodology to create GRHI maps that cover most of Europe appears at hand and appropriate; however, further fine tuning and validation remains on the agenda.

Keywords: geogenic radon hazard index; geogenic radon potential; European map of geogenic radon

1. Introduction

Indoor radon (Rn) is understood as an important health hazard (e.g., [1]). Therefore, it has been increasingly the subject of regulation aimed to reduce radon exposure. For Europe, the key document is the EURATOM Basic Safety Standards (BSS; [2]; similar to the IAEA-BSS [3]) and much literature deals with the many aspects of environmental radon, as well as a number of international research projects, such as RADPAR [4,5], SMART_RAD_EN [6], Rn in Big Buildings [7], and Life-Respire [8]. Some research was initiated to directly support the development and implementation of regulation, while other projects are focused on complementary activities such as to deepen the understanding of Rn behavior in the environment, to develop tools to quantify Rn, from measurement to displaying its distribution in the environment, and to assess its radiological significance. Among recent large-scale projects, the European Atlas of Natural Radiation (EANR; [9,10]) plays a key role, as well as the EURAMET MetroRADON project [11], which is devoted to improving the quality assurance chain from Rn measurement to aggregated products such as Rn maps, which serve as decision tools in Rn policy. Large parts of the work for this paper were carried out in the framework of the latter project.

Indoor radon concentration, which is the target quantity of regulatory concern, is to a high extent controlled by infiltration of radon generated in the ground, known as so-called geogenic radon. While mapping of indoor Rn concentration has been under way for years (shown e.g., in the EANR), this task has turned out more complicated for geogenic radon. So far, no European map of geogenic Rn exists. Geogenic Rn is usually quantified by the *geogenic Rn potential GRP*, a local quantity that characterizes the susceptibility of a location to geogenic radon (e.g., [12–15]).

A further development is the geogenic *Rn hazard index GRHI*, which we understand as a generalized complement and extension to the GRP. The GRHI is more flexible and can deal with data reality which usual GRP definitions cannot handle. Its main application is thought to be large-scale mapping, i.e., on a European scale, in contrast to small-scale characterization e.g., of building sites or medium-scale national maps, of which their objective is supporting legislative and administrative implementation of the tasks posed by the European BSS.

The purpose of this paper is to summarize the current (early 2020) state of conceptualization and definition of the GRHI. We present a brief review of the most promising techniques and attempts used to estimate and map the GRHI. Additionally, glimpses of GRHI maps developed using different techniques are displayed without going into technical detail in this paper.

2. Concepts

2.1. Geogenic and Anthropogenic Factors that Contribute to Indoor Radon

Indoor Rn concentration is controlled by both natural and anthropogenic factors. Natural factors, defined as geogenic factors, are related to radon generation and transport in the ground (e.g., [16–21]), whereas anthropogenic factors relate to construction characteristics of a building, including building materials and usage patterns (e.g., [12,22–24]). Meteorological factors may be considered in relation to both geogenic and anthropogenic systems, insofar as they can influence Rn transport in the ground, migration and accumulation of radon in the indoor environment, and construction style and building occupancy patterns (e.g., [25–29]).

Geogenic factors depend on geology, soil properties, and hydrology. These factors show a geographical trend and a spatial structure [20]. More generally, when a variable spreads in space and exhibits a certain spatial structure, it can be defined to be a regionalized variable (ReV) [30]. Geological, geochemical, and soil properties are subject to geographical trends. From a mathematical point of view, we can assume that environmental variables, i.e., geological, geochemical, and soil properties, are regionalized variables with two complementary aspects:

- A structural aspect that reflects the regional characteristic of the phenomenon, i.e., the trend;
- A random aspect that is the partly spatially structured, partly unstructured variability from one point to another at a local scale around the trend.

The former component reflects variability not captured by the trend and the latter reflects data uncertainty and variability within distance resolved by the estimation grid. The quantity of regulatory concern in radiation protection is the long-term mean indoor Rn concentration, which will be denoted as IRC in this paper. For practical reasons, long-term mean is mostly understood as the one estimated over the largest natural cycle (excluding possible cycles on a geological time-scale), namely the annual one (often though, the annual mean is estimated from shorter measurements, e.g., over three months). On this temporal scale, meteorological factors become climatic factors, which show geographical trends and can, therefore, be considered ReVs. Their temporal stationarity is a matter of debate: whether climatic change will have an impact on IRC is unknown. If this was the case, the IRC would not have a stable long-term mean value. However, we assume that this effect, if it exists at all, is very small and negligible for the near future; we are not aware of literature on the topic.

Finally, the spatial statistical properties of anthropogenic factors are essentially unknown, although their existence can be plausibly assumed. For example, to some degree, climate (variable with geography, hence regionalized) determines construction of buildings and lifestyle. Also, local geology and landform can be assumed to influence construction style.

The most studied geogenic factors are Rn source (i.e., the geogenic radon source), related to geochemical properties of a geological unit, and Rn transport, quantified by the factors that govern the radon movement in the subsurface (i.e., soil permeability, faults and fractures, hydrogeology, and pedology). These factors are combined into a quantity called geogenic Rn potential (GRP), which conceptually, is designed to quantify the movement of geogenic Rn toward the shallow environment, of which its availability is to be exhaled from the ground and infiltrate buildings (e.g., [31]). It is noteworthy that to what extent available Rn leads to an actual IRC depends on anthropogenic factors.

The GRP is considered as the most important regionalized predictor of IRC, that is, the predictor that shapes the geographical variability of the IRC. Therefore, models have been developed that attempt to predict IRC conditional to the GRP. Anthropogenic factors are statistically assumed as the noise terms, which in geostatistical language, is termed the nugget effect. The nugget effect is the short scale randomness or noise in the ReV that quantifies the variability between samples at a very close space in the experimental variograms. This assumption is probably not entirely correct, but spatial statistics of anthropogenic factors affecting the IRC are poorly understood at present. First attempts have, however, been made to include climate as a predicting factor, e.g., [32,33].

Several operational definitions have been proposed for quantification of the GRP. The most popular seems to be the so-called Neznal-GRP [14],

$$\mathrm{GRPNez} = (\mathrm{SRC}\text{-}\mathrm{SRC}_0)/(-\log_{10} k - 10) \quad (1)$$

with SRC denoting soil Rn concentration (kBq/m^3), k, gas permeability (m^2), and $\log_{10}$, the logarithm to base 10. SRC_0, a small value, has been originally introduced for statistical reasons, but is set to zero by many authors, e.g., [34]. In [14], it was set to 1 kBq/m^3. The numerical value of GRPNez depends on the sampling protocol, e.g., sampling depth and collection period (grab sampling or longer-term collection). As an example, for applications outside the Czech Republic [35,36], the German GRP map [34] is also based on the Neznal-GRP, but applies a sampling protocol [37] that is slightly different from the original Czech one.

2.2. History of the Geogenic Radon Hazard Index

A comparatively new concept is the geogenic Rn hazard index (GRHI), which was conceptualized around 2010. It was motivated by the lack of empirical GRP data in most of Europe as sufficient SRC and permeability data exist only in a few countries, namely in the Czech Republic ([35,36] where the concept originated), in Germany [34], where the GRP is used as an IRC predictor to estimate Rn priority areas (RPA), in Belgium [38,39], and in parts of Italy [40], Austria [41], and Spain [42], as well as in a few other countries where there was also no intention to generate country-wide coverage. Some countries chose SRC itself as a risk indicator, e.g., Estonia [43] and others; for some, see [44].

First attempts towards developing a European GRP map were started around 2008 [45], but it transpired that a realization of producing such a map is more complex than initially thought. The reason was—and still is—that in the foreseeable future, no consistent GRP dataset with European coverage is available.

The concept of the GRHI arose from the need to calculate a quantity from whatever geogenic quantities are regionally available. The challenge is to ensure consistency between the GRHI estimates in neighbouring regions if estimated from different predictors. That is, values of the GRHI must be equal between regions with the same objective geogenic controls, but with different data (e.g., in one region, uranium concentration in topsoil and soil granulometry are available, whereas in another region, SRC, soil type, and ambient dose rate). In other words, maps with different input variables must be "stitched together" seamlessly. Optimal prediction of IRC was not envisaged in that first stage of designing the GRHI [45]. Instead, IRC was understood as one of the possible candidates for covariates.

The first attempt to calculate a GRHI was reported by [46–48]. A set of "transfer formulas" to transform point data of SRC (e.g., permeability, uranium concentration in the ground, and ambient dose rate), which are more widely available than SRC and permeability, was reported in [48] into a GRHI. More recently, [49] suggested the attribution of a weight to the classified continuous or categorical input quantities (i.e., the covariates) that reflects its relevance in contributing to the envisaged index. The normalized (ranging from 0 to 1) weighted "mean class" will provide the GRHI, conceived as dimensionless quantity. The weights are the correlations of a covariate with the GRP, estimated in regions where the latter is available (Figure 1). The values of the input variables were associated to a 10 km × 10 km grid, according to the European Atlas of Natural Radiation [9,10], classified in several classes (four, called A to D, in the schematic of Figure 1), and then a weighted mean of the classes was computed. Weights should depend on correlation with a target quantity (e.g., GRP, where available; these regions would serve to "calibrate" the algorithm) and on the reliability of the cell value, quantified by the number (n) of original data aggregated into a cell.

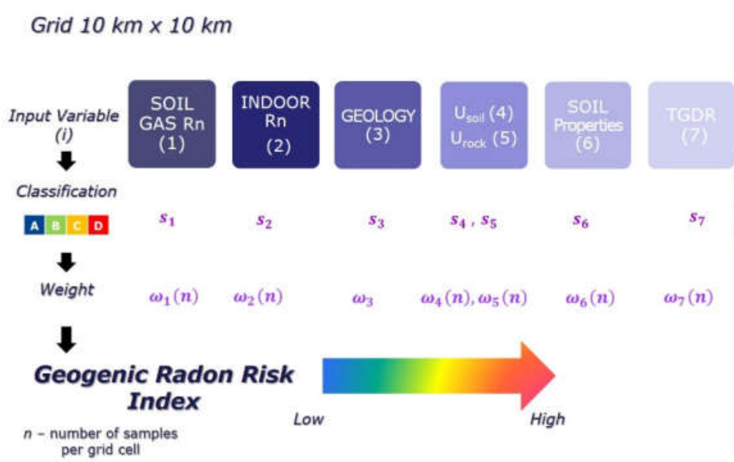

Figure 1. General workflow of multivariate classification approach to construct a geogenic radon hazard index (GRHI) [49]. TGDR—terrestrial gamma dose rate.

A variant without resorting to classification of variables, i.e., leaving numerical variables as they are, has been shown in [50,51]. Covariates were transformed into their distribution functions (percentiles) and weights were defined by their correlation with IRC or GRP.

The application of an explorative statistical technique as performed via a principal component analysis (PCA) on several covariates was developed by [31], thus using the first PC as GRHI. Recent attempts ([32,33,52,53]) utilized machine learning (ML) methods, which are considered particularly powerful for "high dimensional" multivariate settings and in particular, also for confirmative statistical techniques such as spatial regression (i.e., statistical approaches with many predictors).

A certain paradigmatic shift occurred during work on the EURAMET MetroRADON project, which started in 2016. The idea of "sewing" GRHI, estimated separately in various regions out of regionally available quantities, lost prominence against the idea to rely on databases which are available with European coverage. The advantage is that the consistency problem disappears; the drawback is that regional coverage of a quantity may be denser than the global (European) one.

This is the case, most importantly, of the SRC and permeability, which are only available in a few countries, but are certainly very important GRHI predictors (see Section 2.4). Another issue of the newer GRHI conceptualization concerns the roles that the IRC may play and its relation to the GRP (Section 2.4).

2.3. Concept and Desired Properties of the GRHI

The GRHI can be conceptualized in different terms:

- a quantity which measures the contribution of geogenic factors to the potential risk that exposure to indoor Rn causes;
- a quantity which measures the availability of geogenic Rn at surface level;
- a measure of susceptibility of a location or of an area to increased indoor radon concentration for geogenic reasons;
- a measure of "Rn proneness" or "Rn priorityness" (in the logic of the BSS) of an area due to geogenic factors; i.e., a tool to decide whether an area is RPA.

Desired properties of the GRHI are:

(I) consistency, across borders between regions, characterized by different databases used for the estimation; this implies independence of the actual database used,
(II) exhaustiveness, which should reflect as much as possible the available geogenic information;
(III) simplicity, which should be simple to calculate;
(IV) predictor of the IRC, which should be a valid predictor of the geogenic contribution of indoor Rn concentration. This is motivated by its very concept.

These properties can be fulfilled only partly to different degrees by different concepts and are even partly contradictory.

2.4. A Taxonomy of Approaches to Define a Geogenic hazard Index

Over the years, several attempts to define a GRHI have emerged. In Table 1, a tentative classification with some examples is proposed. We identify two conceptually different approaches, termed A and B (see Figure 2), and two variants, denoted by (1) and (2), referring to the exploitation of predictor quantities.

Approach A: Shortcut "geogenic", attempts to construct the GRHI as combination of geogenic quantities such as geochemical concentration, lithology, and soil properties. Some variants include the IRC, motivated by the fact that the IRC also reflects, to some extent, geogenic radon. A combination is performed such that the resulting GRHI represents as much as possible the spatial variability of what is understood as quantifying the availability of geogenic radon for surface exhalation and infiltration into buildings.

Approach B: "Optimal ~ IRC" combines the geogenic variables such that the combination best predicts indoor radon, meeting given criteria. The GRHI is the predicted value, optionally normalized e.g., to [0, 1]. Deviations between predicted and observed IRC are owed to data uncertainty (predictors and IRC), model uncertainty, and additional non-geogenic, i.e., anthropogenic controls of the IRC. The logic is summarized in Figure 2. In all cases, the models are built from all predicting data available in a domain. In some versions, only regions with sufficient data are used for model building.

Variant (1): "Global" or "bottom up", means that the model can be applied only at locations where all predictors and response variable are available. This is typically the case for regression models and models based on physical reasoning. Global models produce consistent results (property I, see Section 2.3) by default.

Variant (2): "Local" or "top down", denotes models that can also be applied if regionally or locally, only some predictors are available. Consistency of results between regions in which different sets of predictors are available is the big challenge of this variant.

Table 1. Taxonomy of GRHI definitions. See Section 3.3 for more details.

	A "Geogenic"	B "Optimal~IRC"
(1) "global"	[54] physical reasoning leading to the radon availability number (RAN). [55–57] classification of factors related to lithology, soil characteristics, relief, soil cover, sealing of the ground, and other. [58,59] cross-classification of control factors SRC, permeability. [60] Classification of lithology, U concentration, and presence of features like faults and mines. [61,62] Classification of geology and ADER. [31] Principal component analysis (PCA) of various geogenic factors. [63] regression of Neznal-GRP vs. soil U concentration, IRC, and ADER. [64,65] Integration of hierarchical multicriteria analysis and GIS, SMCDA, incorporating various geogenic variables.	[14] Neznal-GRP, method: regression IRC vc. SRC and permeability classes [42,66] Neznal-GRP, application [67] logistic regression of IRC vs. lithological classes, TGDR, permeability, faults. [32] ML regression IRC vs. many geogenic predictors (geochemistry, soil properties etc.) [68] Regression IRC vs. many geogenic predictors (geochemistry, soil properties etc.) Multivariate classification through contingency tables: a possible method, no references so far.
(2) "local"	[69,70] multivariate classification: U.S. EPA approach; missing values allowed. [47] transfer models to estimate GRP from various geogenic quantities. [49] weighted mean of classified quantities, see Figure 1. [50] correlation of various geogenic quantities with Neznal-GRP.	[50] correlation of various geogenic quantities with IRC

Approaches A (geogenic) have in common that a kind of weighted mean of predictors is constructed. The weighting may be implicit if in bi- or multi-variate scoring combinations of levels of categorical predictors are assigned certain GRHI levels. Often this seems to be done based on experience about the influence of a certain predictor. In other cases, the weights are defined as correlation coefficients between predictors, via principal component analysis (PCA), or by hierarchical analysis (SMCDA).

Approaches B can be characterized as generalized regressions; among them, traditional multivariate linear regression, general linear model (including categorical predictors), and machine learning (ML, among them, MARS, random forests, and support vector machines).

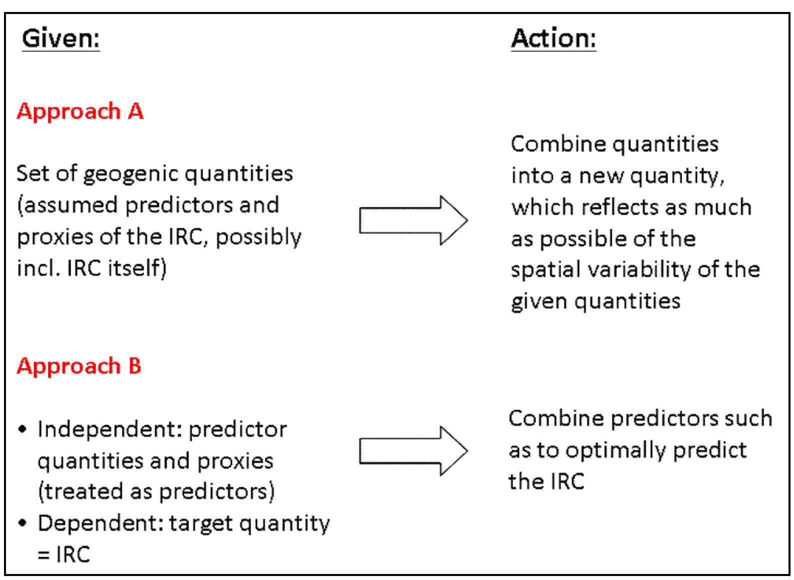

Figure 2. Approaches A and B.

The desired properties, Section 2.3., are fulfilled to different degrees by these approaches and their variants:

The consistency property (I) is automatically fulfilled by variant (1) in the domain in which it is defined. For variant (2), this remains the crucial challenge.

Exhaustiveness property (II) is easier to fulfill for variants (2) than for (1), because for (2), local databases can also be exploited. Whether they are depends on the sophistication of the model.

Simplicity (III) is difficult to achieve for high-dimensional datasets and if spatial modelling is included. Easy for empirical classification and simple regression models.

Predictor of the IRC (property IV) is fulfilled by default by approach B since the models are defined, by virtue of the regression paradigm, as yielding optimal predictors; how good they are differs between models. For models according to approaches A, this has to be checked afterwards.

This is summarized in Table 2.

Table 2. Compliance of approaches A and B and variants (1) and (2) with the desired properties of the GRHI.

	A + (1)	**A + (2)**	**B + (1)**	**B + (2)**
I consistent	yes	difficult	yes	difficult
II exhaustive	no	yes	no	yes
III simple	some not simple	relatively simple	some not simple	relatively simple
IV predictor IRC	to be checked	to be checked	yes	yes

3. Methods

3.1. The Geogenic Radon Potential Compared to the Geogenic Radon Hazard Index

The strict GRP concept consists of building a variable that reflects the Rn generation and transport processes based on their physical knowledge. This quantity is understood as location specific and scale-dependent or, in geostatistical terminology, having a point or block support, e.g., the 10 km × 10 km grid cells used in the European Atlas of Natural Radiation.

The physically most straightforward definition may be

$$GRP = SRC \times k \quad (2)$$

which is the advective Rn flux normalized to the pressure gradient through an interface. It neglects diffusive transport, which is fair except for soil with very low permeability.

The most commonly used definition, the Neznal-GRP [14], already has some traits of the GRHI (type B) because it is derived from matching a combination of SRC and permeability, aggregated into classes, to classes of the IRC by a kind of regression procedure. However, mapping the GRP requires datasets of soil Rn concentration SRC and permeability k, which are only available in few countries, see Sections 2.1 and 2.2.

While the GRP is derived from physics of Rn generation and transport, encompassing SRC (representing Rn source) and k (representing Rn transport), the GRHI is an extension which takes advantage of whatever geogenic quantity is available to quantify Rn availability at the surface and its potential to infiltrate into buildings (Section 2.3). Thus, GRP definitions may be considered as a sub-set of GRHI definitions.

3.2. Databases

To our knowledge, databases available on the European scale, covering almost the entire continent, include:

- Geological maps:
  OneGeology [71] (Developed by EuroGeoSurveys' European Geological Data Infrastructure within the framework of the GeoERA programme, 2018);

IGME 5000: 1:5 Million International Geological Map of Europe and Adjacent Areas [72,73];
Map of the World karst areas [74];
Global Active Fault database (GAF) [75].

- Soil properties: LUCAS database [76]; the database includes the following quantities (among others): topsoil fine fraction (as proxy of the soil permeability); available water content (AWC) (proxy of the soil porosity), chemical properties [77]. Another database of soil information is SoilGrid, containing global data estimated on a fine grid by machine learning [78].
- Geochemistry: GEMAS [79] and FOREGS [80], from which European uranium, thorium, and potassium maps have been created during the work on the European Atlas of Natural Radiation ([9,10] and references there).
- Aquifers (International Hydrogeological Map of Europe (IHME) 1:1,500,000) [81].
- Ambient dose rate: Across Europe, more than 5000 automatic stations continuously monitor ambient dose rate (ADR) as part of national radiological emergency warning systems. The data are stored and displayed by European Radiological Data Exchange Platform (EURDEP) [82,83] and the EANR. Normally, the ADR represents the natural background, of which their terrestrial component ([84]) is mainly due to natural radionuclides U, Th (more precisely their progeny), and K. Therefore, ADR is a proxy to geogenic radon (see below). A problem is that the data originate from technically different systems of which their harmonization is difficult.

Some examples of regionally available databases are:

- Ambient dose rate (ADR): e.g., Spain [85], the Czech Republic [86], Portugal [87], part of Germany [88,89];
- Saturated soil water content: Germany [90];
- Groundwater recharge coefficient: Ireland [91,92];
- Airborne gamma ray spectrometry: Ireland (Tellus project [93]).

Legends of geological maps are often simplified into lithological units which show similar geochemical characteristics and can be merged even though they are characterised by different stratigraphic positions (for example, Jurassic and Cretaceous limestone). The geochemical merging of lithologies is necessary to have sufficient IRC or SRC sample size per geological unit or for computational handling. In an example shown in [94], 178 units of the One Geology map were simplified into 28 units following a scheme proposed by [95].

Given that Rn availability at the surface is physically controlled by Rn source and Rn transport, the estimate of the Rn source term can be reasonably obtained by using geochemistry and geology, as geochemical surrogate. The estimation of Rn transport is, however, more problematic. Although no European database of soil permeability exists, there is hope that soil properties, hydrogeology, and tectonics may serve as proxies of permeability or in general, to emulate the Rn transport in the ground.

Predictors can be exhaustive in the sense that at every point of the domain (e.g., Europe), a predictor value is available. This is typically the case for categorical predictors such as geology, which is available as a map covering the entire domain. Others are available as finite sets of discrete point samples, typical sets of measured soil, or indoor Rn concentrations, geochemical concentrations, ADR, etc. These are sometimes made exhaustive by geostatistics (interpolation) before they can be used further. Other methods have this geostatistical trait intrinsically, typically some machine learning methods.

Conceptually, one distinguishes between proxies (or surrogates) and physical predictors (Figure 3). The latter are ones that are in a causal relationship with the target variable, e.g., uranium concentration in the ground as a physical direct predictor of SRC. Proxies are ones that are statistically related to the target, but not directly linked by physical causality. An example is terrestrial component (TGDR) of ambient dose rate (ADR) as Z_1 in the figure, which is statistically related to IRC (=Z_2) because both share the same predictor, namely the uranium content in the ground (Z_0). However, both ADR and IRC are also influenced by other variables, e.g., ^{137}Cs fallout and Th concentration in soil (Z_0''' and Z_0'') influencing dose rate and ground permeability (Z_0'), the IRC; therefore, their correlation is weak.

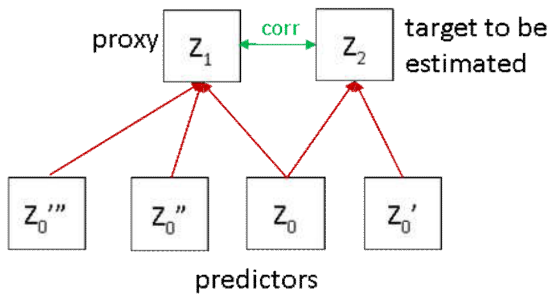

Figure 3. Physical predictors and proxies (see text).

3.3. Estimation Methods

Whichever definition of GRP or GRHI and whichever approach is chosen, the problem remains to estimate these quantities at a certain location or area. Since they cannot be measured directly, they have to be calculated from other quantities. The focus is on extracting information from several, or in some methods, many, regionalized databases. Putting it most generally, at each target point (or spatial target unit, such as pixels or whichever mapping support intended) of the mapped domain, one obtains the GRHI value by combining available data appropriately, where the criterion for appropriateness is different for approaches A and B. With most methods, spatial (or location) dependence of GRHI(x) is implicitly assured by one of its predictors. However, some methods additionally include location (coordinates) as *explicit* predictors. In the case of type B approaches (optimal predictors of IRC), the GRHI would be defined as the model outcome, with the understanding that the residuals IRC (observed)—IRC (modeled) represent anthropogenic factors and factors not accounted for by the geogenic predictors.

3.3.1. Concepts Type A

3.3.1.1 Multivariate Classification

Levels of categorical covariates are combined into levels of the categorical target variable. For example, geological units are levels of the predictor “geology”, in this case, unordered levels—such a variable is called nominal; permeability classes are levels of permeability, in this case, ordered levels—the variable is called ordinal. The target variable can be, for example, GRP classes (ordinal). To a large extent, combination rules are empirical, based on experience.

As an example, in the Czech Republic, a rule has been established to assess the risk class of a location based on cross-tabulation of classes of SRC and permeability [14]. The U.S. EPA [69,70] proposed a scheme incorporating IRC, geological evidence, permeability, U concentration (by airborne gamma ray spectrometry), and “architecture type” (kind of foundation). Missing data are possible, leading to lower confidence of the index value; therefore, the method has been classified into “local” in Table 1, where other examples are also quoted.

3.3.1.2 Principal Component Analysis (PCA)

In a high-dimensional setting, such as for the prediction of geogenic Rn from many potentially predicting quantities, one would first attempt to identify the amount of information that the set of covariates actually contains; many of the predictors tend to be correlated between themselves, hence carrying redundancy. Principal Component Analysis (PCA) is a well-known, explorative method of which its main objective is to reduce the data complexity with minimal loss of information and to create a set of new uncorrelated variables (factors) linearly linked to the original ones. They are arranged such that most information is contained in the first or the first two or three factors.

PCA has advantages and disadvantages. The advantages are: (i) there is no response variable and all variables are, in theory, of equal importance; (ii) it reduces the number of variables to be further considered.

The disadvantages are: (i) principal components as new variables are less easy to interpret than the original ones; (ii) there is no test to verify the goodness of the results; PCA is an exploratory analysis with subjective interpretation, although there are rules for reading the variables in the factorial space; (iii) the number of retained factors must be selected with great care in order to not discard essential (for a given objective) information contained in the original variables; (iv) in classical PCA, only numerical covariates can be included, but not categorical—in particular, nominal ones. Detailed descriptions of PCA technique can be found in [96] and references therein and [97].

The GRHI can be defined as the first PC or as a combination of a few components with highest weight. Regionalization is performed along the line explained at the end of the following sub-section.

3.3.1.3 Transfer Models

A set of formulas or rules is established that transforms available variables into a GRHI; they are of the type GRHI = f (Y_1, …, Y_n); if predictor Y_i is not available, estimate it from different variables U_i as $Y_i = f_{(i)}(U_1, \ldots, U_k)$ and so on. Rules are look-up tables, which associate a level of a categorical variable with a needed Y_i; (e.g., factor = geology, level i of this factor = L_i = quaternary sediment, which has Y_j = mean soil Rn concentration value y_j = 20 kBq/m^3). The transfer formulas are deduced from studies about relationships between geogenic variables.

The idea is to take advantage of whatever data are available in a region. The evident problem is consistency between two neighboring regions, which are physically identical (same geology, same soil type, same geochemistry etc.), but in which different predictors are available and in which the GRHI therefore has to be estimated differently. The consistency problem is visualized in Figure 4.

Two ways of regionalization are conceivable, i.e., establishing the GRHI as spatial function GRHI(x) for every point (or spatial unit) x of the domain. (1) For discrete sample type predictors, estimate them at every needed point of the domain, usually by geostatistical means, and build GRHI(x) = f ($Y^*_1(x)$, …, $Y^*_n(x)$), $Y^*(x)$ the interpolated value. Alternatively, (2), calculate GRHI(x_i) at points x_i, where predictors are available, and afterwards subject GRHI to geostatistics to obtain interpolated GRHI* (x) for every x.

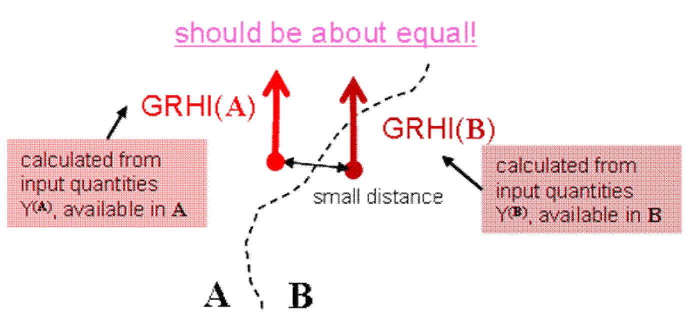

Figure 4. Consistency between quantity GRHI calculated in regions A and B from different sets of predictors, $Y^{(A)}$ and $Y^{(B)}$.

3.3.1.4 Spatial Multi-Criteria Decision Analysis (SMCDA)

GIS-based (or Spatial) MCDA (SMCDA) is a set of procedures that can be used to combine criteria maps (i.e., variable layers) with respect to their relative importance and derive relative weights for the criteria [98,99]. In the context of this work, SMCDA involves combining and handling of different criteria that determine the presence of RPAs, then uses the Analytical Hierarchy Process (AHP) [100] to assess their relative importance and derives the weights for each criterion; then, the final suitability scores ([65]) are calculated by using the weighted linear combination (WLC) of original criteria maps [101]. A more elaborate example is shown in [65].

SMCDA is an explorative technique; it does not make use of a response variable and of validation techniques. SMCDA involves subjectivity (e.g., in choosing the criteria and defining the relative importance of each factor). Result validation can be provided by direct measurements and by sensitivity analysis ([102,103]). Some SMCDA versions can be understood as mathematically optimized multivariate classifications. The technique was developed to help decision makers in sustainability planning and to provide outputs to be easily understood by non-experts. The method has also been applied for finding best consensual solutions in cases of stakeholder conflicts, e.g., [104]. It could be that it can be applied to RPA delineation, including under the constraints of conflicting stakeholder interests, which is a big political issue as current experience shows.

For further resources, see e.g., [105–109] and the Wikipedia entry "Multiple-criteria decision analysis".

3.3.2. Concepts Type B

3.3.2.1 Multivariate Regression (MR)

Regression means, to find the expected value EZ of a response, dependent, or target variable Z, given (or: conditional to) one or several predictors or independent variables Y. This is done by minimizing a loss function, originally the sum of squared deviations of observations z from predicted or estimated $E(Z \mid Y = y)$. The theory has been developed for two centuries, with abundant literature available, and shall therefore not be repeated here. Variants include categorical predictors (general linear model) and non-linear link functions between Z and Y and non-Gaussian error models (generalized linear regression); most importantly, logistic regression, aimed to predict a binary variable (a condition fulfilled or not) or a probability. Among important problems are collinear and nested predictors (i.e., the independent variables are dependent among them), which can invalidate analyses. Including location (coordinates) as predictor leads to the reasoning of geostatistics. Regionalization to obtain Z(x) for every point x in the domain proceeds along the lines described above.

3.3.2.2 Machine Learning (ML)

This class of methods took their name from the idea that the physical structure that underlies a dataset (which can be understood as realizations of a true physical process) shall be recovered from the data themselves, without stipulating a model. The rationale is that in complex situations (many predictors or covariates, related among them, etc.), this model is not only badly known, but is actually difficult to write down explicitly because of its complexity. Instead, the algorithm identifies patterns in the data which are observable representations of the physical reality, which approximate the physical model by numerical decision rules. Once recognized, the patterns can be used to predict a response (e.g., IRC) from observed predictors (e.g., geology, uranium concentration in the ground, climate, …). In this sense, ML is a type of regression without a specified regression model. The conceptual difference against regression is visualized in Figure 5. A standard textbook on ML is [110].

In radon science, ML has first been used, to our knowledge, by [53,67] and [52] for spatial settings and by [111] in time series analysis. Current work at the BfS aims to improve regional GRP and IRC prediction by including high numbers (up to 100) of potential predictors [32].

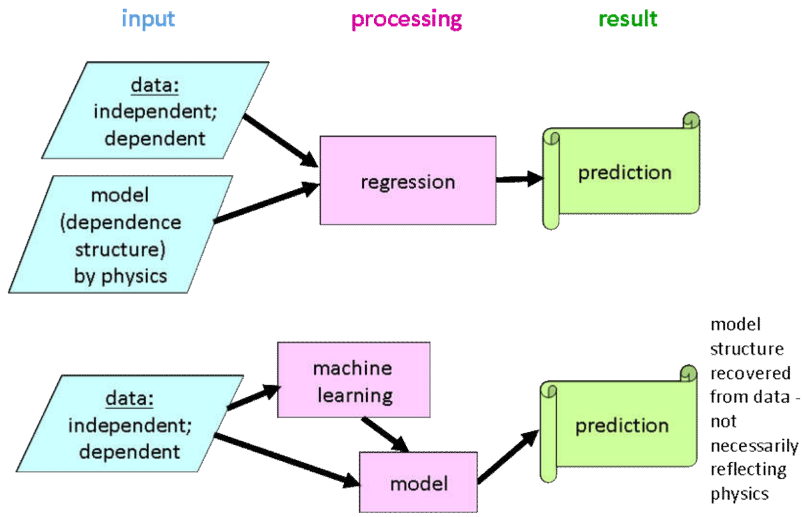

Figure 5. Conceptual difference between classical (generalized) regression and machine learning.

ML offers the possibility to include location (parameterized by the coordinates) as covariates. For Rn estimation, trials at the BfS seem to show that this does not lead to improvement, probably because sufficient spatial information is already contained in the regionalized predictors.

4. Exemplifying Preliminary Results

So far, no authoritative GRHI map exists on a European level. However, sevd m neral attempts have been made to explore the potential of different approaches. Some are shown in this section. Note that these are trials only, of which their objective is to acquire experience with methodology without authoritative relevance.

The maps shown in the following section have certain patterns in common, but also important differences. There may be several reasons for this, from lack of data to misspecification of the model structure or the algorithm.

Maps reported in 4.1 (Figure 6) and 4.4 (Figure 10) belong to approach A, whereas maps of

4.1. Geological Classification

The very first trial was made by [112,113]. Geological units taken from OneGeology were coded or "calibrated" according the Neznal-GRP for units where data were available, mainly in the Czech Republic, Germany, and Belgium. Regions that could not be coded in this way have been left blank in Figure 6. Classes were defined deliberately.

Evidently, this approach suffers from (1) lack of data and (2) the fact that "extrapolating" from units where GRP information is available to nominally the same or geologically similar geological units, but without data, is questionable.

The general geographical pattern is very similar to the one of the European Indoor Radon Map [9,10], as of course it must be, but no correlation analysis or validation was attempted because this trial was a technical feasibility study only. Class 1 is the lowest and 4 is the highest GRHI.

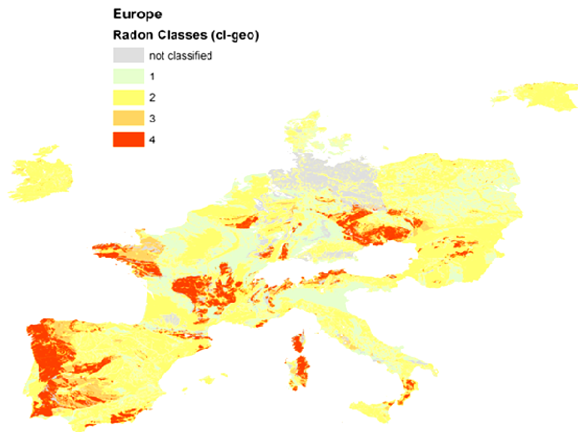

Figure 6. Classification of geological units according to the Neznal-GRP; from [112].

4.2. Multiple Regression

The result was first shown in [68]. Starting with about 100 predictors (database references in Section 3.2):

- Geochemistry: A combination of FOREGS and GEMAS databases, 59 elements; missing uranium values estimated by lanthanum and cerium because these elements are highly correlated; about 5000 data points in Europe.
- Soil properties: from LUCAS; point data projected to geochemical data points by geostatistics. Fine fraction tentatively defined as

$$FF = (\text{clay} + \text{silt} + 0.05\ \text{sand})/(100 + \text{coarse fraction}) \quad (3)$$

as permeability proxy (the definition is debatable);

- Geology: IGME 5000.

Through trying (among others, by inspecting correlations between variables), for further analysis, the set of covariates was reduced to pH, TOC, FF, CF (coarse fraction), soil bulk density, ln(U), K_2O, Al_2O_3, SiO_2, Fe_2O_3, CaO, and geo1; with geo1 = {carbonate, meta-sediments, siliciclastics, Cenozoic sediments, basic igneous rocks, intermediate igneous, pre-Variscan acid igneous; Variscan acid igneous, post-Variscan acid igneous}.

The target variable is AML of the European Atlas of Natural Radiation (AML = AM_{cell}[ln(IRC)] = arithmetic mean of the logarithms of IRC within 10 km × 10 km cell), interpolated to geochemical locations, i.e., AML in hypothetical cells around these locations.

Applying a general linear model with stepwise elimination of irrelevant covariates (F-test) led to {geo1, FF, pH, bulk density, K_2O, ln(U)} as the best predictor, which explains r^2 = 26% of variance. Inclusion of annual mean temperature would increase this to 29%.

The model f(Y)(x) (Y—vector of covariates, x – location) was subjected to ordinary kriging to the original Atlas cell locations and the results quantile rescaled to [0,1] by $z \longrightarrow F_Z(z)$. Different rescaling is equally possibly, e.g., by linear rescaling, $z \longrightarrow (z-z_{min})/(z_{max}-z_{min})$, tgh, or nscore transforms. The result is shown in Figure 7. In the map, 0 is the lowest and 1 is the highest GRHI.

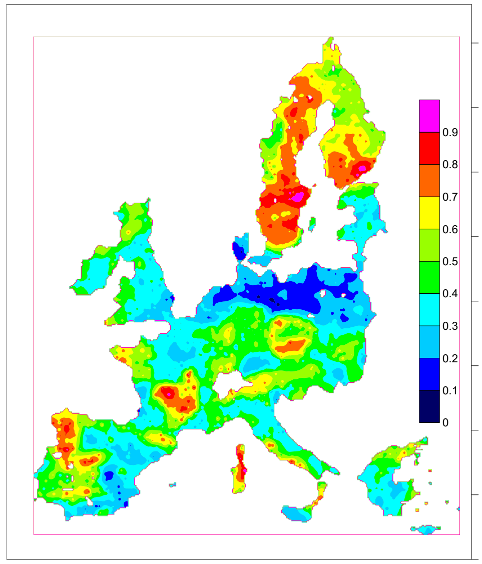

Figure 7. GRHI map created by multiple regression (from [68]).

4.3. Machine Learning

The algorithm Multivariate Adaptive Regression Splines (MARS) (an introduction can be found in [110] and [114]) creates piecewise linear models where each predictor models an isolated part of the original data. For this purpose, each data point for each predictor is evaluated as a split candidate by creating linear regression models. The contribution of the individual terms in the model is evaluated based on the generalized cross-validation (GCV) statistic. In this study, the implementation in the "earth" package [115] in R was used.

The target variable was AML (like above), but only 10 km × 10 km cells with $n > 30$ original indoor Rn data were used for training the model. The model was fitted using >100 candidate predictors using the model inherent predictor selection. The hyperparameters of the final model are degree = 1 (i.e., no interaction between variables) and nprune = 83 (i.e., 83 terms in the final model). The selected predictors comprise:

- Geology: IGME 5000: lithological unit (attribute "Portr_Petr", 92 classes);
- Hydrogeology: IHME 1500 ([116]): attribute "Litho level 2" (85 classes);
- Soil: regions of Europe (285 classes) ([117]);
- Soil physical properties [76]: Silt content, Clay content, available water capacity, bulk density, coarse fragments;
- Soil hydraulic properties: hydraulic conductivity [118]: Saturated hydraulic conductivity (at depths 0 cm, 60 cm, and 200 cm);
- Location: Longitude and latitude.

The result is shown in Figure 8 (first in [68]). The calculated values were linearly rescaled to [0,1], like above. For multiple regression and ML, the pattern is very similar to the one of IRC, which was of course to be expected because IRC is the independent variable in the models. The ML method performed very well with $r^2 = 0.52$ between predicted and observed AM (IRC per 10 km × 10 km cell) of the test dataset (which has not been used for model building). Again, 0 is the lowest and 1 is the highest GRHI.

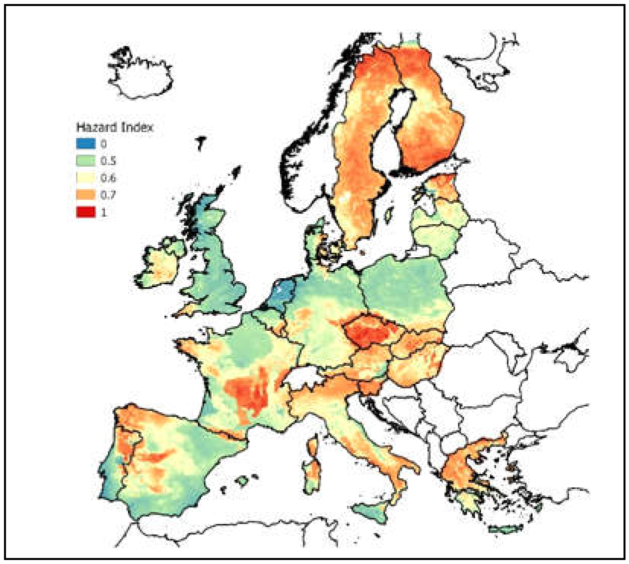

Figure 8. GRHI map created by machine learning (MARS) (from [68]).

However, the model building procedure applied for ML in this study has some limitations, namely

(1) categorical predictor data (geology, hydrogeology, soil regions) could be re-classified with respect to Rn to reduce the classes and the risk of over-fitting.
(2) no external predictor selection procedure was applied, only the model inherent predictor selection. This might result in the appearance of non-informative predictors in the final model and might cause over-fitting.
(3) The cross-validation procedure in this study (stratified sampling) did not account for spatial auto-correlation in the data. This might produce a too optimistic r^2 as a consequence of spatial auto-correlation because test data might be within the correlation length of training data (see [119] for details). Therefore, independence between training and test data is not guaranteed. In newer versions (currently in work), spatial cross-validation is being implemented.

Further, it should be noted that other ML algorithms, especially ensemble techniques (e.g., random forest) might be more powerful than MARS for modelling a noisy target variable such as IRC. Nonetheless, the ML result presented in this study indicates the potential of ML for GRHI mapping and will be even more robust when the previously mentioned methodological specifications will be implemented.

