RESEARCH ARTICLE

On harmonization of radon maps

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Abstract

***Background*:** Maps are important tools for geographic visualization of the state of the environment with respect to resources as well as to hazards. One of the hazards is indoor radon (Rn), believed to be the most important cause of lung cancer after smoking. In particular, as part of Rn mitigation policy and in compliance with the European Basic Safety Standards, EU Member States have to declare areas with elevated indoor Rn concentration levels. However, as this is done by national authorities according to individually chosen criteria, the resulting maps are not easily comparable.

***Objectiv*e:** We aim to identify causes for the lack of compatibility of maps and suggest solutions for the problem.

***Design*:** This study draws from experiences of recent research projects, literature, and personal involvement of the authors in the discussions.

***Results*:** An overview is given on causes and effects of lack of compatibility between maps. Existing experiences are reported. Options for defining lack of compatibility and for identifying it are discussed. Methods for harmonization, that is, remediating lack of compatibility, are addressed.

***Conclusions*:** The difficulty of harmonization increases with the aggregation level of data which support maps. Harmonization is the more difficult, the higher aggregated the data are which support maps. In particular, harmonization of radon priority area maps is technically non-trivial, and theoretical efforts as well as practical tests will have to be undertaken.

Keywords: *radon map*; *radon priority areas*; *harmonization*; *European Basic Safety Standards*; *modifiable areal unit problem*

Providing databases and maps of the state of the environment is an eminent task at local, regional, and national scales, and beyond (e.g. continental and worldwide). It serves information of citizens, public opinion formation, decision-making by authorities, and directing further efforts. This concerns in particular environmental radiation of anthropogenic and natural sources.

Since the Chernobyl accident (1986), the Joint Research Centre (JRC) of the European Commission has been working on compiling harmonized databases and maps of environmental radiation. The latest achievement is the European Atlas of Natural Radiation (1, 2).

The processing of heterogeneous data from different countries and different sources with the objective of joint mapping is a recurring problem that often generates inconsistencies. Although these have been addressed in some research projects such as AIRDOS (3) and INTAMAP (4), they have not been solved satisfactorily until today. Perhaps the most important motivation of investigating inconsistency and its mitigation is that it can impair usability by stakeholders and compromise credibility of Rn maps and acceptance of regulation by the public.

The striving toward data and map harmonization gained momentum with the European EURATOM Basic Safety Standards (EU-BSS; (5)), which oblige EU Member States to identify areas with elevated indoor radon concentration (IRC), called Rn priority areas (RPAs). In most cases, this is realized in the form of maps or as a list of affected administrative units (e.g. municipalities). As every country applies different procedures, depending on the particular national situation (legal and political preliminaries, and available resources), collation

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of RPA maps over Europe results in a patchwork difficult to interpret (see 22).

The EURAMET MetroRADON project (6) paid particular attention to the issues of data processing and harmonization within specific tasks dedicated to Quality Assurance in Rn metrology. The project goal was to develop reliable techniques and methodologies to enable SI-traceable radon (Rn) measurements and calibrations at low radon concentrations. The project was largely motivated by the requirements of the EU-BSS, which is mainly aimed to reduce the risk of lung cancer for European citizens due to high radon concentrations in indoor air.

One major task of the project was to collect and analyse meta-information on radon surveys and databases in European countries, to evaluate the comparability of data and methodologies and their potential harmonization in case of methodical inconsistency. Analysis of indoor and geogenic radon surveys in Europe was carried out based on meta-information from both literature review (7, 8) and questionnaires, which were sent to all European institutions working in this field. In addition, options for the harmonization of indoor and geogenic radon data were developed.

Furthermore, in the framework of MetroRADON, the systematic difference between IRC in dwellings and workplaces has been studied in order to investigate Rn correlation in these two building types (9). The matter is relevant because RPAs are mostly estimated based on IRC data in dwellings, but as stated in the BSS, legal consequences largely pertain to workplaces. The type of indoor space used for RPA estimation is, therefore, another source of potential data disharmony.