4.4. Principal Component Analysis

Reference [31] explored dimensional reduction by PCA of the following set of variables:

- Geochemistry: GEMAS + FOREGS, U, Th, and K, as in the European Atlas of Natural Radiation.
- Soil properties: Fine fraction FF in topsoil from LUCAS, as in the Natural Atlas.
- Tectonic fault lines: global fault layer from ArcAtlas, ESRI; areal density.
- Earthquake epicenters: [120].
- Geothermal and volcanic areas: in terms of heat flow (the heat flow map of Europe has been obtained by analyzing the Global Heat Flow (International Heat Flow Commission of the International Association of Seismology and Physics of the Earth's Interior, IASPEI).

Note that indoor Rn (IRC) is not among the variables, nor is soil Rn (SRC). All data were projected into the 10 km × 10 km grid of the European Atlas of Natural Radiation; map of the heat flow was obtained by kriging point data; maps of the fault and earthquake density were obtained by kernel density estimation; maps of the FF, uranium, thorium, and potassium were available from the database of the European Atlas of Natural Radiation. Values of the variables were assigned to the 10 km × 10 km grid centroids in order to obtain the dataset for the PCA. The raw (unrotated) PCA result is shown in Figure 9. One can recognize two essential groups: (U, K), which represent the source term and FF, faults etc., which represent transport properties.

The GRHI at point x is defined as

$$GRHI(x) = \sum_{(\text{over variables } j)} w^{(1)}_j \, y_j(x) \quad (4)$$

where $y_j(x)$—value of variable j (e.g., U concentration etc.) at location x, $w^{(1)}_j$—loading of variable j in the first principal component = abscissa (F1) value in Figure 10.

The resulting GRHI is mapped in Figure 10. While the expected geographical pattern is partly apparent, it does not seem appropriate in other parts of Europe, notably Scandinavia, the Bohemian Massif, and the Pannonian Basin, if compared to the maps in Figures 7 and 8. The difference is owed to the fact that it is generated by a different approach, namely A instead of B.

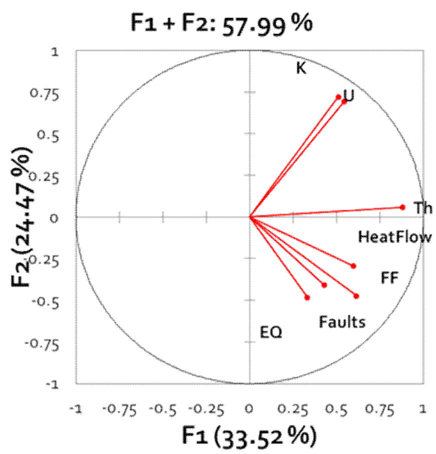

Figure 9. Raw PCA result. Loading plot, showing the coefficients of each variable for the first component versus the coefficients for the second component. This graph shows which variables have the largest effect on each component. Percentages: Explained variance (in percentages) of first principal components F1 and F2 (From [30]).

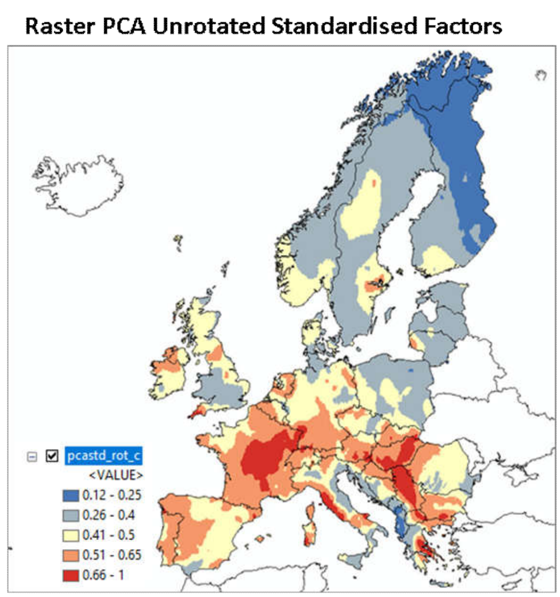

Figure 10. GRHI map derived from the first principal component (From [30]).

5. Conclusions

Mapping geogenic radon appears to be neither a straightforward nor a technically easy task. The reasons lie in its definition; in particular, would we like to first capture the geogenic variability (approach A) or optimal predictability of indoor Rn (approach B)? Furthermore, concerning the estimation technique, which technique to use? How will various predictors be included?

Different trials for approximately the last 10 years led to variably satisfying results, but in any case, served to gain experience with different approaches and techniques. The first version of the European Atlas of Natural Radiation did not include a European map of geogenic Rn because it was felt that the concept and techniques were not yet sufficiently developed. It seems that we are now converging towards a robust European geogenic Rn map, or perhaps several, reflecting different properties, represented by approaches A and B, which both have their justifications.

At the moment, it seems that of all the methods investigated, for approach A ("geogenic"), the most promising method is PCA, while for B ("optimal to IRC"), machine learning is most powerful, but methodologically has not yet been fully explored. However, further multivariate methods should be explored, notably spatial multi-criteria decision analysis for A and B and varieties of PCA, for approach A.

We hope that this work serves as an incentive for further research. We see two open fields:

Conceptual: Refinement of GRHI definitions; specify which definition serves which purpose. Probably different definitions will lead to different maps. In the end, different definitions should be given different names to avoid confusion.

Technically: improvements are certainly possible in existing methodology, but it would also not be a big surprise to see new methods appearing, given the current dynamic in radon science.

The main motivations behind conceiving the GRHI are (1) to create a unified measure of the natural availability of geogenic radon which can be estimated from different types of geogenic quantities and (2) to generate a methodically homogeneous European-scale map of geogenic radon. Consequently, methods and results shown here were tailored to exploit databases that cover most of Europe. However, there is no reason why the same rationale should not be applicable on a regional scale, possibly in higher resolution.

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Acronyms

AD(E)R	ambient dose (equivalent) rate (usually nSv/h or μSv/h, ADR also nGy/h)
AM	arithmetic mean
BSS	Basic Safety Standards
EANR	European Atlas of Natural Radiation
FF	fine fraction of soil matter (dimensionless)
GIS	Geographic information system
GRHI	geogenic radon hazard index (dimensionless)
GRP	geogenic radon potential (usually treated as dimensionless value)
IRC	long-term mean indoor radon concentration (usually Bq/m^3)
k	gas permeability of the ground (m^2)
MARS	multivariate adaptive regression splines
ML	machine learning

MR	multivariate regression
PC(A)	principal component (analysis)
ReV	regionalized variable; variable which refers to a location
RL	reference level of indoor Rn concentration, according the BSS
Rn	radon; here Rn-222
RPA	radon priority area: area, in which a high fraction of indoor spaces has or is expected to have IRC above the RL, and in which particular action according BSS has to be taken.
SMCDA	spatial multicriteria decision analysis
SRC	soil radon concentration (usually kBq/m³)
TGDR	Terrestrial gamma dose rate (usually nSv/h or nGy/h), terrestrial component of AD(E)R

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16ENV10 MetroRADON

Activity 4.4.2

Radon mapping exercise

Lead organisation: Austrian Agency for Health and Food Safety (AGES)

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EMPIR EURAMET

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Inhalt

1. Motivation

The purpose of the MetroRADON project, funded within the European Metrology Programme for Innovation and Research (EMPIR) is to develop reliable techniques and methodologies to enable SI traceable radon activity concentration measurements and calibrations at low radon concentrations. The need for this project has been largely motivated by the requirements of the implementation of the European Council Directive 2013/59/EURATOM (EU-BSS) (EU, 2014), one aim of which is to reduce the risk of lung cancer for European citizens due to high radon concentrations in indoor air. Furthermore, it is a goal of the project to enable uptake and exploitation of its results and experiences by all stakeholders concerned with radon, from regulators and policy makers, professionals in designing, performing, evaluating and interpreting radon surveys, radon instrument manufacturers to the construction industry and scientific community. More details about the MetroRADON project can be found at the project website (MetroRADON, 2020).

Article 103 of the EU-BSS requires, that member states identify areas where the radon concentration in a significant number of buildings is expected to exceed the relevant national reference levels. Those areas are in practice referred to radon priority areas (RPA). Definition and delineation of RPA is relevant, as specific (mandatory) measures of the radon strategy of countries depend on it (e.g. radon measurements at workplaces, preventive measures, awareness programs). Therefore, the delineation of RPA is an important tool within the transposition of EU-BSS and radon action plans in the countries, which should be implemented appropriate, accurate and reliable.

A specific work package is included in the MetroRADON project with the aim to analyse and develop methodologies for the identification of radon priority areas. As the definition of RPA in the EU-BSS allows a wide range of interpretation, different concepts and methodologies have been proposed and some already adopted. One activity of the work package is to evaluate the concept for RPA and methods of radon mapping which are already used in different countries and their usage for other countries and the harmonisation of radon priority areas across borders.

Within this framework, an activity carried out within the MetroRADON project was, to apply existing mapping methods used in different countries using harmonised data sets of various variables (e.g. indoor radon, gamma dose rate, geology, soil gas radon). The activity was focused on evaluating their comparability and their usability for other countries and is referred to as “the radon mapping exercise” and discussed in this report. The results and findings from the exercise will be included in the discussion of possibilities of harmonisation of RPAs across borders and incorporated in a guideline on the definition, estimation and uncertainty of radon priority areas for MetroRADON stakeholders.

2. Introduction

2.1 Mapping methods and radon priority areas

Radon mapping and definition of radon priority areas (RPA) are very complex topics. As discussed above, the definition of RPA in the EU-BSS allows a wide range of interpretation and therefore different concepts and methodologies have been proposed and, in some countries, already adopted. Radon mapping was also relevant already before the new EU-BSS, so in many countries, radon maps exist for many years as part of the national radon strategies. The used mapping methods and the visualisation are very different, depending on the purpose of the map and the data behind it. These different methods are based on different developments, strategies and ideas in radon protection for many years in the countries, and most of the time the basic mapping strategies and methods applied in a country remain the same, even when revised or new legal requirements apply. Consequently, a basic bottom-up harmonisation approach of mapping methods or definition of RPA will not be enforceable. Therefore comparison, evaluation and discussion for possibilities of top-down harmonisation are important.

As a starting point for this "radon mapping exercise" report, some basic information about different possible and used radon mapping methods and definitions of RPA is given, for better understanding of the situation and framework of the radon mapping exercise.

As said, radon mapping can be done (and is done in practice) with various different methodologies. The methodologies are composed of different parts, like the mapped parameter (P), the mapped unit (U) and the used display method (D). Table 1 shows an overview of possibilities for the mentioned three parts of the methodology (no guarantee to be complete!). The mapped parameter can be either the raw measurement value of e.g. indoor radon concentration or soil gas radon or an already processed (e.g. normalised) measurement value (e.g. application of seasonal correction factor, taking into account building characteristics) or a combination of different parameters (e.g. often used geogenic radon potential, defined by soil gas concentration and permeability). The units can be administrative unit, a regular grid cell or geological unit. For display methods either simple descriptive statistics like arithmetic or geometric mean of the parameter or the percentage of houses in a certain unit, which exceed a certain threshold (e.g. the reference level) can be used. Also, qualitative risk classes could be applied (e.g. parameters are classified according to risk classification scheme) or a risk index defined (e.g. classification of the different parameters and combination for an overall index to classify). The options (1-3 or 1-5) within the three different parts (U, P, D) can be combined with each other – so there are various possibilities of different overall mapping methodologies, as we can see also in practice.

Some applied examples in countries: Austria was following (and will also follow in the future for the planned new radon map and delineation of RPA) the scheme U1-P2-D1, with standardised indoor radon measurements (use of standard house), averaged for a municipality (Friedmann, 2005). Several countries follow the scheme U1/2-P1-D2/3, by using the indoor radon measurement values and displaying the percentage or probability of houses above the reference level per administrative unit or grid cell. This method is very common, as it reflects most directly the definition of the EU-BSS – areas, where the radon concentration in a significant number of buildings is expected to exceed the relevant national reference levels. But using this methodology for an accurate delineation of RPA needs a high number of representative measurements in the respective grid cells or administrative areas. A simplified display method is to use risk classes (e.g. low, medium, high risk), which can be defined by different input parameter. USA uses a risk index (multivariate classification) for radon mapping, following the scheme U1-P3-D5, taking into account indoor radon measurements, geology, air-borne gamma ray spectrometry , soil parameters and foundation types with classification on county level. Each parameter is classified according to defined criteria and then the classification of all parameters is summed up to a risk index (EPA, 1993). The concept of a geogenic radon risk index with multivariate classification is also discussed for Europe with scheme U2-P3-D5, driven by activities by the European Commission, Joint Research Centre (JRC) (EC JRC, 2020; Bossew et al., 2016) and to further develop this (Radon Hazard Index, RHI) also a main aim of this work package of the MetroRADON project.

Table 1: Overview of possible radon mapping methodologies

Unit (U)	**Parameter (P)**	**Display method (D)**
1 - Administrative Unit (e.g. municipality)	1 - Measurement value (e.g. indoor concentration)	1 - Descriptive statistics (e.g. mean, med, max)
2 - Grid cell	2 - Modelled value (e.g. seasonal correction, reference house)	2 - % of houses/measurement values above RL
3 - Geological unit	3 - Combination of different parameters (e.g. radon conc., geology, permeability)	3 - Probability that RL is exceeded
		4 - Risk classes (qualitative)
		5 - Risk index

Besides the mapping methodology, each country has to decide about a definition of RPA. A threshold needs to be set, when an area (e.g. administrative unit, grid cell) is considered to be a radon priority area. In the EU-BSS it says “areas, where the radon concentration in a significant number of buildings is expected to exceed the relevant national reference levels defined in the EU-BSS”. What is considered to be a significant number of buildings needs to be decided by the countries and will be dependent on the radon potential of the country and on economic and political considerations, as the measures dependent on delineation of RPA need to be also manageable. Therefore also for the definition of RPA different concepts are adapted in the countries, some examples are listed in Table 2 (not complete list). Several countries define RPA with a threshold of 10% of houses above the respective RL, but also 1% (UK) and up to 30 % (Czech Republic) are used. Some countries, e.g. Austria, do not refer their RPA to the percentage of houses above RL, but use descriptive statistics in administrative units instead.

As shown, the mapping methodologies are various and so are the definition of RPA - to evaluate the situation in Europe and possibilities for harmonisation between countries and on borders was the driving factor for this work package within the MetroRADON project and also for this mapping exercise.

Table 2: Examples of radon priority areas (RPA) definitions in different European countries.

Country	Definition of RPA
Austria	modelled AM > 300
Belgium	Prob (C > 300) > 5%
Cyprus	AM (C) > national average
Czech Republic	Prob (C > 300) > 30%
Finland	Prob (C > 300) > 10%
Germany	Prob (C > 300) > 10% with 90% confidence
Ireland	Prob (C > 200) > 10%
Lithuania	Prob (C > 300) > 10%
Luxembourg	Prob (C > 300) > 5%
Malta	Prob (C > 200) > 1%
Spain	Prob (C, ground or 1. floor > 300) > 10 %
UK	Prob (C > 200) > 1%

2.2 The MetroRADON mapping exercise

The activity 4.4.2 within MetroRADON project, which we call "the mapping exercise" was defined in the project description as:

A4.4.2	AGES, BfS and UC will test existing mapping methods used in various countries (e.g. indoor radon, gamma dose rate, geology, soil gas radon) with different datasets accessible to JRC and BfS (e.g. national data from other countries, Austrian data set from extensive survey in 6 municipalities and the JRC database) and evaluate their comparability and their usability for other countries. Prior to the start of this exercise the methods and data which can be used for this exercise will be selected based on their applicability and ensuring sufficient data are available for a region.	**AGES**, BfS, UC

So, the idea for the exercise is, to use a provided data set and apply the individual mapping method and definition of RPA used in the country or was proposed by experts to the provided data. Afterwards the mapping and classification results for the provided data sets in the relevant areas will be compared and the usability evaluated.

The first step was to find data sets, which can be used for the exercise. The idea was to use at least two different data sets possibly different in geology, scale, co-variables, etc. to increase the scope and benefit of the exercise. As planned already from the beginning, the data set from extensive survey in six municipalities in Austria was available. As second data set Cantabria, Spain was chosen to be used for the exercise. It was important, that the data sets fulfil our needs and are available by MetroRADON partners and no data protection issue occur.

The data sets then were prepared for the exercise to reach best usability for the participants. The data were arranged in a uniform format, where necessary some anonymisation measures were taken and all data were georeferenced and either shared as table or as shp-file. All details about the data sets can be found in chapter "Exercise data".

To find volunteers for the exercise, experts from different countries, which are known to work in the field of radon mapping, were asked, not limited to MetroRADON partners. Of course to fulfil this task – applying their mapping method to unknown, new data – needs some time and human resources, which was not applicable for all asked experts and institutions, especially if not MetroRADON partners, and no funding could be provided for it, even if a lot of interest was shown in the exercise by most of them. In the end experts from five institutes from five different countries did participate with their methods or did provide extensive data set analysis. The data set analysis and the applied methods and results are discussed in the chapters “data set analysis” and “methods and results”, the names of the experts and institution, who did the main work for each chapter are listed. Thanks to all the participants for their voluntary and important contribution!

In the end, discussed in chapter “summary and discussion”, some comparisons of methods and some interpretations of the results is done. These results and discussion will be part of the MetroRADON Deliverable D5 “Report and Guideline on the definition, estimation and uncertainty of radon priority areas (RPA)”.

In the chapters, the name of the participants who performed the major work for the chapter are listed. AGES might have added some text and explanations to the chapters and did some editing. The chapters were no names are listed were mainly written by AGES, with the help of the co-authors.

3. Exercise data

The MetroRadon exercise uses data of different radon measurement campaigns in Austria (six municipalities) and Spain (Cantabria). The data include indoor radon measurements, building characteristics of measured dwellings, soil air radon activity concentration, permeability estimation, activity concentration of soil samples, ambient dose rate and maps of geogenic parameters derived from other sources (e.g. geology, soil type, airborne radiometry). All data are georeferenced and provided in shape files (point and polygon) or TIFF raster files. Additionally, csv files are added to the data set as robust reference data for point data.

3.1 Austrian data set

The Austrian data set covers six municipalities and is separated in two distinct areas in the North and in the South of Austria (AUT North, AUT South), each consisting of three adjacent municipalities with an overall area of about 220 km² (Figure 1), about 40km² in AUT North and 180 km² in AUT South.

The area AUT North is located in the Bohemian Massif which is one of the areas in Austria with the highest geogenic Radon potential due to the predominant geology of granites and gneisses. AUT North features a homogeneous geology of a granitic pluton and interlaying migmatites (partly molten during metamorphosis). The geology of AUT South is more heterogeneous and also features a variety of felsic igneous and metamorphic rocks with a high radon potential, but also different sediments with a low radon potential.

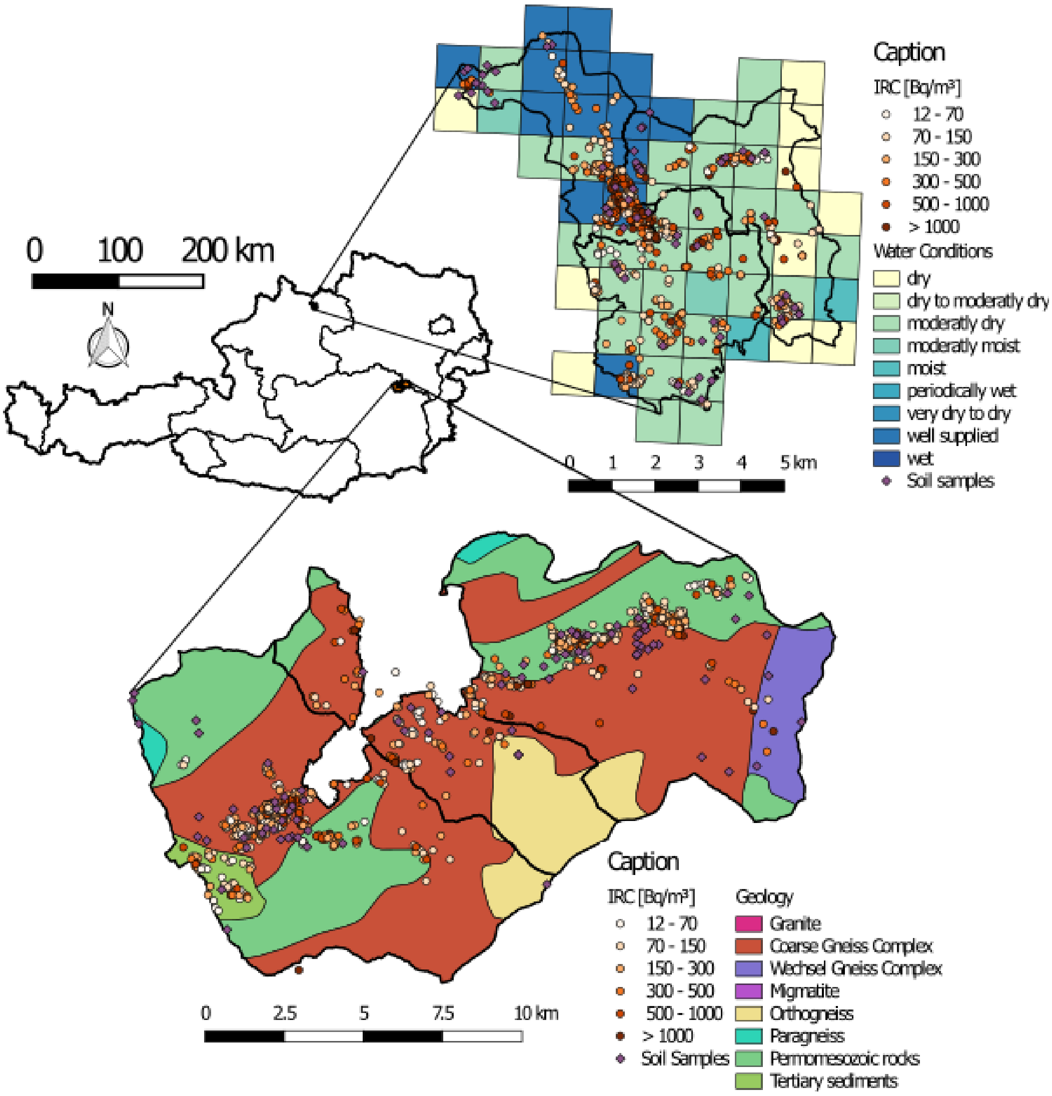

Figure 1: The Austrian data set with selected variables and a map of Austria showing the position of the areas AUT North and AUT South.

The **indoor radon concentration (IRC)** includes data of detailed indoor radon measurement campaigns in dwellings carried out 2010 and 2012 in six municipalities in Austria. Participation rate was 60 to 90 % of all households in the municipalities. IRC was measured with solid-state nuclear track detectors (SSNTD) (Raduet, RSKS Radosys). The measurement periods varied between four to six months, half winter and half summer. The detectors were located in the two most used rooms of the dwellings. Additionally, the participants completed a questionnaire of building characteristics. The data of 1.638 houses was provided, including 3.241 IRC measurements. Because of partly different questionnaires of the measurement campaigns, some data was only available for certain areas (e.g. type of heating). The data was anonymized and a small random term has been added to the original coordinates, whereby the spatial attributes of the shape files (municipality, geology and soil map) have been preserved for the new locations. Table 3 summarizes the variables stored in the IRC data set and gives examples of the attributes.

Table 3: Variable description of the indoor radon concentration data set.

Variable	Description	Unit	Examples
rn_c_r1	Radon concentration room 1	Bq/m³	120, 304, 56
rn_c_r2	Radon concentration room 2	Bq/m³	120, 304, 56
rn_c_1_err	Error radon concentration room 1	%	12, 30, 5
rn_c_2_err	Error radon concentration room 2	%	12, 30, 5
b_rn_c_AM	Arithmetic mean of radon room concentrations	Bq/m³	120, 304, 56
r1_type	Type of room 1		sleeping room, kitchen
r2_type	Type of room 2		sleeping room, kitchen
r1_floor	Floor of room 1		3, -1
r2_floor	Floor of room 2		3, -1
r1_earthb	Is room 1 earthbound?		y, n
r2_earthb	Is room 2 earthbound?		y, n
b_basement	Has the building a basement?		fully, no, partly
b_ac_units	Total number accommodation units		1, 2, ≥ 3
b_year	Building year of dwelling		1986, 2001
b_year_i	Building year of dwelling in interval		1971-2000, < 1900
b_type	Type of building		one family dwelling
b_hill	Is the property located on a slope?		y, n
b_neigh	Neighbourhood position of building		solitary, built together
b_found	Foundation of house		no foundation, strip foundation
b_floor	Floor construction in zone of foundation		screed, sand
b_walls_eb	Main material of earthbound walls		brick, concrete
b_walls	Main material of walls		brick, concrete
b_window	Air tightness of windows		low, well
b_therm	Thermal construction of building		passive, low energy
b_heating	Type of heating		central heating, electric heating
b_older_14	Number of persons in household older than 14		2, 0
b_young_14	Number of persons in household younger/equal 14		2, 0
b_rem	Remediation or extension of building		no, 1970-2000
b_m_start	Start of radon measurement		08.02.2010, 30.01.2013
b_m_end	End of radon measurement		01.07.2010, 24.06.2013
b_altitude	Altitude of building	m	373, 820

The data of **soil air radon activity concentration, permeability, soil activity concentration and ambient dose rate** originate from different measurement campaigns of radon activity concentration in soil air. 148 locations have been measured in the municipalities of the indoor radon survey (Figure 1). Additionally, permeability, soil activity concentration and the ambient dose rate have been measured on selected locations (approximately 100).

The provided **soil air radon activity concentration** [kBq/m³] was calculated on the basis of three single measurements for every location. Steel probes of 1.6 m length and a diameter of 12 mm were used. The intended sample depth was 1.4 m. The principle of the lost tip was used to generate a cavity, which represents the effective probe volume. Soil air was vacuumed with a syringe (200 ml) attached airtight on the steel probe. The first 200 ml of vacuumed air were rejected, due to a mixture of atmospheric and soil air. The next sample of 100 ml vacuumed air were directly transferred to an Alpha Guard® for measuring the radon activity concentration. For some locations, where the intended depth of 1.4 m was not reached, the single measurements were normalized to a depth of 1.4 m. The given results are the arithmetic mean of the depth-corrected soil air radon activity concentration of the three single measurements at the sample locations.

Estimations of soil **permeability** [m²] were carried out at the same locations as the measurement of the soil air radon activity concentration. Soil air was vacuumed from the steel probe with a pump capacity of 1 litre per 60 sec (AlphaPUMP). Flow rate and pressure were measured with a flow meter. The geometry parameters (depth, length of effective probe volume, width of probe) and the flow meter results were used to calculate the permeability after Damkjaer & Korsbech (1992). The results show the arithmetic mean of three single measurements at the sample locations.

Activity concentration in soil samples [Bq/kg] of K-40, Pb-210, Ra-226, Ra-228, Th-228, U-238 were measured with gamma ray spectrometers (HPGe, LEGe). The soil samples were taken at selected locations with core samplers (2 cm diameter, 1 m profile) in the centre of the three single measurements of the soil air radon activity concentration measurements. The soil samples were dried for 24 hours in a drying cabinet (105°). Afterwards they were transferred into gas-tight loading cells. The sealed samples were stored for three weeks to ensure a radioactive equilibrium of the U-Ra radioactive series.

Note, that for the results of the radionuclide concentration, a fixed value was assigned to the limit of detection and the corresponding error was set to zero in order to avoid data loss. A conservative approach regarding the handling of detection limits is used. Thus, only numerical values for the parameters are given. This ensures data consistency.

The **ambient dose rate (ADR)** was measured in a height of 0.5 m for five minutes with a dose rate meter (Automess, 6105AD) and scintillator probe (Automess 6105AD-b/E). The built-in mean calculation of the dose rate meter was used, which ensures that the relative standard deviation is below five percent.

The following Table **4** summarizes the variables soil air radon activity concentration, permeability, soil activity concentration and ambient dose rate.

Table 4: Variable description of the soil data set.

Variable	Description	Unit
rn_sair	Radon activity concentration in soil air	kBq/m³
rn_sair_er	Radon activity concentration in soil air error	kBq/m³
permea	Permeability estimation	m²
ADR	Ambient dose rate	µSv/h
K_40	K-40 activity concentration	Bq/kg
K_40_er	K-40 activity concentration error	Bq/kg
Pb_210	Pb-210 activity concentration	Bq/kg
Pb_210_er	Pb-210 activity concentration error	Bq/kg
Ra_226	Ra-226 activity concentration	Bq/kg
Ra_226_er	Ra-226 activity concentration error	Bq/kg
Ra_228	Ra-228 activity concentration	Bq/kg
Ra_228_er	Ra-228 activity concentration error	Bq/kg
Th_228	Th-228 activity concentration	Bq/kg
Th_228_er	Th-228 activity concentration error	Bq/kg
U_238	U-238 activity concentration	Bq/kg
U_238_err	U-238 activity concentration error	Bq/kg
altitude	Altitude of measurement location	m

Data from literature include **airborne radiometry, tectonic, geological** and **soil maps.**

Airborne radiometry data derive from the geological survey of Austria (GBA) database and represents the uranium concentration of the uppermost soil layer (equivalent Uranium eU). A gamma ray spectrometer (PICO ENVIROTIC GRS410) with sodium-iodide crystals was used for the surveys. A fixed cruising altitude of 80 m, a profile distance of 200 m and a flight velocity of 125 km/h were intended. Data processing included various manipulations such as cruising altitude correction, topographic correction, vegetation correction, cosmic ray correction, radon correction and the consideration of the Compton Effect as well as the conversion of counts per peaks to concentration (IAEA, 1979). The data was only available for three municipalities of the Austrian data set (AUT North).

The data source for **geological maps and tectonic lineaments** is the geological survey of Austria with geological map of scale 1:500.000 (GBA, 2020). For the region of AUT North, an additional geological map with a finer resolution of 1:50.000 was added (GBA, 2020).

The **soil map** is a generalized data set of the Austrian soil map in a 1 x 1 km grid and includes variables as soil type, soil water content, permeability and soil depth (BFW, 2020).

3.2 Cantabrian data set

The data set in Spain covers the region Cantabria with a total area of about 5.300 km². The data set consists of different measurement campaigns of indoor radon concentration, radon concentration in soil gas, ambient dose rate and various compiled data from literature (Figure 2).

The geology of Cantabria predominantly features detritic sediments and carbonates which usually show a low to intermediate radon potential, but especially high permeability in carbonates can also locally lead to a higher radon potential. Also occurring Metasediments and volcanoclastics usually show a low radon risk and compared to the Austrian regions Cantabria has a lower geogenic radon potential.

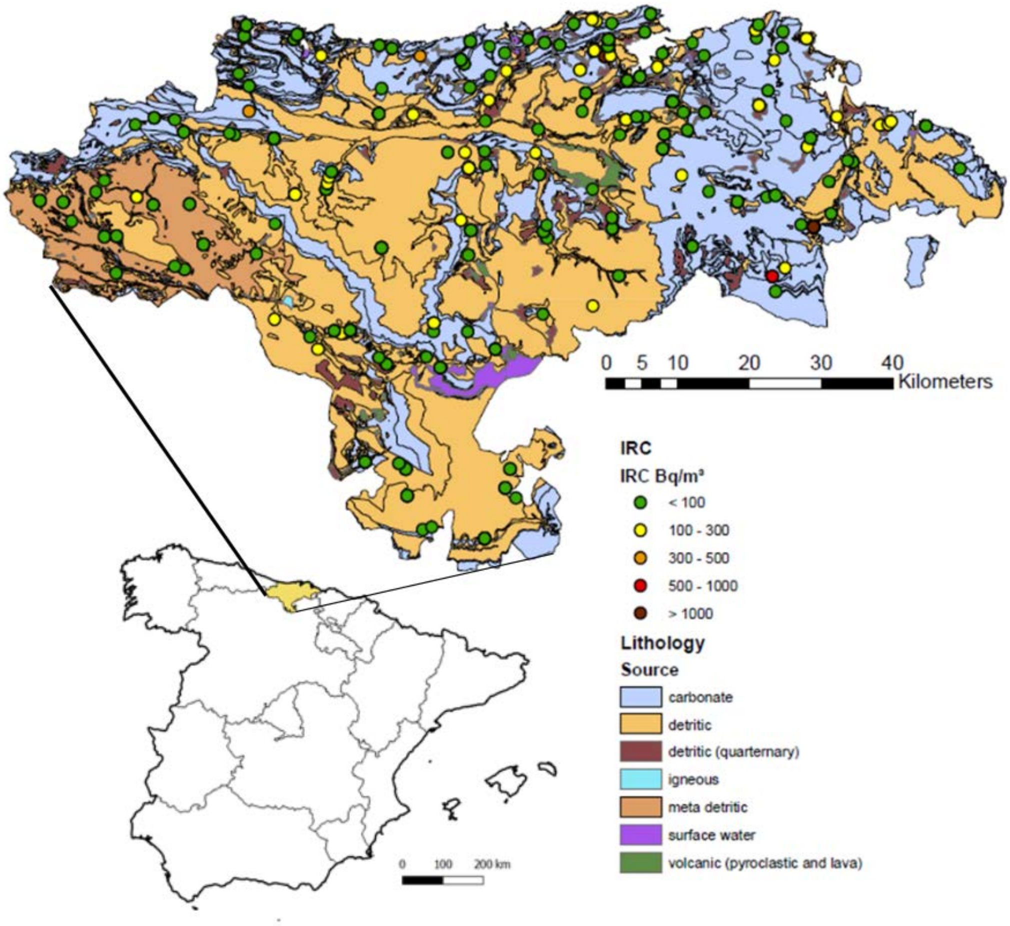

Figure 2: Map of Cantabria with selected variables and the position of Cantabria in Spain.

The data on **indoor radon concentration** in homes was obtained from the Spanish Radon Map Expansion Project. Between 2011 and 2016, the project was promoted by the Spanish Nuclear Safety Council (CSN) and the University of Cantabria (UC) with collaboration of the University of Santiago de Compostela (USC) and the Autonomous University of Barcelona (UAB). Since the 1980s, a compilation of measurements is available from the Radon Group of UC. Measurements were carried out on the ground floor of dwellings or, failing that, on the first floor, using CR-39 trace detectors following the internal location protocol of the Laboratory of Radioactivity of the University of Cantabria (LaRUC) (Sainz-Fernandez et. al., 2014). The data includes indoor radon concentration [Bq/m³] and the location of the sample. Note that this location represents the location of the main city where the measurement was performed within a 10 x 10 km grid rather than the actual measurement position.

The **radon concentration in soil gas** was measured in 260 samples and was collected from 2011 to 2016. The measurements were performed with using a sampling technique based on the collection of a soil gas sample from a depth of about one meter (Czech Method; Neznal et. al, 2004). A sampling probe was prepared with a tip at the lower end and pounded to a depth of about one meter. The punch wire into the probe was inserted and the sharp tip moved a few centimetres lower, which created a cavity at the lower end of the probe. A rubber tube was inserted into the sampling probe and the gas was extracted with a syringe. The gas sample was introduced into a previously evacuated ionization chamber. The detection principle of the measuring system is called RM - 2 and is based on an ionization chamber operating in a current mode.

The **ambient dose rate** (ADR) in the region of Cantabria was collected in the context of the MARNA Project (Suarez et al., 1997). In 1991, the Marna project, developed in Spain, evaluated the rate of exposure to terrestrial gamma radiation at a height of one meter above the surface of the ground.

Data from both parameters, **lithology** and **permeability** originate from the geological map of Spain at a scale of 1:200,000 (IGME, 2020). Besides lithology, the map features a permeability estimation and a classification of the petrological origin. The IGME main criterion for the graphic representation was mapping of the units with significant lithostratigraphic development. It incorporates units with a high hydro-geological interest because of their lithological nature (e.g. high permeability) and because they were considered as the essential part of the definition of aquifers.

The assigned permeability values are indicative for the hydro-geological capacity (aquifer permeability) of the bedrock and do not reflect the permeability of the first meters of soil (surface formation). However, the first meters of soil are most relevant to the explanation of radon transport and furthermore to the presence or absence of radon in buildings.

Nevertheless, the map classifies lithostratigraphic units with different hydrogeological characteristics. The classification of the petrological origin groups the lithostratigraphic units in seven categories: carbonated rocks, detritic rocks, Quartenary detritic rocks, evaporite rocks, igneous rocks, volcanic rocks and meta-detritic rocks.

Data origin of **faults** is the 1:1,000,000 IGME failure map (IGME, 2020a), developed within the framework of the One Geology project.

Compiled data of the **activity concentration in soil** derive from the FOREGS (2020) and GEMAS (2020) database. The data is provided in regular grid (10 x 10 km) with the variables Potassium [%], Uranium [ppm] and Thorium [ppm]. For Potassium, the arithmetic mean was used to calculate the cell means. For Thorium and Uranium, the geometric mean was used to calculate the cell means.

Karst data is a simplified version of the IGME karst map indicating presence or absence of karst areas (IGME, 2020b).

3.3 Data set analysis

(Alcides Pereira, Filipa Domingos, University of Coimbra)

Different data sets are available for the three study areas. The data sets differ in basic characteristics as size, sample density, data extent, quality and resolution. Methods to characterize radon priority areas for the two data sets may require adequate data manipulations for different methods. Table 5 gives an overview and comparison of the Austrian and the Cantabrian data set regarding the data density, similarity of data and the origin of data (e.g. measured or derived from literature). In addition detailed analysis of the available data were carried out. In this chapter a summary of descriptive statistics is provided (Table 6, 7, 8) for the three study areas and some box-plot graphs are shown for selected characteristics. The results of a more detailed data analysis with different methods (Kruskal-Wallis test, Spearman rank correlation, variograms) can be found in the appendix. A summary of correlations is given in Chapter 3.4, Table 9.

Table 5: Overview of existing variables in the Cantabrian and the Austrian data set.

Variable	Cantabria	Austria (AUT North and AUT South)
IRC	location approx., low sample density	exact location, high sample density
Soil air Rn	*measured;* sample density similar	*measured*; sample density similar
Act. conc. in soil	European K, Th, U in soil maps (JRC) 10x10 km grid AM/GM (FOREGS, GEMAS)	^{40}K, ^{210}Pb, ^{226}Ra, ^{228}Ra, ^{228}Th, ^{238}U measurements
ADR	*measured*; sample density similar	*measured*; sample density similar
Faults	map; similar	map; similar
Geology	map; similar	map; similar
Permeability	estimates derived from lithological units	Soil permeability *measurements* + estimates derived from soil units
Karst	Binary, derived from lithological units	-
Building characteristics	-	Questionnaire; at location of IRC
Soil map	-	Soil unit, water conditions, soil depth, …
Airborne radiometry	-	eU; measured only AUT North

Austria: North Region (AUT North)

Austria North has the highest indoor radon concentrations of the data set areas. Table 6 summarizes the distributions of the numerical data. Some interesting correlations of numerical and categorical data are shown in Figure 3 – 6. The radon concentration of soil gas is positive correlated with the soil water content (Figure 3) which is in agreement with known effects in the literature (Arvela, H. et. al 2016). Although the geology of AUT north is the most homogenous, minor differences in the ADR can be observed for different rocks (Figure 4). Figure 5 shows that IRC measured in rooms that are earthbound are higher than rooms which are not earthbound. Figure 6 visualises the higher indoor radon concentrations in lower floors.

Table 6: Descriptive statistics of data from region AUT North

Variable	eU	SGR	Perm.	ADR	K-40	Pb-210	Ra-226	Ra-228	Th-228	U-238	IRC AM	IRC
Unit	(ppm)	kBq/m³	m²	µSv/h	Bq/kg						Bq/m³	
Valid N	3732	60	60	60	30	30	30	30	30	30	653	1294
Mean	1.58	104	2.83E-11	0.17	888	47	50	62	63	54	362	361
Geometric mean	n.d.	91	4.40E-12	0.17	842	46	48	57	58	53	232	223
Median	1.42	93	6.72E-12	0.16	800	46	48	57	59	52	226	216
Minimum	-0.85	13	9.00E-15	0.12	465	23	29	28	28	27	12	10
Maximum	7.65	304	1.59E-10	0.24	1630	101	115	138	139	105	2640	2765
Lower quartile	0.81	69	1.52E-12	0.15	657	39	39	43	46	45	118	112
Upper quartile	2.20	127	4.91E-11	0.19	1040	52	58	70	70	61	483	438
Standard deviation	1.01	52	4.62E-11	0.03	303	14	17	27	27	15	371	404
Skewness	0.82	1	1.89E+00	0.54	1	2	2	1	1	2	2	2
Kurtosis	0.81	3	2.52E+00	-0.38	0	7	7	1	1	4	5	7

SGR – Soil gas radon; Perm. – Permeability; ADR – Ambient dose rate; IRC AM – Arithmetic mean of indoor radon concentrations; IRC – Indoor radon concentrations of room 1 and 2 combined

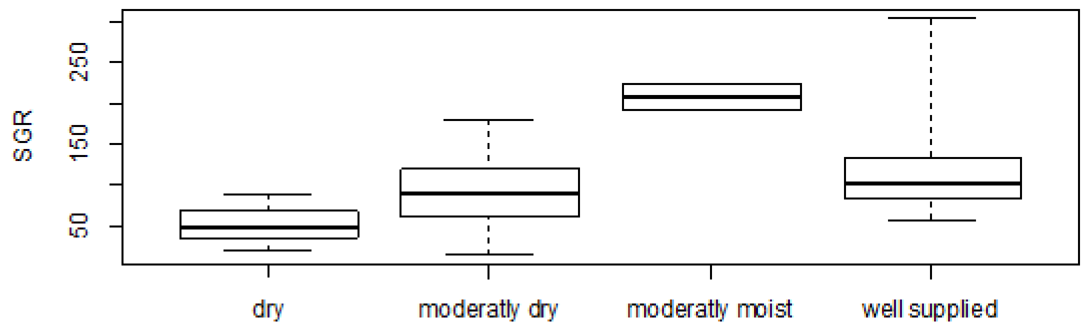

Figure 3: Box-plots of radon concentration in soil gas [kBq / m³] grouped by water content in the region AUT North.

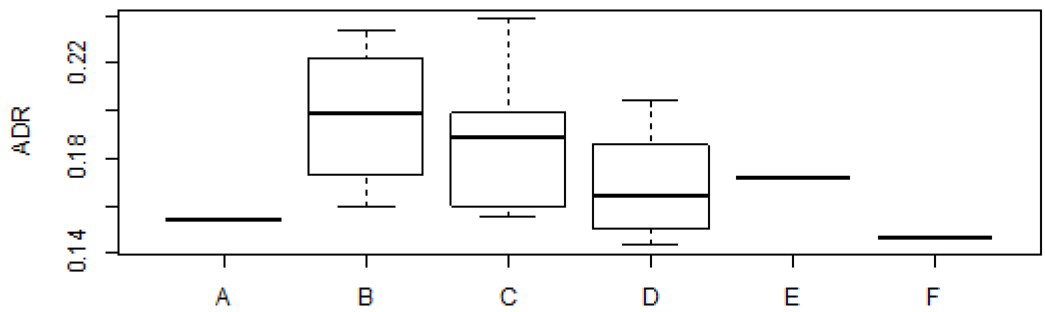

Figure 4: Box-plots of ambient dose rate [µSv/h] grouped by bedrock (fine geology) for region AUT North. A - alkaline to intermediate plutonic rock; B - coarse- to very coarsegrained biotite granite (Weinsberger); C - fine grained two mica granite (Altenberger); D – fine to intermediate grained migmatite (Meta- Diatexite), granodioritic; E – intermixing zone and fluid transition of coarse grained biotite granite and migmatite; F - valley infill.