Another focus of the project was the analysis and development of methodologies for the identification of RPAs and of the concept of a geogenic radon hazard index (GRHI). A comparison of RPAs across some borders in Europe has been carried out to evaluate comparability and identify harmonization problems.

This article gives an overview on the current state of knowledge concerning (in-)consistency of Rn maps and their harmonization and represents the current state of the discussion. Open problems are identified as guide to possible future research.

Concepts, definitions, and terminology

Harmonization presupposes a concept of ‘harmony’ (e.g. consistency or coherence). Generally, we want *comparable* and mutually *interpretable maps*, that is, map features (legends and supports) are the same. This requires a methodological *consistency*, while deviation indicates a lack of *harmony*. The task of rendering them more consistent is called *harmonization*.

A *perceived* ‘disharmony’ (inconsistency) consists in a felt or observed implausible step (i.e. abrupt value change within a short distance not explained by physical reasons) of a response quantity across a border between two regions of interest. This refers to neighboring geographical units (countries or even regions within) or consecutive time periods.

A *methodical* disharmony occurs if a quantity is truly the same across a border, due to the same controlling natural phenomenon, but it is built from different predictors on either side of the border, or from the same predictors defined or measured differently, or built with different methodology. It is not necessarily perceivable in the result, not even statistically significant, since different methods can lead to the same result.

The inconsistency of a result or map can only be decided by statistical tests used to reply the questions: 1) which quantity is being tested? 2) which is the criterion or the metric upon which the decision about consistency rests? 3) which statistical margin (P-value) is deemed adequate for deciding? In other words, the question is how to measure harmony?

If a test indicates inconsistency between two maps, although the natural controls are truly the same, one may speak about *objective* disharmony.

If disharmony has been identified, one will think about how to deal with it. We call *bottom-up* harmonization (Fig. 1), a procedure that relies on common choice of predictors and common methodology (experimental design, measurement, and modeling), leading to a consistent result. However, the more common situation is that one has disharmonic results that have to be harmonized a posteriori; this is called *top-down* harmonization.

There are essentially two options of top-down data harmonization (Fig. 2): 1) data can be *filtered* according to the attached meta-information (e.g. only IRC values in ground floor rooms are considered, such as in the European Indoor Radon Map in (2)) and 2) data can be *normalized* to a common standard through modeling (e.g. IRC values from floors ≠ ground floor are transformed to a hypothetical ground floor value, based on a model of

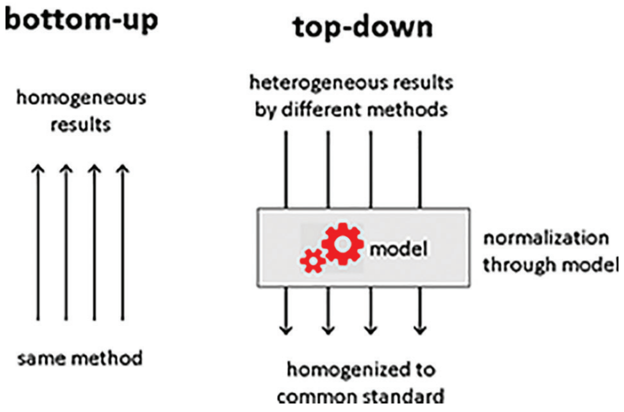

Fig. 1. Concepts of bottom-up and top-down harmonization.

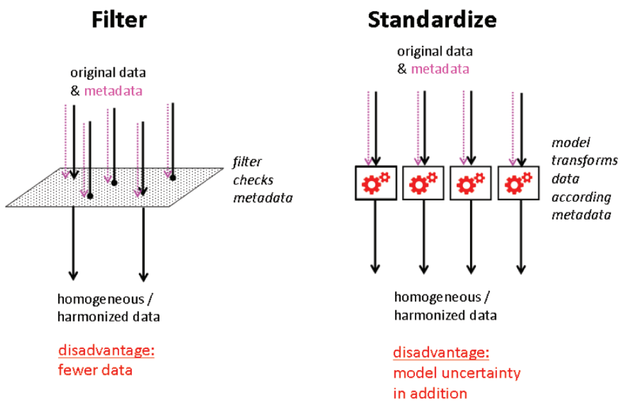

Fig. 2. Top-down harmonization by filtering and modeling.

floor-dependence of the IRC (Friedmann's RP, (10)). Both options require metadata whose variability sufficiently explains the local variability of the target variable (IRC in the example). The filtering leads to data loss and to an increase of coefficient of variation that scales as about $1/\sqrt{n}$, where n is the number of measured dwellings (11). In contrast, standardization has the drawback of introducing model uncertainty; for example, normalizing floor level relies on a model derived from data, which implies estimation and prediction uncertainty, since buildings behave differently.

Sources of disharmony

Sources of methodical disharmony can be 1) data, 2) mapping methods, where a map is understood as an outcome of spatial estimation, and 3) so-called political parameters.

Data

Data that underlie a map can be the source of disharmony in various ways.

(a) Measurement uncertainty. It only adds to random noise within one estimation method, but it can lead to systematic differences if the mean measurement uncertainty is systematically different between two regions, for example, if the target quantity of a map is the probability (P) that IRC exceeds a threshold such as the reference level (RL). Given a true (unknown) P, two estimated P' and P'' are in general different (however, both $> P$) if they are subject to different mean measurement uncertainties that inflate variance underlying estimation (12).

(b) Sampling design. The nominal same quantity can be numerically different if measured differently; for example, IRC measured during different seasons is in general systematically different, while the long-term mean is the same. Deviation from representative (random) sampling could be source of biases: for example, voluntary sampling tends to over-sampling in RPA. This may become critical if databases are merged, which have been acquired for different purposes.

(c) Obsolete data. Measurements performed decades ago (as the case in some Rn databases) may be not representative anymore because over time, building styles, building regulations, and living habits are changed. Whether, or under which circumstances, this issue could be serious has not yet been investigated to our knowledge.

(d) Semantic uncertainty. Legends of geological and other maps used as predictors of Rn quantities may be different between regions; for example, geological maps display the outcropping rocks that 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 used terminology (13). If geological units are classified, for example, according to their age, different maps will be produced if different levels of the chronostratigraphic chart are considered (e.g. system, series, or the stage; for terminology, see https://en.wikipedia.org/wiki/System_(stratigraphy)).

(e) Scale and resolution dissonance. The geological maps can be drawn at different scales. This may cause different degree of detail and misclassification of areas according to the map scale (e.g. size of the displayed objects) and the spatial resolution (the smallest distance that can be recorded between two independent objects). In small-scale maps, a generalization of the map objects is needed to guarantee a reasonable representation of geological units. This involves selecting the features to be displayed, and simplifying, smoothing, or aggregating existing features (14). Geometrical consistency between maps is more likely if the maps have a similar spatial resolution and the same scale (13). A 'bottom-up' type way – if feasible – to contribute to consistency is the harmonization of the sampling plan for the geogenic variables, which must also consider the data available at different scales. For instance, the geological maps at 1:1,000,000 scale are usually designed from the aggregation and simplification of data at larger scales (e.g. 1:200,000 or higher scale); if a sampling plan considers the geological units identified at the higher (finer) scale, which may be different from a plan based on the lower (coarser) one, a joint map generated of ones of different scales will likely be more consistent.

Mapping methods

Data must be transposed into maps via aggregation of points into area units (mapping supports) according to the mapping objective. Data may also be interpolated through geostatistical techniques to estimate values at unsampled locations and create continuous maps. Different methods are plausible for a purpose, but, though in general, they yield different results; this cannot be expected to be a source of major inconsistency in most cases; see also (15). More serious are the following.

(a) Mapping support and modifiable areal unit problem (MAUP). In this paragraph, due to their importance in the context of map harmonization, a more detailed discussion of the problems related to mapping support is presented. Mapping supports can be different between neighboring maps, for example, municipalities, districts, grid cells, etc. The map shall display mean values of the target quantity within the chosen support (choropleth maps); therefore, data must be aggregated into the support unit by some statistical method. On the other hand, a certain country may require a continuous map over its territory (isopleth map), for which the target quantity has to be estimated at 'point' (i.e. the pixel) locations.