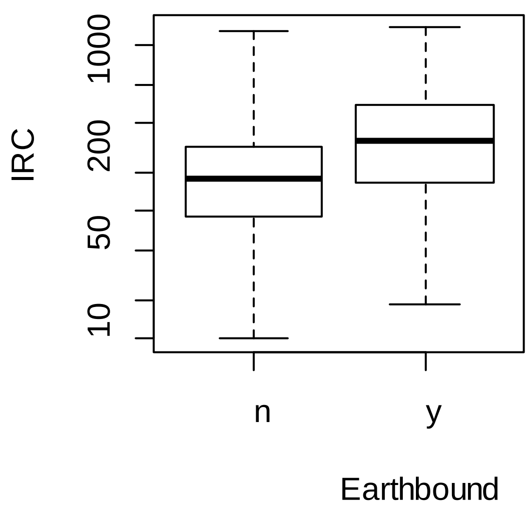

Figure 5: Box-plots of IRC grouped by earthbound (y) and non-earthbound (n) rooms (AUT North). Y-axis in logarithmic scale.

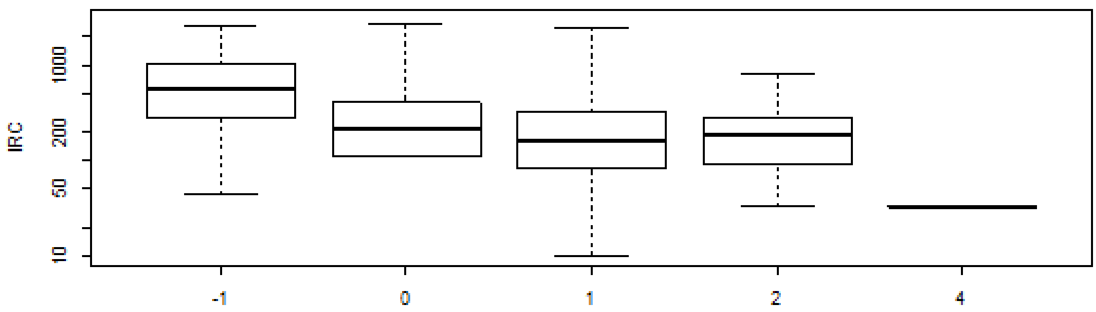

Figure 6: Box-plot of IRC grouped by floor of the measured room (AUT North). Y-axis in logarithmic scale (minimum values of zero are not displayed).

Austria: Southern Region (AUT South)

Austria South has the highest number of indoor radon measurements, but concentrations are lower than in Austria North.

Table **7** summarizes the distributions of the numerical data. AUT South is not the typical radon area in Austria and diverse in geology. The Radium concentrations are slightly lower than in AT North, Uranium concentration is clearly higher. The mean ADR is higher in Austria South and differs stronger among the bedrock types, highest in Orthogneis (see Figure 7).

Table 7: Descriptive statistics of data from region AUT South

Variable		**SGR**	**Perm.**	**ADR**	**K-40**	**Pb-210**	**Ra-226**	**Ra-228**	**Th-228**	**U-238**	**IRC AM**	**IRC**
Unit		**kBq/m³**	**m²**	**µSv/h**	**Bq/kg**						**Bq/m³**	
Valid N		88	8.80E+01	88	82	82	82	82	82	82	984	1933
Mean		86	1.22E-11	0.20	664	43	47	36	36	39	247	246
Geometric mean		55	7.51E-12	0.19	552	37	42	32	31	33	152	149
Median		55	1.33E-11	0.20	721	37	40	34	33	32	139	135
Minimum		1	4.20E-14	0.07	14	9	14	7	4	12	16	16
Maximum		953	2.74E-11	0.30	1190	136	168	78	81	140	4655	5218
Lower quartile		34	5.15E-12	0.18	480	25	35	24	24	22	78	76
Upper quartile		98	1.89E-11	0.23	880	48	52	45	46	44	274	275
Standard deviation		115	7.69E-12	0.04	289	27	27	17	16	26	337	351
Skewness		5	-6.22E-02	-0.31	0	2	3	1	1	2	5	6
Kurtosis		38	-1.18E+00	0.45	0	3	8	0	0	5	49	54
Kolmogorov - Smirnov	**D**	**0.2297**	0.0932	0.0951	0.0998	**0.2207**	**0.2070**	0.0681	0.0751	**0.2038**	**0.2472**	**0.2556**
	p	**< 0.01**	> 0.20	> 0.20	> 0.20	**< 0.01**	**< 0.01**	> 0.20	> 0.20	**< 0.01**	**< 0.01**	**< 0.01**
Shapiro-Wilk	**W**	**0.5125**	**0.9490**	0.9743	**0.9630**	**0.8077**	**0.7276**	**0.9573**	0.9787	**0.7758**	**0.5563**	**0.5355**
	p	**< 0.001**	**0.0017**	0.0768	**0.0183**	**< 0.001**	**< 0.001**	**0.0081**	0.1900	**< 0.001**	**< 0.001**	**< 0.001**

SGR – Soil gas radon; Perm. – Permeability; ADR – Ambient dose rate; IRC AM – Arithmetic mean of indoor radon concentrations; IRC – Indoor radon concentrations of room 1 and 2 combined

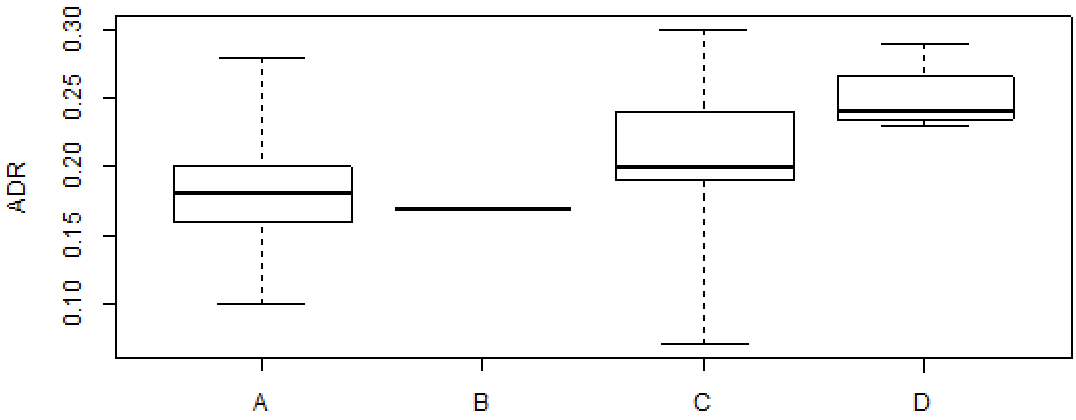

Figure 7: Box-plot of ambient dose rate according to bedrock for region AUT South. A - Carbonate rock, siliciclastics, porphyry (generally metamorphic); B - Marl, sand, gravel, limestone; C - Mica schist, paragneiss; D – Orthogneiss.

Cantabria

For Cantabria dataset a bit different parameters are available than for Austrian data sets, descriptive statistics of the numerical data is summarised in Table 8. For the much larger area, quite few IRC data are available and the IRC concentration is clearly lower than for Austria. Also the mean soil gas radon concentration is clearly below the ones in Austria. Note that the units are different for the Austrian data for K, TH, U, ADR.

Figure 8 and Figure 9 shows the ADR and the SGR by sources (carbonate, detritic, detritic quaternary, meta detritic, volcanic). It is interesting, that the ADR and the SGR have opposite distribution according to their source - e.g. carbonate origin has lowest ADR but highest SGR. Figure **10** visualises the higher mean indoor radon concentration in areas with karst.

Table 8: Descriptive statistics of data from region Cantabria

	IRC (Bq/m³)	SGR (kBq/m³)	K_2O* (%)	Th* (ppm)	U* (ppm)	ADR* (mR/h)
Valid N	482	238	70	70	70	77
Mean	97	23.7	1.7	7.5	1.7	7.1
Geometric mean	55	10.3	1.7	7.4	1.7	7.0
Median	54	14.0	1.7	7.2	1.7	6.9
Minimum	6	0.1	1.1	5.8	1.4	4.9
Maximum	2895	209.2	2.6	10.9	2.0	10.7
Lower quartile	29	4.5	1.4	6.8	1.6	6.4
Upper quartile	93	32.4	2.0	7.7	1.8	7.6
Standard deviation	221	29.0	0.4	1.1	0.1	0.9
Skewness	9	2.8	0.5	1.3	0.1	0.9
Kurtosis	86	10.8	-0.5	1.8	-0.7	2.6
IRC – Indoor radon concentrations; SGR – Soil gas radon; ADR – Ambient dose rate. *Zero values were excluded.						

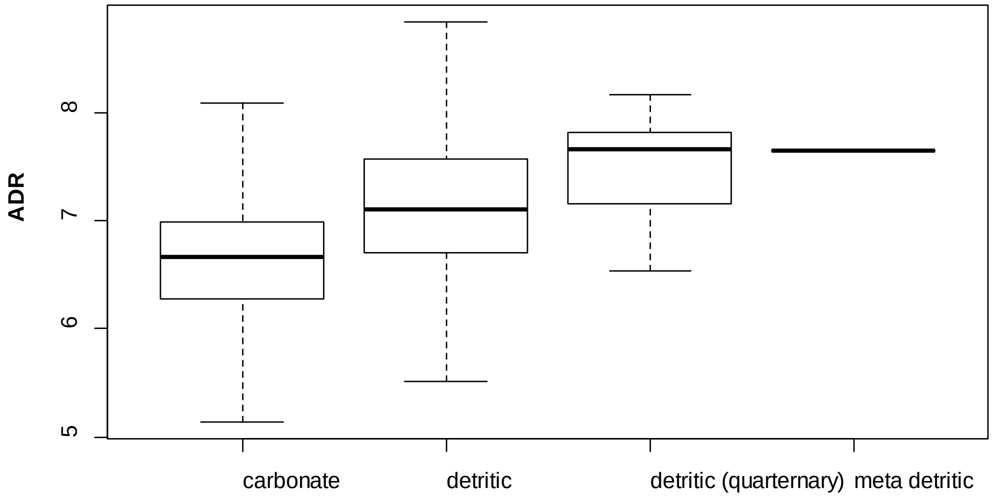

Figure 8: Box-plot of the ambient dose rate by geological source for the Cantabria region.

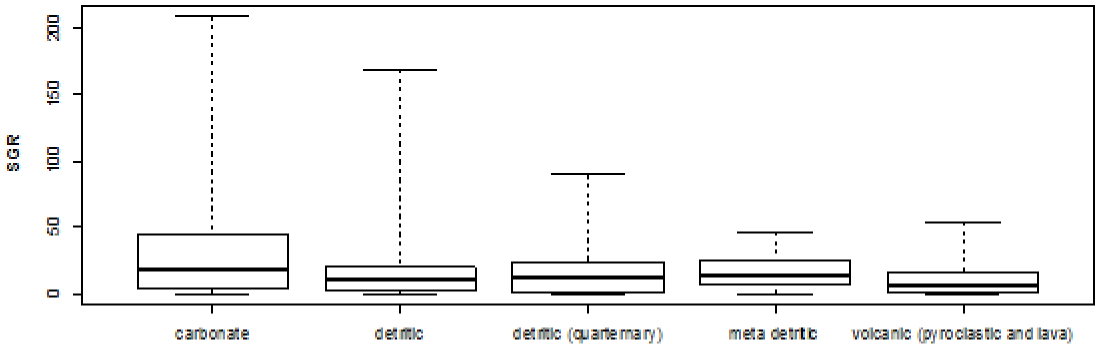

Figure 9: Box-plot of Soil gas radon by geological source for the Cantabria region.

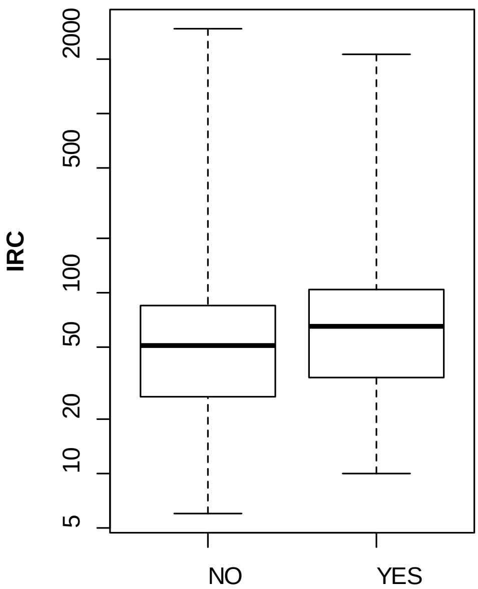

Figure 10: Box-plot of indoor radon concentration by karst for the Cantabria region (yes - karst present, no - no karst present). Y-axis in logarithmic scale.

3.4 Summary of data sets

A sound data basis is required for the delineation of radon priority areas (RPAs). The provided data sets include a variety of data from different sources and may be of interest for different concepts to identify RPAs. Radon data usually is noisy and incomplete and the same is true for the data set of this exercise. The analysis of the exercise data shows that grouping of populations, the type of correlation and the rate of spatial correlation of the same variables are not equal in different regions (Table 9).

This is especially interesting for the Austrian data set, where the measurement methods, the geogenic maps and the sampling density are comparable or even identical for both regions. For example, in the region AUT North different groups of geogenic variables show significantly different IRC, which cannot be observed in the region AUT South (see Annex, Table 27, Table 31). Furthermore, when analysing both regions together, the number of geogenic variables that show significant different IRCs increases, because the variability of IRC increases as well if considering both regions. On the other hand, both regions show similarities, such as the lack of statistical differences of the radionuclide content according to soil types or the lack of spatial correlation of almost all geogenic factors.

However, the next chapter will focus on different methods to identify RPAs and the approach how to deal with the data set. It will be interesting to see, which data are used by the different methods applied and how the data will be edited and manipulated to serve as a solid basis for the identification of RPAs.

Table 9: Data set grouped in populations, type of correlation and rate of spatial correlation in different regions.

AUT North			
	significant difference among groups	**significant correlation**	**spatial correlation**
ADR	bedrock (fine), soil map (source)	K-40, Th-228, Ra-228, TGDR	weak
eU	bedrock (fine), soil map (source)	x	strong
soil gas	soil map (type, grain size, water content)	U-238	weak
Pb-210	bedrock (coarse)	U-238, Ra-226	no
Ra-226	x	U-238, Ra-226	no
U-238	x	soil gas, Ra-226, Pb-210	no
TGDR	x	ADR, K-40, Ra-228, Th-228	no
IRC	permeability, bedrock (fine), soil map (water content), building characteristics (RT, EB, B, BT, FO,FL)	x	weak
AUT South			
ADR	bedrock	soil gas, Ra-226, TGDR	weak
soil gas	x	ADR, K-40, Pb-210, Ra-226, U-238, TGDR	no
Pb-210	x	soil gas, K-40, Ra-226, Pb-210, Ra-228, U-238, TGDR	no
Ra-226	x	soil gas, ADR, K-40, Ra-226, K-40, Pb-210, Ra-228, Th-228, U-238, TGDR	no
Ra-228	soil map (source, grain size)	K-40, Ra-226, Th-228, U-238, TGDR	no
Th-228	soil map (source, grain size)	Ra-226, Ra-228, U-238, TGDR	no
U-238	x	soil gas, K-40, Pb-210, Ra-226, Ra-228, Th-228, TGDR	no
TGDR	x	soil gas, ADR, K-40, Ra-226, K-40, Pb-210, Ra-228, Th-228, U-238, TGDR	weak
IRC	building characteristics (RT, EB, B, BT, FO,FL)	x	no
Cantabria			
ADR	lithology, source, permeability	soil gas (-), Th, K	strong
Soil gas	lithology, source, permeability	IRC, ADR (-), U (-)	no
IRC	lithology, karst	soil gas, U (-)	no

4. Exercise methods and results

The interplay of available data and the intended method usually defines the applied strategy for the delineation of RPAs. This is different in this exercise, because the available data is predefined. The comprehensive radon data sets provided in this exercise aim to be a solid basis for different strategies to identify RPAs. However, as already mentioned in the previous chapter, there is room for improvement regarding data quality. This chapter presents the methods applied for the identification of RPAs with the current data sets.

4.1 Basic analysis based on indoor radon data

(Sebastian Baumann, AGES)

The definition of RPA utilising IRC data commonly follows two basic concepts: a) The average IRC (e.g. AM, GM) of the area is compared to a threshold (e.g. 300 Bq/m³) and b) the percentage of measurements exceeding a threshold in an area is compared to a percentage threshold (e.g. 10 %). Common approaches to define radon priority areas use IRC thresholds of 100 to 300 Bq/m³ and percentage thresholds of 1 to 30 percent (see chapter 2.1. and Table **2**).

The IRC distributions differ in the regions of the exercise data sets and the concentrations are considerable higher in Austria than Cantabria (Figure 11). This is of course also true for the aggregates of the distributions that might be used for basic radon risk prediction.

Table 10, Table 11 and Table 12 give examples of descriptive statistics of the IRC in different regions and geological units, along with the number and density of the radon measurements. The spatial distribution of the IRC and geology for the different regions is shown in Figure 2, Figure 12 and Figure 13. For the Austrian data set a majority of households in the municipalities have been tested and therefore the spatial pattern of measurements mimics the distribution of overall households. The high measurement density in the Austrian regions show that low and high IRC can occur virtually in neighbouring houses, which seems – at a first glance - to contradict the concept of geogenic radon potential. However, one also needs to take into account that beside the geogenic factors also the type of building or the location of the measurement in the building (floor) largely influences the IRC. Therefore, using subsets of data e.g. by floors is a common approach to achieve comparable IRC and often is applied for radon risk prediction. The measurement density of the Cantabrian data set is much lower compared to the Austrian regions and radon risk prediction solely on the basis of IRC might show high uncertainties.

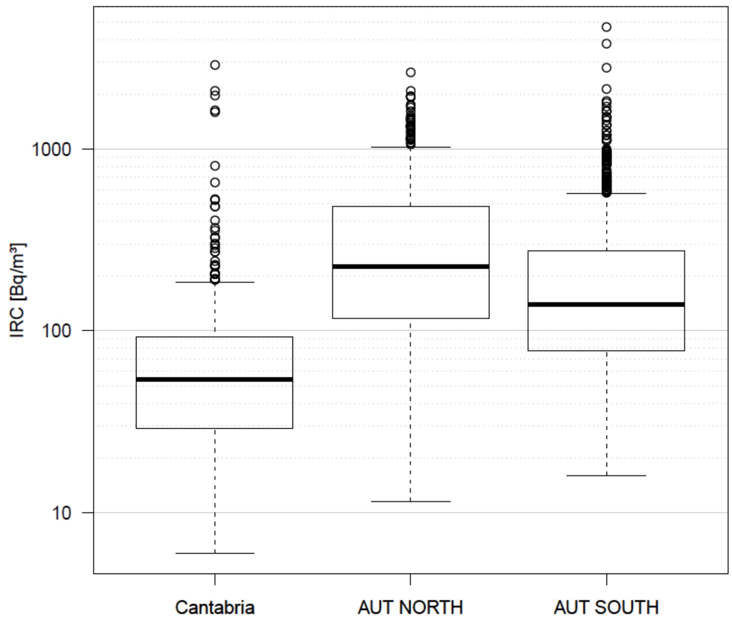

Figure 11: Boxplot shows IRC distribution in log scale for the different regions of the exercise data.

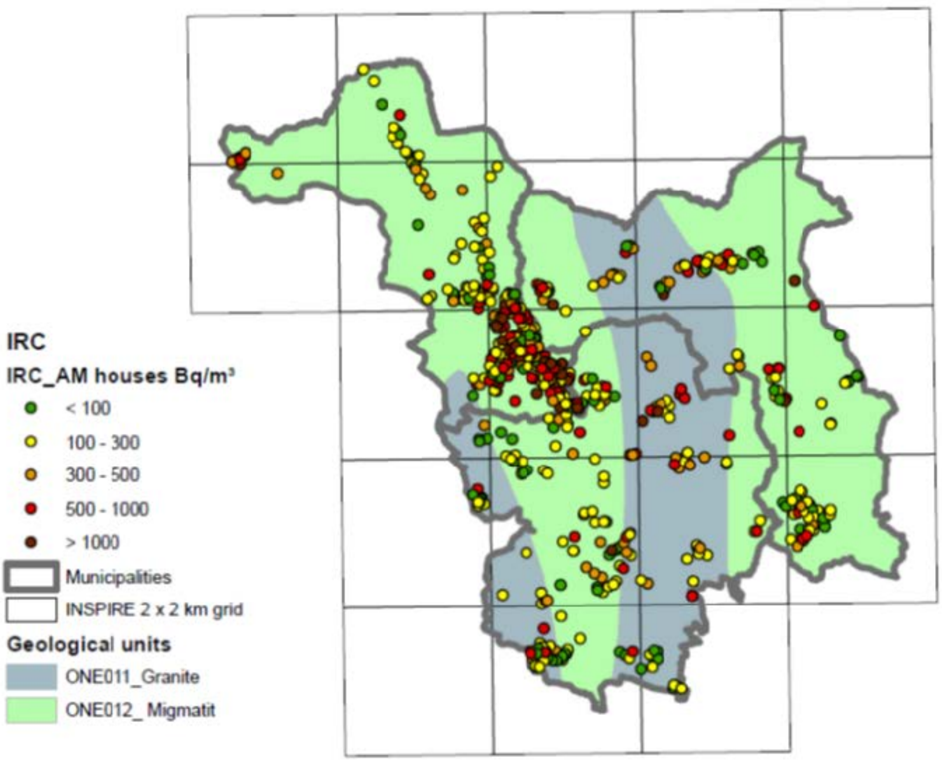

Figure 12: Indoor radon concentration (IRC) measurements and geological units in AUT North.

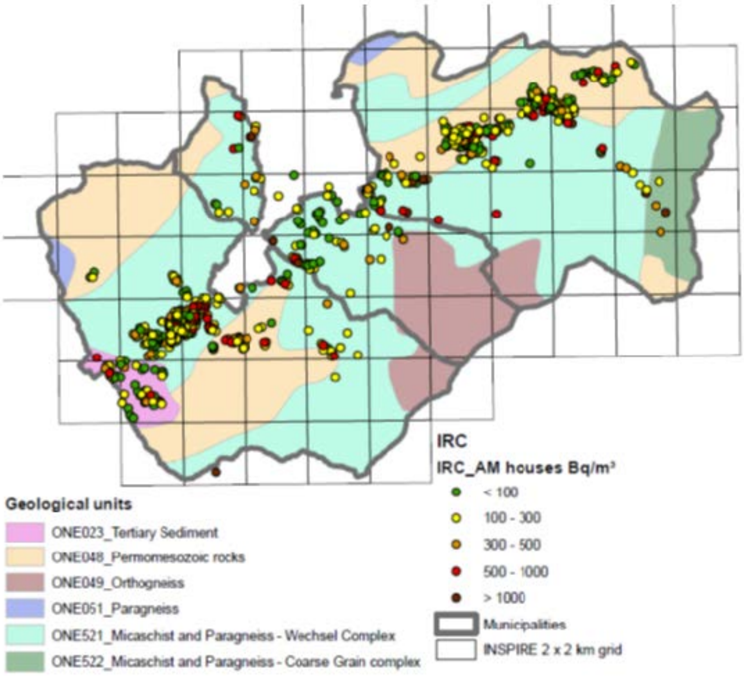

Figure 13: Indoor radon concentration (IRC) measurements and geological units in AUT South.

Table 10: Descriptive statistics per municipalities in Austria and the study region in Spain.

Country	Austria	Austria	Austria	Austria	Austria	Austria	Spain
Region	North	North	North	South	South	South	Cantabria
Municipality ID	1	2	3	4	5	6	-
Area [km²]	15	13	10	32	76	73	5328
Number of measurements (dwellings)	200	138	315	88	469	421	482
IRC samples per km²	13.7	10.5	32.9	2.7	6.2	5.8	0.09
Arithmetic mean (Bq/m³)	289	313	429	289	251	234	97
Geometric Mean (Bq/m³)	196	207	273	165	157	146	55
Median (Bq/m³)	197	213	266	168	144	130	54
% > 100 Bq/m³	76	77	83	64	65	61	22
% >200 Bq/m³	49	52	60	45	37	32	7
% > 300 Bq/m³	31	36	45	28	22	21	3

Table 11: Descriptive Statistics per geological unit in Austria (according to Figure 12 and Figure 13)

Geology unit	Granite	Migmatite	Tertiary sediment	Permo-mesozoic rocks	Ortho-gneiss	Micaschist and Paragneiss (coarse grain complex)	Micaschist and Paragneiss (Wechsel complex)
Area [km²]	12	26	4	52	17	105	9
number of measurements (dwellings)	143	510	56	356	1	561	4
IRC samples per km²	12	20	14	7	0.1	5	0.4
Arithmetic mean (Bq/m³)	352	364	210	210	455	266	1159
Geometric Mean (Bq/m³)	229	233	136	140	455	161	494
Median (Bq/m³)	229	225	134	130	455	145	355
% > 300 Bq/m³	41	38	20	21	-	24	-
% > 200 Bq/m³	58	54	32	33	-	37	-
% > 100 Bq/m³	78	81	63	60	-	66	-

Table 12: Descriptive Statistics per geological unit in Cantabria. Only units with more or equal to 20 IRC summarized.

Geology unit	Reef lime-stones	Gravel, sand, silt	shale, sandstone, conglomerate and sandy limestone	slate, lutite, sandstone, coal and limestone	motley clay and gypsum	sandstone lutite, marl	marl, limestone and loamy limestone
Area [km²]	**6915**	**2554**	**13625**	**3649**	**1036**	**3060**	**2337**
number of measurements (dwellings)	88	81	74	29	22	22	20
IRC samples per km²	0.012	0.032	0.005	0.008	0.021	0.007	0.009
Arithmetic mean (Bq/m³)	167	75	52	60	83	197	72
Geometric Mean (Bq/m³)	63	55	40	43	59	59	48
Median (Bq/m³)	47	62	44	47	59	62	40
% > 300 Bq/m³	8	1	0	0	0	5	5
% >200 Bq/m³	14	4	1	7	14	5	10
% > 100 Bq/m³	32	21	9	7	18	23	20

4.2 Generalized additive mixed model (GAMM)

(Christian Laubichler, Oliver Alber, AGES Graz)

The method applied in this chapter is based on the methodology used in Austria for the delineation of radon areas but taking into account more available variables than in the methodology for Austria. The method is applied in this exercise for the Austrian and Cantabria data sets.

Based on IRC measured in Austria and Cantabria, the goal is to

- identify relevant explanatory variables,
- predict the expected indoor radon concentration for a specified grid,
- assess the variability of predictions;

The IRC in dependency of explanatory variables will be estimated with the generalized additive mixed model (GAMM). The results of the final model will be used to predict the expected IRC and to calculate confidence intervals.

Subsequent modelling and analyses are carried out with the statistical programming language R version 3.5.1, using the packages gamm4 and mgcv.

Statistical Models

The additive mixed model

$$\log(IRC_{ij}) = \beta_0 + \beta_1 z_{ij} + \cdots + \beta_m z_{ij} + s(x_j, y_j) + u_j + \epsilon_{ij} \qquad (Equation\ 1)$$

$$u_j \sim N(0, \sigma^2_{house}), \quad j = 1, \dots, n_{house}$$

$$\epsilon_{ij} \sim N(0, \sigma^2_{\epsilon})$$

is fitted to the Austrian data set, whereby the living unit u_j is taken as a random effect, thus introducing a positive correlation of measurements within the same living unit. A slightly different model, an additive model without random effects, is used for the Cantabrian data set. The Cantabrian data set qualifies as multilevel data, as the data contains multiple measurements within each location. However, introducing a random effect for location, thereby assuming a positive correlation within a location is not feasible in this case. In Cantabria measurements from a relatively large area are assigned to a particular location. Influencing factors, such as geology, etc., in such an area could be inherently different, which would contradict the positive correlation induced by the random effect.

Resulting in the additive model:

$$\log(IRC_{ij}) = \beta_0 + \beta_1 z_{ij} + \cdots + \beta_m z_{ij} + s(x_j, y_j) + \epsilon_{ij} \qquad (Equation\ 2)$$

$$\epsilon_{ij} \sim N(0, \sigma^2_{\epsilon}), \quad j = 1, \dots, n_{location}$$

In both cases, the smooth functions $s(.)$ pertain to the class of thin plate regression splines. The z_{ij} terms represent explanatory variables and the pair (x_j, y_j) represents the coordinates of a living unit or location j.

The final model should only contain variables that show a significant influence on log(IRC). To identify these variables, a stepwise forward selection using 5-fold cross validation is applied. All available variables were used in the stepwise forward selection.

Stepwise Forward Selection

Starting with the simplest models

$$\log(IRC_{ij}) = \beta_0 + s(x_j, y_j) + u_j + \epsilon_{ij} \quad (Austria) \qquad (Equation\ 3)$$

and

$$\log(IRC_{ij}) = \beta_0 + s(x_j, y_j) + \epsilon_{ij} \quad (Cantabria) \qquad (Equation\ 4)$$

variables are added one after the other. Those variables with the highest explanatory power are chosen for the final model.

The explanatory power is determined by a 5-fold cross validation (CV) for each step, splitting the data into five blocks, whereby four blocks are used to fit the model and the fifth block serves as testing data. For measuring the error of the fitted values compared to the test block, the mean squared error of actual IRC and fitted IRC is used.

Non-relevant variables result in non-significant improvements in cross validation error. The following figures (Figure 14, Figure 15) show the differences in cross validation errors by adding variables.

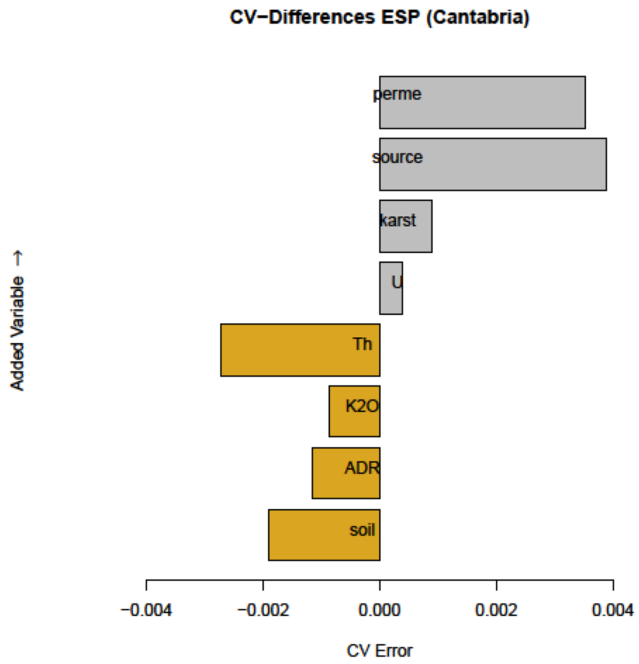

Figure 14: Difference in cross validation errors in Cantabria. Gray colored variables are not included in the model.

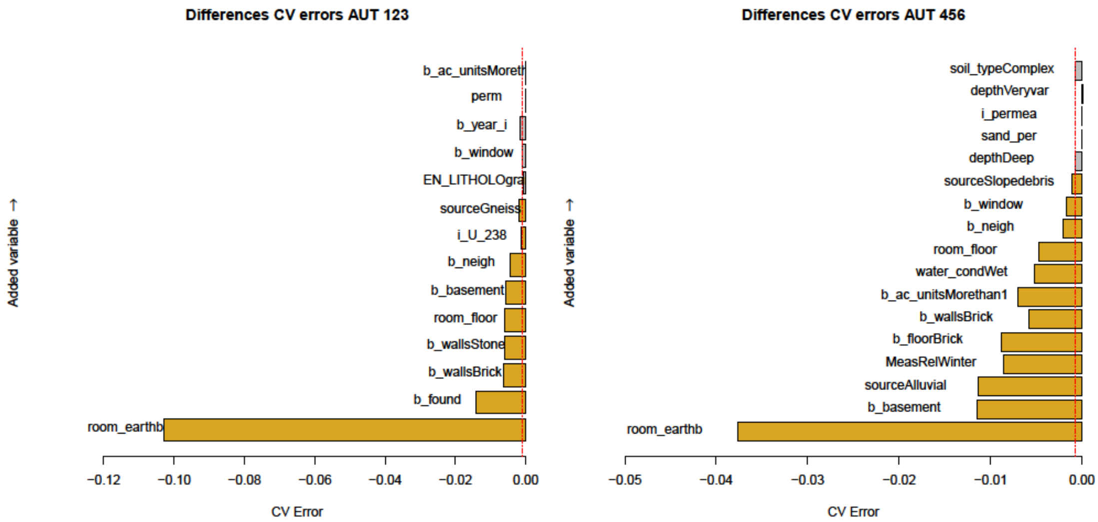

Figure 15: Differences in cross validation errors in Austria (left: AT North, right AT South). Gray colored variables are not included in the model.

Variables are only added to the final model, when the reduced cross validation error is deemed to be significant (Figure 14 and Figure 15). For Cantabria (Figure 14) the variable "Th" (Thorium activity concentration in soil) reduces the CV error significantly and the variables following "Th" increase the CV error, thus all variables up to "Th" are included in the final model (see Table 13). In Austria, Figure 15, the red striped vertical line represents the first quartile of differences in cross validation errors. The final model contains all variables which result in a reduction in CV error that is above the red line. For the Austrian data set, these are mainly building characteristics and geology units ("source"), for AUT South also water content is relevant (see Table 14 and Table 15).

The optimal basis dimension k for the smooth functions $s(.)$ was obtained before the stepwise forward selection. By using cross validation it became apparent that the optimal basis dimension k is 90 and 100 for Cantabria and Austria, respectively.

Final Models

Table 13, Table 14 and Table 15 contain the results of the final models in both study areas, Cantabria and Austria. The final models are fitted using the variables and k from the cross validation.

Table 13: Estimated coefficients of the final model for Cantabria (Soil: radon concentration in soil gas, ADR: ambient dose rate, K2O: potassium activity concentration in soil, Th: Thorium activity concentration in soil).

	$\hat{\beta}_i$	Std.Error	p-value	
Intercept ($\hat{\beta}_0$)	2.313	1.758	0.189	
Soil	0.019	0.008	0.020	*
ADR	0.273	0.245	0.266	
K2O	-1.320	0.673	0.050	.
Th	0.240	0.143	0.094	.

*** significant at $\alpha = 0.001$; ** significant at $\alpha = 0.01$
* significant at $\alpha = 0.05$; . significant at $\alpha = 0.10$

Table 14: Estimated coefficients of the final model for AUT North (municipalities 1, 2 and 3) – the building characteristics variables (b_) are explained in Table **3**, the soil data set variables (i_) in Table 4, source: geological unit) .

	$\hat{\beta}_i$	Std.Error	p-value	
Intercept ($\hat{\beta}_0$)	4.181	0.589	0.000	***
b_room_earthb	0.255	0.079	0.001	**
b_found_foundation partly	-0.144	0.176	0.415	
b_found_no foundation	0.129	0.177	0466	
b_found_strip foundation	0.101	0.091	0.265	
b_walls_Brick	0.379	0.107	0.000	***
b_walls_Stone	0.432	0.165	0.009	**
b_room_floor0	-0.406	0.098	0.000	***
b_room_floor1	-0.614	0.129	0.000	***
b_basement_no	0.085	0.144	0.554	
b_basement_partly	0.202	0.101	0.045	*
b_neigh_solitary	0.526	0.200	0.009	**
i_U_238	0.019	0.009	0.036	*
source_Gneiss	-0.508	0.215	0.019	**

*** significant at $\alpha = 0.001$; ** significant at $\alpha = 0.01$
* significant at $\alpha = 0.05$; . significant at $\alpha = 0.10$

Table 15: Estimated coefficients of the final model for AUT South (municipalities 4, 5 and 6) – the building characteristics variables (b_) are explained in Table 3, the soil data set variables (i_) in Table 4, source: geological unit, water_: water content data from soil map).

	$\hat{\beta}_i$	Std.Error	p-value	
Intercept ($\hat{\beta}_0$)	3.820	0.555	0.000	***
b_room_earthb	0.307	0.086	0.000	***
b_basementno	0.347	0.114	0.002	**
b_basementpartly	0.591	0.094	0.000	***
Source_Alluvial	0.649	0.129	0.000	***
Meas_RelWinter	1.167	0.893	0.191	
b_floorBrick1	0.911	0.271	0.000	***
b_wallsBrick1	0.222	0.073	0.002	**
b_ac_units_Morethan11	-0.189	0.062	0.002	**
water_cond_Wet1	0.523	0.171	0.002	**
b_room_floor0	-0.383	0.122	0.002	**
b_room_floor1	-0.558	0.130	0.000	***
b_neigh_solitary	0.183	0.100	0.067	.
b_window_very tight	0.222	0.092	0.016	*
source_Slopedebris	0.247	0.171	0.151	

*** significant at $\alpha = 0.001$; ** significant at $\alpha = 0.01$
* significant at $\alpha = 0.05$; . significant at $\alpha = 0.10$

Prediction of IRC

The final model is used to predict log(IRC) for a specified grid. In Austria, it is of interest to set a particular house of reference; i.e. selecting levels of the categorical explanatory variables to represent an Austrian house. For example, a standard house can be described by selecting those levels that occur most frequently. This house of reference is then assigned to the coordinates of the midpoints of the grid-cells. In Cantabria, predictions are based on the midpoints of the grid-cells and the specific values of the explanatory variables associated with that grid.

In the case of Austria, the focus is on municipalities when predicting IRC. Predictions for municipalities can be calculated by averaging over those grid-cells that are allocated in the certain municipality.

To obtain a final IRC prediction, either for a grid-cell or a municipality, the prediction must be converted into Bq/m³ with the following equation:

$$\widehat{IRC}_{\frac{cell}{municipality}} = \exp\left(\widehat{log(IRC)}_{\frac{cell}{municipality}} + \frac{\sigma^2_{house} + \sigma^2_{\epsilon}}{2}\right) \qquad (Equation\ 5)$$

or

$$\widehat{IRC}_{cell/municipality} = \exp\left(\widehat{log(IRC)}_{cell/municipality} + \frac{\sigma^2_{\epsilon}}{2}\right) \qquad (Equation\ 6)$$

for Cantabria.

Figure 16 shows the prediction of the IRC in grid cells (10x10 km). Figure 17 and Figure 18 show the prediction of IRC in grid cells (2x2 km) and per municipality.

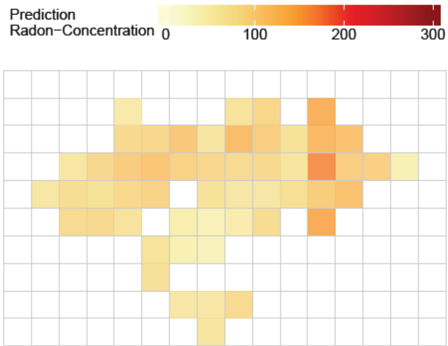

Figure 16: Prediction of radon concentration [Bq/m³] of cell midpoints in Cantabria.

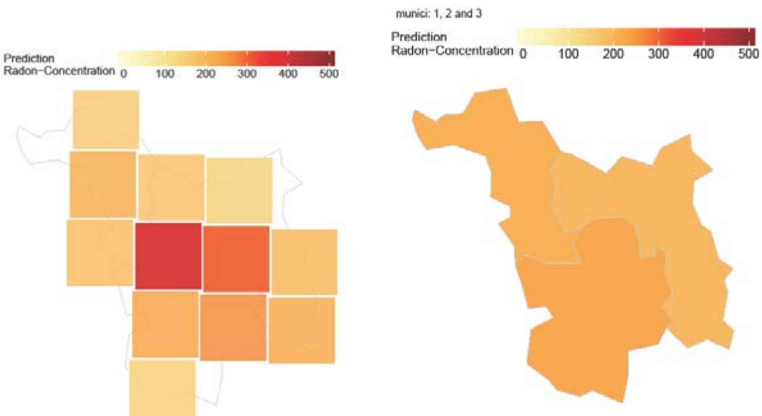

Figure 17: Prediction of radon concentration [Bq/m³] of cell midpoints and municipalities for AUT North (municipalities 1, 2 and 3).

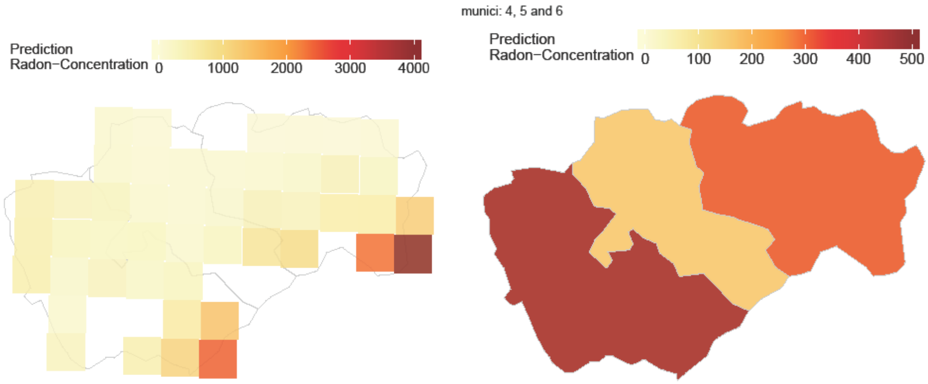

Figure 18: Prediction of radon concentration [Bq/m³] of cell midpoints and municipalities for AUT South (municipalities 4, 5 and 6).

Confidence intervals

To validate pre-defined IRC boundaries or to get an idea about the variation of predictions, confidence intervals can be of interest. Using the distributional results of estimators from the GAMM (generalized additive mixed model) theory, variances of predictions or variances of linear combinations of predictions can be obtained. Confidence intervals, at a specified level of significance ($\alpha = 0.05$), can be calculated. Figure 19 shows the confidence intervals for the grid cell prediction of the radon concentration of Cantabria, Figure 20 indicates the confidence intervals for the predicted radon concentration in the six Austrian municipalities.

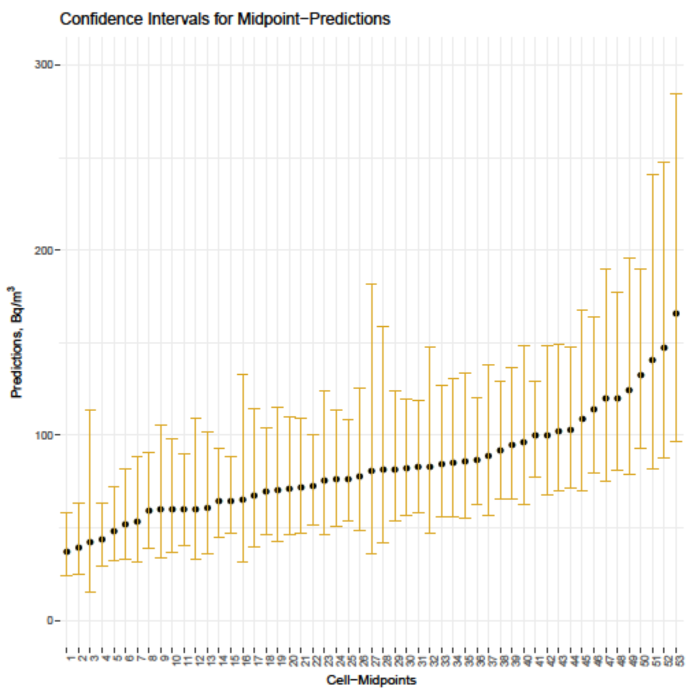

Figure 19: Confidence intervals for grid-cell midpoint predictions in Cantabria.