Spatial aggregation by using different supports is sometimes necessary to create meaningful units for the analysis (e.g. census areas for population, geological units, etc.) or to make inference about a region of interest (e.g. average temperature of an area, grade of a block of ore). This leads to two practical problems: 1) data reaggregation, that is, from one type of support into another type and 2) harmonized maps of the same quantity but mapped with different type of supports.

The aggregation of 'noisy' data (i.e. with high local variability for natural reasons or for data uncertainty) can be necessary to identify spatial structures; this amounts to data smoothing. The change of the variable support (averaging, merging, and reaggregation) creates a new variable with different statistical and spatial properties from the original one. For example, the aggregation of point data into areal units (i.e. increasing support size or upscaling) increases their spatial autocorrelation compared to the point data, particularly if it is based on overlapping units (e.g. moving averages). This is because the variance between group means is smaller than the total variance.

Problems related to the support of mapped data have been discussed since the 1930s under the term modifiable areal unit problem (MAUP) (i.e. the same input data can cause different results when aggregated in different ways) (16–19). The MAUP applies to two different problems of spatial data analysis. The 'scale effect', where the same set of areal data is aggregated into several sets of larger areal units; each combination may lead to different data values and inferences. The 'zoning effect', where a given set of areal units is recombined into zones having the same size, but different location. Often, this results in different apparent patterns when data are aggregated to areal units of different geometry (e.g. local administrative units, grid squares, postcode sectors, geological polygons, etc.).

Figure 3 shows a schematic example of the aggregation of four data in nine different ways by computing arithmetical means over different support shapes. The resulting patterns are very different, and they cannot be 'recalculated' between each other without knowing the original data.

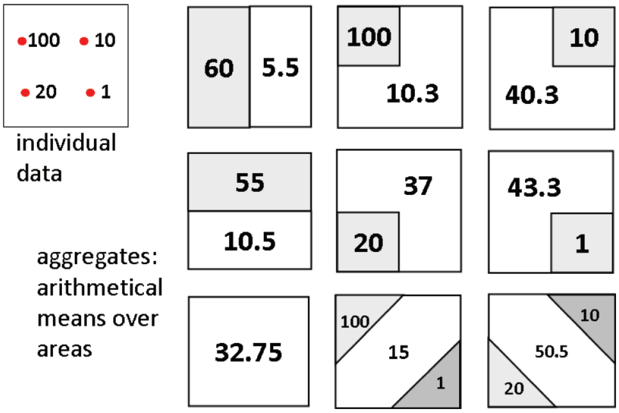

Fig. 3. An artificial example. Four data (upper left) are aggregated in nine different ways.

Figure 4 shows a real-world example of the aggregation of Rn concentration in soil-gas in Lazio (Italy) into three different mapping supports: municipalities, census tracts, and 5 km × 5 km grid cells. The maps look very differently although they are based on the same data and are all methodically correct. If two neighboring regions generate maps of the same quantity (e.g. IRC) based on different mapping supports, they are evidently incompatible, even though they are both correct. This effect may add accidentally sources of error and/or misinterpretation of the results or may be used to intentionally manipulate the results.

A further example of the harmonization problem has been reported in (20), which summarized the state of radon mapping in Europe in 2005. The difficult to interpret patchwork-like picture was among the motives to engage in creating a harmonized European indoor radon map, whose latest version has been published in the European Atlas of Natural Radiation (2).

The problem of 'recalculating' maps from one to another support without knowing the original data cannot be solved exactly, in general. A special case is merging of areas into larger ones if statistical parameters are known (e.g. mean, standard deviation, number of data, etc.). For example, if the arithmetical means in non-intersecting areas A and B equal AM(A) and AM(B) based on $n(A)$ and $n(B)$ data, respectively, the $AM(A \cup B)$ of A merged with B simply equals $AM(A \cup B) = [AM(A)\, n(A) + AM(B)\, n(B)] / [n(A) + n(B)]$.