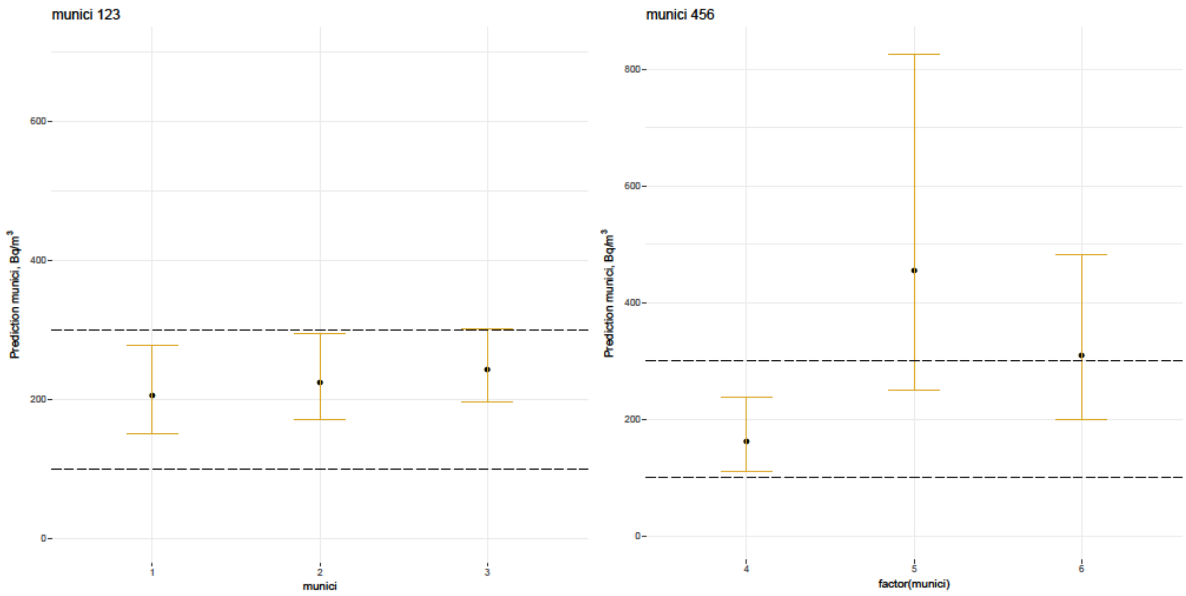

Figure 20: Confidence intervals for municipality predictions in Austria, AUT North on the left and AUT South on the right side.

4.3 Empirical Bayesian Kriging (EBK) Regression Prediction

(Giancarlo Ciotoli, Italian National Research Council)

Methodology

The Empirical Bayesian Kriging Regression Prediction is a geostatistical interpolation method that uses Empirical Bayesian Kriging (EBK) with known explanatory variable rasters to affect the value of the data that should be interpolated. This approach combines kriging with regression analysis to make predictions that are more accurate than either regression or kriging can provide on their own. More details about EBK can be found here (ESRI, 2020).

The method EBK Regression Prediction was used to generate a radon soil gas map of Cantabria. Therefore, only data from Spain (Cantabrian data set) were used in this prediction method.

The estimation by EBK Regression Prediction uses radon concentration in soil gas as response variable and raster layers of the available parameters (permeability, ambient dose rate, K-40, U-238, Th-232, fault density, presence of karst areas) as proxies (see Figure 21). The proxies were interpolated on raster cells with a resolution of 500 x 500 m by the following operations:

1. Application of the “Spatial Join” tool between the lithology layer and the geochemical soil data in order to assign average values of measured K-40, U-238, Th-232 to the lithology layer. Afterwards, the “Polygon to Raster” transformation tool was applied to obtain raster layers of the proxies.
2. Application of the kernel density algorithm to obtain a raster of the density map of faults.
3. Application of ordinary kriging to obtain a raster map of the estimated ambient dose rate.
4. Merging of the karst layer and the region boundary to obtain two polygons: karst area and no karst area. The polygons were classified by using a binary code 1 (karst area) and 0 (no karst area). The layer was transformed into a raster by using the “Polygon to Raster” transformation tool.

5. A permeability value was assigned to the lithology layer according to the qualitative description reported in the attribute table: very high (10^{-10}), high (10^{-11}), medium (10^{-12}), low (10^{-14}), very low (10^{-16}). Logarithmic values were considered to simplify calculations.
6. Application of the EBK Regression Prediction algorithm in ArcGIS Pro environment, considering the soil radon concentration as response variable and U-238, Th-232, K-40, fault, permeability, ambient dose rate and karst as independent variables.

EBK Regression Prediction results

The Root Mean Square Standardised Error indicates that EBK Regression Prediction has a good performance, though the cross-correlation graph (Figure 22) shows an underestimation of the highest values.

The map of the geogenic radon potential (Figure 23) for the Cantabrian region, obtained by using EBK Regression Prediction, suggests that mainly faulted areas and zones of high permeability affect the radon distribution in soil air. To group the areas of the geogenic radon potential map into radon priority areas, according to their concentration, the following classification is recommended:

Low radon risk area: concentration < 15 kBq/m^3

Medium radon risk area: concentration between 15 – 60 kBq/m^3

High radon risk area: concentration > 60 kBq/m^3

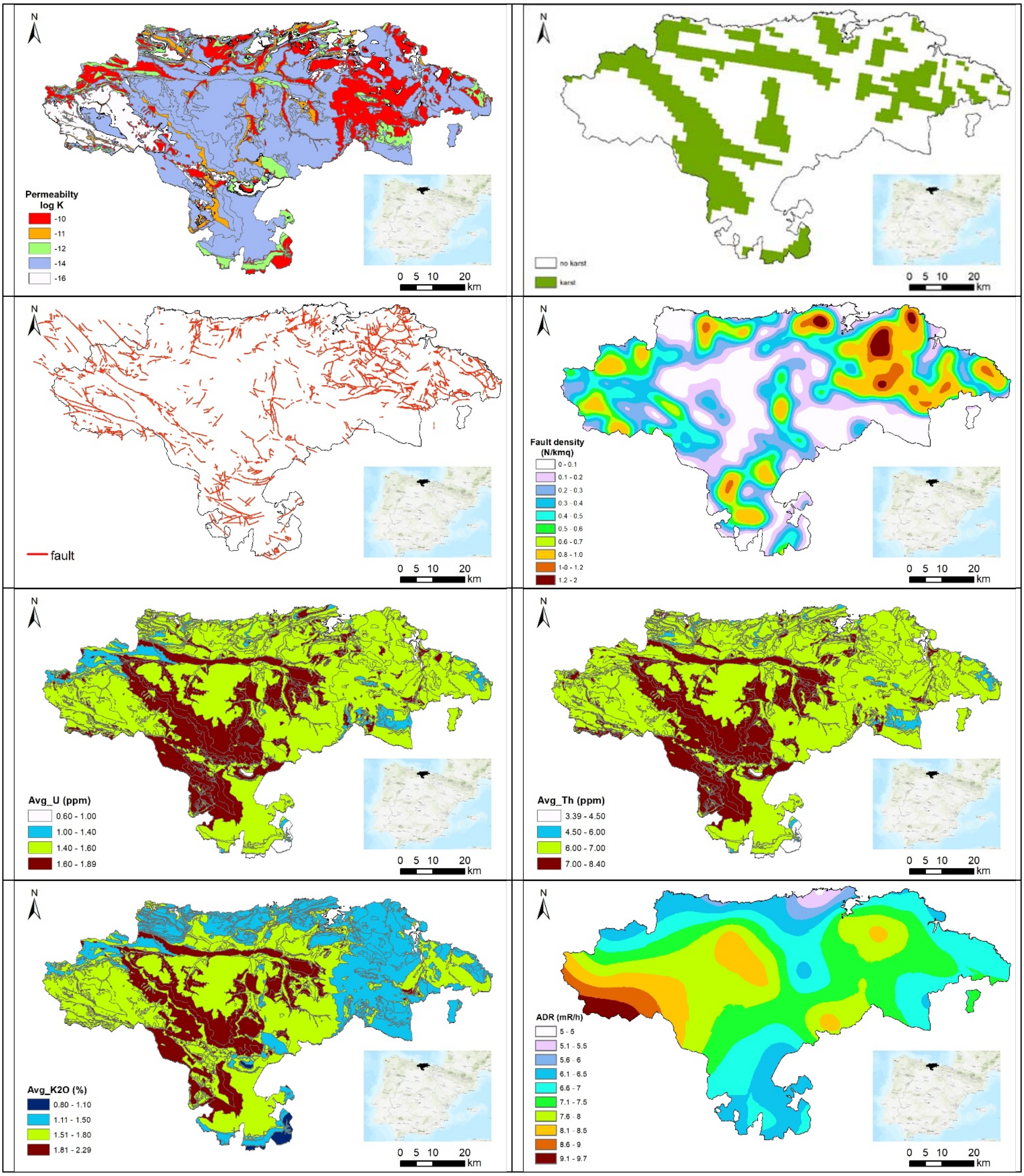

Figure 21: Maps of the available proxy variables for Cantabria

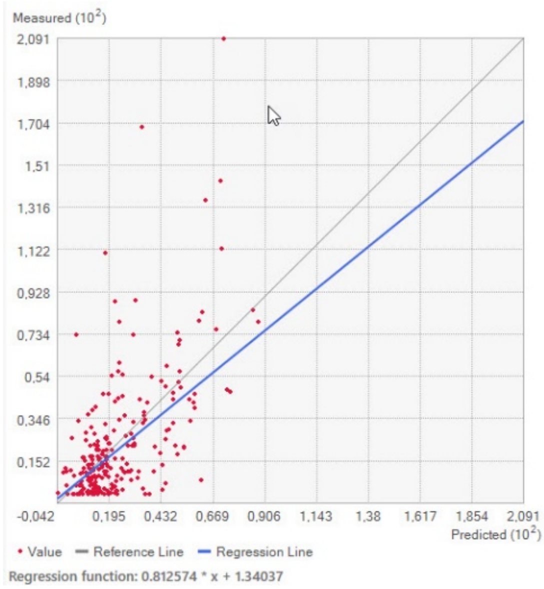

Figure 22: Cross validation graph: Measured values (y-axis) versus predicted values (x-axis)

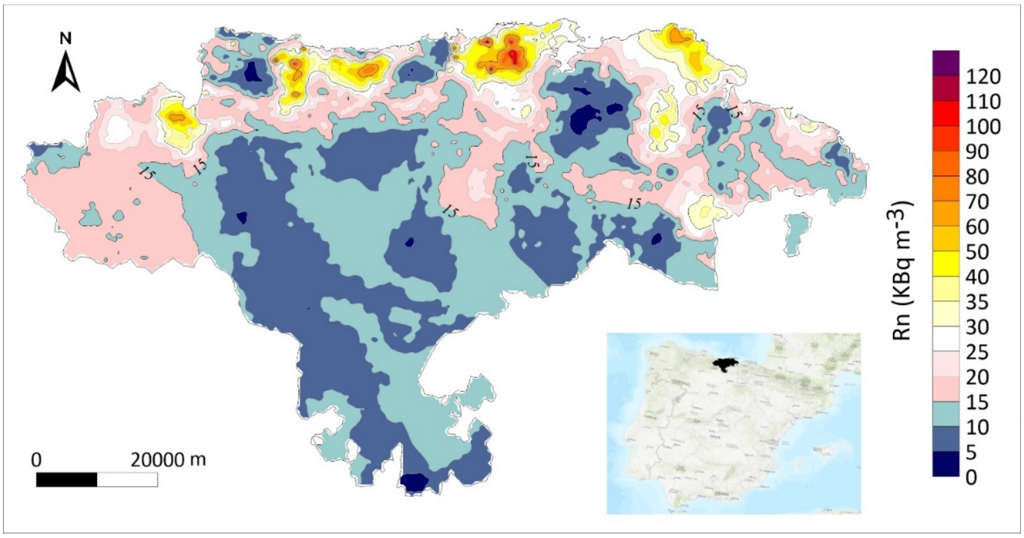

Figure 23: Geogenic radon potential map of the Cantabrian region calculated by using Empirical Bayesian Kriging Regression.

4.4 Ordinary Kriging (OK) and Indicator Kriging (IK)

(Eric Petermann, Peter Bossew, BfS - Bundesamt für Strahlenschutz)

This method describes the prediction of the indoor radon concentration in areas by using the Kriging method. This method is applied for both, the Austrian and the Cantabrian data set.

Austria

Analysis of variance (ANOVA) was performed for the following target variables: indoor radon (only ground floor measurements were considered), soil radon, soil permeability and the geogenic radon potential after Neznal et al. (2004) derived thereof (a function of soil radon and soil permeability). ANOVA revealed significant ($p < 0.05$) differences for the target variables dependent on pedological and geological characteristics such as source material (source) and soil thickness (depth) as well as texture (EN_LEG_TEX) and lithology (EN_LITHOLO), respectively. However, differences between pedological and geological characteristics – although being significant – are not very prominent. Under consideration of the high density of indoor radon measurements in populated areas (897 measurements for AUT North; 1191 measurements for AUT South), a pure geostatistical approach using ordinary kriging and indicator kriging without any additional predictor seemed to be sufficient to estimate the radon risk for populated areas.

Spatial prediction of indoor radon concentration

The software R was used to execute ordinary kriging (Package „gstat“, function „krige“). First, the spatial autocorrelation of indoor radon concentration was tested by calculating variograms. For both Austrian areas, separate variograms were calculated (Figure 24 and Figure 25).

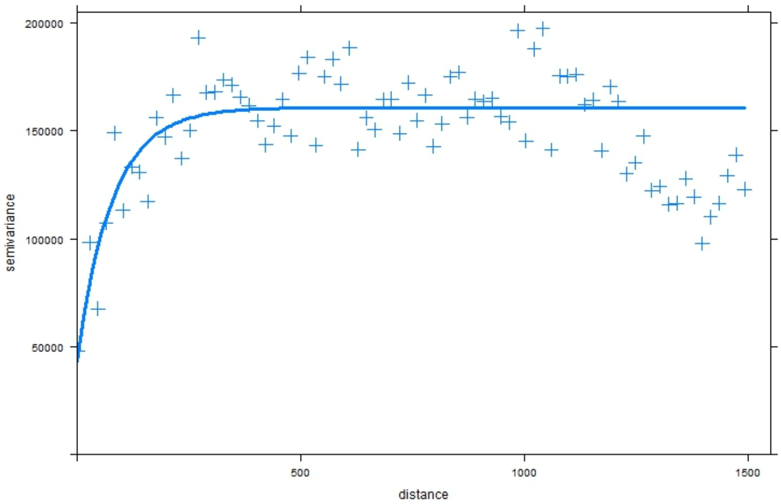

Figure 24: Variogram of ground floor indoor radon concentration for AUT North. Empirical data (crosses), fitted model (solid line).

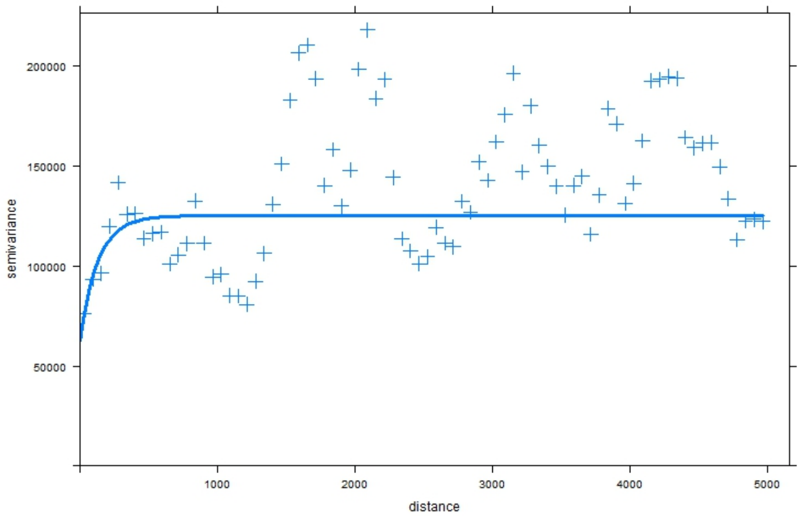

Figure 25: Variogram of ground floor indoor radon concentration for AUT South. Empirical data (crosses), fitted model (solid line).

The variograms of both Austrian areas (Figure 24 and Figure 25) reveal spatial autocorrelation over a short range of approximately 500 m. The nugget effect (local variability at distance 0) is large for both areas, but even more striking for AUT South. Both areas were tested for anisotropy of spatial autocorrelation by visual inspection of directional sample variograms for directions North, East, South and West as well as for directions North-East, South-East, South-West and North-West. Since anisotropy could not be identified, spatial autocorrelation was assumed to be isotropic. For both areas, an exponential model was fitted to the empirical variogram data (Table 16).

Table 16: Variogram model parameters for indoor radon concentration at ground floor.

	AUT North	**AUT South**
Nugget	43136	62345
Range parameter for exponential model	79	134
Partial Sill	117485	62775

Based on these variogram models and the empirical data, indoor radon concentration was kriged (Figure 26 and Figure 27) for a raster cell size of 200 m. Due to the low range of spatial autocorrelation, the estimates at large distances from the nearest observation (> 1 km) are equivalent to the mean of the whole area.

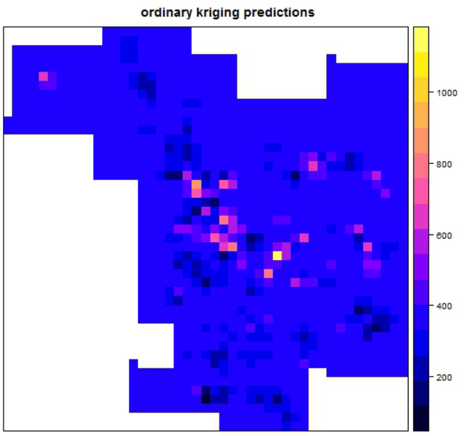

Figure 26: Estimated indoor radon concentration at ground floor based on Ordinary Kriging in AUT North.

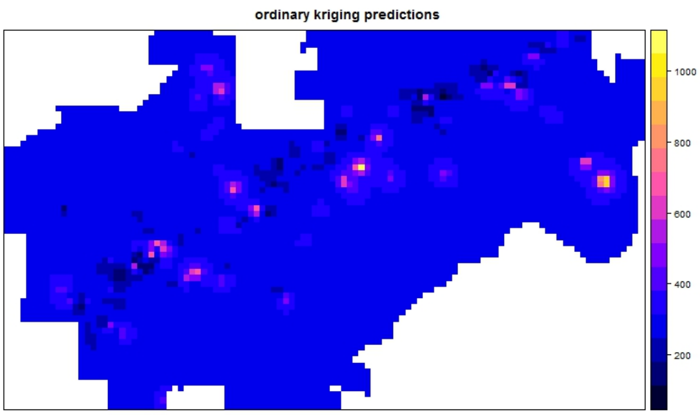

Figure 27: Estimated indoor radon concentration at ground floor based on Ordinary Kriging in AUT South.

Spatial prediction of exceeding a probability of indoor radon concentration of 300 Bq/m³ (Indicator Kriging)

The radon risk mapping was conducted using indicator kriging. Therefore, indoor radon concentration was transformed into a binary code with 0 for all observations that are smaller than 300 Bq/m³ and 1 for all observations that are greater or equal to 300 Bq/m³. Afterwards, a new variogram model was fitted to the binary coded data (see Figure 28, Figure 29 and Table 17).

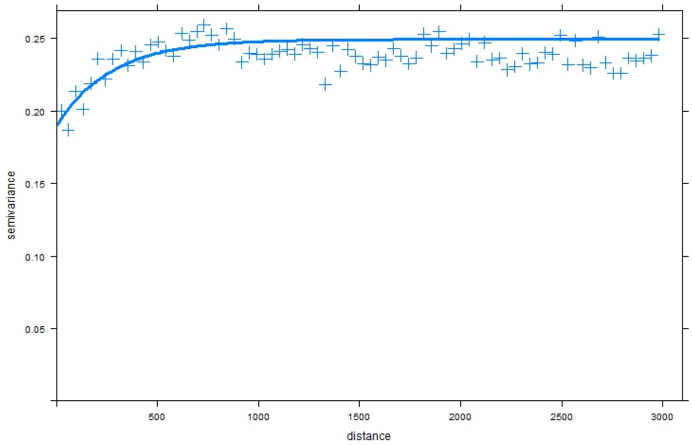

Figure 28: Variogram of binary coded ground floor indoor radon concentration for AUT North (0 = observation < 300 Bq/m³, 1 = observation ≥ 300 Bq/m³). Empirical data (crosses), fitted model (solid line)

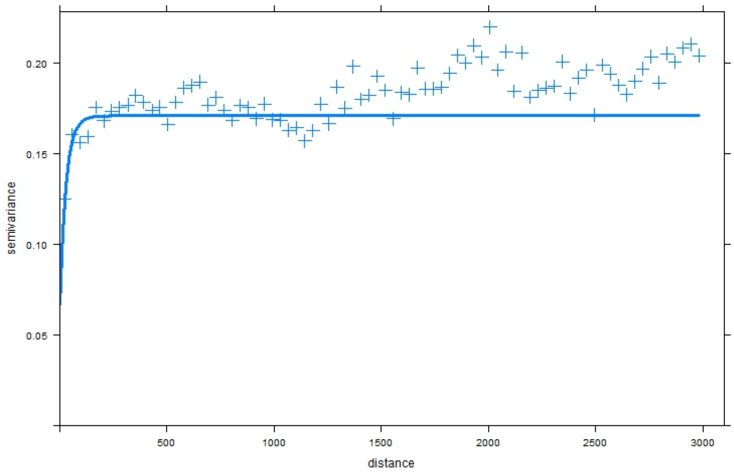

Figure 29: Variogram of binary coded ground floor indoor radon concentration for AUT South (0 = observation < 300 Bq/m³; 1 = observation ≥ 300 Bq/m³). Empirical data (crosses), fitted model (solid line);

Table 17: Variogram model parameters of binary coded indoor radon concentration on ground floor level.

	AUT North	**AUT South**
Nugget	0.19	0.07
Range parameter for exponential model	275	31
Partial Sill	0.06	0.10

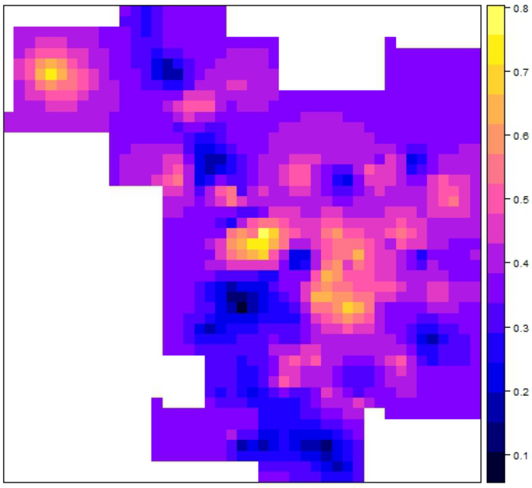

Figure 30: Estimated local probability to exceed an indoor radon concentration of 300 Bq/m³ at ground floor level based on Ordinary Kriging in AUT North.

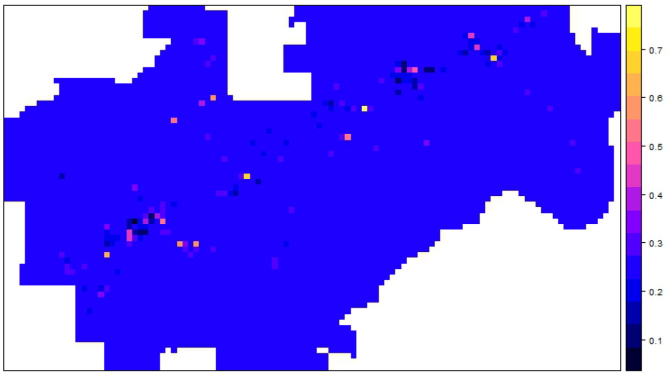

Figure 31: Estimated local probability to exceed an indoor radon concentration of 300 Bq/m³ at ground floor level based on Ordinary Kriging in AUT South.

In summary, all cells with observed values that are greater or equal to 0.1 are assigned as radon priority areas. Both Austrian regions are therefore mostly radon priority areas (except for three individual cells in the AUT South area), shown in Figure 30 and Figure 31.

Spain

Regarding data quality, the Cantabrian data set differs from the Austrian data set. For the Cantabrian data set, it is not clear whether the indoor radon measurement was conducted on the ground floor or on the first floor. This indicates that using data only from ground floor measurements, as it is the case for the Austrian data set, is not feasible.

Another characteristic of the Cantabrian data set is that coordinates, which are attributed to the indoor radon measurements, are not as accurate as desirable. All measurements from one municipality have the same coordinates. This lack of knowledge regarding radon measurement and assigned floor level and exact coordinates causes a loss of valuable information.

In order to make the data ready for kriging, all measurements from one municipality were merged into one value by calculating the arithmetic mean. Thus, each unique location is assigned to one value for indoor radon concentration.

Spatial autocorrelation of indoor radon concentration was tested but not detected, i.e. the empirical data could not be fitted in a meaningful way to the variogram model (Figure 32). Hence, kriging was not a feasible option for the delineation of radon risk areas in Cantabria.

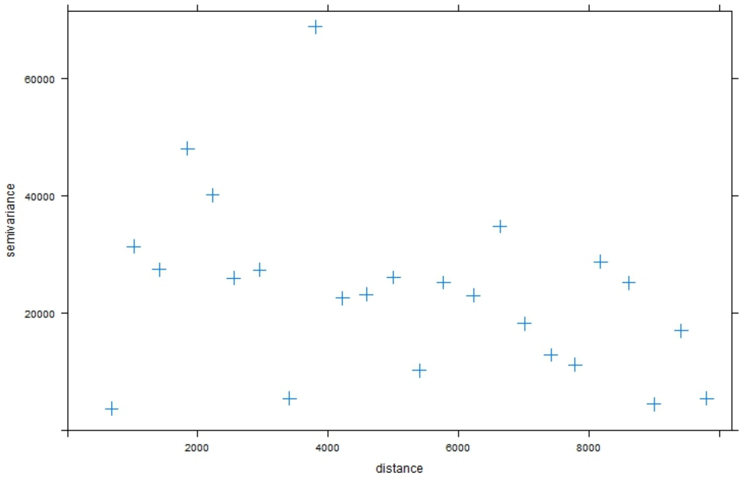

Figure 32: Variogram of indoor radon concentration for the Cantabrian data set. Empirical data (crosses); a variogram model could not be fitted due to the lack of spatial autocorrelation.

The lack of spatial autocorrelation may be a result of:

- measurement data was merged per municipality,
- distances between individual samples are larger than the range of spatial autocorrelation
- not much differentiation between ground floor and first floor measurements was given (in general, higher radon concentration would be expected on ground floor level)

Instead of geostatistical analysis of indoor radon data, the geogenic radon potential as a function of soil gas radon and soil permeability was calculated.

Kriging, based on an exponential variogram model with parameters, was conducted with the radon concentration of the soil gas (Figure 33 and Figure 34).

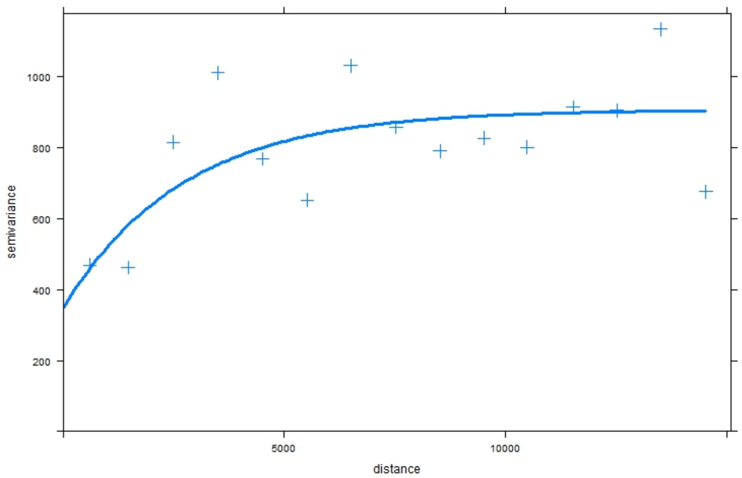

Figure 33: Variogram of radon concentration in soil gas for Cantabria. Empirical data (crosses), fitted model (solid line). Parameters (nugget: 346, partial still: 559, exponential range parameter: 2718).

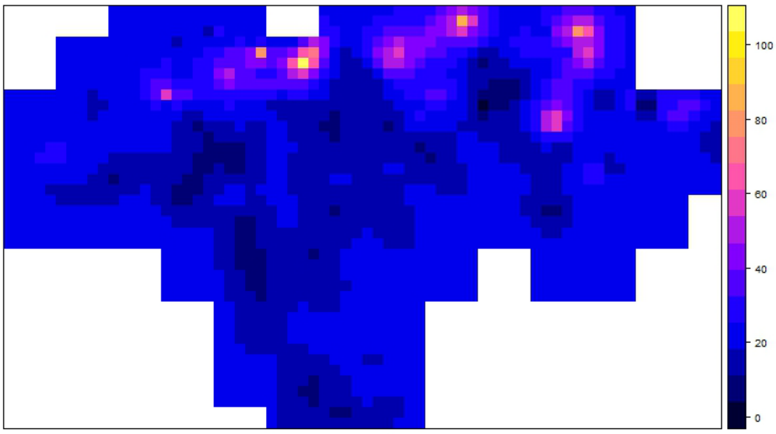

Figure 34: Estimated radon concentration in soil gas for Cantabria based on Ordinary Kriging.

Data on soil permeability was assigned to five permeability classes, depending on the lithological type. Consequently, it was not possible to use the Neznal geogenic radon potential (GRP, Neznal et al., 2004). According to the Cantabrian data set, the GRP was defined as

$$GRP = Soil\ Rn * Permeability^2 \qquad (Equation\ 7)$$

The five permeability classes ("very low", "low", "medium", "high" and "very high") were converted into numerical values (1 = "very low", 2 = "low", 3 = "medium", 4 = "high" and 5 = "very high"). Permeability data was provided as vector data, which required a transformation into raster data.

Data on soil gas radon and data on permeability are both given as raster data with the same spatial resolution (grid cell size of 2000 m). The geogenic radon potential was therefore calculated according to equation 8. Results are displayed in Figure 35.

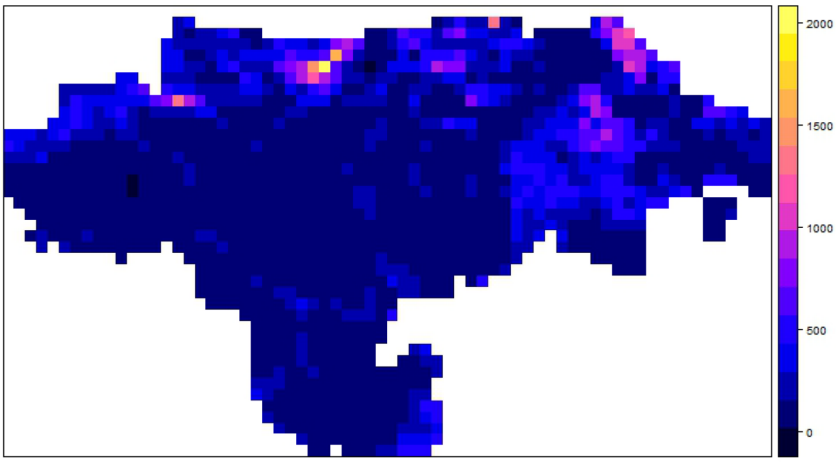

Figure 35: Geogenic radon potential (GRP) calculated from soil gas radon measurements and soil gas permeability.

In the next step, correlation between the calculated GRP and indoor radon concentration was tested. The goal was to calculate a threshold GRP value that coincides with the 10 % exceedance probability of 300 Bq/m³ indoor radon concentration at a tolerated error rate. However, there is only a weak correlation between both quantities with a Pearson correlation coefficient of 0.12 ($p<0.05$) and a spearman rank correlation coefficient of 0.08 (Figure 36). The determination of radon risk areas (radon priority areas), based on the GRP/Indoor Radon Relationship, is therefore not meaningful for the Cantabrian data set.

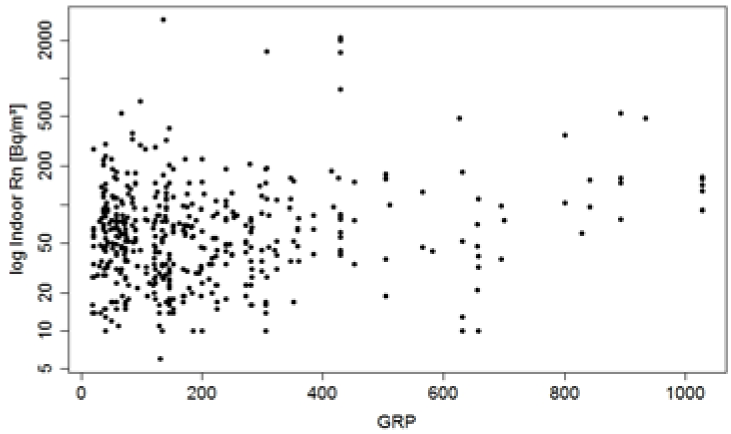

Figure 36: Correlation between geogenic radon potential (GRP) and indoor radon concentration (log).

4.5 Belgian radon risk mapping software (BRRMS)

(François Tondeur, ISIB-HE2B)

Only the Austrian data set was used for the following Belgian radon risk mapping method.

The Belgian radon mapping software

The Belgian radon risk mapping method is similar to the British one. Cinelli et al. (2011) developed the method and the corresponding software is described in Tondeur & Cinelli (2014).

The principle is to map the variations of the radon risk within geological units with the moving average method, while geological units with significantly different levels of risk are considered separately. When contiguous geological units have similar mean radon levels, they are treated as a single unit. Within a given unit, the moving average of the nearest 20 data is calculated (more precisely, the log mean, or the log median) for any chosen coordinate set, e.g. the nodes of a square grid. The percentage of data locally bypassing a chosen threshold is also predicted, assuming a lognormal distribution. The threshold used here is the European reference level of 300 Bq/m³ and the lognormal distribution is only fitted to data above the median (Cinelli & Tondeur, 2015).

The method does not include a classification of the nodes. A classification in five risk classes is used in the Belgium method for municipalities (AFCN, 2018) but was not included in the software.

Data selection

Only the highest concentration, measured on the ground floor, is kept.

Geological context

The Austrian data provided for the exercise come from two distinct rather small radon-affected areas. Each area includes different geological formations. However, the radon statistics give rather similar values for the geometrical mean indoor radon concentration in the different geological units of each area, why they were considered as a single mapping unit (Table 18).

Table 18: Geometrical mean indoor concentration in different geological units of AUT South and AUT North.

Geological unit	**Number of data**	**Geometrical mean indoor Rn**
AREA AUT North		
Granite	123	254
Migmatite	455	248
AREA AUT South		
Coarse Gneiss Complex	460	186
Permomesozoic rocks	266	161
Tertiary sediments	47	174
Other	9	233

Maps on a 500 x 500 m grid

The Belgian software evaluates the radon risk at given coordinates, e.g. at the nodes of a square grid. It does not give an average value for each square of the grid. Because of the good sampling density, the local sampling of the nearest 20 measurement data often covers a surface much smaller than the squares of the suggested 2 x 2 km grid, with the consequence that a significant part of the data might not be taken into account. Therefore, a finer grid was chosen (500 x 500 m), defined by dividing the 2 x 2 km grid initially provided, but excluding mesh points too far from any data (see Figure 37 and Figure 38).

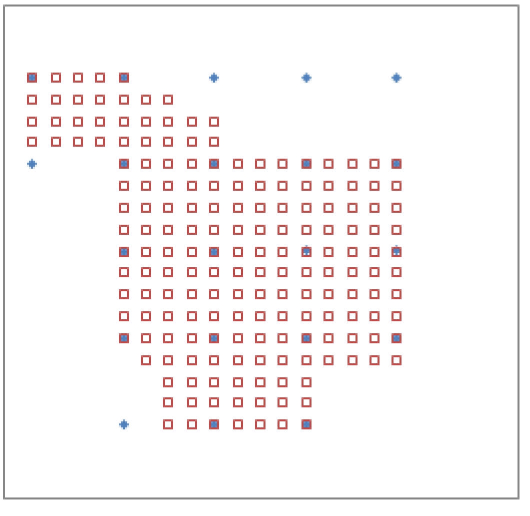

Figure 37: Grid for AUT North superimposed to the initial grid.

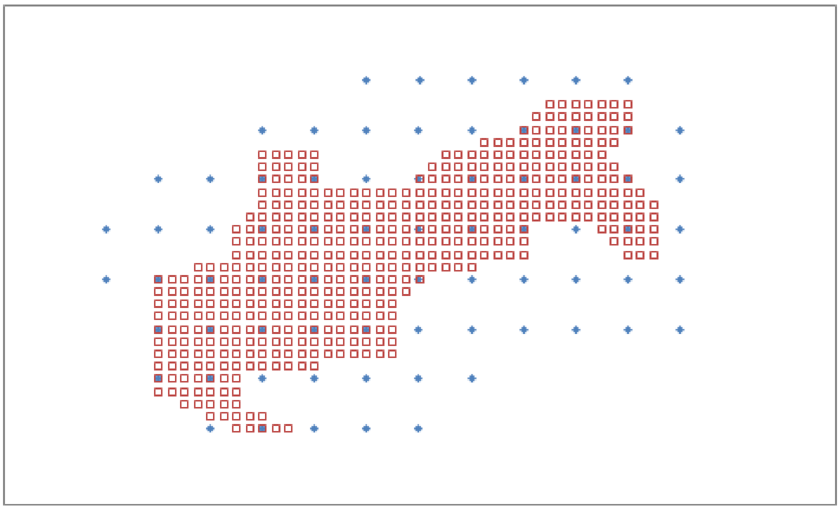

Figure 38: Grid for area AUT South superimposed to the initial grid.

Colour scales and map appearance

The colour scales used in the maps are adopted for Belgium and were chosen in order to display the contrast between unaffected areas and affected areas.

The areas considered here are affected in all their parts. Therefore, only the few colours appear in the map that correspond to radon concentration of too high and very high radon risk. The maps are given as square pixels. Note, that each pixel represents the prediction at the centre of the square, not the mean value within the square (Figure 39, Figure 40, Figure 41, Figure 42).

Figure 39: Map of the median indoor radon concentration in area AUT North.

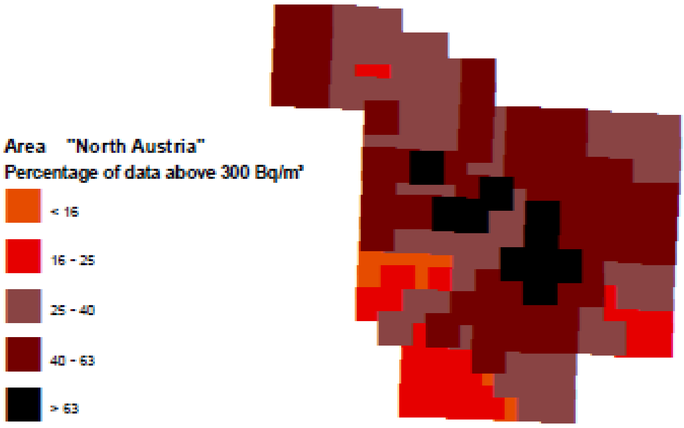

Figure 40: Map of the percentage of data above 300 Bq/m³ in area AUT North.

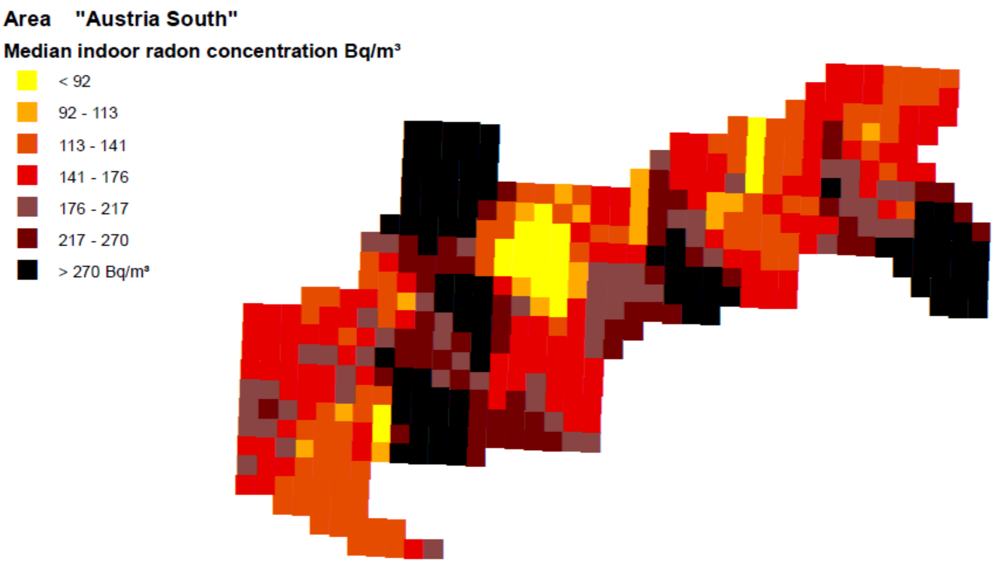

Figure 41: Map of the median indoor radon concentration in area AUT South.

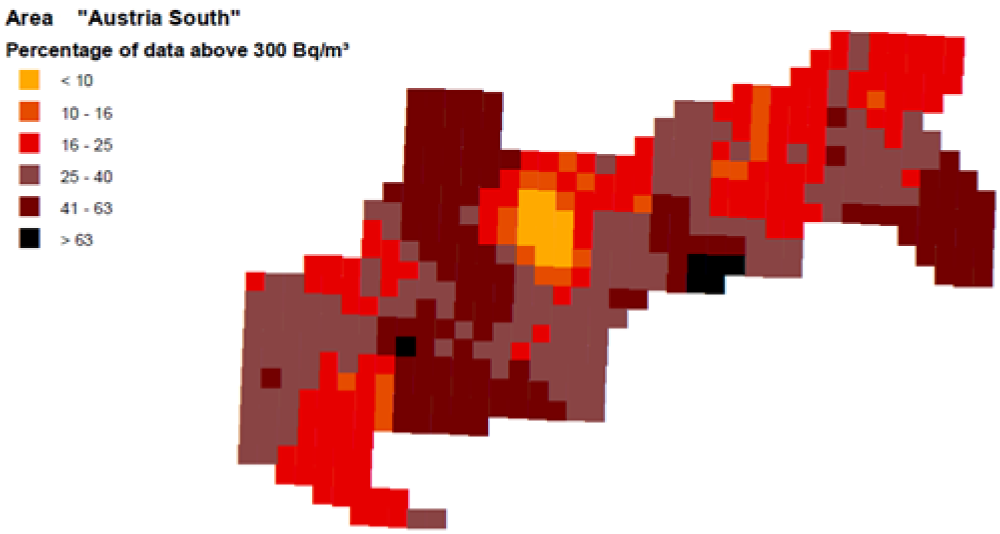

Figure 42: Map of the percentage of data above 300 Bq/m³ in area AUT South.

Conclusion

Despite the weakness of the variability related to geology, the two areas show an important variability of the percentage of dwellings above the European reference level of 300 Bq/m³. In AUT North, this percentage ranges from 7% to 67%, whereas AUT South shows a range from 11% to 78%. According to the classification used in Belgium, almost all nodes of the two areas from Austria (AUT South, AUT North) would belong to the upper risk class. Therefore, all six municipalities in the exercise would be considered as radon priority areas.