Block kriging is a particular upscaling technique that extends the kriging method to estimating the means over areas (see any geostatistics textbook for details, for example, (21), section 13). This method may generate more accurate aggregated means than simple averaging all data within the support areas because it also considers spatial autocorrelation, contrary to simple aggregation.

The opposite procedure (i.e. downscaling or re-aggregation) is more difficult. Approximate methods may

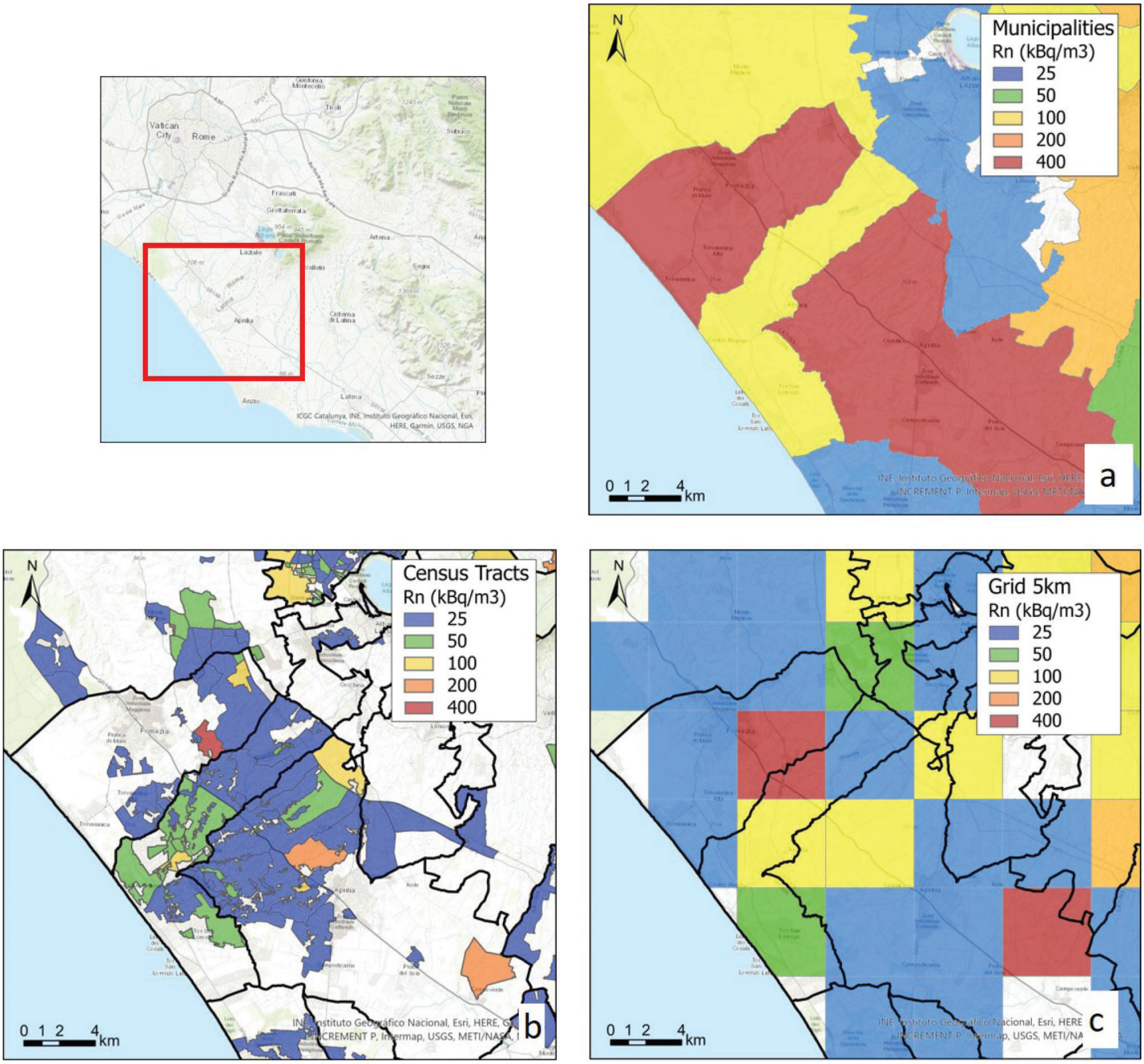

Fig. 4. This figure shows an example of a scale and zoning effects of the modifiable areal unit problem (MAUP). Soil gas radon concentrations collected in the Lazio region (23) are aggregated according to different grouping scheme: municipalities (a), census tracts (b), and 5 km grid (c).

generate artificial data sampled out of choropleths based on the known statistical properties (means over areas and differences between neighboring areas) and reaggregate these into new supports. This is a non-trivial procedure, evidently prone to uncertainty.

(b) Technical 'hyperparameters'. Choices that are to some degree deliberate concern technicalities, for example, choice of loss function in optimization problems, cross validation schemes, number of realizations, and stopping criteria in simulation-based algorithms. Different but equally plausible choices may lead to different results.

(c) Smoothing, 'roughness' of the map. The degree of required smoothing is critical for mapping of extremes and anomalies. For example, kriging maps show a reduced variability due to the smoothing effect, and the use of high number of values increases the smoothness (see (21), pp. 328, 365, 430). Similar behavior can be observed for machine learning techniques (22). As a consequence, the smoothing effect tends to overestimate small values and underestimate high values causing inconvenience in estimating zones with anomalous values.

(d) Statistical assumptions. Geostatistical methods (e.g. kriging) require specific statistical assumptions such as the second-order stationarity (i.e. the covariance is independent of locations). Certain type of anomaly (common in environmental reality) is defined as deviation from this assumption, which can lead to serious misestimation in its vicinity. Different treatment of the problem would lead to different maps and, consequently, to inconsistency between them. Another important common assumption is univariate log-normality (LN) of data within an area, which is used for estimating exceedance probability as tail area of the distribution. Deviation from the assumption or ill-estimation of the LN parameters can lead to misestimation of the probability. Data below detection limit, whose handling can be a critical issue in environmental statistics, do not seem to be a major issue for Rn because concentrations are usually high enough.

(e) Association and dependence models. Methods that link input data (point data and exhaustive nominal data such as geological maps or ordinal, for example, airborne gamma-ray spectrometry data) to the mapped target variable may undergo several steps of estimation and modeling. This involves estimation uncertainty (the model is estimated from limited and in general uncertain data), and the uncertainty of the selected method (models may be approximate or simplified and, if not given by physical reasoning, their specification may depend on the analyst). Newer methods of supervised machine learning may circumvent this restriction, but lead to models whose physical interpretation is difficult, which some experts find unsatisfying.

Political parameters

These do not follow from nature or from computational constraints, but from extrinsic decisions such as Rn concentration RL, definitions for RPAs (how they are defined; RL; probability threshold if applicable; geographical support) or restrictions of input quantities (e.g. only rooms on ground floor considered).

One issue that should be investigated in the future is whether increasingly stricter data protection rules (e.g. as a consequence of the European General Data Protection Regulation GDPR) that impede data acquisition and processing can lead to map inconsistency problems.

Specific disharmony issues depending on map purpose and type

IRC maps

It appears that sources of disharmony consist of five topics:

1) Definition of the target quantity: IRC in rooms representing the building stock of a region, or restricted to ground floor, and all rooms or only the living rooms.

A problem specific to IRC mapping is that 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, usage, and also of their different 'building physics' in terms of air circulation and radon accumulation and dilution. Rn level and RPA maps based on either may, therefore, be different. This problem has already been pointed out in some papers but with controversial conclusions (see (24, 25) and references therein and further details in (26)). As a further issue, Rn mitigation and remediation, is increasingly performed in dwellings and workplaces; there are discussions whether respective data should be included for mapping. The discussion is ongoing; probably, it depends on the objective of a map.

2) Temporal sampling design: 1-year measurements or shorter periods; even if chosen to cover all seasons, uncertainty is higher than for 1-year measurements.

3) Sampling design/choice of participants: truly representative sampling is costly and labor intensive (10); other schemes may lead to bias. In available literature on European IRC surveys, authors in most cases did not fully assess whether representativeness of survey was achieved or not. This complicates map harmonization (8).