5. Summary

In the previous chapters the idea, the data sets and the applied methodologies of the mapping exercise were discussed. The main purpose of the exercise was to apply a radon classification scheme (following the concept of RPA) by using given data sets and applying different mapping methods.

Two different **data sets** were used for the exercise, Cantabria and six municipalities in Austria. The data sets differ in basic characteristics as size, sample density, data extent, quality and resolution, as shown in Table 5. In chapter 3.3 the data sets were analysed in detail, regarding significant differences among groups (e.g. soil type, geology unit), correlations among the variables and spatial dependencies for all variables, summarized in Table 9. Table 5The analysis of the exercise data shows that grouping of populations, the type of correlation and the rate of spatial correlation of the same variables are not equal in different regions.

The data sets are complex and difficult to analyse and correlations were less significant than expected. The Austrian data sets represent only small areas (6 municipalities), which seems to be too small and too geological homogenous for geogenic correlations and modelling. The Cantabrian data set represents a larger area, but the data came from different surveys and literature (e.g. GEMAS and FOREGS), which seem to be not compatible. In addition, also the data set has low sampling density and no detailed coordinates for IRC, which makes the use of IRC for modelling also challenging.

The fact, that the data are inhomogeneous and not perfect in several aspects makes it a good exercise, since also in practice, most of the time the data which are available for mapping are neither perfect nor complete which would be desirable. Consequently, the exercise can show, how different mapping methods can perform also with incomplete or heterogeneous data sets, and how classification of RPA can be done with them.

To apply the different **mapping methods** the data sets may require adequate data manipulations and not all data is used for each mapping method, and also not every mapping method can be used for the data set. Table 19 gives an overview of the applied mapping methods (see chapter 0) and the data which were used for the respective method. In general, mapping methods are mostly specified to use either IRC as target variable (e.g. basic statistics methods, Kriging IRC) or geogenic variables (EBK regression, Kriging GRP). BRRMS, the Belgium mapping method, combines IRC and geogenic variables, by taking into account geological units. The methods using IRC with building characteristics could be only applied for the Austrian data sets, as no information about building characteristics is included in the Cantabrian data set. Only the GAMM method used all available variables as well for the Austria and the Cantabrian data set. Except the basic statistic methods (IRC mean over threshold and probability of IRC over threshold per municipality or geological unit) all methods used interpolations to map the radon concentration or radon potential or radon risk.

Table 19: Overview of different methods and variables used in the respective method.

Method	IRC	Building characteristics	Soil Gas	Radionuclide contents	Geogenic factors	Interpolation
IRC mean over threshold	yes	possible subset data	no	no	no	no
Probability of IRC over threshold	yes	possible subset data	no	no	no	no
GAMM	yes	yes	yes	yes	yes	yes
EBK regression	no	no	yes	yes	yes	yes
Kriging IRC (AT)	yes	subset data	no	no	no	yes
Kriging GRP (ES)	no	no	yes	yes	yes	yes
BRRMS	yes	subset data	no	no	yes	yes

A summary of the **results** for Cantabria and the six municipalities in Austria is shown in Table 20. The table gives an arithmetic/geometric mean, median value for the IRC or the percentage of measurements above 300 Bq/m³ in Cantabria and each of the six Austrian municipalities. The results of the specific methods were discussed in detail in chapter 4. The methods which delivered results for grid cells were aggregated for the basis of region Cantabria and the municipalities for Austria, as overview and for the possibility of better comparison. The table only shows results for IRC predictions and not for geogenic radon potential (GRP). The results show that the predicted radon concentration is clearly lower for all methods in Cantabria than in Austria, and also in most cases lower in the 3 municipalities in AT South compared to AT North. The GM of Cantabria data from basic statistics and the GAMM correspond very well, also for AT Mun. 2 and 4, for the other municipalities it deviates quite strong, especially for Mun. 5 and 6. The BRRMS median concentration per municipality compared to basic statistics median deviates about 10 to 30 %, a bit stronger for the values of percentages about 300 Bq/m³. The Ordinary Kriging IRC prediction per municipality delivers clearly higher values than the basic statistics and BRRMS method. The results are compared and discussed in more detail in chapter 0.

Table 20: Results for different methods and regions for IRC (Austria and Spain)

	AM (Bq/m³)	GM (Bq/m³)	Med (Bq/m³)	% > 300	Med (Bq/m³) BRRMS	% > 300 BRRMS	GM (Bq/m³) GAMM	AM (Bq/m³) OK	% > 300 IK
Cant.	97	54	54	3	-	-	54	-	-
AT North Mun.1	289	196	197	31	231	40	243	352	36
AT North Mun. 2	313	207	213	36	240	41	201	360	39
AT North Mun. 3	429	273	266	45	230	39	208	367	39
AT South Mun. 4	289	165	168	28	209	38	153	305	26
AT South Mun. 5	251	157	144	22	183	32	241	300	26
AT South Mun. 6	234	146	130	21	173	31	310	304	26

6. Discussions and Conclusions

In the previous chapters, the data and applied mapping methods were discussed and also the results summarised. In this final chapter the methods and results should be compared and discussed and conclusions from the exercise should be drawn. As discussed in the introduction, the exercise and the delineation of radon priority areas is a multiple-step process – collecting and preparing the available data or in practice, performing the measurement campaign to get the data, selecting or developing the best mapping method for the situation and applying it to the data, and classifying the results according to the definition of RPA. The definition of RPA is mostly a political decision and not only a scientific one. As shown in chapter 2.1, different definitions of RPA concepts are adapted in the individual countries, some examples are listed in Table 2. In this chapter the results of the different applied mapping methods for the three areas (AUT North, AUT South, Cantabria) are classified and characterised according to some commonly used definitions of RPA and comparability and usability is discussed.

Correlations

The methods discussed in chapter 4 provided results for either the predicted IRC or the predicted GRP per grid cells. In Table 20 the IRC results were summarised on the basis of administrative areas, which is used also for the classification discussion below. The correlations between mapping methods were also analysed in more detail. Correlation analysis is only meaningful for methods, which provide the same variable as result (IRC, GRP) and the results need to be aggregated to the same grid cells. The GAMM method used larger grid cells for predictions and therefore have only few data points for the AT areas, which makes correlation analysis more difficult. In Figure 43 and Figure 45 two examples of correlations between different methods are shown. Figure 43 compares the EBK regression (Chapter 4.3) with the Ordinary Kriging (OK) (Chapter 4.4) for the predicted GRP for Cantabria. The data were aggregated in a 5x5 km grid and the coefficient of determination (r^2) is 0.59. The correlation between the two methods for the area is acceptable good. In Figure 44 the results (GRP predictions) of the two methods are displayed in the map (5x5 km grid). The two maps show a corresponding picture, with only some higher GRP in the North of Cantabria. In general the level of GRP prediction by OK method is a bit above the one by EBK regression.

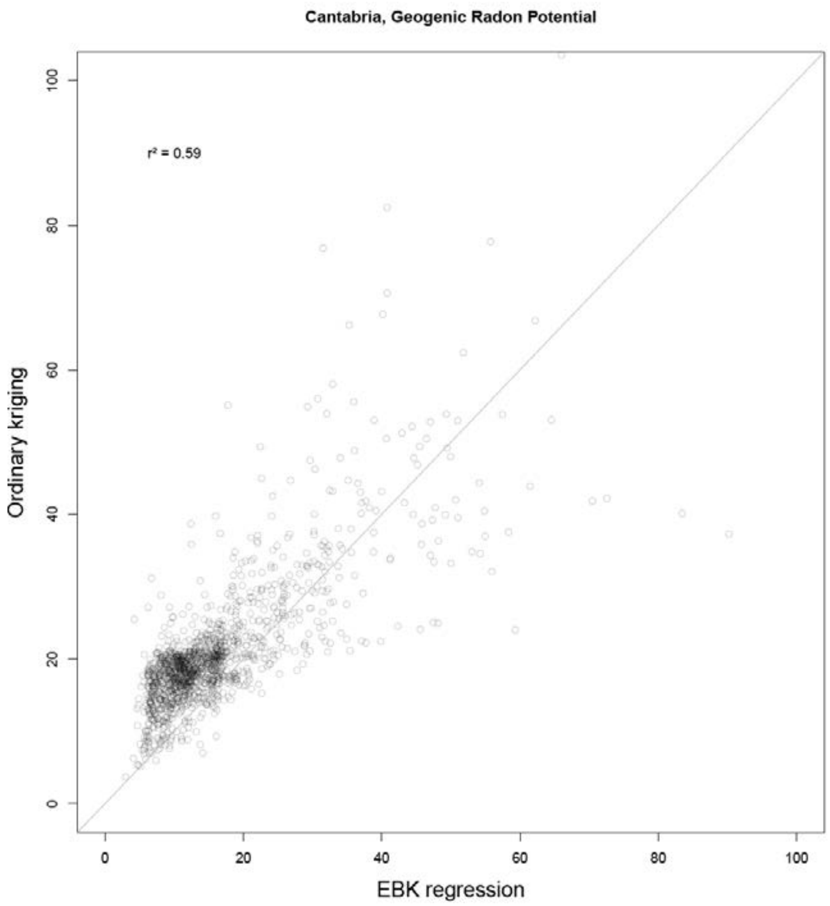

Figure 43: Correlation between 2 different mapping methods for the geogenic Radon Potential (GRP) for Cantabria data set – Ordinary Kriging (OK) (Chapter 4.4) vs. EBK regression (Chapter 4.3)

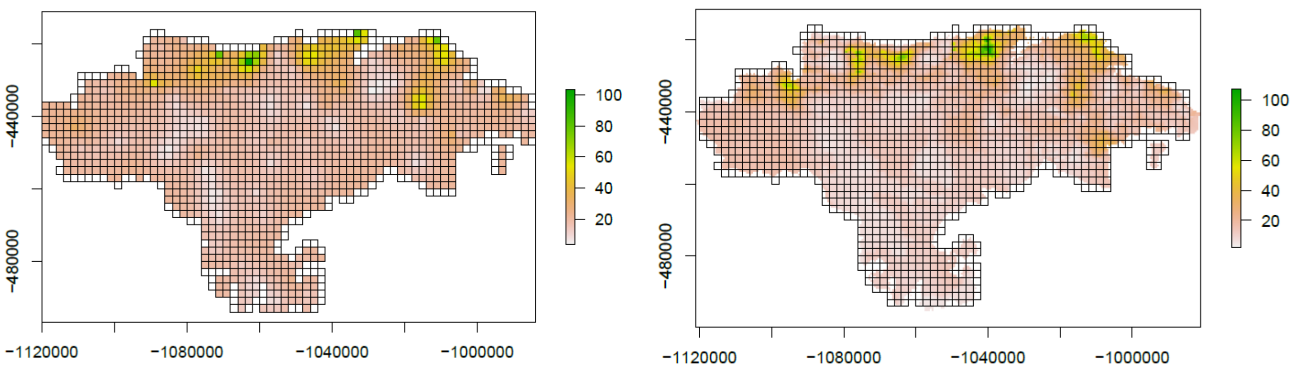

Figure 44: Mapping the GRP prediction in 5 x 5 km grid for Cantabria with Ordinary Kriging method (OK) (Chapter 4.4, left handside) and EBK regression. Predictions were aggregated for 5x5 km grids (Chapter 4.3, right handside).

Figure 45 compares the Belgian Radon Risk Mapping Software (BRRMS, Chapter 4.5) with the Indicator Kriging (IK, Chapter 4.3) for the predicted percentage of measurements above 300 Bq/m³ for the area AUT North. As basis for the comparison the coarser 500 x 500 m grid of the BRRMS was used and compared with the cell of the 200x200 m kriging raster closest to the midpoint of the BRRMS grid cell. The coefficient of determination (r^2) is 0.41, which is still a satisfying correlation. In Figure 46 the results (% of measurements over 300 Bq/m³) of the two methods are displayed in the map. The two maps show a quite similar picture, with some cells with highest radon potential in the centre. In general, the level of prediction by BRRMS method is a bit above the one by IK.

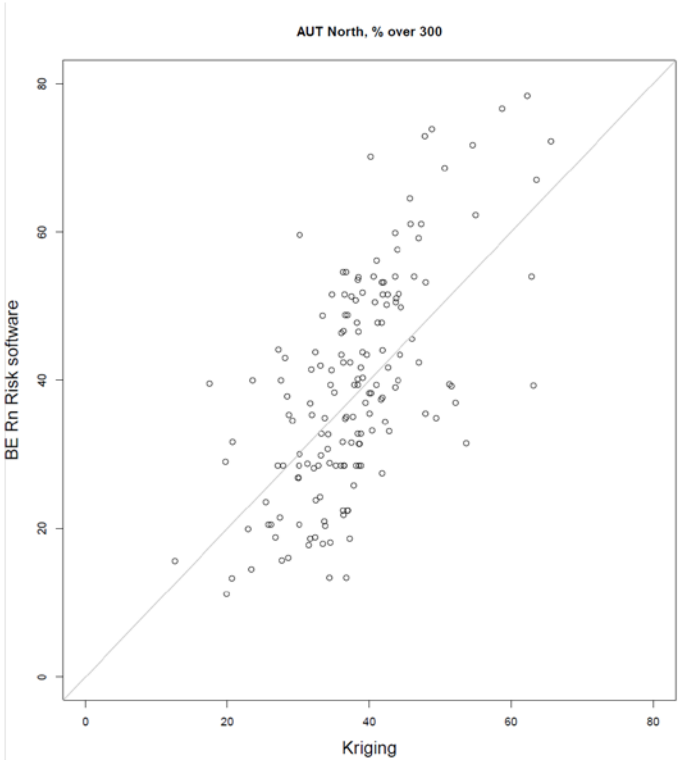

Figure 45: Correlation between 2 different mapping methods for the % above 300 Bq/m³ for the AT North data set – Belgian Radon Risk Mapping Software (BRRMS, Chapter 4.5) vs. Indicator Kriging (IK, Chapter 4.3)

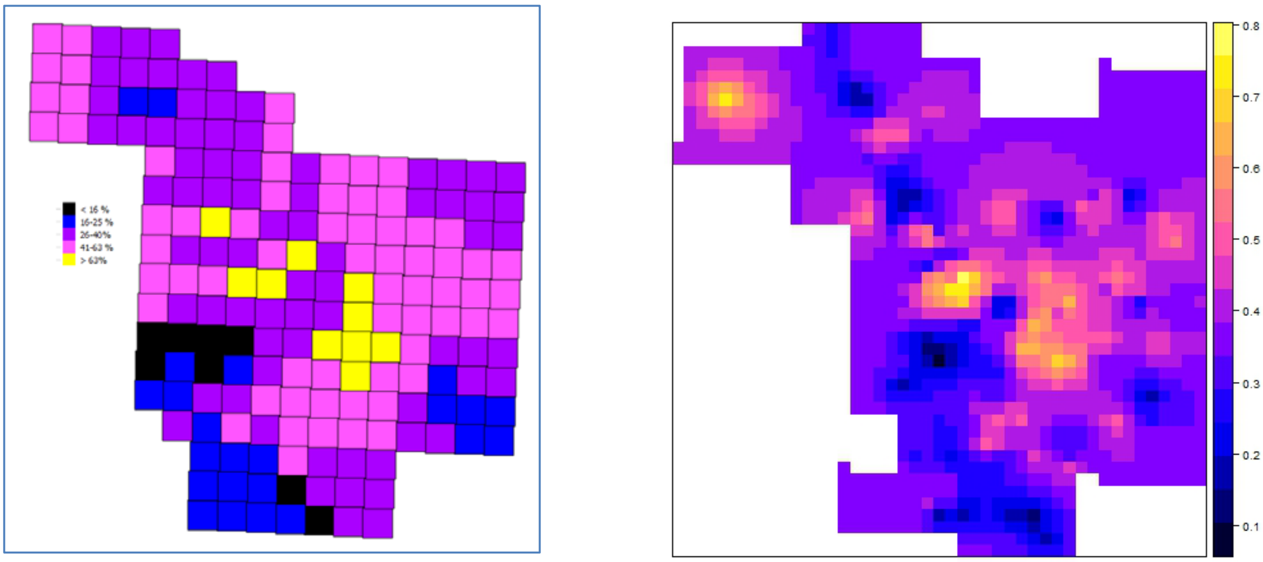

Figure 46: Mapping the prediction of % above 300 Bq/m³ for the AZ North data set with Belgian Radon Risk Mapping Software (BRRMS, Chapter 4.5, left handside) and Indicator Kriging (IK, Chapter 4.3, right handside)

The two examples show quite good correlations for the predicted cells which indicates, that they should be interchangeable for harmonisation purposes. In general, the selection of a mapping method for a certain area, will be highly depend on the available data sets. Not all mapping methods are applicable to all data and all areas as depending on data quality, sample density, heterogeneity of the area, etc. In our example the methods using building characteristics for the prediction of IRC were not possible to use for the Cantabrian data set, where this information was not available. On the other hand, methodologies based on differences between geogenic factors (e.g. EBK regression) could not be adapted to the very small, quite geogenic homogeneous areas of Austria. Also for the BRRMS, taking into account information of geological units, had problems within the AUT North area with only very few geological areas. All this information needs to be evaluated and taken into account when choosing a mapping method for a certain area or a certain available data set. If a survey for delineation of RPA (as requested in the EU-BSS) is started from scratch, the mapping method and display/classification method for the map (e.g. % above RL in administrative area) should be decided at the beginning, so that the survey (measurement density, analysed parameters, etc.) can be optimised to these requirements. For harmonisation of mapping or delineation of areas (e.g. on a European basis) a method using less parameters might be preferable, as easier to apply to different data sets.

Classification of Radon priority areas (RPA)

As discussed above, different definitions of RPA concepts are adapted in the countries. In Table 20 the results of the different methods for the administrative units (six municipalities in Austria and the region of Cantabria) were summarised. The comparison in chapter **Fehler! Verweisquelle konnte nicht gefunden werden.** showed, that some of the results correspond very well, while others not, e.g. the Ordinary Kriging IRC prediction per municipality delivers clearly higher values than the basic statistics and BRRMS method.

Here we want to evaluate, how these different results provided by different mapping methods would have an impact on the classification or delineation of RPAs. Table 21 and Table 22 show the same results as Table 20, but two common RPA classification definitions were applied to the results – mean/median/GM above a certain threshold (Table 21) and percentage of measurements/predictions above a threshold (Table 22). If the threshold of above AM/Med/GM is set to 300 Bq/m³, all six Austrian municipalities would be classified as RPA with the OK method, municipality 2 and 3 with the basic statistics method (AM) and municipality 6 with the GAMM method (marked in purple in Table 21). If, on the other hand, the threshold of above AM/Med/GM is set to 100 Bq/m³ all six Austrian municipalities with all applied methods would be classified as RPAs (marked in red and purple in Table 21). Cantabria would not be considered as RPA for all methods and classification thresholds. This shows, that the chosen threshold for the classification of RPA has a major impact, depending on the level of radon concentration in the area. For Cantabria which has a very low radon concentration, the differences in the results of the different methods do not impact the RPA classification. Whereas the Austrian municipalities show radon concentrations in the range about 150 to 400 Bq/m³, depending on municipality and mapping method. Therefore, the differences (even when small) in the radon concentration for the different methods for the same municipality can have an impact in RPA classification, when the threshold is chosen in the range of the variability of the results (e.g. 300 Bq/m³ as shown in the example). If the threshold is set with 100 Bq/m³ all municipalities are classified the same, as this threshold does not lie within the range of the measurement/prediction results and therefore the variability of the results of the different methods do not have an impact on the classification of RPAs.

If, in Table 22, the threshold of percentage of measurements/ predictions is set to 30 %, a definition which is used only in Czech Republic, all municipalities in AT North would be classified to be RPA with all three applied methods, and for all six municipalities for the BRRMS method (marked in purple in Table 22). Applying the commonly used definition of RPA in Europe (10 % of dwellings above 300 Bq/m³), all six municipalities in Austria would be clearly considered as RPA, independent from the mapping method (marked in red and purple in Table 22). As discussed above, the variability of the results of the different methods only impact the classification of RPA when the set threshold lies within the range of the predicted/measured results.

Figure 47 displays the same results as shown in Table 21 for the three municipalities of the Austria North and Austria South area. The results (AM/GM/Med) per municipality for the respective methods is plotted and the colouring shows, for which threshold the municipality would be considered to be RPA (yellow) and Non-RPA (green).

Table 21: Results for different methods and regions related to Median, GM or AM of measured/predicted IRC with applied classification definition of RPA (purple: AM/Med/GM > 300 Bq/m³; red: AM/Med/GEM > 100 Bq/m³)

	AM (Bq/m³)	GM (Bq/m³)	Med (Bq/m³)	Med (Bq/m³) BRRMS	GM (Bq/m³) GAMM	AM (Bq/m³) OK
Cant.	97	54	54	-	54	-
AT North Mun.1	289	196	197	231	243	352
AT North Mun. 2	313	207	213	240	201	360
AT North Mun. 3	429	273	266	230	208	367
AT South Mun. 4	289	165	168	209	153	305
AT South Mun. 5	251	157	144	183	241	300
AT South Mun. 6	234	146	130	173	310	304

Table 22: Results for different methods and regions related to % of measurements/predictions above 300 Bq/m³ with applied classification definition of RPA (purple: > 10 % above 300 Bq/m³)

	% > 300	% > 300 BRRMS	% > 300 IK
Cant.	3	-	-
AT North Mun.1	31	40	36
AT North Mun. 2	36	41	39
AT North Mun. 3	45	39	39
AT South Mun. 4	28	38	26
AT South Mun. 5	22	32	26
AT South Mun. 6	21	31	26

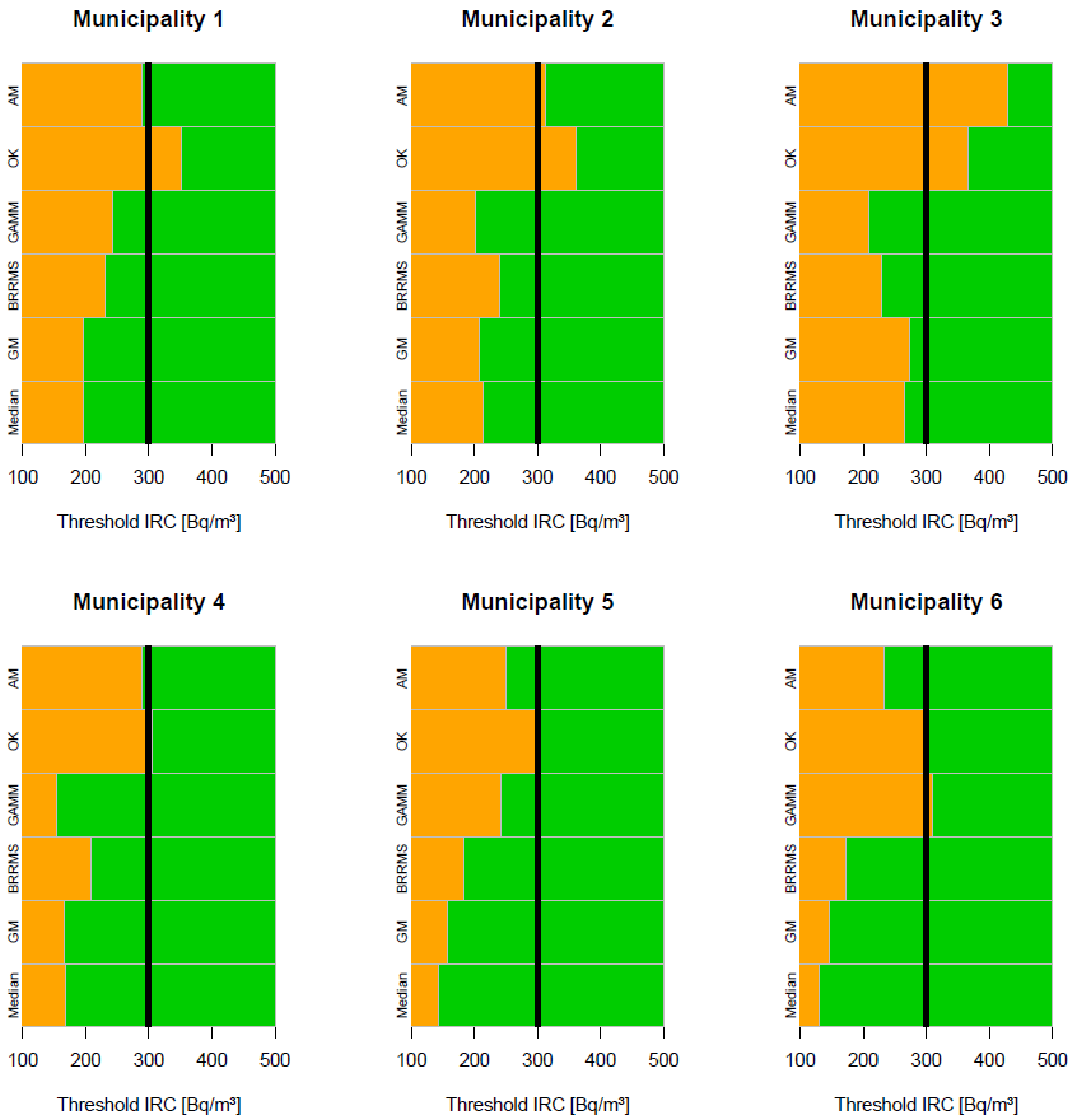

Figure 47: Classification of RPA for the 6 municipalities in Austria with different methods and for different thresholds (green: no RPA, orange: RPA – further explanation in the text)

As known and shown also within this exercise and this report, mapping methodologies are various and so are the definitions of RPAs. To evaluate the situation in Europe and possibilities for harmonisation between countries and on borders was the driving factor for the work package within the MetroRADON project, where this mapping exercise is part of. As a general conclusion from this exercise, it can be said, that applying a mapping method using data sets, which were not designed for the specific requirements of the mapping method, is challenging. Usually, data sets always have specific characteristics and are rarely comparable, even not for the same variable. Therefore, harmonisation is always a challenge. But some examples in this exercise show quite good correlations for the predicted cells which indicates, that they should in principle be interchangeable for harmonisation purposes. In general, the selection of a mapping method for a certain area, will be highly depend on the available data sets. Not all mapping methods are usable for all data sets or areas, depending especially on data quality, sampling density, or heterogeneity of the mapping area. For harmonisation of mapping (e.g. on a European basis) a method using less parameters might be preferable, as it would be easier to apply to different data sets.

Usually the final goal of mapping is the delineation of RPA, as this is requested in the EU-BSS. It was shown in this exercise, that independent of the applied method for large intervals of classification threshold the same RPA classification is predicted. Different methods often deliver same results in RPA classification, depending on the definition of RPAs. So, the definition of thresholds is a very important factor in the process of delineation of RPA and might be as relevant as harmonising mapping methods.

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Annex to Chapter 3.3 – Data set analysis

(Alcides Pereira, Filipa Domingos, University of Coimbra)

Austria: Northern Region (AUT North)

Analysis of soil data (acquired by physical sampling and airborne spectrometry)

According to soil type, soil grain size, soil source and bedrock, the data analysis shows that the content of Ra-226, U-238, K-40, Ra-228 and Th-228 is not statistically different (significance level of 0.05) between the various types of soil and bedrock. This also applies for the different soil source types (Table 23). The ambient dose rate, however, is statistically different among different bedrock types and soil source types. The ADR is higher on gneissic and silicate sources compared to granitic soil sources. The ADR is higher in the Weinsberger biotite granite and the two-mica Altenberger granite, followed by migmatite rocks, alkaline to intermediate plutonic rocks and valley infills. As the ADR is significantly influenced by soil source and/or bedrock type, the terrestrial gamma dose rate (TGDR) was computed for the purpose of comparison of the combined content of radionuclides according to soil type, soil source and bedrock type. The TGDR was computed from U-238, Th-232 (assuming secular equilibrium between Th-228 and Th-232) and K-40 activity concentration [Bq/kg] according to the following equation:

$$TGDR = 0.0417 \times {}^{40}K + 0.462 \times {}^{238}U + 0.604 \times {}^{232}Th \qquad (Equation\ 8)$$

The dose conversion factors [Bq/kg] of 0.0417, 0.462 and 0.604 were retrieved from UNSCEAR (2010). The results of the Kruskal-Wallis test show the lack of statistically significant differences of the TGDR among groups.

The analysis of the soil gas radon and permeability data according to soil type, soil grain size, soil source and bedrock shows that the soil gas radon concentration is statistically different at a 0.05 significance level between the different soil types, soil grain size and soil water content (Table 24). Radon concentration in soil gas is higher in sediment brown earth compared to rock brown earth and silt compared to loamy sand. Radon concentration in soil gas is also higher in moderately moist soils compared to other moisture contents (dry, well supplied and moderately dry).

The eU concentration, determined by airborne gamma spectrometry, shows statistically significant differences among different soil sources, bedrock and soil water content (Table 24). Colluvium soils present higher eU contents, followed by soils derived from gneiss, granite and silicates. Alkaline to intermediate rocks present higher eU contents, followed by the fine grained two-mica granite (Altenberger) and the intermixing zone and fluid transition of coarse-grained biotite granite and migmatite. The fine to intermediate grained migmatite (Meta-Diatexite), valley infill sediments and the coarse to very coarse grained biotite granite (Weinsberger) present the lowest average eU contents. The permeability is not statistically significant between different soil and bedrock units, soil sources and soil water content (Table 24).

Table 23: Analysis of radionuclides concentration data, terrestrial gamma dose rate (TGDR) and ambient dose rate (ADR) by soil and bedrock type (statistically significant differences are marked in bold).

Variable	**Soil type**	**Soil grain size**	**Soil source**	**Bedrock (geology_fine)**	**Bedrock (geology_coarse)**
Ra-226	H(1;28) = 0.3899; p = 0.5323	H(1;28) = 0.3899; p = 0.5323	H(2;28) = 2.0819; p = 0.3531	H(2;14) = 4.5; p = 0.1054	H(1;27) = 0.1102; p = 0.7399
U-238	H(1;28) = 0.1989; p = 0.6556	H(1;28) = 0.1989; p = 0.6556	H(2;28) = 3.5252; p = 0.1716	H(2;14) = 4.5; p = 0.1054	H(1;27) = 0.1959; p = 0.6580

K-40	H(1;28) = 0.1274; p = 0.7212	H(1;28) = 0.1274; p = 0.7212	H(2;28) = 0.68; p = 0.7118	H(2;14) = 1.6236; p = 0.4441	**H(1;27) = 6.3394; p = 0.0118**
Ra-228	H(1;28) = 0.9629; p = 0.3265	H(1;28) = 0.9629; p = 0.3265	H(2;28) = 2.0862; p = 0.3524	H(2;14) = 0.5914; p = 0.7440	H(1;27) = 0.1102; p = 0.7399
Th-228	H(1;28) = 0.7958; p = 0.3724	H(1;28) = 0.7958; p = 0.3724	H(2;28) = 1.4113; p = 0.4938	H(2;14) = 0.2714; p = 0.8731	H(1;27) = 0.1294; p = 0.7191
Pb-210	H(1;28) = 0.2865; p = 0.5925	H(1;28) = 0.2865; p = 0.5925	H(2;28) = 1.1626; p = 0.5592	**H(2;14) = 8.2229; p = 0.0164**	H(1;27) = 0.0122; p = 0.9119
TGDR (calc)	H(1;28) = 0.5093; p = 0.4754	H(1;28) = 0.5093; p = 0.4754	H(2;28) = 3.2833; p = 0.1937	H(2;14) = 2.1429; p = 0.3425	TGDR: H(1;27) = 2.0694; p = 0.1503
ADR	H(1;57) = 2.2415; p = 0.1344	H(1;57) = 2.2415; p = 0.1344	**H(2;57) = 6.7742; p = 0.0338**	**H(2;41) = 8.9202; p = 0.0116**	H(1;56) = 3.1127; p = 0.0777
H – Kruskal-Wallis H test; the degrees of freedom and number of data are indicated within brackets, respectively.					

Table 24: Analysis of soil gas radon, eU content and permeability data by water content, soil and bedrock type (statistically significant differences are marked in bold).

Variable	Soil type	Soil grain size	Soil source	Bedrock (g_fine)	Bedrock (g_coarse)	Soil water content
Soil gas radon	**H(1;57) = 5.0859; p = 0.0241**	**H(1;57) = 5.0859; p = 0.0241**	H(2;57) = 1.8905; p = 0.3886	H(2;41) = 1.4992; p = 0.4726	H(1;56) = 0.4773; p = 0.4896	**H(3;57) = 10.3603; p = 0.0157**
eU (ppm)	**H(3;3732) = 13.9654; p = 0.0030**	**H(2;3732) = 6.4935; p = 0.0389**	**H(3;3732) = 80.895; p = 0.0000**	**H(3;3732) = 80.895; p = 0.0000**	**H(1;3732) = 32.5135; p = 0.00000**	**H(4;3732) = 87.2186; p = 0.0000**
Permeability	H(1;57) = 0.3179; p = 0.5729	H(1;57) = 0.3179; p = 0.5729	H(2;57) = 0.3295; p = 0.8481	H(2;41) = 0.0874; p = 0.9572	H(1;56) = 0.3101; p = 0.5776	H(3;57) = 2.9429; p = 0.4005
H – Kruskal-Wallis H test; the degrees of freedom and number of data are indicated within brackets, respectively.						

The correlation between soil gas radon (Rn-222), radionuclide concentration (K-40, Pb-210, Ra-226, Th-228, U-238), ADR, TGDR and airborne eU concentration was evaluated in Table 25. For comparing soil and airborne data, the closest value (raster cell centre) to the soil data sampling location was chosen. Soil gas radon is significantly correlated with U-238. The ADR is correlated with K-40, Ra-228/Th-228 and the TGDR. The correlation between Pb-210, Ra-226 and U-238 activity concentration is significant which indicates an equilibrium in the U decay chain. However, there is no correlation with the ADR or airborne eU. Ra-228 and Th-228 are strongly correlated, indicating an equilibrium in the Th-232 decay chain.

Table 25: Spearman rank correlation matrix. Correlation coefficients are statistically significant at a 0.05 significance level and indicated in red

	Rn-222 [kBq/m³[	ADR	K-40 [Bq/kg]	Pb-210 [Bq/kg]	Ra-226 [Bq/kg]	Ra-228 [Bq/kg]	Th-228 [Bq/kg]	U-238 [Bq/kg]	TGDR	eU [ppm]
Rn-222 [kBq/m³]	1.00									
ADR	-0.06	1.00								
K-40 [Bq/kg]	-0.07	0.49	1.00							
Pb-210 [Bq/kg]	0.32	-0.08	-0.05	1.00						
Ra-226 [Bq/kg]	0.11	0.11	-0.19	0.56	1.00					
Ra-228 [Bq/kg]	-0.06	0.37	0.27	0.26	0.30	1.00				

Th-228 [Bq/kg]	-0.07	0.39	0.31	0.27	0.33	0.97	1.00			
U-238 [Bq/kg]	0.37	0.09	-0.06	0.48	0.82	0.15	0.14	1.00		
TGDR	0.03	0.48	0.74	0.26	0.26	0.76	0.79	0.29	1.00	
eU [ppm]	0.10	0.02	-0.07	0.25	0.31	-0.17	-0.16	0.32	-0.06	1.00

The correlation between Ra-226, U-238 and eU data is evaluated in Figure 48. The results show poor correlation (not statistically significant) between the eU and the soil map data using both the closest eU value to the sampling location as well as the average of the closest values.

The omnidirectional variograms for the radionuclides (Pb-210, Ra-226 and U-238), soil gas radon, permeability ($x10^{10}$), ADR, the calculated TGDR and eU were computed for evaluating spatial correlations within the data set (Figure 49). Apart from the eU data, no clear spatial correlation is observed (see discussion below for more details). The eU data was mapped with the variogram presented in Figure 49. The modelled data presented in Figure 50 show a high degree of variability of the eU data, particularly within each square km of the "soilmap" layer.

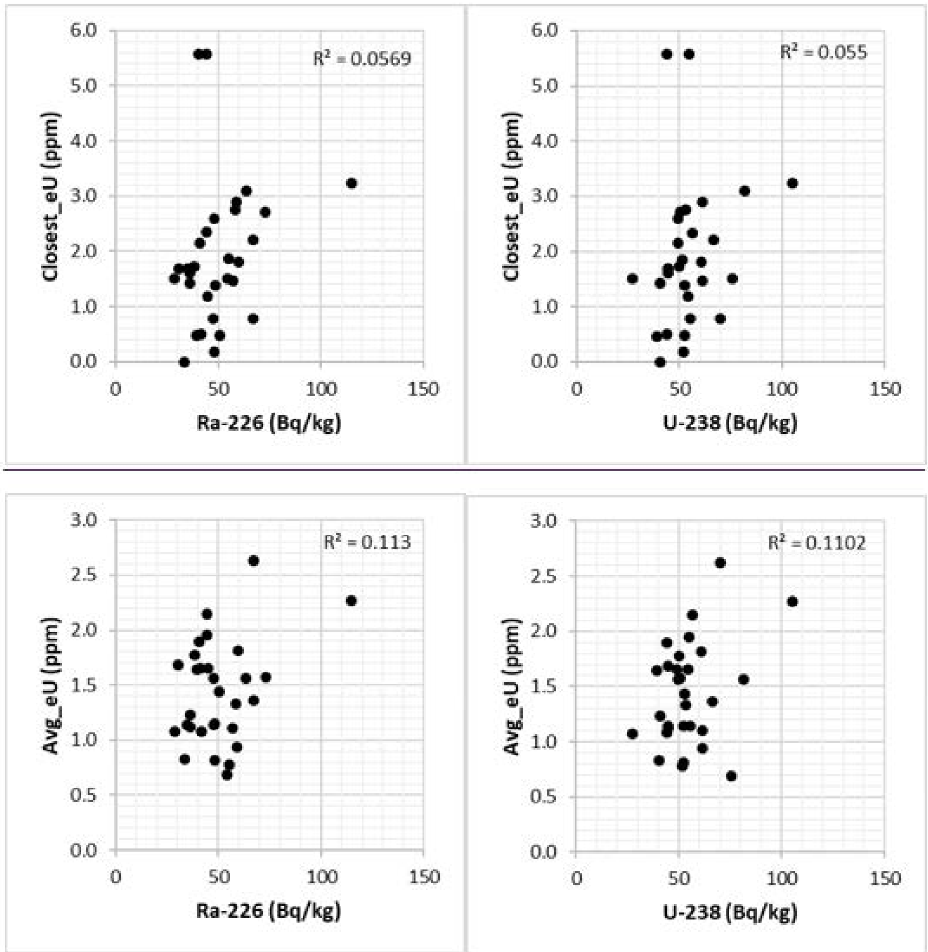

Figure 48: Correlation between Ra-226 or U-238 and airborne eU data (avg – average of eU data within a 500 m range were calculated and compared to the location of the sample; close – the closest eU value to the location of the samples were chosen to compare eU data to the radionuclide data).

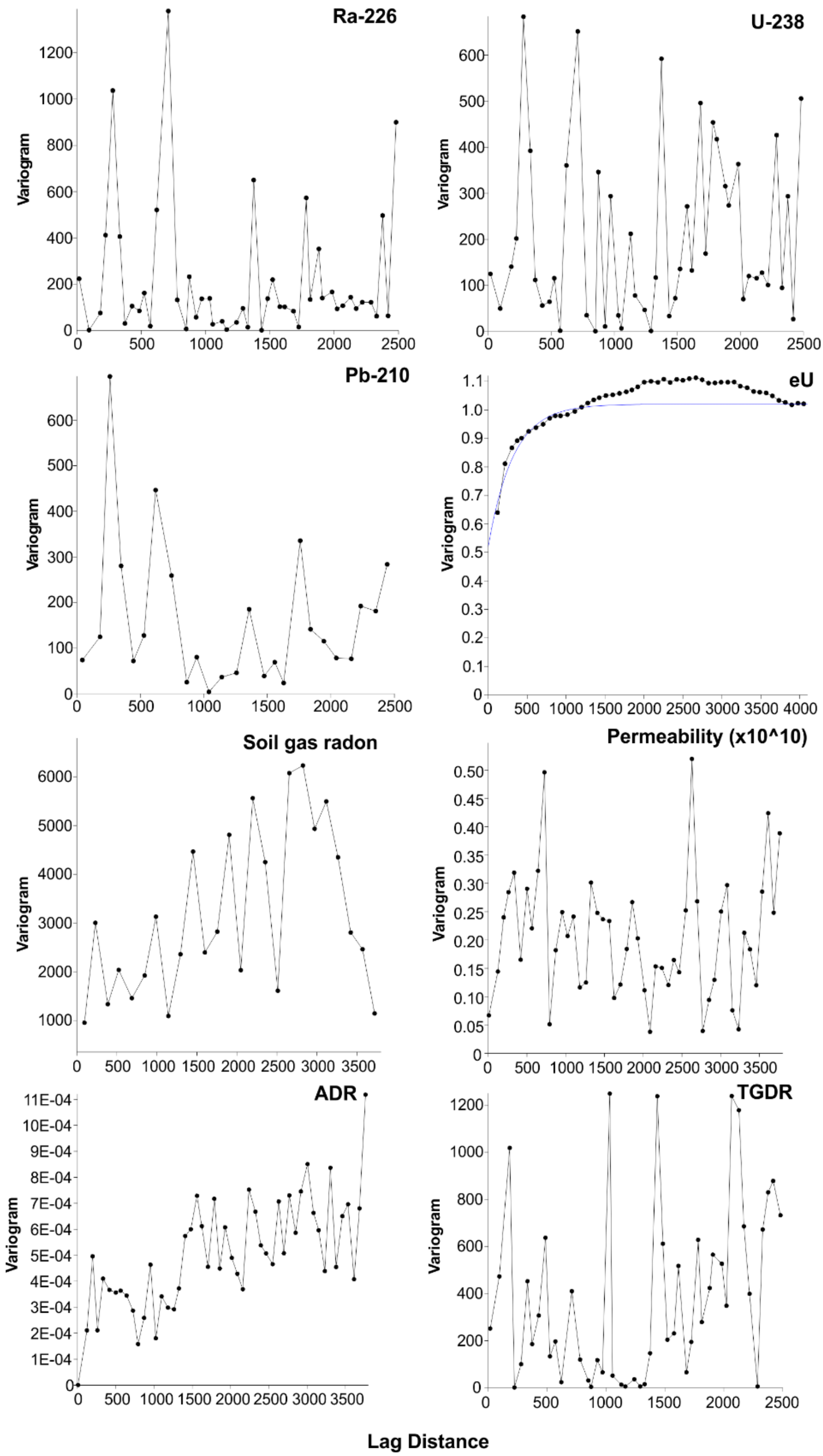

Figure 49: Omnidirectional semi-variograms of Ra-226, U-238 and Pb-210 activity concentration, airborne eU data, soil gas radon, permeability, ADR and TGDR.

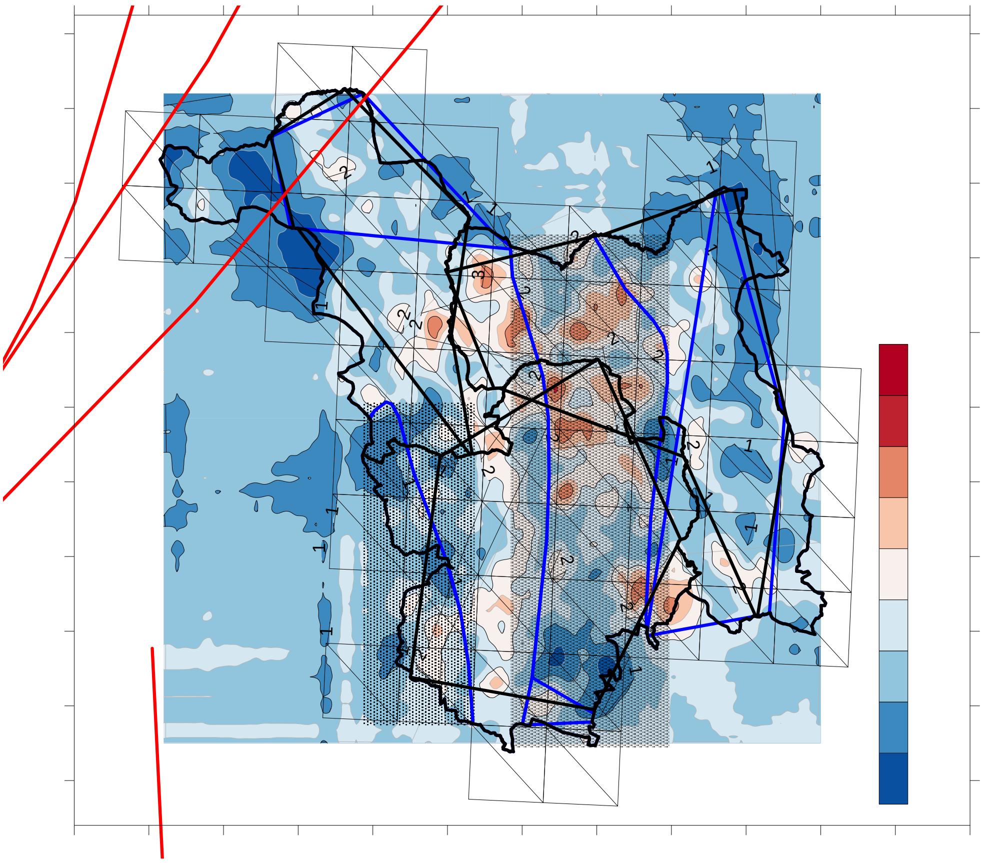

Figure 50: Map of eU data, modelled according to the variogram in Figure 49. The municipality limits and "soilmap" grid are superposed to the eU model. Shaded areas, limited by the blue line, correspond to the "granite bedrock" unit while unshaded areas correspond to the "migmatite, migmatitic paragneiss, coarse grained porphyritic granite with magmatic foliation" unit from the "geology _coarse" layer. The red lines correspond to faults (Austria GK M31 coordinate system).

Analysis of indoor radon concentration (IRC)

Data from both regions of Austria were only considered when appropriate; groups with n=1 observations were excluded from the analysis. The analysis of the indoor radon concentration data indicates that the IRC is statistically different at a 0.05 significance level between room types, earth- and non-earthbound divisions, basement, building, floor and foundation types (Table 26). The results of the multiple comparisons suggest that the data from "basement" is generally different from the data acquired in other divisions. The data from earthbound divisions is generally higher than the data acquired in non-earthbound divisions, which is also reflected in differences between the data according to basement type ("full", "partial", "none"). Weekend home data is different from data acquired in other types of buildings.

As a better correlation between the soil/bedrock radon exhalation rate and indoor radon concentration of earthbound divisions is expected, IRC earthbound data were analysed according to soil data properties (Table 27). The analysis of the data, considering both regions, indicates statistically significant differences among different groups of soil type, soil grain size, permeability, soil source, bedrock and water content (Table 27). The results for the AUT North region only indicate statistically significant differences according to the permeability and soil water content.

Omnidirectional variograms for the IRC data set (total and including earthbound data) were computed (Figure 51). No clear spatial correlation is observed considering the arithmetic mean of the data, however, a spatial correlation is observed considering data from both rooms, particularly clear when only earthbound data is considered.

Table 26: Analysis of indoor radon concentration (IRC) by building characteristics (statistically significant differences are marked in bold).

Variable	IRC	Multiple comparisons
Room type	**H(7;3039) = 41.46, p < 0.001**	"Basement" different than "bed room", "kitchen", "living room", "child's room", "dining room", "home office"
Earthbound Room	**H(1;2924) = 272.15, p < 0.001**	"yes" and "no" are different
Floor	**H(6;3188)=171.90, p < 0.001**	"-1" different from "0", "1" and "2"; "1" different from "0".
Basement	**H(2,3201) = 234.39, p < 0.001**	"fully" different from "partly" and "no"
Building type	**H(4;3167) = 19.25, p = 0.0007**	"weekend home" different from "one family dwelling", "farm" and "public building";
Building foundation type	**H(3,2824) = 91.16, p < 0.001**	"Foundation fully" different from "strip foundation", "no foundation" and "foundation partly"; "strip foundation" different from "no foundation"
Building floor type	**H (4;3006) = 78.72, p < 0.001**	"brick" different from "screed" and "tural and concrete"; "screed" different from "tural (sand, soil)"
Building neighbour	**H(1;3198) = 16.52, p < 0.001**	"built together" different from "solitary"
H – Kruskal-Wallis H test; the degrees of freedom and number of data are indicated within brackets, respectively.		

Table 27: Analysis of indoor radon concentration (IRC, earth bound rooms) by soil and bedrock type, permeability and soil water content (statistically significant differences are marked in bold).

Variable	IRC, earthbound rooms (both regions)	IRC earthbound rooms (AUT North)
Soil type	**H(3;555) = 8.36, p = 0.0392**	H(2;392) = 3.14, p = 0.2080
Soil grain size	**H(3;555) = 11.50, p = 0.0093**	H(2;392) = 3.14, p = 0.2080
Permeability	**H(3;555) = 19.63, p < 0.001**	**H(2;392) = 26.28, p < 0.001**
Soil source	**H(10;555) = 23.78, p = 0.0082**	H(3;392) = 3.57, p = 0.3112
Bedrock (g_fine)	**n.d.**	H(5;393) = 10.49, p = 0.0624
Bedrock (g_coarse)	**H(4;555) = 21.57, p < 0.001**	H(1;392) = 0.69, p = 0.4045
Soil water content	**H(4;555) = 14.02, p = 0.0072**	**H(3;392) = 29.47, p < 0.001**
H – Kruskal-Wallis H test; the degrees of freedom and number of data are indicated within brackets, respectively; n.d. – not determined.		

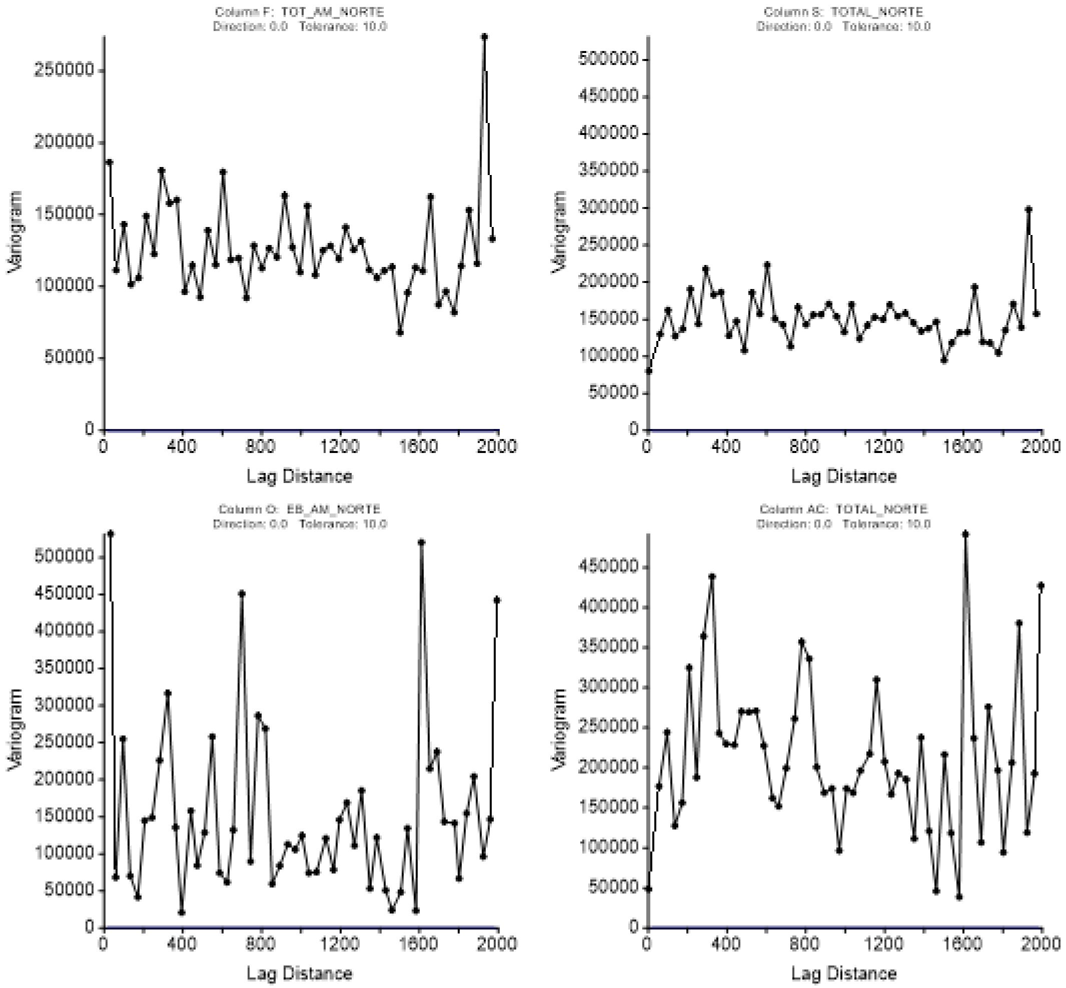

Figure 51: Omnidirectional semi-variograms of the arithmetic mean of IRC data (top left); room 1 and 2 data combined (top right), arithmetic mean of earthbound IRC data (bottom left) and room 1 and 2 data earthbound data (bottom right).

Discussion of results – Data Set Austria North

The results of **ADR** and **eU** indicate that there are statistically significant differences among different soil sources and bedrock units (of the "geology_fine" layer) while the results of **radon concentration in soil gas** indicate significant differences among soil type, grain size and water content. Apart from K-40 data comparison according to bedrock units (of the "geology_coarse" layer), the results of **permeability** and the **radionuclide content** are not statistically different among different soil types and sources, bedrock units and water content.

While ADR and eU are representative measurements of the superficial portion of the media, the radionuclide content, permeability and soil gas radon are representative of a deeper portion of the soil. As the classification of soil properties and bedrock refers to the outcropping portion of these units and because sampling took place in profiles with a depth of 1 m, the lack of statistically significant differences between the radionuclide data among different soil properties may be due to the lack of representativeness of those properties with increasing depth. This could indicate that the content of radionuclides may not be representative of the superficial portion of the soil, due to sampling of different horizons of the soil along the 1 m profile. While K-40, Ra-228 and Th-228 are correlated with the ADR thus indicating otherwise, no correlation is observed between eU and the radioisotopes of the U decay chain. This suggests that the content of U may be less representative of the superficial portion of the soil compared to other radioactive families, likely due to the higher mobility of U.

Permeability data acquired *in situ* is not statistically different among soil types, bedrock units or other soil properties. The variogram of permeability also shows a lack of spatial correlation. This implies that permeability data is site-specific, hence, difficult to model (interpolate or extrapolate).

Soil gas radon presents significant positive correlations with U-238, however, no correlation is observed with Ra-226 despite the strong correlation the later presents with U-238. The correlation observed between U-238 and Ra-226 is stronger compared to the correlation observed between Ra-226 and Pb-210. This indicates that disequilibrium in the U-238 decay chain is more intense in the last portion of the decay chain, likely due to radon migration.

The omnidirectional **variograms** for the radionuclides (Pb-210, Ra-226 and U-238), soil gas radon, permeability, ADR, the calculated TGDR and eU show that, apart from the eU data, no clear spatial correlation is observed. This is either due to the lower number of data or to the fact that the sampling interval is greater than the scale of spatial variation of the data. In fact, a high degree of variability of the concentration of eU is observed in the study area (**Fehler! Verweisquelle konnte nicht gefunden werden.**), thus, a high variability of the geogenic radon potential is expected. The eU data variogram may, however, have been altered following all correction and smoothing processes (ex. altitude, topographic, vegetation, cosmic ray and radon corrections, and the Compton Effect), leading to an increase of the spatial correlation.

Indoor radon data was evaluated according to the building and soil properties (Table 26, Table 27). The analysis shows statistically significant differences between room types (where basement is usually different), earth- and non-earthbound divisions, building, floor and foundation types. As earthbound divisions present generally higher IRC than the data acquired in non-earthbound divisions and as a better correlation between soil gas radon exhalation rate and IRC data of earthbound divisions is expected, the analysis of IRC data excluding non-earthbound data was carried out. IRC of **earthbound data** show statistically significant differences among different sources of the soil, soil water content, and/or bedrock units, permeability and soil type and soil grain size including all data. For the northern region, statistically significant differences are observed according to permeability and soil water content.

Austria: Southern Region (AUT South)

Analysis of soil data (acquired by physical sampling)

According to soil type, soil grain size, soil source and bedrock, the data analysis shows that the content of Ra-226, Pb-210, U-238 and K-40 is not statistically different (significance level of 0.05) between the various types of soil and bedrock. This also applies for soil source types (Table 28). Ra-228 and Th-228 are both statistically different between different soil grain size and soil source.

The ADR is statistically different among different bedrock types. The ADR is higher on orthogneiss followed by the remaining bedrock types (mica-schist, paragneiss, carbonate rocks, siliciclastic, porphyry, marls, sands, gravel and limestone). As the ADR is significantly influenced by the bedrock type, the TGDR was computed for comparing the content of radionuclides according to soil type, soil source and bedrock type. The TGDR was computed from U-238, Th-232 (assuming secular equilibrium between Th-228 and Th-232) and K-40 activity concentration [Bq/kg] according to the equation 8. The results of the Kruskal-Wallis test show the lack of statistically significant differences of the TGDR among groups.

According to soil type, soil grain size, soil source and bedrock, the data analysis shows that both, the radon concentration in soil gas and permeability are not statistically different (significance level of 0.05) between the various types of soil, soil grain size and soil water content (Table 29).

The correlation between soil gas radon, radionuclide concentration, ADR and TGDR was evaluated in Table 30. Soil gas radon is significantly correlated with U-238 and Ra-226. The ADR is correlated with Ra-226 and the TGDR. The correlations between Pb-210, Ra-226 and U-238 activity concentration are significant which indicates an equilibrium in the U decay chain. The correlation of U-238 with Ra-226 is higher than its correlation with Pb-210. Ra-228 and Th-228 are strongly correlated, indicating an equilibrium in the Th-232 decay chain. The TGDR is correlated with all isotopes, including soil gas radon, and with ADR.

The omnidirectional variograms for the radionuclides Ra-226, U-238, Pb-210 and K-40, soil gas radon, permeability ($x10^{10}$), ADR and the calculated TGDR were computed for evaluating of spatial correlations within the data set (Figure 52). No clear spatial correlation is observed, however, the variograms of ADR and TGDR suggest a regional trend.

Table 28: Analysis of radionuclide concentration data, terrestrial gamma dose rate (TGDR) and ambient dose rate (ADR) by soil and bedrock type (statistically significant differences are marked in bold).

Variable	**Soil type**	**Soil grain size**	**Soil source**	**Bedrock (geology_coarse)**
Ra-226	H(2;78) = 0.6355; p = 0.7278	H(1;78) = 0.1095; p = 0.7407	H(5;78) = 2.5356; p = 0.7711	H(3;78) = 2.9471; p = 0.3999
U-238	H(2;78) = 0.7682; p = 0.6811	H(1;78) = 0.0007; p = 0.9794	H(5;78) = 3.8102; p = 0.5771	H(3;78) = 3.764; p = 0.2881
K-40	H(2;78) = 2.5118; p = 0.2848	H(1;78) = 1.2586; p = 0.2619	H(5;78) = 7.8251; p = 0.1661	H(3;78) = 0.4535; p = 0.9290
Ra-228	H(2;78) = 2.1581; p = 0.3399	**H(1;78) = 5.3653; p = 0.0205**	**H(5;78) = 12.2718; p = 0.0312**	H(3;78) = 2.3585; p = 0.5014
Th-228	H(2;78) = 1.6092; p = 0.4473	**H(1;78) = 6.6286; p = 0.0100**	**H(5;78) = 12.3222; p = 0.0306**	H(3;78) = 1.9137; p = 0.5905
Pb-210	H(2;78) = 3.1064; p = 0.2116	H(1;78) = 0.0225; p = 0.8808	H(5;78) = 3.5023; p = 0.6230	H(3;78) = 4.4262; p = 0.2190
TGDR (calc)	H(2;78) = 1.2955; p = 0.5232	H(1;78) = 0.093; p = 0.7604	H(5;78) = 6.0924; p = 0.2973	H(3;78) = 0.696; p = 0.8742
ADR	H(2;84) = 0.6891; p = 0.7085	H(1;84) = 0.0017; p = 0.9670	H(5;84) = 2.7345; p = 0.7408	**H(3;84) = 12.678; p = 0.0054**
H – Kruskal-Wallis H test; the degrees of freedom and number of data are indicated within brackets, respectively.				

Table 29: Analysis of soil gas radon and permeability data by soil and bedrock type and water content (statistically significant differences are marked in bold).

Variable	**Soil type**	**Soil grain size**	**Soil source**	**Bedrock (g_coarse)**	**Soil water content**
Soil gas radon	H(2;84) = 0.1702; p = 0.9184	H(1;84) = 2.0023; p = 0.1571	H(5;84) = 7.7606; p = 0.1699	H(3;84) = 6.5767; p = 0.0867	H(3;84) = 5.0991; p = 0.1647
Permeability	H(2;84) = 1.7576; p = 0.4153	H(1;84) = 0.7104; p = 0.3993	H(5;84) = 9.3292; p = 0.0966	H(3;84) = 3.2349; p = 0.3568	H(3;84) = 5.9129; p = 0.1159
H – Kruskal-Wallis H test; the degrees of freedom and number of data are indicated within brackets, respectively.					

Table 30: Spearman rank correlation matrix. Correlation coefficients are statistically significant at a 0.05 significance level and indicated in red.

	Rn-222 [kBq/m³]	ADR	K-40 [Bq/kg]	Pb-210 [Bq/kg]	Ra-226 [Bq/kg]	Ra-228 [Bq/kg]	Th-228 [Bq/kg]	U-238 [Bq/kg]	TGDR
Rn-222 [kBq/m³]	1.00								
ADR	0.33	1.00							
K-40 [Bq/kg]	0.54	0.10	1.00						
Pb-210 [Bq/kg]	0.25	0.18	0.42	1.00					
Ra-226 [Bq/kg]	0.36	0.27	0.44	0.72	1.00				
Ra-228 [Bq/kg]	0.12	0.17	0.22	0.15	0.40	1.00			
Th-228 [Bq/kg]	0.06	0.17	0.18	0.18	0.42	0.94	1.00		
U-238 [Bq/kg]	0.24	0.14	0.48	0.60	0.72	0.42	0.46	1.00	
TGDR	0.40	0.22	0.75	0.58	0.69	0.62	0.63	0.83	1.00

Analysis of indoor radon concentration (IRC)

Data from both regions of Austria were considered when appropriate; groups with n=1 observations were excluded from the analysis. The analysis of the IRC data presented in As a better correlation between the soil/bedrock radon exhalation rate and indoor radon concentration of earthbound divisions is expected, IRC earthbound data were analysed according to soil data properties (Table 27). The analysis of the data, considering both regions, indicates statistically significant differences among different groups of soil type, soil grain size, permeability, soil source, bedrock and water content (Table 27). The results for the AUT North region only indicate statistically significant differences according to the permeability and soil water content.

Omnidirectional variograms for the IRC data set (total and including earthbound data) were computed (Figure 51). No clear spatial correlation is observed considering the arithmetic mean of the data, however, a spatial correlation is observed considering data from both rooms, particularly clear when only earthbound data is considered.

Table 26 indicate statistically significant differences between room types, earth- and non-earthbound divisions, basement, building, floor and foundation types. Thereby, similar to the analysis carried out for AUT North, IRC data were analysed according to the soil data properties after separation of earthbound data (Table 31).

The analysis of the IRC data, considering both regions, indicates statistically significant differences among different groups of soil types, soil grain size, permeability, soil source, bedrock and water content (Table 27, Table 31). The results for the AUT South region show no statistically significant difference between the various soil properties and bedrock units (Table 31).

Table 31: Analysis of indoor radon concentration (IRC, earthbound rooms) by soil and bedrock type, permeability and soil water content (statistically significant differences are marked in bold).

Variable	IRC earthbound rooms (both regions)	IRC earthbound rooms (AUT South)
Soil type	**H(3;555) = 8.36, p = 0.0392**	H(2;163) = 4.98, p = 0.0830
Soil grain size	**H(3;555) = 11.50, p = 0.0093**	H(1;163) = 0.45, p = 0.5045
Permeability	**H(3;555) = 19.63, p < 0.001**	H(2;163) = 3.05, p = 0.2175
Soil source	**H(10;555) = 23.78, p = 0.0082**	H(7;163) = 8.23, p = 0.3129
Bedrock (g_coarse)	**H(4;555) = 21.57, p < 0.001**	H(2;163) = 4.84, p = 0.0890
Soil water content	**H(4;555) = 14.02, p = 0.0072**	H(2;163) = 0.31 p = 0.8577
H – Kruskal-Wallis H test; the degrees of freedom and number of data are indicated within brackets, respectively; n.d. – not determined.		

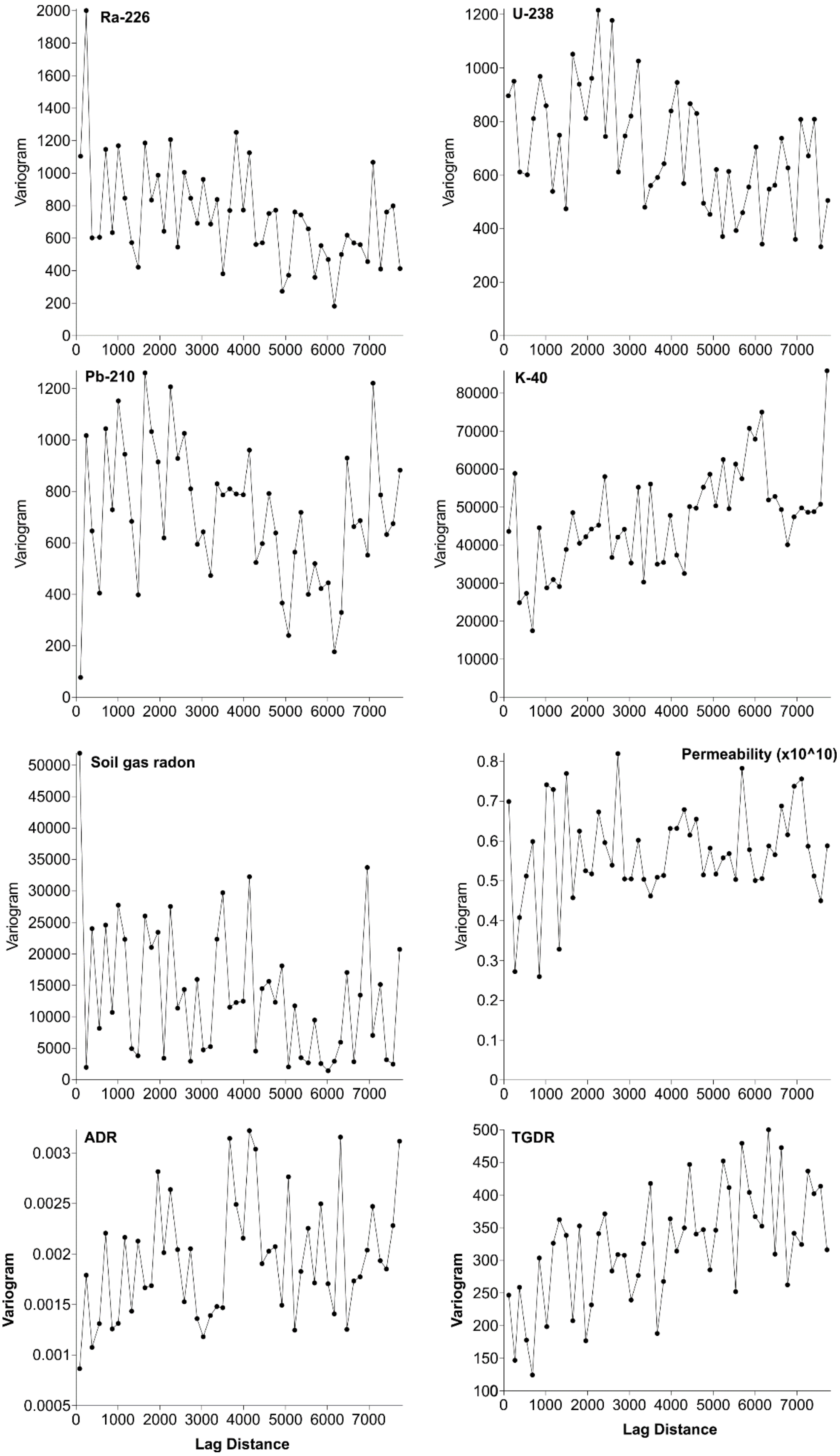

Figure 52: Omnidirectional semi-variograms of Ra-226, U-238 and Pb-210 activity concentration, airborne eU data, soil gas radon, permeability, ADR and TGDR.

The omnidirectional variograms for the IRC data set (total and including earthbound data) were computed (Figure 54). No clear spatial correlation is observed considering either the total data set (top) or only earthbound data (bottom), thus the data are spatially independent.

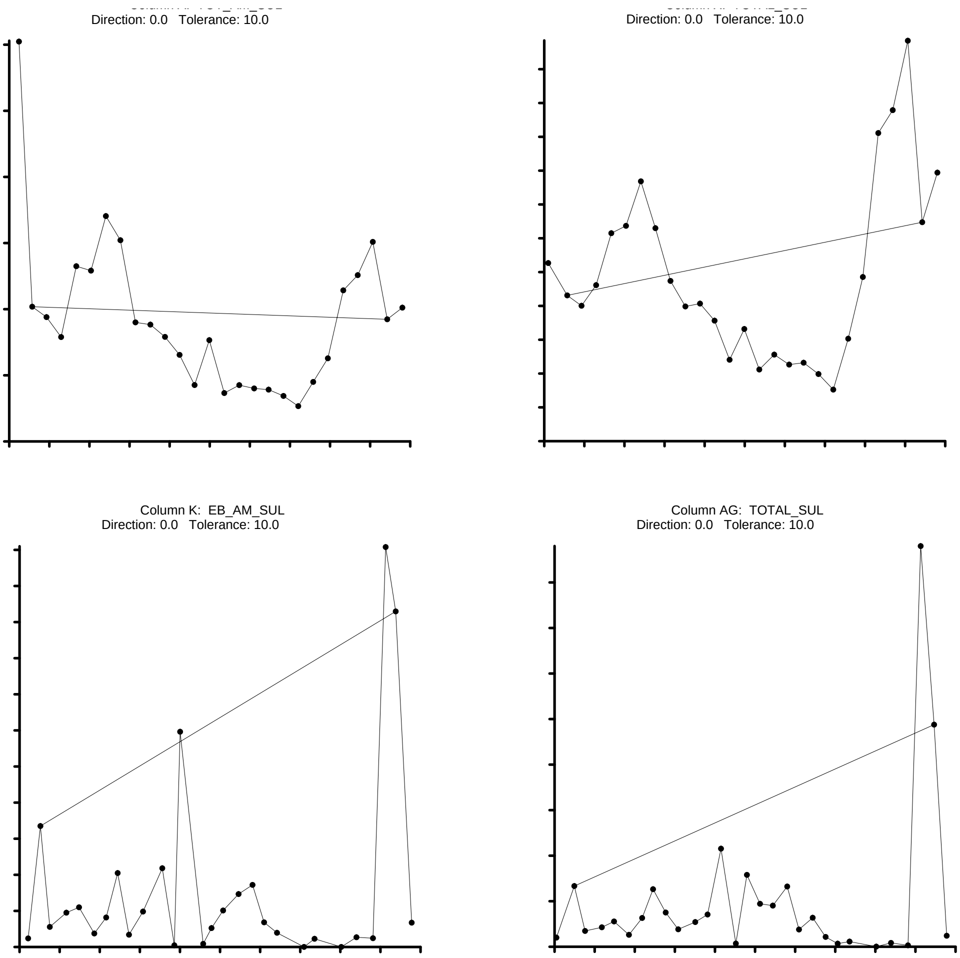

Figure 53: Omnidirectional semi-variograms of the arithmetic mean of IRC data (top left); room 1 and 2 data combined (top right), arithmetic mean of earthbound IRC data (bottom left) and room 1 and 2 data earthbound data (bottom right). Discussion of results – AUT South

Discussion of results – Data Set Austria South

The results of **ADR** indicate that there are statistically significant differences among different bedrock units (of the “geology_coarse” layer) while the results of **soil gas radon** do not indicate significant differences among soil type, grain size or water content. Apart from Ra-228 and Th-228 data, the results of **radionuclide content** and **permeability** are not statistically different among different soil types, sources and bedrock units.

Similar to results of the discussion from the AUT North region, there is a lack of statistical differences of radionuclide composition regarding soil types. This could furthermore indicate the lack of representativeness of those properties at depth or the lack of representativeness of the radionuclide data in the superficial layer of the soil due to sampling of different horizons along the 1 m profile.

Soil gas radon presents significant positive correlations with U-238, Ra-226 and Pb-210. There is a higher correlation between U-238 and Ra-226 compared to the correlation between U-238 and Pb-210, suggesting a higher degree of disequilibria towards the end of U-238 decay chain, likely due to radon exhalation from the ground.

Similar to results of the discussion from AUT North, the omnidirectional **variograms** for radionuclides (K-40, Pb-210, Ra-226 and U-238), soil gas radon, permeability, ADR and the calculated TGDR show no clear spatial correlation. This is either due to less data or because of the fact that the sampling interval is greater than the scale of spatial variation of the data.

The permeability data acquired *in situ* is not statistically different among soil or bedrock types and the variogram of permeability furthermore shows a lack of spatial correlation. This implies that permeability data is site-specific, hence, difficult to model (interpolate or extrapolate).

Indoor radon data of **earthbound data** for AUT South does not show statistically significant differences among different sources of soil, water content and/or bedrock units, permeability and soil type and grain size including all data, contrasting with AUT North. The incompatibility of the data and the lack of spatial dependence constrains the use of geostatistical tools to interpolate the data and predict the geogenic radon potential.

Cantabria

Analysis of soil data (acquired by physical sampling)

The analysis of ADR, soil gas radon and IRC data according to bedrock, soil source, permeability and karst is shown in Table 32. Both the ADR and radon concentration in soil gas present statistically significant differences among different bedrock units, soil sources and permeability. Indoor radon concentration behaves differently, according to bedrock type and the presence or absence of karst. The indoor radon concentration is higher when karst is present. Radon concentration in soil gas is statistically not different and therefore not influenced by the presence or absence of karst (Table 32). Glacier deposits, dolomitic rocks and the F. Bundsandstein present higher ADR than the remaining bedrock units. The radon concentration in soil gas is higher in the “dolomite, calcarenite” unit, followed by the “limestone, limestone of Picos” unit. The “Silts, clay, organic material and salt”, “clay” and “dolomite, calcarenite” present the highest IRC.

Table 32: Analysis of ambient dose rate (ADR), soil gas radon and indoor radon concentration (IRC) data by karst, bedrock type and permeability (statistically significant differences are marked in bold).

Variable	Lithology	Source	Permeability	Karst
Ambient dose rate	**H(18;62) = 33.1549; p = 0.0160**	**H(3;62) = 10.0935; p = 0.0178**	**H(4;62) = 9.9015; p = 0.0421**	H(1;77) = 0.5702; p = 0.4502
Soil gas radon	**H(27;259) = 43.518; p = 0.0232**	**H(4;259) = 10.9856; p = 0.0267**	**H(4;259) = 9.7716; p = 0.0445**	H(1;260) = 0.1338; p = 0.7146
IRC	**H(25;482) = 43.172; p = 0.0134**	H(4;482) = 7.8012; p = 0.0991	H(5;482) = 5.6215; p = 0.3448	**H(1;482) = 4.9472; p = 0.0261**
H – Kruskal-Wallis H test; the degrees of freedom and number of data are indicated within brackets, respectively.				

The Spearman rank correlation coefficient between ADR, soil gas radon and IRC was computed in Table 33. A small positive correlation is observed between soil gas radon and IRC, whereas a negative correlation between soil gas radon and ADR is observed when the closest point is chosen for the comparison of the data.

Table 33: Spearman rank correlation between soil gas radon, ambient dose rate (ADR) and indoor radon concentration (IRC) (statistically significant correlations are marked in bold).

	Average of the closest points	**Closest point**
IRC x ADR	r(224) = 0.04, p = 0.5035	r(482) = -0.02, p = 0.7350
IRC x Soil gas radon	r(276) = 0.04, p = 0.5480	**r(482) = 0.11, p = 0.0099**
Soil gas radon x ADR	r(68) = -0.14, p = 0.2481	**r(260) = -0.18, p = 0.0030**
Soil gas radon x IRC	r(113) = 0.13, p = 0.1668	r(260) = 0.02, p = 0.6997
ADR x IRC	r(60) = -0.10, p = 0.4630	r(77) = -0.19, p = 0.0922
ADR x Soil gas radon	r(55) = -0.26, p = 0.0586	r(77) = -0.13, p = 0.2468

The Spearman rank correlation coefficient between ambient dose rate, soil gas radon and indoor radon concentration with the radioisotope content in soil (GEMAS and FOREGS data) was estimated. For calculating the correlation, point data (ambient dose rate, soil gas radon and indoor radon concentration) was compared to the isotope concentration of the grid cell that the point falls into. The ambient dose rate presents positive correlation with Th (r(64) = 0.25, p = 0.0499) and K (r(64) = 0.25, p = 0.0496). However, the ambient dose rate is not correlating with U (r(64) = 0.08, p = 0.5307). Soil gas radon presents a significant negative correlation with U content (r(250) = -0.23, p < 0.001). Indoor radon concentration also presents a significant negative correlation with U content (r(482) = -0.13, p = 0.0046).

The omnidirectional variograms for the ADR, soil gas radon and IRC are displayed in Figure 54. The ambient dose rate displays spatial correlation (Gaussian model with 0.5 scale and 10000 length). Soil gas radon and indoor radon concentration data are spatially independent.

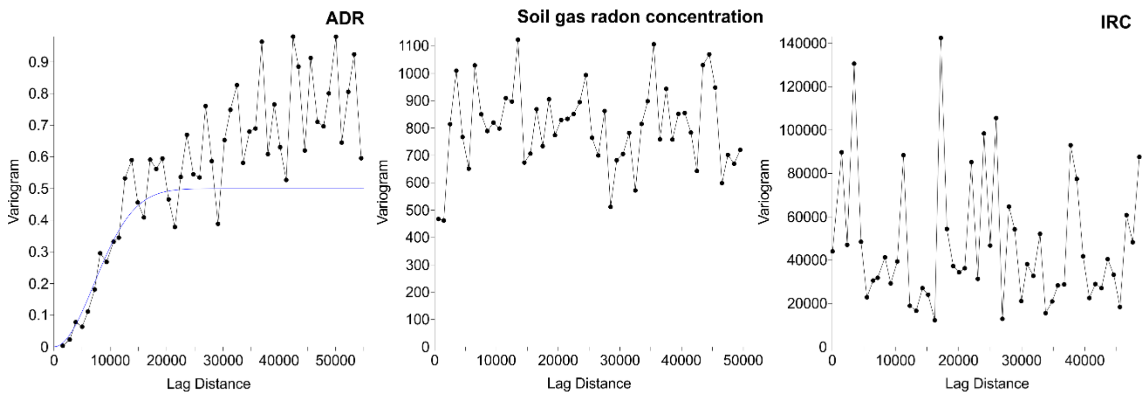

Figure 54: Omnidirectional semi-variograms of the ambient dose rate (ADR), soil gas radon and indoor radon concentration (IRC).

Discussion of results - Cantabria

The results of **ADR, radon concentration in soil gas** and **IRC** indicate that there are statistically significant differences among different bedrock units. ADR, soil gas radon and indoor radon concentration are not correlated. Soil gas radon as well as indoor radon concentration present significant negative correlations with U content, estimated from GEMAS and FOREGS data. This indicates that the data are not compatible. The ADR is correlating with Th and K, but not with U.

The omnidirectional variograms for soil gas radon and indoor radon concentration show no clear spatial correlation which is either due to less data or because of the fact that the sampling interval is greater than the scale of spatial variation. However, the variogram of indoor radon concentration is altered due to the changed location of the dwellings. The variogram of the ADR indicates a spatial dependence of the data. However, ADR is not correlating with U, soil gas radon or indoor radon data. Therefore, ADR cannot be used as a predictor of the remaining data. The incompatibility of the data and the lack of spatial dependence constrains the use of geostatistical tools to interpolate the data and predict the geogenic radon potential.

Inst	No.	motivation, objective	target var
BfS	101	Relation indoor Rn+Th with U+Th in ground; dose assessment	indoor Rn+Tn
BfS	102	spatio-temporal var. of outdoor Rn near waste pile from U mining	outdoor Rn
BfS	103	relation between indoor and soil Rn	indoor Rn
BfS	104	relation between soil Rn, Ra in soil and soil type	soil Rn
BfS	105	Explaining variability of indoor Rn by geogenic quantities	indoor Rn
BfS	106	Relation Rn exhalation rate ~ADR,Ra in soil	Rn exhalation rate
VINS	201	Developing a metodology that can be used for construction of GRP maps	soil gas radon
VINS	202	developing metodology for indoor radon potential map	indoor radon potential
VINS	203	To correlate indoor radon with geogenic radon surrogates and geology and to test whether surrogate data can be used to judge the radon risk without performing indoor Rn measurements.	radon potential (extracted from indoor Rn, based on Friedmann,2005)

VINS	204	To derive metodology to produce a single map of the geogenic radon potential that will help authorities to take decisions and target actions in RPA	radon potential (low, moderate, high)
VINS	205	To make risk prediction map based on on geological maps, soil gas and indoor measurements	indoor radon, i.e. probability that annual indoor Rn exceeds 200 Bq/m3 (ground floor)
VINS	206	pilot study of soil gas radon measurements and its parents 238U and 226Ra in soil measurements	outdoor Rn
VINS	207	The aim of this work was to study the factors influencing indoor radon concentrations in Switzerland using univariate analyses that take into account biases caused by spatial irregularities of sampling	indoor Rn
VINS	208	Authors tested a new method for GRP mapping, namely regression-kriging, using spatially exhaustive auxiliary environmental variables related to geogenic radon potential.	outdoor Rn
VINS	209	to obtain a cohesive and reliable picture of spatial variation of the actual and expected levels of indoor radon concentration in Poland	indoor Rn

VINS	210	this study tests to what extent expert knowledge of radon potentials of different bedrock types can be used in predicting and mapping residential radon concentration.	indoor Rn
VINS	211	mapping of radon-prone areas by maping of potential radon emanation from rock units	radon within the rock/soil pore space
VINS	212	INDOOR RADON VERSUS GEOLOGY IN FAIRFAX COUNTY	indoor Rn and geology
VINS	213	can airborne gamma ray spectrometer measurements can be used to estimate levels of radon hazard	Indoor Rn,

VINS	214	Determining the influence of subterranean airflows on the indoor Rn	Indoor Rn prediction
VINS	215	Evaluating the usefulness of expert geological knowledge by verifying correlation between bedrock type and residential radon concentration	Indoor Rn
VINS	216	Identify possible correlation between geological factors and indoor radon levels and determine if the geological data is usefull in radon risk analysis	Indoor Rn
VINS	217	Determining the locations and orientations of faults and karst cavities and determining current geodynamic activity	karst map
UC	301	Improve of indoor Rn maps with soil geochemical data and airborne geophysical data	indoor Rn potential

UC	302	comparison of map based on indoor Rn data, and map based on Tellus Project (including geological data)	indoor Rn potential
UC	303	To elaborate a cross border radon potential/risk map (at a scale 1:100 000) based on geogenic parameters.	radon index
UC	304	Explaining variability of indoor Rn by geogenic quantities	indoor Rn
UC	305	Relation uranium, organic carbon & radon indoor	Rn in house, uranium in soil & emanation of radon
UC	306	Correlation between 3 parameters related with radon	Rn in soil, Rn exhalation & terrestrial gamma
UC	307	Problems inherent in correlating indoor radon with geology	Indoor Rn
UC	308	Relation between indoor Rn,indoor gamma dose rate, soil type (permeability) and building materials	Indoor Radon

UC	309	Correlation between Rn Concentration and 226Ra in soil to estimate the potential natural radiation hazard	Radon concentration in soils, Radium content,Radiological parameters
UC	310	Predictive map of radon potential (RP)	Indoor Rn, Airborne gamma ray,
UC	311	Convine data from uranium concentration with Rn indoor to improve the Rn in houses predcition	Indoor Rn
UC	312	Determine the Rn hazard	Radon in soil distribution Rn hazard
UC	313	Correlate Indoor Rn with gamma dose rate, geology and house features	Indoor Rn
UC	314	Determine Radon Prone Areas in municipality scale	Radon index
UNSPMF	401	A linear regression model has been developed for the prediction of indoor 222Rn in Danish houses.	Indoor radon - annual average living-room radon concetration

UNSPMF	402	ANOVA is used to show the total variation of indoor radon concentrations in England and Wales	Variation in indoor radon concentration
UNSPMF	403	The scope for using airborne gamma-ray spectrometer data for the Tralee–Castleisland area of county Kerry and county Cavan to predict the radon potential (RP) in two distinct areas of Ireland is evaluated in this study.	High indoor radon concentrations
UNSPMF	404	Generalized geologic province information and data on house construction were used to predict indoor radon concentrations in New Hamp-shire (NH).	Indoor radon concentration
UNSPMF	405	To identify any spatial pattern in radon variation and to relate this to the lithology, and to use geology as an indication of where radon levels are likely to be large.	Potential radon concentrations indoors and radon soil gas
UNSPMF	406	Investigation on how several factors, such as geology typologies of the soil and a range of building characteristics, impact on indoor concentration focusing on how concentration changes as a function of the floor level.	data from Lombardy campaign of 2009-2010

UNSPMF	407	In this paper a geological type is assigned to each empirical RP value in Austria and residual, stochastic component of the RP variability are modeled by means of geostatistics.	Measured indoor Rn concentrations from Austrian Radon Survey.
UNSPMF	408	To test whether indoor 222Rn concentration for data gathered over the winter and summer seasons in Virginia, USA differ significantly by rock units.	Indoor radon activities and geological characterisation
UNSPMF	409	A radon risk map for the Walloon region in Belgium. The data are organized into geological units	two database of indoor radon measurements from the South of Belgium have been used
UNSPMF	410	Estimation of radon radiation risk in the area with high radiation background	soil gas radon measurements in volcanic region and permeability data.
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BfS	104	Phong Thu Huynh Nguyen et al. (2018): Soil radon gas in some soi	
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UNSPMF	406	6. R. Borgoni et al., Hierarchical modeling of indoor radon concentra
UNSPMF	407	7. P. Bossew et al., Investigations on indoor radon in Austria, part 2
UNSPMF	408	8. Brown C.E. et al., Statistical Analysis of the Radon-222 Potential
UNSPMF	409	9. Cinelli G. et al., Development of an indoor radon risk map of the
UNSPMF	410	10/ Cinelli G. et al., Soil gas radon assessment and development of

predictors	method: sample
U,Th in ground, building type	Rn:TE; soil: gamma spec NaI
ADR, U in ground	Rn:TE; ADR: GM; eU: in situ-gamma
ground Rn, geology	indoor Rn:TE; soil Rn: Alphaguard, 0.7 m
Ra in soil, soil type	soil Rn: Rad7, various depths
geol., aerogamma, geochem. of topsoil and stream sediment	
Ra in soil, ADER, geology	Rn exhal: soil samples in chamber; Ra: gamma spec. of samples
eRa concentration (from Homogenous Geological Map), **ePermeability** (hydrogeologycal map), **Fault density** (map of fault lines), **digital terrain model** (proxy for meteo. param.)	Rn in soil; in field analysis using Lucas cells (published and unpublished data)
basement Rn concentration; equivalent U concentration from surface gamma-ray measurements, U concentration in sediments, bedrock units and surficial deposits	not indicated; data are taken from available datasets
soil-gas Rn, permeability, 238U, 228,226Ra, 228Th, 210Pb, 40K concentrations, ambient dose equivalent rate 1m above ground, geological units	The selection of the sites was based on a broad variety of geological units in combination with accessibility and undisturbed soil structure. Soil gas Rn: average from 3 measurements performed at corners of triangle at 1.5m depth. Permeability at the same points measured. RPn estimated according to Neznal; Soil samples: in the center of triangle at 40-80cm depth; ambient dose: 1m above ground

geologic variables: geology, lithology, U content, fracturing (presence of faults), underground mines, and thermo-mineral sources	not applicible
radon in soil gas with the local geology and a set of parameters derived from the prevailing housing conditions	
U, Ra, Rn in soil	Radon detection in the soil gas: SSNTDs (CR-39); soil: gamma spectrometry on HP Ge
Rn	passive electret or alpha track detectors
Rn in soil	soil gas radon activity: RAD7; soil gas permeability: Radon-JOK
crystalline (igneous and metamorphic) rocks; sedimentary rocks; glacial and fluvioglacial Pleistocene sediments. **Detailed geology**	CR-39 in appropriate diffusion chambers; in rooms on the first storey over the ground

every bedrock type in the USGS geology map was assigned to one of the 7 classes (regarding Rn potential) based on the genesis of the rock and its uranium composition	short-term test with charcoal canisters (4-7 days). The average concentration over the last 3 days of exposure is used as the value for the tested dwelling
Uranium	A modified alpha-track detection system (with polycarbonate foil) for direct measurements of radon in soil/rock pore gas. Up to 28 days.
geology, Geotechnical data leading to aeroradioactivity map	Fairfax County database
airborn gamma, bedrock geology and drift geology	indoor Rn from national survey; Airborne gamma via drone.

Geochemical analyses of bedrock,sediments and groundwater	samples from the local bedrock, soil gas
bedrock geology	bedrock classification: expert assigned radon potential to each bedrock type (not explained further) indoor Rn: charcoal canisters
bedrock, radium content, permeability, air leakage, ventilation rate, watter supply	bedrock type determined from geological maps; radium content and permeability were determined for each bedrock type based on the available data, with assupmtion of equilibrium between U-238 and Ra-226; indoor Rn concentrations from previous survey in 2000 and 2001, CR-39 detectors; classification of basement, walls, water supply, ventilation system and aeration habits from questionnaires
radon concentrations expressed as equivalent eman	Radon measurements in a stream of subsoil air (depth 0.8 m - 1 m) with RANag-1 air radiometer and other non-specified devices
U,Ra, Th and K in ground,	remote soil gamma spec

airborne Kair,estimated eU, eTh, K; soil U, Th, Ca, Si, Fe; ground permeability **and soil K, U, Th, Zr, Y, Ca, Si, Al and Fe concentrations**	remote soil gamma spec
Rn in soil concentration	818 measurements of Rn in soil concentration
geol., aerogamma, geochem. of topsoil and stream sediment	
Uranium, radon indoor & radon emanating	charcoal activated & chemical analysis
Rn, external gamma and radon exhalation	passive detectors, radonbox using continuous measurements adnportable germanium
Geology, surface gamma-ray and Radon in soil	charcoal canister and alpha-traxk detectors, equivalent uranium from surface gamma-ray measurements and Radon in soil (grab samples 0.75-1m)
Geology(subestructure category);Soil type(permeability and U Concentration); Building type	Indoor Rn(passive alpha track); Indoor gamma (TLD-dosemeter)

*Geology (Rn Concentration and 226Ra, 232Th, 40K in soil)*Potential natural radiation hazard: ‘‘The radium equivalent activity’’ (Raeq), ‘‘Absorbed Dose Rate’’ (D), ‘‘Outdoor Annual Effective Dose’’ (E),‘‘External and Internal hazard Index’’ (Hex and Hin), ‘‘Gamma radiation hazard index’’ (Icr), and ‘‘Excess Lifetime Cancer Risk’’(ELCR),	Rn concentration in soil (RTM1688-2 radon monitor); Ra content (gamma-ray spectrometric system with a coaxial high purity germanium detector HPGe, GC7020, Canberra)
*Geology (uranium) , airborne gamma ray spectrometry (AGRS)	*Indoor Rn: long-term alpha track *Airborne gamma ray spectrometry(sensor elevation 60 m)
Indoor Rn concentration Uranimun concentration	2590 radon gas measurements from the 614 homes with alpha-track detectors. Spatial U concentration from airborne γ-rays emitted 214Bi.
Rn in soil point Radiactive content in soil Geological units	238U, 232Th 40K with HPGe detector Rn in soil: Pipe 64mm x 1.5 m at 1 m depth. Cellulose nitrate film as track detector
Gamma dose rate Indoor Rn Geological characteristics	Gamma dose rate: TLD Rn: CR-39 35 rock samples
Radionuclide soil content IndoorRn Geological characteristics Gamma dose rate Houses ages	 Rn: LR-115 Data obtaindes from databases
The model includes nine explanatory variables, of which the most important ones are house type and geology	1 year measurements with CR-39 track detectors

ANOVA was used to calculate the proportion of the variation of log-transformed indoor radon explained by bedrock geology, superficial geology, and intra-geological unit variation. The fraction of the variation explained by geological groups was determined from the sum of squares between group means.	
Linear regression models of the relationship between airborne radiometric data and results of indoor radon measurements in dwellings	
A mixed-effects regression model was used to predict the geometric mean (GM) short-term radon concentrations in 259 NH towns. Bayesian methods were used to avoid over-fitting and to minimize the effects of small sample variation within towns.	three winters (short term measurements) - track detector
Regionalised Variable Theory	CR-39 track detectors
Hierarchical mixed model for modeling indoor radon concentration	multilevel analysis - methodology for the analysis of data with complex patterns of variability, CR-39

Geological classes are used to model the deterministic (drift or trend) component of Radon potential (Friedmann's RP) in Austria. Geological classes can serve as predictors for mean RP within the classes.	RP is used accordin to Friedmann's concept and modified by Bossew and Lettner (2002) in some computational details. Data collected by track-etch, electret and active charcoal.
Statistical analysis were used and rocks have been ranked according to the observed 222Rn concentration by transforming the average rand of indoor 222Rn concentrations to z-score.	Seasonal indoor radon data from homes in Virginia starting from the winter 1986-1987. Kruskal-Wallis test
Methodological approach for construction of radon risk map based on indoor radon measurements and on geological information. An average logarithmic standard deviation is calculated together with logaritmic mean.	charcoal canisters for short-term and track-etch Makrofol detectors for long-term
Statistical analysis of existing data on radon in soil gas measurements including geostatistics and Kriging method, radon index was calculated following Barnet methodology - with hypothesis of locally normal or log-normal distribution of soil gas radon data	radon risk assessment based on soil gas and permeability data lead to radon map

with type of dwellin gs in a hilly area. Inddor and Built Envioronment xx. DOI: 10
ration in the atmosphere. Gamma dose rate. Atmos. Environment 174, 54-65; c
and indoor environmentof Afyonkarahisar Province. Arabian Journal of Geoscie
l types in the rainy season in Ho Chi Minh City, Vietnam. JER 193-194, 27-35: c
ngland explained by topsoil and stream sediment geochemistry, airborne gamm
ogy of some Serbian spas. Journal of Radioanalytical and Nuclear Chemistry 3

l techniques to construct the geogenic radon potential map of the Lazio region:
Quebec indoor radon potential map, Science of the Total Environment 473–474

sampling design	temporal	sample size	area
representativeness:? Rn det: suspended 1 m from floor	seasonal	n.a.; ~100 from graph	Coonoor, Tamil Nadu, India
acc. objective	seasonal	20	village SW Poland
rnd. sampling	seasonal	46 dwellings, 28 workplace	Afyonkarahisar, Anatolia, TR
per soil type	wet sason	18; each 8 probes in diff. depths don to 1 m.	Ho Chi Minh City, Vietnam
indoor: pop. prop.; aerogamma: exhaustive; geochem: representative point samples		indoor Rn:197464; aerogamma 684384; soil geochem: 987; stream geochem: 3382.	SW England
rnd. points acc. geology	dry	31	Kursumlija municipality, Serbia
not specified, sampling technique that minimizes influence of meteo factors. Soil gas RN: reported in cells: 1x1km2, if more data per cell, GM or Rn data per cell	not indicated (according to sample size, whole season is assumed)	7625	Lazio region
not indicated	not indicated (according to sample size, whole season is assumed)	3082 (of the basement radon measurement)	Quebec, Canada
	Upper Austria: SSNTD 6 months (Dec/Jan-Jun/Jul); soil gas (spring/autumn); Styria: indoor Rn (6months half winter-) soil gas (autumn, spring)	Upper Austria: 680 dwellings indoor Rn, 60 soil gas; Styria:960 dwelling indoor Rn, 100 soil gas	6th municipalities in 2 regions in Austria (Upper Austria and Styria)

not applicible	not applicible		Burgundy
Regionalisation on 3km*3 km grid, for interpolation of radon risk on municipality level: 500m*500m.Regional radon signature of geological units adjusted by their soil gas radon characteristics.		database of Rn measurements and geological information: 4240 sampling sites; 24000 soil gas measurements, 10361 houses with indoor Rn measurements	Germany
In the soil over the metamorphic rocks, 6 sampling points, on limestone 11 and on lake and river sediments 4 sampling points	seasonal (3 seasons)	21	Sharr-Korabi zone
indoor	seasonal (3 months)	212000	Switzerland
Site selection followed stratified, conditional random sampling; grid 10 km x 10 km; three measurement sites were assigned in each cell sampling	seasonal (summer)	145 GRP sites	Panonian basin
Measurements were performed in buildings situated on all main tectonic units of Poland, taking into account the lithology of rocks lying at the depth of up to about 500 m b.s.l.	quarterly exposures were seasonal	129 buildings in relation to the geological conditions of their foundation	Poland

basements of single-family houses with well known location of test kit in a dwelling and construction characteristics	predominantly during the home heating season (November– April).	10,164 (59% of available dataset 1987-2004).	State of New Hampshire
70 sites, representing all different exposed rock formations in Israel	dry summer time	70 sites. From 32 up to 260 samples per site.	Israel
Fairfax County database	seasonal	> 1000	Fairfax County
Indoor Rn and Geological survey of Norway.	winter, 2 months	indoor Rn: 80000 dwellings of which 6326 in the area covered by the airborne gamma measurement	Oslofjord region

Geology:One borehole was drilled in the topographic lowest part of the residential area and the other borehole in the area of highest elevation; Water from the same holes; 18 lateral profiles; soil-gason the location.	Indoor Rn: June-August, October and January-February.	27 bedrock samples, 18 lateral profiles, 130 dwellings	Kinsarvik, Western Norway
Rn measurements: voluntary participation, 4-7 days exposure, exact locations of dwellings not available due to privacy issues	heating season (November - April)	10164 (only measurements in the basements of single story buildings were used)	New Hampshire
random sampling in 114 of 435 municipalities https://www.dsa.no/publikasjon/straalevernrapport-2001-6-kartlegging-av-radon-i-114-kommuner.pdf	N/A	Indoor Rn: 1618 dwellings	7 municipalities in Norway
Radon was measured in grid points, grid was several meters by several meters, depending on the specific survey (spacing was 1 m to 25 m)	N/A	208 + 510 + 523	Moscow (0.05 km²), Blagoveshchenskiy District (0.2 km²), Kentau Kazakhstan (1 km²)
1 data collected with a density of 1 sample per 2 km2 in rural areas and 4 per km2 in urban areas	not indicated		Northern Ireland

1 data collected with a density of 1 sample per 2 km2 in rural areas and 4 per km2 in urban areas	not indicated		Northern Ireland
818 soil gas Rn measurement test sites situated in the Czech part of LJK map (663), the German part (61) and the Polish part (94)	not indicated	818 measurements	Border Poland/Czec h Republic/Ger many
indoor: pop. prop.; aerogamma: exhaustive; geochem: representative point samples		indoor Rn:197464; aerogamma 684384; soil geochem: 987; stream geochem: 3382.	SW England
233 soil samples, 188 single houses	winter for radon in houses summer and fall for soil samples	six areas, 100 square kilometer	Ohio Shale
6 soil radon profiles, 113 soil radon exhalation and 19 in situ gamma	different seasons from 2011-2015	Aristotle University campus area	Thessaloniki, Greece
Main data from previous surveys and info from USEPA and USGS	For Rn in soil: dry stable periods (spring and summer)		USA
*Indoor Rn: Use of National database (50 000 dwellings), sample desingn with three ranges of Rn concentration; *U Concentration: Indoor gamma dose rate correlates with uranium content both in soil and building material was used as a substitute for the uranium content of the soil;*Permeability: Classification of soil types used as a substitute for permeability; *Air leakage: classification of substructures used as a substitute for the air leakage from the subsoil into the house	Annual	*Indoor Rn: 28 dwellings from each of the three concentration classes were selected.	*4 municipalities : 3 in the Lahti area ŽLahti, Hollola and Nastola the fourth is Tampere

*Rn and Ra, Th, K concentration in soil: sampling points along a line with a difference geology	?	*Rn concentration in soil: 20 sampling points along a line with a difference geology *Ra: 21 sampling points at the same radon measuring point	Southern Thailand (Songkhla province, Namom district)
*Indoor Rn: Use of National database (120,880 masurements, selected 15,698 dwellings geo-referenced) * Airborne gamma ray spectrometry (AGRS 11 surveys) were flown and processed independently in different years and therefore the calibrations used to convert gamma counts into eU concentrations differ slightly between them.* Radon Potential Map: converting the equivalent uranium map	Annual	*airborne gamma ray spectrometry (AGRS):11 surveys	southeast Norway (most populated part around Oslo)
Population-based case–control (Rn) National uranium resource evaluation' (NURE) (U)	Rn detectors during 1 year to expunge seasonal trends.	2590 radon indoorfrom 614 homes on each floor U concentration uniform distributed in the Iowa's 99 counties	Iowa (USA)
Measurements in every geological unit spaced less than 1 km	Rn in soil exposure during 1 week	49 measurements of Rn in soil	Pescara city (Italy)
Rn and gamma: 2 detector per house (living room + bedroom) Questionnaire house features	3 months (Feb. To May) Rn Annual average corrected multiplying summer season by 2	Indoor gamma radiation levels and indoor Rn in 95 dwellings	Fen Area (Norway)
National Database of indoor Rn Own measurements (2 detectors per house)	?	150 000 records for indoor radon Radiometric map in scale 1:500000 35 lithological classes Five classes of Rn in soil	Czech Republic divided in munucipalities
The model provides proxy radon concentrations for about 21,000 houses in a Danish case–control study on the possible association between residential radon and childhood cancer (primarily leukaemia). The model was calibrated against radon measurements in 3116 houses. An independent dataset with 788 house measurements was used for model performance assessment.	1 year	Radon predictions for 7679 apartments and 13,657 singlefamily houses	275 Danish municipalities, single-family houses

Indoor house radon results were allocated to 1-km/bedrock-superficial geology (parent material) polygons derived from BGS 1:50 000 scale data in England, Wales and Scotland and 1:250 000 scale data in Northern Ireland using a simplified geological classification		more than 500 000 indoor radon measurements	England, Wales
The probability of homes in Ireland having high indoor radon concentrations is estimated on the basis of known in-house radon measurements averaged over 10 km × 10 km grid squares			Ireland, Tralee-Castleisland area
	short term (during winter)	1814 dwellings in 232 of New Hampshire's 259 towns were monitored	New Hampshire (NH), USA
Hieararchical sampling (nested sampling scheme with seven stages)		grid 7500 m x 7500 m	Heterford and Worcester, England
data from the Lombardy campaign 2009-2010, municipalities stratified into 5 groups and 22 minicipitalities are randomly selected, in each selected municipitality 5 to 15 were choosen, the measurements were conducted on different floors - only housing units, in total 721 rooms in 380 different buildings.	long term measurements - 2 consecutive 6-month period	In total 721 rooms in 380 different buildings.	Lombardy municipalities

Data collected through the Austrian Radon Survey.	individual results for long-term measurements (track-etch, electret) and by means of two simultaneous replicate measurements for short-term measurements (active charcoal)	in total 25498 data generated in 8833 buildings, 25160 cases at 7280 locations	Austria
The data used in this investigation derive from basement measurements of homes in Fairfax County, Virginia.	seasonal measurements for one year	Total number of samples 3282.	Fairfax County, Virginia
2 database short-term and long-term from previous campaigns were analysed.	short term - charcoal canisters 3-4 days and long term track-etch Makrofol detectors 3 months	5000 short term measurements 1990-2004 and 7500 long term measurements 1995-2000	Walloon region in Belgium
a square grid-based sampling design, with cell sizes about 100 m, soil gas probe was inserted down to an approximate depth of 60-70 cm + 8 soil samples for estimation of the permeability	short term measurements - RAD7 radon monitor and standard soil probe.	campaign of soil gas rdaon measurements - 63 sampling stations distributed within the urban area of Bolsena and including part of its outskirt + 8 soil samples	Bolsena, Central Italy - Vulsini Volcanic district

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A methodological proposal for the European Atlas of Natural Radiation, Journal of Environmental Radioactivity ›
· (2014) 372–380

area characteristic	area size
mountainous	?
valley	~ 100 m^2
mountain?	~ 50 km^2
flat	several 100 km^2 ?
flat-hill	8841 km^2
hill	~800 km^2
extensional tectonics developed basins that trend:NNw-SSE/NW-SE; clastic sediments and volcaniclastic deposits fills these basins; Geol. Form.:carbonate platforms, palagic-slope basins, continental and marine deposits, volcanics and glysch	17207 km2
not given in the article	
Upper Austria: relatively uniform geological situation; Styria: much divers geological background compared to Upper Austria	

covering whole Germany, therefore with diverse geological units	
Mountain	~ 50 km²
whole county	41285 km²
valley	5400 km²
	whole country was covered, ~313000 km^2 covering the three most important tectonic units

a region known for its granite bedrock	
sedimentary rocks, ranging in age from Paleozoic sandstones up to recent soils	
hill and plain	252,828 acres
hill and plain	~10000 km²

steep hillsides and several tributary valleys	0.5 km2
mountains and forests in the central and northern part, with lower terrain in the southeast towards the Atlantic	24214 km²
mainly forested mountains and valeys, but all terrain types are present	around 7500 km²
area over karst: urban, river valey, hills	1.25 km²
rural and urban	?

rural and urban	
administrative Cross Border	
flat-hill	8841 km²
glacial, lacustrine and fluvial deposits	100 km2
not described	not included
Glaciated areas of the USA, such as the Northern Appalachian Highlands.	
Urban	(unknown)

Flat terrain surrounded by mountains and hills	9x18 km (aprox.)
Urban	*180 x102 km * Indoor Rn (2x2km grid)
Small number of large cities Data clustered. Measurement sparse due to rural countryside distribution	145744 km²
stratigraphic units are heterogeneous and con-sist of several rock types	34.4 km^2
carbonatites(carbonate rocksof volcanic origin)	Circle with 3 km diameter
	78867 km^2
The main source of high levels of indoor radon is the soil immediately below the house, house construction characteristics, outdoor air is very low in radon (a typical level for Denmark is 5 Bq m3), and the air-exchange rate is therefore another important house factor.	Whole contry

clay- silt (mainly impermeable alluvium), diamicton (mainly glacial till, which is generally, though not always, relatively impermeable), sand and gravel (mainly permeable glaciofluvial deposits but also raised terrace, raised marine, marine beach and river terrace deposits), head (congeliturbate) deposits and peat	
High radon concentrations in buildings are associated with Carboniferous limestone and uranium-rich Namurian shales in both County Kerry and County Clare	Tralee–Castleisland area of county Kerry and county Cavan in Ireland
A geologic province consisting of glacial deposits and marine sediments was associated with significantly elevated radon levels, after adjustment for radium concentration and building type.	259 NH towns, USA
marine Limestones	Three areas of the English Midlands were surveyed

1:2000000 geological map of the Austrian Geological Survey - 111 polygons were produced each corresponding to a geological unit.	The whole Austria.
The rocks associated with the highest median indoor radon concentration are specific rocks in the Mesozoic Culpeper basin, including shale and siltstone units with Jurassic diabase intrusives, and mica schists in the Peidmont physiographic province.	
for each house for which a radon measurement is available, the database includes the geographical coordinates, the radon concentration and the local geological unit determined with the digital geological map (GSB)	
volcanic origin - Quaternary potassic volcanic belt of Roman Magmatic province	mostly the urban area of Bolsena

method: analysis
simple regression

simple regression

simple regression

simple regression

ANOVA, multiple regression, CODA

simple regression

global (Ordinary
Least Squares, OLS) and spatial (Geographically Weighted
Regression,
GWR) multivariate regressions

Created 4 groups based od eU, 4 groups from geochemistry and 2 groups from geology; Thresholds based on p-value from Kruskal-Wallis one way ANOVA. In total 32 scenarious possible. ANOVA was used to check which group was statistically similar. Out of 32 scenarious, 4 groupings were created: low RP, medium RP, high RP, very high RP

descriptive statistics from 11 geol. Units an 1:500000 scale; more detailed from 1:50000 scale: 30 units, correlations between different data sets and geological information, Spearman Rank Correlation Coefficient when regrouping of geological data; Finally, geological units were devided in 3 classes for each parameter separately. Rn in soil, Ra in soil, ambient dose and permeability, each having 2 limits, which were chosen to have at least >3 geological units within one class. Classes were compared with RP_A

The methodology can be divided into 3 stages: (1) evaluation and mapping of the radon source potential of the geological units from their U content (measured or extrapolated), Some additional identification of U rich rocks based on lithology and stratigraphy (2) optimisation of the first map by taking into account additional parameters which may facilitate the radon migration in the ground, (fauults, shafts, thermal mineral waters) and (3) synthesis and final categorization to obtain a map of the geogenic radon potential

For each location, a geological unit is assigned by reference to a digital geological map covering the considered area. A loop searches for matching geology of sampling sites and the centre of grid elements. For each raster element, a selected number of nearest measurement points with the same geology is allocated. The distance weighted averaged radon activity concentration within the geological unit is attributed to the raster element. Influence of regional, geological and specific house type parameters on indoor radon in the ground floor, estimated from series of analyses of variance based on geological parameters, soil gas, indoor measurements and the questionnaire data.

simple regression

simple regression; Kolmogorov-Smirnoff test

regression Kriging; multiple regression

arithmetic and geometric annual mean, the median, the range and the geometric standard deviation were calculated. Comparison between different regions, and buildings founded on sedimentary, metamorphic and igneous rocks

Area is divided in cells 800x800m, a total of
43,464 cells. Each
cell was used as a sample point in the kriging process.
For a cell containing multiple measurements the geometric mean of these measurements was used in the interpolation. natural base logarithmic transformation to the cell values and kriging interpolation

The mean, standard deviation, median and the 10th, 25th, 75th and 90th percentiles for all rock units in Israel are given, with detailed information on the various formations within the Mount Scopus Group.

Descriptive statistics, directional trend analysis, Spatial autocorrelation, ANOVA

least square regression on binned data

normalised summer values
of soil radon, linear correlation

Two ranks of the bedrock types were compared, one based on indoor Rn (kriging interpolation by Geostatistical Analyst program) and the other on expert-assigned Rn potential

Kruskal-Wallis analysis of variance and Mann-Whitney test

Radon surveys were conducted in the selected areas (<= 1 km^2) and known karst maps were compared with isoeman maps

Multivariate linear regression

Least squares linear regression models for multivariate analysis

Simple linear regression

ANOVA, multiple regression, CODA

Bivariate linear regresion & multiple linear regression

Linear fitting between variables analyzed

Multiple regression analysis

*Indoor concentration: multiplicative covariance (logarithmic transformation to linear model); t-test (for comparisons of means); Fisher’s exact test (form independence of two factors)

*Simple regression (correlation between Rn Concentration and 226Ra in soil) *Average ± 2 SEM (Radiological hazard assessment)

11 airborne gamma ray spectrometry (AGRS) produce an equivalent uranium map *Uranium RP Model:Wilson score interval method with continuity correction * Analysis of variance (ANOVA) to relationship between indoor radon concentrations and external eU concentrations from AGRS surveying *Radon Potencial Map: generated by combaining indoor Rn + airbone gamma ray spectromety (the percentage of radon values equal to or above 200 Bq/m3)

Bayesian Geostatistical model that combines spatial info (U concentration) + point source (Rn indoor)
MC algorithms

linear interpolation of triangles

Student t-test
Pearson correlation

Linear regression models with log(GM)
Neural network models
Bagged Neural Network

Linear regression model

Mathematical prediction

Airborne radiometric data

Bayesian statistics

The data were analyzed using methods embedied in geostatistics

airborne radiometric data

geological grouping - statistical tests, contingency alaysis - geological vs. RP classes, log normal distribution of RP considered, frequency distribution, the stochastic component for mapping

Statistical analysis

radon risk map with geological information, assuming log-normal distribution, moving average method, logaritmic mean radon concentration at every node of a 1 km grid.

data from soil gas campaign were integrated with previous information on high background radiation area - creating both a soil gas radon map and a conjunct radon risk map as well as identification of radon prone areas. Geostatistics,

main results	correlation	residuals
seasonal variability; variability between building material; relation to U/Th in ground sign. For Rn; doses	Rn~U: r=0.85; Tn~Tn: r=0.61	distrib. of res. indicates different pop. or missing predictor
Dependence on alt. above ground; no horizontal trend; seasonal dependence; Corr. Rn~ADR,U.	Rn~ADR: r=0.8; Rn~eU: r=0.8	res. of Rn~eU may point to 2 different populations
means of indoor Rn and soil Rn per geological region (n=4) are strongly correlated	indoor~soil Rn: r^2=0.97, but only 4 points	
moderate corr. soil Rn~Ra; good corr with soil pH per soil type; but data points are soil Rn and pH ast one site at several depths	soil Rn~Ra: r=0.43	Rn~ Ra: 2 apparent outliers, but sample size too small
Topsoil geochem (41 elements) has highest exploratory power (41%). Adding geology + aerogamma: 47%		
moderate corr. Rn emanaition rate and Ra conc.; no corr between ADR and Ra	r=0.458, p?	
log-normal dis. of SGR; **all variables are positively spatially autocorrelated** (Morans indexes), **high values of the studied variables are clustered at a global scale** (Getis-ord indexes), **GWR model explains very high amount of variance** (R2adj=0.935) compared to OLS model (0.152)	GWR explains better (R2>0.7) radium enriched, one one side and highly fractured and permeabile rocks on the other side. Worse correlation (R2<0.5) in regions with stronger local variability	
Created RP map from basement radon measurements and map of predicted RP. Efficiency of predicted RPA (or not): 85% for less than 20% of dwellings exceeds 200 Bq/m3; 32% for 20%-40% of dwellings above 200Bq/m3; and 41% of more than 40% of dwellings exceeds 200Bq/m3		
descirptive statistics from 11 geol. Units; poor correlations between different parameters if no regruping of geological units (Rn-soil vs Ra:0.57(AM) and 0.51 (GM); H*vsRa:0.57). good correlation between RN_A and RN_N only for Rn in soil gas >60kBq/m3 (R2=0.72); Regrouping geological data into few groups gave much better results.Scoring attempt by classes was quite satisfactory for geological units that have more than 10 indoor radon measurements	Spearman Rank Correlation Coefficient (with regrouped geological units) with significance on a 5% level: RPA-Rnsoil=0.94; Rnindoor-Rnsoil=0.89; RPN-RPA=0.89, Rnindoor-RPA=0.94	

As the result Geogenic radon potential map of Bourgogne. Was produced		
Procedure acounts for isolated outcrops of known geology without measurements and avoids interpolation across geological boundaries. Importance of sufficiently detailed map is demonstrated. Indoor Rn for each region follows lognormal dist. Desc.Stat. is given. Geom. mean of transfer factors for different age of house and counties points to a general problem of prediction of Rn conc. in houses. Interpolated prediction map of prob. to exceed 200 Bq/m3 based on transfer factor that would be necessary for each grid to reach chosen indoor Rn concentration	significant correlation between indoor Rn and soil gas Rn;	the effect of building-specific parameters, estimated by the ratio of indoor and soil gas activity. Transfer factor roughly 2 per mile
The highest value for 238U and 226Ra were found in limestone and the highest value for 222Rn was found in metamorphic rocks	238U-226Ra: 0.57;222Rn-226Ra:0.3	
significant relationships between indoor radon concentrations and all variables taken into consideration	the log-transformed concentrations measured on the ground floor versus the log-transformed concentrations measured in the basement: correlation coefficient 0.65; first floor versus the second floor: 0.89	
Summary statistics of the observed and predicted GRP for 145 sites	N/A	
mean monthly values (M) and mean quarterly values (Q) in each building from detectors in 3 diffusion chambers. The values of mean annual radon concentrations were calculated based on 12 monthly and 4 quarterly exposures.		

143 of 153 bedrock types overlap with the low prediction uncertainty areas. When all 143 bedrock types were ranked based on the mean residential radon concentration values and were compared with the rank based on the expert-assigned radon potential levels, the Spearman Rank Correlation Coefficient was 0.08. When only 15 largest bedrock types (64% of the total area of the low-uncertainty area) are used for the comparison, Spearman Coefficient reached 0.6.	The R between the Spearman Coefficient and the average area of the used bedrock types is 0.81 - 0,85
Measured radon levels as a function of the thickness of the overlying rocks. Radon concentration decreases exponentially according to the normal solution for the diffusion equation. Comparison with indoor radon data. Evaluation of the seasonal effect	
1.based on the pattern of summer radon measurements, we cannot reject the null hypothesis that summer radon measurements are evenly distributed and have a random pattern across the study area. 2.The study quantified the indoor radon spatial autocorrelations between geology, slope, elevation and aeroradioactivity. 3.in this part of northern Virginia, geotechnical knowledge is apparently not useful in making maps that can be used to delineate areas of lower than average, or higher than average indoor radon 4. aeroradioactivity is a poor predictor.	n.a.
Areas with equivalent uranium concentrations of 4 ppm or above are assigned a “high” hazard level while areas with lower concentrations	r2=0.82
Areas with equivalent uranium concentrations of 4 ppm or above are assigned a “high” hazard level while areas with lower concentrations are assigned a “moderate” level.	

In highly permeable building grounds, temperature/ pressure driven airflows between areas of different elevation can cause anomalously high seasonal changes in soil and indoor radon concentrations. Even though significant correlations can be obtained between indoor and soil radon concentrations, assessments of indoor radon concentrations should not be based on single soil gas measurements	0.75 summer, 0.76 winter	
Expert knowledge might be more accurate on major bedrock types; The properites of the major bedrock types might be more directly reflected in the indoor Rn; The first two conclusions might be wrong - alternative solution is that the interpolation overly smoothed the values for minor bedrock types	Spearman's R= 0.08 when all 143 bedrock types were ranked; R=0.6 for 15 largest bedrock types	N/A
Geology and radon risk are related; permeability is also related with radon risk Correlation between floor level and radon level (decreasing with floor level); radon concentration decreases with ventilation time and higher with mechanical ventilation, compared to balanced; higher radon concentrations with public water supply in 4 out of 7 municipalities; High radon risk in areas with: exposed bedrock with elevated levels of radium; highly permeable unconsolidated sediments derived from all rock types and moderately permeable sediments containing radium rich rock fragments	p<0.05 considered statistically significant, correlations not quantified, KWH results given and MW results	N/A
maps of isoemans, isobackgrounds, graphs of radon concentrations etc. can be used to map karst; measurements may be used to determine necessary thickness of clay deposits over karst to prevent surface collapse	N/A	N/A
good agreement between existing indoor radon maps and maps generated from Tellus project	r around 0,3 between Rn geometric mean and Tellus U	

good agreement between existing indoor radon maps and maps generated from Tellus project, including new geological information	correlation coefficients up to 0,52, and around 0,3 between U, Th, K and Radon Potential	
Mapping of Radon Index in a cross border area with results about the correlations between average indoor Rn concentration and average Rn in soil	r = 0,87 between Indoor Mean Rn and Mean Rn in soil	
Topsoil geochem (41 elements) has highest exploratory power (41%). Adding geology + aerogamma: 47%		
Very good correlation r > 0.9	R^2 > 0.9 between U & organic matter&indoor radon	Critical the effects of the thickness and texture of the sediment overburden
Good correlation > 0.8	Soil Rn vs Exhala.:good soil Rn vs terrest:very good exhalat Rn vs terrest: very good	The measurements are not taken at the same time in the soil selected
Areas unaffected by glaciation: bedrock geology can be successfully used to predict indoor radon in basement homes. Areas affected by glaciation:	R^2 between 0,21 and 0.96, depending of type of grouped data (bedrock, glacial deposit). High correlation between indoor radon and soil radon when grouped by glacial deposits.	
*Rn Concentration: 1.There are no houses with low radon concentration in the high risk substructure category and no houses with hight radon concentration in the low risk category; 2.Most of the houses in the highest exposure category are built on soil of the highest permeability, and most of the houses in the lowest exposure category on the impermeable soil types. * Indoor gamma dose rate: Exists a positive correlation between dose rate and indoor radon concentration *The most prominent features of the results were the effects of substructure and soil permeability * In areas of moderately homogenous uranium content of the soil, the main reasons for high indoor radon concentrations are high permeability of the soil and substructure types that allow radon leaks into dwellings	*R2=68%; *Rn Concentration-Indoor gamma dose rate: 0.52 Wooden houses, 0.54 stone houses, 0.55 all houses	**

*positive correlation coefficient between exhaled radon in soil gas and radium concentrations *correlation depends on the geologic structure in the region when this region contains different rock formations such as granites, gneisses, schist and quartzite. *Radiological hazard assessment: the high radiation exposure is likely to cause additional radiological health risks to the population	*Rn Concentration in soil gas and Ra Content in soil samples R2 = 0.72 *Average concentrations in soil samples = 226Ra-Rn(108 ± 26), 232Th-Rn (114 ± 22)and 40K-Rn(1081 ± 278) Bq kg-1 respectively	**
*Radon Prone Map: between 31% -38% of homes with ground floor living spaces exceed the maximum limit of 200 Bq/m3 and 11.4% of the population reside in this area * geology explains 40% of the observed variance in ln RP nationally, AGRS explains 70%	**	**
Add spatial info from uranium concentration with Rn indoor remove factors and	Rn~U r=0.3	
Map of concentration curves	Rn in soil ~ U concentration r=?	
Low correlation gamma-Rn due to high 232Th concentration in rocks: gamma increasing Next study: Thoron in air	gamma~Rn r=0.4	
Radon index from municipalities with enough data is used to predict the others municipalities Bias can be added by lack of data		
A linear regression model has been developed for the prediction of indoor radon in Danish houses. The model uses nine explanatory variables, all of which are available from central databases.	The model has an R2 of 40%, which is somewhat better than prediction models from most other countries.	

The fraction of the variation explained by mapped geological units increases with the level of detail. This has implications for the geogenic radon mpr. For radon potential mapping, it is important to separate units with significantly different radon potential.

The cumulative percentage of variation explained by grouping measurements by geology and 1-km grid square is 34–40% for the geological units evaluated.

A radon potential mapping system was developed using radiometric data from the airborne surveys, subsoil parent material and bedrock geology data, and indoor radon data and applied in the Tralee–Castleisland and Cavan areas in Ireland

The goodness of fit between % > RL estimated from indoor radon data and RP predicted using linear regression models was evaluated by calculation of the mean squared deviation (MSD) in the Tralee–Castleisland area.

Bayesian modeling helps reduce the effects of sampling variation allowing more precision than possible in analyses based on available monitoring alone. The approach appears to work well in predicting short-term indoor radon distributions at a scale as small as individual towns.

About 18% of the variance in individual house log radon measurements is attributable to the fact that some towns have elevated concentrations compared to others.

Hierarchical analysis of variance provide a reliable and efficient tool that can provide information to guide the choice of a suitable method of estimating radon, and in some instances a sampling interval for a more detailed study where accurate mapping is required.

Radon gas accumulation depends on building materials, water supply and on air circulation. The type of soil connection and the type of building (attached vs. detached) were not found to have a significant impact on radon concentrations. When considering buildings already present in the teritory, the obtained results help to identify what type of dwellings should be monitored more carefully and which parameters it would be best to intervene on for reducing IRC when necessary.

The capability of geological classes for regional prediction of the geometrical mean of the Radon potential (RP) has been shown. If the geological units choosen for classification are broad, the variability of RP within them is large and prediction is very uncertain. RP distribution within geological classes is usually log-normal - that allows regional risk estimation based on log-normal modelling of the variability within tha class. But in many cases there are alsostrong deviations in the upper distribution tails. The presence of "hot spots" makes the log-normal risk estimates non-conservative.	RP can be grouped according to geological classes and also according to individual geological units belonging to the same class.
The geologic units have been ranked according to the potential for releasing 222Rn by means of the Kruskal-Wallis test. The data show seasonality in terms of 222Rn concentration. Median 222Rn concentrations are highest during winter. Geologic units are associated with different concentrations of indoor 222Rn at the 5 percent significance level.	Correlation between geological unit and indoor radon and seasonal and regional difference
The first tadon risk map for the Walloon region with geological information. Several nodes of the grid show uncertain results or no results at all - insufficient number of data.	
The results of the radon risk assessment, based on soil gas radon and permeability data, is a map where alluvial area is characterized by a probability of being in an area with high Radon Index lower than 20%, while probability is higher than 30% in the northernmost part of the map characterized by volcanic products.	Radon risk assessment - correlation between soil gas radon and permeability data

results transferable	comment
perhaps to areas with similar climate and building types	simple regr. not sufficient, because of mix of populations (probably building type). GLM should be used. Tn results and conclusions questionable.
	authors: indication that ADR and in situ-gamma can be used for RPA delination. - My comment: reliability (classification errors) would have to be studied thoroughly
perhaps to areas with similar climate and building types	Relation within geological regions not examined. Regr. yields high inztercept which is difficult to explain be contrib. of building materials
not easily	Authors: low corr Rn~Ra "unexpected"; but it is known that also other factors contribute, correctly stated by the authors.
yes, if data available	Local Rn variability removed by aggregating into grid cells intersected with geo.units, leaving lateral var. Explained variance (rel. to lateral var.) very high compared to most approaches. Complicated due to CODA approach. - To be done: validation, prediction capacity?
no	sample size too low. Dependence model more complicated.
yes! Derived methodology for mapping GRP can be applied to any region;	the GWR model exhibited a higher mapping performance than the global regression models; Additional datasets of explanatory variables could be included in analysis (gamma dose rate, soil characteristics, climate), indoor radon… Predictions are worse for regions with stronger local variability
yes, since the main result is derived metodology for estimating RP, it can be applied in any regions, with same or similar predictors	poor statistics, a large area covered with not enough Rn measurements. Results would be more convincing with more data
To be investigated if conclusions could be applied to different geological units in Austria or even abroad. Autor stated that if analysed variables give indications for the radon risk and if all of these variables point approximately to the same radon risk (class) then it is a strong sign for a correct estimation.	

Authors did not prove agreement with any measurements. If good agreement is obtained, methodology can be applicable for other regions as well	Authors stated that validity was checked previously and that it is good agreement with measurement results, This is not convincing since da4a are not published and it is stated without references.
Yes, in the sence of methodology. House characteristics of investigated regions are necessary in order to apply proposed method	
no	sample size too low
yes	Authors: This work is essential for the development of more complex predictive models to map IRC in Switzerland
yes	Authors: All of these outputs provide useful contribution to spatial planning, radon action planning and decision making.
no	The authors did not analyse the relation between 222Rn activity concentration and the building type and structure, or the building materials used.

approach could be repeated elsewhere	Authors adopted the assumption zhat basement and winter measurements have the same spatial pattern as that of the annual average residential radon concentration in an area.
	preko 20 godina star rad. Pitanje je da li postoji jos nesto radjeno na tu temu u Izraelu… kako ovakav komentar dati fino? :)
not easily	
yes	

not easily	
results suggest that expert knowledge on geology can be used to create radon potential classification in other areas, but the usefulness is limited in areas with bedrock types with small areas	expert knowledge of only one geologist was used
yes to areas with similar housing construction, questionable to other areas	
yes	
potentially to similar areas	The experience showed in this paper could be of interest to areas with maps containing sufficient statistics of indoor Rn

	The paper is based on a relevant database,but its experience could be reproduced probably only when similar statistical power is available.
Transferable to all administrative borders	The methodology is widely applicable and the degree of correlation between variables is determined by the size of the available data sample.
yes, if data available	Local Rn variability removed by aggregating into grid cells intersected with geo.units, leaving lateral var. Explained variance (rel. to lateral var.) very high compared to most approaches. Complicated due to CODA approach. - To be done: validation, prediction capacity?
Perhaps to areas with similar geological composition	The methodology is not appropiate to the study and the explanation of results look very evident without technical support.
The study yes but under appropiate conditions	The number of measurements is very low to conclude relationhip between the variables measured. Some methodological errors are detected.
Transferable to all countries whith well known geology and a big Radon data available	Interesting to reproduce it in an area (country) with "updated" Rn measurements results with a quality control and homogeneus conditions
Perhaps to areas with similar climate and building types	

Yes	Authors: Apply the Monte Carlo model, which is the most powerful, is computationally intensive. They only apply models with regional averages
Yes	Rn in soil explicable with Uranium concentration . Dependence with water table position. Anomaly founded without clearly explanation
indoor Rn and U are available to carry ut the same analysis	
Gamma dose rate map and indoor Rn in dwelings	
Most data available	With enough data seems a relative easy way of obtain the radon index
The actual model found in the present work is specific for Denmark as it uses explanatory variables available from Danish central databases. Similar models could, however, be established in other countries	The model could act as a simple screening tool for finding high-radon houses.

The fraction of the variation explained by mapped geological units increases with the level of detail. This has implications for the geogenic radon map of Europe. For radon potential mapping, it is important to separate units with significantly different radon potential.	This study confirms the importance of radon maps that show the variation of indoor radon concentrations both between and within mapped geological boundaries
yes	The results show the potential for using airborne radiometric data for producing RP maps.
The approach used in this paper has provided a means to use radon survey screening data and other explanatory variables to more precisely predict short-term indoor radon concentrations	Predictions based on statistical models of this type have the potential to provide guidance as to which geographic areas require the most urgent attention for such measures as intensive radon monitoring or mitigation.
yes	These results have considerable implications for radon mapping.
yes. The analysis were used on the existing data and it is transferable to any other.	Interesting testing of hierarchical modeling of indoor radon concentration - different factors were taken into account (geology and building factors). This model can be used in other cases.

The paper deals with different open questions and all findings could be used as advice in future studies.	Although log-normal distribution and Kriging model may be very useful, there are some problems with "hot spots" which are local in phenomena and could be used covariance model which holds for the bulk of the data. In practice, there must be a sufficient number of data points (measurements) distributed as uniformly as possible within one unit to allow reasonable determination of the trend component.
Yes, this model could be used for studies of other areas.	This study is in agreement with results of studies in other areas.Simple method.
Yes, this model could be used for studies of other areas.	Indoor radon risk maps have to include geological data as well.
Yes, this model could be used for studies of other areas.	In order to have proper radon maps of the area different factors have to be included in the analysis.

Deliverable D5, Annex 7

Publications in context of WP4

Links to conference presentations can be found on the Metro Radon homepage, http://metroradon.eu/index.php/documents/

1 Peer-reviewed journal articles (all open access):

Bossew P. (2018): Radon priority areas – definition, estimation and uncertainty. Nuclear Technology & Radiation Protection 33 (3), 286 - 292; http://doi.org/10.2298/NTRP180515011B

Bossew P. (2019): Radon priority areas and radon extremes – initial statistical considerations. Radiation Environment and Medicine 8 (2), 94 – 104 http://crss.hirosaki-u.ac.jp/wp-content/files_mf/1568795052Web_REMVol828_PeterBossew.pdf

Bossew, P., Cinelli, C., Ciotoli, G., Crowley, Q.G., De Cort, M., Elio Medina, J., Gruber, V., Petermann, E., Tollefsen, T. (2020): Development of a Geogenic Radon Hazard Index - Concept, History, Experiences. Int. J. Environ. Res. Public Health 2020, 17(11), 4134; https://doi.org/10.3390/ijerph17114134

Pressyanov D., Quindos Poncela L.S., Georgiev S., Dimitrova I., Mitev K., Sainz C., Fuente I., Rabago D. (2019): Testing and Calibration of CDs as Radon Detectors at Highly Variable Radon Concentrations and Temperatures. Int. J. Environ. Res. Public Health 2019, 16, 3038; doi:10.3390/ijerph16173038

2 Peer-reviewed journal articles in preparation (by 12 Nov 2020; incomplete):

JERA, special issue scheduled first half 2021:

- Gruber V., Baumann S., Alber O., Laubbichler C., Bossew P., Petermann E., Ciotoli GC, Pereira A., Domingos F., Tondeur F., Cinelli G., Fernandez A., Sainz C., Quindos-Poncela L.: Comparison of Radon Mapping Methods for the Delineation of Radon Priority Areas - an Exercise
- Trevisi R., Leonardi F. et al.: Are radon priority areas, identified on survey in dwellings, representative of radon levels in workplaces? (working title)
- Bossew P., Čeliković I., Cinelli G., Ciotoli GC., Domingos F., Fuente Merino, I., Gruber V., Leonardi F., Nikolov J., Pantelić G., Pereira A., Petermann E., Sainz C., Todorović N., Trevisi R.: On harmonization of radon maps.

3 Conference presentations:

IWEANR 2017, 2nd International Workshop on the European Atlas of Natural Radiation. Verbania, Italy, 6 – 9 Nov 2017:

- Valeria Gruber, Baumann S., Ringer W., Alber O., Kuchling S., Laubichler C., Schleicher C. (2020): An extensive indoor radon measurement campaign to define radon priority areas in Austria.

- Bossew P. (2017): Determination of radon priority areas – a classification problem. Presentation
- Bossew P., Cinelli G., Tollefsen T., De Cort M. (2017): The geogenic radon hazard index – another attempt. Presentation
- Ciotoli G., Bossew P., Finoia M.G.(2017): A preliminary exercise to derive the map of potential radon release at European scale. Presentation
- Bossew P. (2017): State of BSS implementation – definition of Rn priority areas. Presentation

Workshop, GARRM; Geological Aspects of Radon Risk Mapping, Prague, Czech Republic, 18 - 20 September 2018

- Bossew P. (2018): Estimation of Radon Priority Areas – sources of error and uncertainty.
- Petermann E. & Bossew P. (2018): Estimation of spatial continuous soil gas air permeability using physical and statistical models as a support for geogenic radon risk mapping.
- Gruber V., Baumann S., Ringer W., Sainz C., Quindós-Poncela L., Cinelli G., Gutiérrez Villanueva JL, Ciotoli G., Laubichler C., Alber O., Pereira A., Domingos F., Petermann E., Bossew P., Tondeur F. (2018): A radon mapping exercise within the European MetroRadon project.

Bossew P. (2018): Radon priority areas as random objects. Pres., IAMG 2018, 2 - 8 September 2018, Olomouc, Czech Republic

Bossew P. (2018): Radon priority areas – definition, estimation and uncertainty. Pres., geoENV-12, Belfast 3-6 July 2018.

Bossew P. (2018), Radon priority areas and radon extremes - an initial study. Invited presentation, ICHLERA 2018, 9th International Conference on High Level Environmental Radiation Areas, September 24-27, 2018, Hirosaki University, Aomori, Japan

Cinelli G., Bochicchio F., Bossew P., Carpentieri C., Gruber V., Leonardi F., Tollefsen T., Trevisi R., Venoso G. (2019): Risultati dell'analisi dei questionari MetroRADON sulle indagini di misura del radon in ambienti chiusi. Pres., VII Convegno Nazionale Agenti Fisici, 5-7 giugno 2019, Stresa, Italia

3rd Conf. Radon in the Environment, Kraków, 27 – 31 May 2019:

- Petermann E., Bossew P. (2019): High-resolution mapping of the geogenic radon potential using machine learning. Pres.
- Cinelli G., Bochicchio F., Bossew P., Carpentieri C., Gruber V., Leonardi F., Tollefsen T., Trevisi R., Venoso G. (2019): Results of analysis of MetroRADON questionnaire data on indoor radon surveys. Pres.
- Bossew P., Cinelli G., Ciotoli GC., Crowley Q., De Cort M.,Elío J., Gruber V., Petermann E., Tollefsen T. (2019): Development of a geogenic radon hazard index GRHI. Pres.
- Trevisi R., Leonardi F., Buresti G., Bucci S., Cinelli G., Gruber V., Gutierrez Villanueva J-L., Heinrich T., Holmgren O., Bossew P. (2019): Are radon priority areas, identified on survey in dwellings, representative of radon levels in workplaces? Pres.

Bossew P., Janik M., Cinelli G., Tollefsen T., De Cort M. (2019): Radon Regulation and Research in Europe - Is It Relevant for the Asian-pacific Region? Pres., 16th Annual Meeting, Asia Oceania Geosciences Society AOGS, Singapore 28 July – 2 August 2019

XXX Symposium of the Society for radiation protection of Serbia and Montenegro, 2-4 October 2019, Divčibare, Serbia:

- Čeliković I., Pantelić G., Živanović M., Vukanac I., Krneta Nikolić J. (2019): Sources of uncertainty in classification of radon zones
- Gordana Pantelić G., Živanović M., Čeliković I., Krneta Nikolić J., Vukanac I. (2019): MetroRADON – Project to improve radon measurements in Europe

Petermann E., Bossew P. (2019): Modelling the probability of indoor radon concentration exceeding 300 Bq/m³ – new approaches using machine learning. 9th Conference on Protection against Radon at Home and at Work, 16 - 20 September 2019, Prague, Czech Republic. Pres.

Bossew P., Gruber V. (2019): The Metro Radon project as support for the implementation of the EURATOM Basic Safety Standards. Pres., RAP, Intl. Conf. on Radiation Applications, 16 – 19 Sept 2019, Belgrade, Serbia:

Vienna Radon Week, 24 - 28 Feb 2020:

- Janik M., Bossew P. (2020): Radon regulation and research in Asian-Pacific region – is it possible to adopt European strategy?; Pres.
- Bossew P. (2020): The MetroRADON questionnaire on geogenic radon surveys; Pres.
- Bossew P., Cinelli G., Ciotoli GC., Crowley Q., De Cort M., Elío J., Gruber V.., Petermann E., Tollefsen T. (2020): The Geogenic Radon Hazard Index; Pres.
- Bossew P. (2020): Objective of WP4and its position in Metro Radon: Pres.
- Gutierrez-Villanueva JL., Bossew P., Cinelli G., Gruber V. (2020): Impressions of Metro Radon / WP4; Pres.
- Ciotoli GC., Bossew P. (2020): Spatial multivariate analyses for the mapping of the European geogenic radon potential; Pres.
- Trevisi R., Leonardi F., Buresti G., Cinelli G., Gruber V., Gutierrez Villanueva JL, Heinrich T., Holmgren O., Torri G., Salvi F., Bossew P. (2020): Study on possible different distributions of indoor radon levels in dwellings and workplaces: preliminary results; Pres.
- Ielsch G., Greau C., Sainz Fernandez C. (2020):Task 4.3.3: Estimation of Rn priority areas based on Rn extremes, with case studies in France and Spain,
- Gruber V., Baumann S. (2020): The radon mapping exercise,
- Greau C. and Ielsch G. (2020): Task 4.4.1: Harmonization of radon priority areas across borders : focus on some West European borders.
- Cinelli G., Bossew P., Gruber.V., Elio J., Peterman E., Gutierrez Villanueva JL. (2020): Overview of radon maps and data in Europe: differences and challenges for harmonization.

4 Reports:

Deliverable 5: Report and Guideline on the definition, estimation and uncertainty of radon priority areas (RPA); with annexes:

- Annex 1: Report: *Review and Evaluation of the concepts of the definitions of radon priority areas*, P. Bossew, V.Gruber, R. Trevisi, F. Leonardi, G. Ielsch, G. Cinelli, C. Sainz, L. Quindos, G. Pantelic, I. Celikovic, M. Zivanovic, I. Vukanac, J.K. Nikolic, MetroRADON Activity Report 4.1.2

- Annex 2: Report: *Relationship between indoor radon concentration and geogenic radon,* P. Bossew, L. Szücs, G. Ielsch, C. Greau, G. Cinelli, C. Sainz, L. Quindos, J.L. Gutierrez-Villanueva, J. Nikolov, N. Todorovic, G. Pantelic, I. Celikovic, M. Zivanovic, I. Vukanac, J. K. Nikolic; MetroRADON Activity Report 4.2.3

- Annex 3: Paper: *Development of a Geogenic Radon Hazard Index - Concept, History, Experiences*, Bossew, P., Cinelli, C., Ciotoli, G., Crowley, Q.G., De Cort, M., Elio Medina, J., Gruber, V., Petermann, E., Tollefsen, T, Int. J. Environ. Res. Public Health *2020*, *17*(11), 4134 (see also journal articles above)

- Annex 4: Report: *Radon mapping exercise.* V. Gruber, S. Baumann, K.Himmelbauer, C. Laubichler, O.Alber, P. Bossew, E. Petermann, G. Ciotoli, A. Pereira, F. Domingos, F. Tondeur, G. Cinelli, C. Sainz, L. Qunidos-Poncela, A. Fernandez, J.L. Gutierrez Villanueva, MetroRADON Activity Report 4.4.2

- Annex 5: Table with results of literature survey in WP 4.2.1, <Lit-4_2_1_4--all-190424.xls>

Deliverable 6: Report on the concept and establishment of a Radon Hazard Index (RHI) including an RHI map of Europe showing areas with high geogenic radon potential and conclusions on the relationships and correlation between indoor Rn concentration and quantities related to geogenic Rn; with annexes:

- Annex 1: Approximation formulae and bias correction

- Annex 2: Dobromir Pressyanov, Luis Santiago Quindos Poncela, Strahil Georgiev, Ivelina Dimitrova, Krasimir Mitev, Carlos Sainz, Ismael Fuente, Daniel Rabago (2019): Testing and Calibration of CDs as Radon Detectors at Highly Variable Radon Concentrations and Temperatures. Int. J. Environ. Res. Public Health 2019, 16, 3038; doi:10.3390/ijerph16173038 (see also journal articles above)

- Annex 3: Report on Activity A.4.3.2: SUBG Results for Radon in Air, Radon in Soil-gas and Radon exhalation from soil, obtained in the frames of “METRORADON: Intercomparison on indoor radon at LNR Saelices el Chico (Salamanca, Spain)”, organized by LaRUC

- Annex 4: Table A: Geological characteristics associated with cells identified as hot spots.

Geogenic Radon Potential: 1) Short overview; 2) Summary of literature. Szücs L., Nagyné Szilágyi Zs., Nagy Á., Nagy P., Botos R., Árva F., Szabó N., Rósza K., Párkányi D.

Rationale and Summary of Work Package WP4

The very large work package 4 of MetroRADON is called *"Radon priority areas (RPAs) and the development of the concept of a 'geogenic radon hazard index' (RHI)"*. WP 4 resulted in two deliverables, D5 and D6.

Contents

1 Rationale of WP4

Motivation

The new European EURATOM Basic Safety Standards (BSS) lay down several requirements regarding the radon protection of the European citizens. Three articles are dedicated to radon - radon in workplaces (Art. 54), indoor exposure to radon (Art. 74) and the radon action plan (Art. 103). In addition, Annex XVIII provides a list of items to be considered in the national action plan. Article 103 states that member states shall identify areas, where the radon concentration in a significant number of buildings is expected to exceed the relevant national reference level. Article 54 requires that in those defined areas of Art. 103, radon measurements have to be carried out in all workplaces in ground floors and basement. According to article 74, MS shall ensure that local and national information is made available on indoor exposure and the associated health risks, on the importance to perform radon measurements, and that action should be promoted to identify dwellings with radon concentrations exceeding the reference level. These requirements make (among others) radon measurements, radon surveys and radon mapping (delineation of radon priority areas) necessary and obligatory in all MS for the implementation of the European BSS.

Delineation of Rn priority areas (RPAs) is generally considered an essential tool in the overall target of reducing the radon risk of the population. Given its possibly important economic, logistic and political consequences, RPA definition has become a highly politicised issue in some countries. One step in the quality-assured implementation of European BSS requirements should therefore be proper discussion and involvement of stakeholder interests, since this provides the necessary condition for an Rn protection policy that satisfies the needs of society. While the overall aspects of impact on society are addressed in WP6, specific issues which imply action on a technical level are addressed in this WP.

Aim of WP4

The aim of this work package is to analyse and develop methodologies for the identification of radon priority areas, to investigate the relationships between indoor Rn concentration and quantities related to geogenic Rn, including soil exhalation (see WP3, Task 3.2) and to develop the concept of a "geogenic radon hazard index" (RHI) as a tool to help identify radon priority areas.

Article 103 of the European BSS requires that member states identify areas where the radon concentration in a significant number of buildings is expected to exceed the relevant national reference level – referred to as radon priority areas in this document. The definition of RPAs will influence political and technical decisions, which in turn will have economic effects in these countries, such as mandatory radon measurements in workplaces in these areas according to Art. 54 EU-BSS, as well as mandatory preventive measures or priority of awareness programmes.

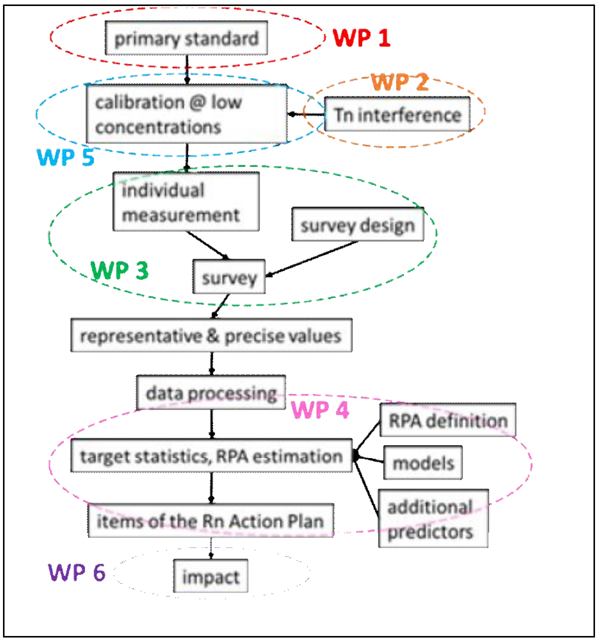
The high number of participants (12; from 9 countries and the EC) in WP4 indicates the high relevance which is attributed to the topics addressed in this WP.

Radon priority areas in the context of metrological QA

a) The QA chain

Although MetroRn is a metrology project, it is not one in the conventional sense only, i.e. concerned with QA of determining a given measurand. Instead, it deals with the chain – or parts of it - from defining a target, determining an appropriate experimental design, actual measuring under the premises of a diversity of methods and protocols whose compatibility and consistency is not known a priori, to harmonization, evaluation and reporting. It could be called QA of a chain, or rather a net of partly parallel, partly subsequent procedures having in view a product that is needed by the society. In the context of MetroRn, the "consumer end products" are methodological support to to Rn action plans and defining Rn priority areas. In consequence, the proposed project is thematically rather diverse; it may be called metrology in an extended or generalized sense. One may summarize the rationale by stating that from the point of view of the BSS, not a particular value of Rn concentration is the requested end product, but certain action; the objective of all action is reducing Rn exposure.

MetroRn connects the necessary steps in the implementation of the European BSS, from metrology through to the delineation of RPA. Quality assured delineation of RPAs is necessary, as it will be the basis for (politically and economically relevant) decisions and actions (e.g. measurements at workplaces) according to the European BSS. Therefore, traceability of measurements and calibration is essential also for quality assured delineation of RPA for liability.



In particular, WP4 discusses concepts, definitions and estimation of RPAs, which may be considered the endpoint of the chain starting from quality assured measuring of radon concentration.

A rough flow scheme of Metro Rn is shown in Figure 1. One can note that WP1, 2 and 5 address issues of "classical" metrology, whereas WP3 and 4 are concerned with higher aggregation levels in the chain.

Figure 1: Rough logical scheme of Metro Rn. The spheres of the different work packages are indicated.

A similar flow scheme is shown in Figure 2. The experimental part of the chain, i.e. measurement, must 1) be designed according the purpose, i.e. with respect to decision which it serves, and 2) be itself QAed. Importantly, 1) includes survey design. Without adequate design, the measurement may be correct as such but may not be useful for the objective (correct decision).

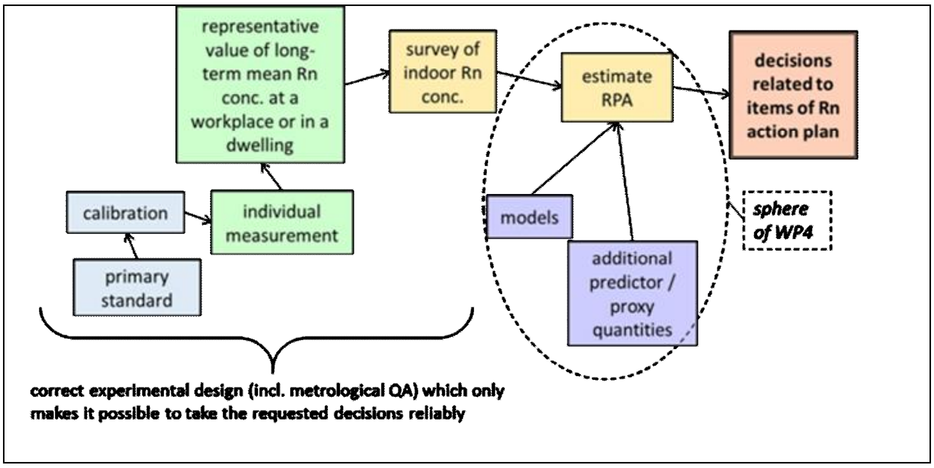


Figure 2: Flow scheme emphasizing the importance of metrological QA for the quality of decisions which are the "end user product".

Summing up, we are concerned with a pathway from correctly measured individual Rn concentrations to a reliable end-user product, i.e. items of Rn action plans aimed to reduce Rn exposure.

For the overall purpose of reduction of Rn exposure, one is not interested in actual Rn concentrations; but these being correctly measured, is a condition of the validity of all subsequent aggregation steps, which serve the end-user product.

b) Specifically: QA in WP4 context

One may ask what QA means in detail in the context of WP4. While these details will be addressed below in the specific sections, the following are among the rules which were kept in mind when developing the subjects of WP4.

- Definitions should be as clear and unambiguous as possible;
- For numerical output quantities, an uncertainty budget should be attempted;
- For categorical output, assessment of misclassification probability should be attempted;
- Where possible, reproducible rules or flow schemes for establishing these should be given;
- The possible impact of uncertainty to the “product” of a task – a map, a decision about action, a statement about compliance with a legal item etc. – should be addressed.

c) Decisions

As expounded above, the endpoint of the “supply chain” is a decision for a certain action according the radon action plan. A QAed decision can be called one, which is reliable, that is, reproducible and therefore transparent. This means that it must consider only arguments or criteria which have been defined as relevant preliminaries of the decision, but not for example personal preferences of the person who decides.

The reliability of a decision depends on two factors: 1., it must logically correctly depend on its preliminaries; 2. the higher uncertainties of the preliminaries, the less reliable a decision. The reliability of a decision is quantified by the probability with which an alternative decision may have been taken, given preliminaries and decision options. If a decision is clear-cut, the probability that another decision might have been taken is low and the decision is reliable. The question is: how to translate uncertain premises into decisions which are binary (yes / no) or multinomial (decide A / decide B / decide C /…) by nature, with mutually excluding options (a measurement can only be performed or not performed), although in an unclear or conflicting situation society can of course decide for introducing additional options, responding to the situation.

> Example 1: in an area, the probability that indoor Rn concentration exceeds a reference level (RL), is above a threshold (Tp) deemed sufficient to initiate certain action. On the other hand, economical constraints are considered such that the action cannot fully be fulfilled.

> Example 2: Often in historical buildings (castles, churches), which are workplaces, high Rn concentration occurs due to ancient building style. Remediation is next to impossible because preservation requirements or structural stability do not allow constructional modification.

A mathematical apparatus called decision theory has been developed over the last decades. Its purpose is to provide a quantitative framework for QA-able decisions. The theory shall not be expounded here; introduction and literature can be found in the Wikipedia entry https://en.wikipedia.org/wiki/Decision_theory . Further introductions and tutorials can be easily found by googeling. One method originating from, and used in decision theory, called spatial multi-criteria decision analysis (SMCDA), has been addressed in work package 3.4 about the geogenic radon hazard index.

d) Four levels of QA

Summarizing, one may distinguish different “trophic” levels of QA (Bossew 2018c):

1. Design QA: An investigation, experiment or survey has to be designed such that the target can be met with given tolerance. This concerns geographical or demographic survey designs, where the criterion of the design are representativeness (affecting accuracy, related to positioning of observations) and precision (implying sample size).

2. Data QA: This concerns "classical" metrological QA, i.e. correct experimental procedures, in particular calibration and measurement, proper consideration of uncertainty that occurs in different stages of the procedure and of detection limits.

3. Evaluation QA: This part deals with selecting proper evaluation methodology, selection of adequate models, correct statistics, considering - as far as feasible (because this can be complicated!) - model-induced uncertainty.

4. Decision QA: A correct decision shall be taken about which action to take. Correctness of a decision is based on the quality of preceding steps. The probability of a wrong decision shall be below a threshold; however, assessing such "mis-decision" chance seems to be a complicated problem, beyond the scope of Metro Radon.

Implementation of proper QA can be demanding, but is a prerequisite for a valid end product. However, one has to concede that for example a complete uncertainty budget is often difficult to achieve, in particular in spatial studies which may include a rather long chain of aggregation and modelling steps.

Part of proper QA (level 3) is adequate and correct statistical treatment. Also this can require advanced methods; just to name the missing data problem (incl. measurements below detection limit), bias correction of statistics (typical: standard deviation), or respecting the composite nature of certain quantities (typical: geochemical data).

2 Formal and logical structure of WP4

The *formal* structure of WP4 according to the JRP can be shortly summarized as follows:

- 4.1: Objective and definition of RPA
    - role of stakeholders
    - RPA pertaining to dwellings vs. workplaces, public buildings
- 4.2: Relation of geogenic Rn and IRC
    - 4.2.1 Radon potential
    - 4.2.2 Association between geogenic quantities and indoor Rn concentration
- 4.3: New developments
    - 4.3.1 Estimation of RPA, classification uncertainty
    - 4.3.2 CD/DVD method for RPA estimation
    - 4.3.3 RPA assessment based on extremes
    - 4.3.4 Rn hazard index (GRHI)
- 4.4: Harmonization issues
    - 4.4.1 differences across borders
    - 4.4.2 Cross usage of estimation methods; mapping exercise
    - 4.4.3 Obstacles against harmonization

The *logical* structure of WP4 is comparatively complicated and somewhat labyrinthic, reflecting its diversity and conceptual novelty in many respects (Figure 3).

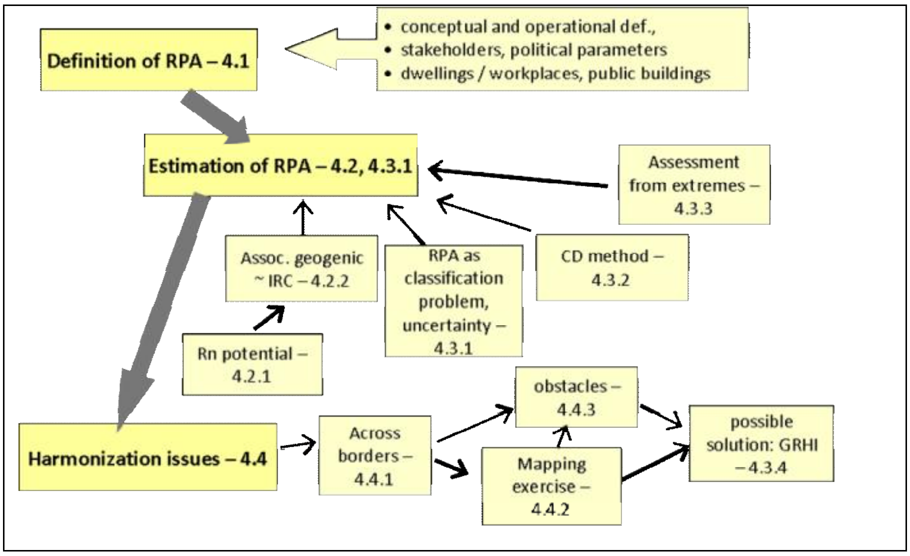
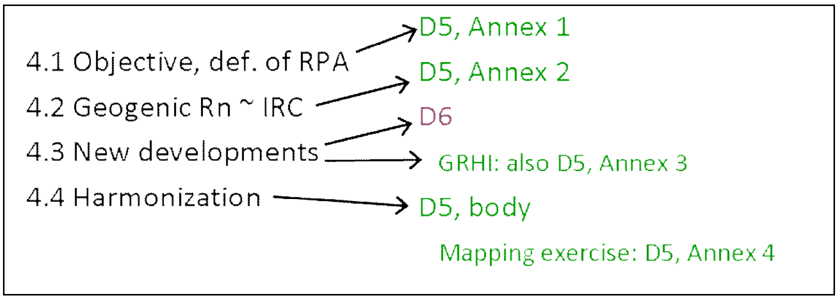


Figure 3: Logical structure of WP4



The different tasks and actions are assigned to the deliverables of the projects according Figure 4.

Figure 4.

3 Deliverable D5: Report and Guideline on the definition, estimation and uncertainty of radon priority areas (RPA)

The report covers tasks 4.1 *(Evaluation of the concepts for the definitions of radon priority areas)*, 4.2 *(Relationship between indoor radon concentration and geogenic radon)* and 4.4 *(Harmonisation of radon priority areas across borders)* of the work package. For task 4.3, see D6, below.

As a conclusion of task 4.1, it appears that conceptual and theoretical work about RPAs is well advanced. This concerns understanding of the concept, definitions which serve to translate the concept into an operational definition (i.e. a formula with which can be worked in regulatory practice) and estimation methods. For the latter, quite a variety has been developed, depending on the data which are available for the purpose. Available data depend on national policies of surveying radon related variables, from indoor concentrations in dwellings to various geogenic quantities, which control geogenic and indoor radon to different extent.

Often dwelling and workplaces show significant differences in the IRC distribution even if, they are hypothetically located on the same site and thus subject to the same geogenic radon influence. This is a consequence of different construction styles, different occupation factor, and usage and also of their different "building physics" in terms of air circulation and radon accumulation and dilution. These differences in IRC are already pointed out in some papers but so far with controversial conclusions. For further clarification, radon data from Austria, Finland, Germany and Italy have been analysed. Preliminary results put in evidence that IRC in dwellings and in workplaces are concordant; however their statistical distributions are different. Moreover, also the distribution of IRC within the category "workplaces" is not homogenous: analysis carried out on data of schools, public buildings and general workplaces highlighted that although in schools radon data can have a distribution similar to the one of dwellings, they are not necessarily representative of all workplaces. The matter is relevant, because RPAs are mostly estimated based on data of indoor radon concentration in dwellings, but legal consequences as stated in the BSS largely pertain to workplaces.

For evaluating the cross-usage of concepts, different mapping methods were compared and the agreement of the different methods was discussed by means of several parameters. Mapping methodologies are various and so are the definitions of RPAs. As a general conclusion about the cross-usage of concepts, it can be said, that applying a mapping method using data sets, which were not designed for the specific requirements of the mapping method, is challenging.

For the delineation of RPA it turned out that different mapping methods often, but not always, deliver the same results in RPA classification, depending on the definition of RPAs. Among sources which contribute to inconsistency, perhaps most important are thresholds and criteria which define RPA.

Task 4.2: The idea of radon potential (RP) as a quantity which "subtracts" individual physical properties of buildings to indicate the natural conditions that control long-term mean indoor Rn concentration (IRC), has been around for more than 30 years. Concepts were reviewed in this task. One may distinguish between "top-down" approaches (Figure 5), whose initial variable is observed indoor Rn concentration, which is normalized with regard to house, room and usage properties, i.e. the anthropogenic factors which control IRC.

An alternative is the "bottom-up" approach, which starts from geogenic control quantities. The GRP (geogenic radon potential) is a particular kind of RP; it is defined physically from quantities which control Rn generation and transport in the ground. In this action, definitions are discussed as well as the geogenic quantities which are its input, and their measurement. Problems of representativeness of measured values for a measurement location are addressed, which are mainly owed to the temporal variability of some control quantities.

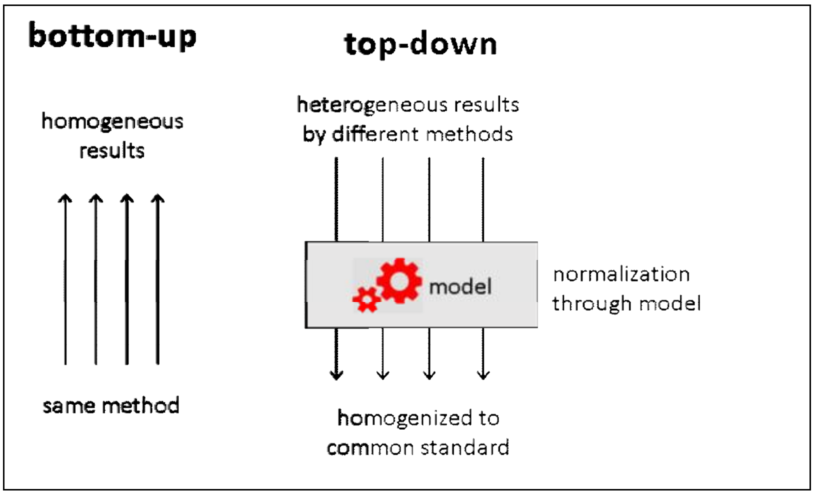
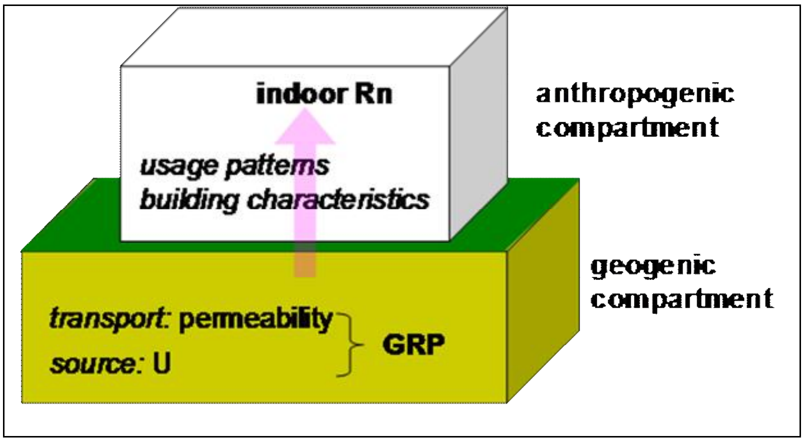


Figure 5:Bottom-up and top-down harmonization

Regarding mapping, the rationale of the RP in general and the GRP in particular is that the geographic pattern of IRC mainly reflects the one of its geogenic controls. The reason is that the geographic dependence of anthropogenic factors is relatively minor compared to the geogenic ones, at least on regional scale, i.e. anthropogenic ones appear as statistical noise on top of the geogenic pattern. In mathematical terms, the anthropogenic factor appears as a scalar factor relating IRC and its geogenic controls (or predictors) that has to be found by regression-type analysis.

Many regression studies have been performed for many years. In this task of Metro Radon, a literature review of relationships between geogenic quantities which control geogenic and indoor Rn concentration has been performed and the results interpreted. In particular, the often poor correlation between IRC and geogenic quantities has been discussed. The main problem seems to be that models have been developed regionally, obviously considering only regionally variable controls, about constant ones regarded as fixed and entering regression coefficient. However, on larger scale, e.g. Europe, the latter controls are also geographically variable, if over larger distance compared to the regionally variable ones. Therefore, regionally developed models, though correct regionally, may not be applicable beyond the region in which they have been developed. This problem remains a challenge; first European-scale studies have been initiated only recently. Their further development and evaluation remains a task for the future. The question is closely related to analysis of the spatial statistical properties of the anthropogenic factors, about which so far only very initial studies exist. These have not entered discussion in Metro Radon.



Conceptually:

(indoor Rn)
=
(anthropogenic factors)
×
(geogenic Rn)

Figure 6: Geogenic and indoor Rn

A further open problem, not addressed in Metro Radon, is the one of anthropogenically modified geogenic factors. This is typical for urban and built-up environments where geogenic controls - including geology itself - may not be equal to the one in its surroundings, i.e. open land, where data are usually being acquired in field studies (e.g. due to pavements, landscaping, landfills, historical construction activities etc.). The problem is important because most people live in strongly altered built-up environments. In particular in old European cities, this may challenge correct IRC estimation based on geogenic factors. It is recommended that the topic is addressed thoroughly in future investigations.

Methods to estimate the RP or GRP, respectively, have been addressed in this action. To illustrate it, case studies from two European countries are shown.

Task 4.4: Consistency across borders can be jeopardized by differences semantics (e.g. legends) or scale of predictor quantities. Legends of geological and other maps which serve as predictors of Rn quantities may be different between regions; for example geological maps display the outcrop of rocks which are classified hierarchically according to their composition, texture, genesis and/or age. The boundary between geological units is constrained not only by scientific knowledge and the mapping techniques but also by the terminology used. If geological units are classified according to their age, different maps will be produced if different levels of the chronostratigraphic chart are considered (ex. system, series, or the stage). The geological maps can be drawn at different scales, which may cause different degree of detail and misclassification of areas as the map scale determines the size of the objects that can be displayed as well as the smallest distance that can be recorded between two independent objects (related with the spatial resolution). In small-scale maps a generalization of the map objects is needed to guarantee a reasonable representation of geological units which involves selecting the features to be displayed, simplifying, smoothing or aggregating existing features. These choices will depend mainly on the map authors

A further issue is the very definition of RPA. This usually has as main feature a threshold (or several thresholds, in case of multinomial classification) of the quantity that underlies RPA definition (e.g.

probability that the IRC exceeds a RL), which defines the RPA status of a location or a map unit. If these are different between two neighbouring regions, so will be the RPA status in spite of objectively same natural conditions.

Harmonization of existing maps (i.e. top-down harmonization) remains a challenge, the bigger, the higher the aggregation level of the quantity displayed in the map. This is true in particular for RPA maps, whose aggregation chain may be intricate. Within Metro Radon, challenges were identified and direction of necessary further research indicated. One issue to be further discussed is that heterogeneity is owed to lack of coordination between European countries regarding definition and estimation of RPAs.

4 Deliverable D6: Report on the concept and establishment of a Radon Hazard Index (RHI) including an RHI map of Europe showing areas with high geogenic radon potential and conclusions on the relationships and correlation between indoor Rn concentration and quantities related to geogenic Rn.

Deliverable D6 covers the rather large task 4.3, "*New developments in estimation of radon priority areas*" of WP 4, which has several different subjects: (1) Estimation of RPA and classification uncertainty; (2) Application of retrospective Rn measurements to RPA assessment; (3) RPA classification based on extremes and (4) Geogenic Radon Hazard Index (GRHI).

(1) Quality assurance of RPA delineation is often ignored. As results of an estimation procedure, RPAs are uncertain, in the sense of misclassification: An area declared RPA can, with some probability, be no RPA in reality, and inversely, an area declared non-RPA, can in reality be one. This uncertainty cannot be avoided by nature of statistics, but it should be assessed. Future research may be concerned with the foloowing topics: Different approaches of RPA definition and estimation are used across Europe, but the legal process laying down a certain definition is not yet finished. For some, uncertainty assessment is not yet clear. A final assessment is therefore not yet possible. Implementation will remain on the agenda.

(2) Since 2015 the CD/DVD method was used to identify and study RPAs. Within MetroRADON project CDs were exposed at Saelices and Chico laboratory under highly variable conditions. A novel DVDs-based version of the CD/DVD method was developed, with increased sensitivity and compensated temperature influence, suitable for wide range of applications, incl. for radon in soil-gas. Overall, the new results provide strong support to conclude that the CD/DVD method provide reliable results even at extreme conditions and can be used for identification of RPAs.

(3) Several methods have already been developed to map RPAs. Generally, this concerns areas with a significant proportion of indoor radon concentrations exceeding a reference level of a few hundreds of Bq/m³ (maximum 300 Bq/m³ as given by the European BSS). A complementary approach was tested to focus on the identification of areas that could be concerned by a significant proportion of dwellings with very high indoor radon concentrations of several thousands of Bq/m³. This method was tested in France and Spain, where such cases occur regionally. It was based on the analysis of available quantities such as the geogenic radon potential, measurements of indoor radon concentration, dwellings characteristics etc., complemented by statistical modelling. The results provide first useful elements to target areas where more precise studies are needed to acquire more indoor radon data precisely located and the characteristics of buildings associated with the measurements. An analysis of both geological features and building characteristics (mainly the interface between the soil and the building, the building materials, ventilation systems etc.) need to be realized to identify the best indicators of highest indoor radon values. Such a method would allow developing specific prevention (communication and construction rules for new buildings) and remediation actions in heavily affected regions to significantly reduce the exposure in buildings.

(4) The GRHI can be understood as a generalized complement and extension to the geogenic Radon Potential GRP to characterize susceptibility of a location to geogenic radon, as one important control of indoor Rn. The GRHI is more flexible and can deal with data reality which usual GRP definitions cannot handle. Its main application is thought to be large-scale mapping, i.e. on European scale, in contrast to small-scale characterization e.g. of building sites or medium-scale national maps, whose objective is supporting legislative and administrative implementation of the tasks posed by the European Basic Safety Standards (BSS). Previously existing GRHI attempts were evaluated and "taxonomies" of concepts and estimation methods established. Different concepts correspond to different objectives, while methodology is adapted to availability of data and technical complication which shall be allowed. In course of the project, new methods were conceived and tried. Proposals of Europe wide GRHI maps are presented. Future research may cover these topics: (i) Different approaches will have to be refined and evaluated comparatively. (ii) Uncertainty budgeting of highly aggregated quantities like the GRHI is difficult and is yet to be tackled.

5 Open problems identified during work on WP 4

During work on work package WP 4, a number of open problems were identified, whose investigation would improve estimation and mapping of radon priority areas. Solving the problems was not included in the work plan of Metro Radon, because they have been found and defined only during work.

- In many instances, available data of indoor radon concentration (IRC) are not sufficient for regionalized RPA estimation. Therefore, IRC predictor, controls and proxies are included in estimation. This leads to the necessity of regression models and geostatistics. Many regression studies have been performed on regional scale. It has turned out, however, that – while correct as such – they may not be extendable to other regions. It is recommended that large-scale, i.e. European studies be performed which may lead to more universally applicable IRC prediction models.
- The matter is closely related to the one of spatial (geographical) properties of anthropogenic factors. To remind, IRC can be conceptualized as product of geogenic and anthropogenic factors. Its geographic pattern reflects the ones of the two groups of factors. While the one of geogenic factors has been relatively well explored, this is not the case for the anthropogenic factors.
- Most residential buildings and workplaces are on anthropogenically modified territory, i.e. altered by construction, land fill, historical activity etc. These geogenic conditions are different from the ones in open land, where in most cases geogenic variables that serve as IRC predictors have been measured in field studies. The effect of altered geogenic compartments (including "urban geology") still remain to be studied.
- The geogenic radon potential is composed of Rn source and Rn transport. Both can be measured in the field or estimated from other geogenic predictors. In some instances, notable for soil Rn concentration and gas permeability, this is done by grab sampling. The values reflect the condition at a certain time, which may be temporally variable to different extent. In the best case, the variability which results in uncertainty of estimated means of target quantities, enters as random noise; but not necessarily so: Depending on the design of sampling campaigns, it can lead to regional bias. Solutions have been proposed, some discussed in Metro Radon: (a) resort to long-term measurement; (b) replace by modelling based on temporally stable quantities. In the future, the options should be evaluated and compared more thoroughly.

- One alternative to the GRP is the radon hazard index RHI (or its geogenic specification, GRHI). The concept and possible variants have been introduced in Metro Radon. However, further development including estimation methods and evaluation of practical viability remain for future investigations.
- Rn quantities, notably IRC and GRP, tend to spatially and temporally extreme behaviour. This results in the occurrence of local anomalies. Including them in regression or geostatistical modelling is challenging, as such phenomena defy certain statistical preliminaries which are valid for "background" estimation. Initial investigations have been performed in Metro Radon. The question how to estimate and map anomalies adequately will remain an issue for same time, among other due to its statistical complication.
- An important issue consists in the fact that residential buildings and workplaces and public buildings have different physical characteristics, in general, in particular concerning their "response" to geogenic Rn. Studying systematic differences concerning their Rn behaviour between different types of buildings has been initiated in Metro Radon (Annex 1), but it turned out that the matter is complex and should be investigated further; in particular with respect to RPA estimation and definition.
- Harmonization of existing maps remains a challenge, the bigger, the higher the aggregation level of the quantity displayed in the map. In particular for RPA maps, whose aggregation chain may be intricate, harmonization is an open topic. Within Metro Radon, challenges were identified and direction of necessary further research indicated. A particular possible source of disharmony are differences of geological regarding legends or scales, if these are used as predictors of GRP or RPA. This issue may be serious and should be investigated in detail.
- Questions of more political nature pertain to stakeholder interests. These largely determine delineation of radon priority areas. The process of national transposition and implementation of the EURATOM BSS were underway during the Metro Radon project (discussion in Annex 1). Therefore, no final assessment is possible. However, it seems that it will result in a patchwork of RPA definitions across Europe which are not compatible across borders in spite of identical conditions that control IRC on either side. It will be interesting to follow this political process, to assess consistence of RPAs, or its lack, and in the future find ways to deal with the problem, which may be a challenge to Rn risk communication. Harmonization issues have been addressed in WP4, but the topic will remain on the agenda.
- More work is necessary to be done when it comes to the assessment of the dose due to radon exposure. It is common in some areas that workers commute between countries and work in different RPA's. Countries may have different criteria when it comes to dose evaluation.