4) If predictors or proxies are used to estimate IRC, their choice and linkage methodology influence the result.

5) Mapping support, that is, the spatial units to which the mapped values are assigned by simple aggregation (mean per unit) or by geostatistical means (e.g. block kriging), such as grid cells at different resolution, administrative units, or geological regions (8). In addition to choropleth maps, isopleth maps have been proposed (see Mapping methods section). For a survey on IRC maps, see (27).

Geogenic Rn maps

Various variables can be used to characterize geogenic Rn, from soil-gas Rn to the geogenic Rn potential (GRP), which can be defined differently (28) or further to maps of predictors (geology, soil properties, and geochemistry) or proxies (ambient dose rate, ADR), and finally aggregated quantities such as the GRHI. Evidently, resulting maps look differently, apart from the aspects addressed for IRC maps.

Although the variety of maps may look confusing to stakeholders, the problem is less urgent than for IRC or RPA maps (below), as geogenic Rn maps usually serve (apart from scientific objectives) as predictors of IRC or RPA.

Classed maps

One tool of Rn mitigation policy is the concept of RPA – areas that are particularly affected and in which resources for Rn surveys and remediation should be allocated with priority. The BSS (Art. 103) provides a conceptual definition of RPA, as areas with greater occurrence of high-radon buildings than average. Operational definitions as implemented by EU Member States (and other European countries that implement similar schemes) include the following common types ((9); Activity report 4.1.1/4.1.2):

(a) an area U is RPA if mean(IRC within U) > RL; mean could be arithmetic or geometric mean;

(b) an area U is RPA if in U, prob(IRC > RL) > P; common choices are RL = 300 Bq/m^3 and $P = 0.1$;

(c) an area U is RPA if certain conditions are fulfilled, such as dominant geology in U is granite, mean ground permeability is high, mean ADR > certain level, etc.

For types (a) and (b), whether the condition is fulfilled may be decided by predictor or proxy quantities of the IRC, if the number of IRC values is deemed not sufficient for reliable estimation, or in order to improve it. This requires additional modeling inducing another contribution to the uncertainty budget.

The decision whether a condition is fulfilled in an area is equivalent to classifying the area by attributing its RPA status (yes/no) as a binary random variable. Also, multinomial classification is possible (e.g. RPA status as 'low/middle/high'). The procedure amounts to classification of a territory into two (or several) classes. Like every outcome of an estimation procedure, also the variable 'RPA status' has uncertainty. It is quantified by first- and second-type error probabilities, that is, an area labeled RPA, although in reality it is not (1st kind error), or non-RPA, although in reality it is (2nd kind error).

Sources of disharmony between RPA maps can be

- different definition of RPA, either type (a, b, and c) or choice of parameters (RL, P, etc.)
- if the definition is the same, the estimation procedure is prone to 1st and 2nd type error; thus, an area with some (unknown) true RPA status can erroneously be attributed a wrong status. This causes inconsistency with another area with objectively same status that has been estimated correctly.
- if the definition is the same, data or modeling inconsistency (see previous section) between two areas of *true* same status can lead to attribution of different *estimated* RPA status.

The pathway from data to a class map can be quite complex. Often such maps are highly aggregated, meaning that they result from a complex procedure with several modeling or estimation steps. In any case, the classification step that is performed at some stage of the procedure is a transformation that cannot be reversed (it is not bijective). By classification, information contained in the supporting data is lost (but not needed in the class map). This is a crucial issue in harmonization of RPA maps.

Lessons from MetroRADON

Design, realization, and evaluation of IRC and geogenic Rn surveys

Overall design of IRC surveys is quite diverse, and it is difficult to find two completely same survey approaches. Comparability is, therefore, reduced. Most critical appeared to be the survey representativeness. An important aspect in harmonization is to apply seasonal standardization to account for seasonal periodicity of IRC, if it is measured only for fractions of a year; this is, however, a controversial issue in literature. Furthermore, a non-negligible effect of reported IRC could be due to thoron influence. Not many countries have performed geogenic radon surveys, and therefore, European coverage is poor. On the other hand, surveys and data sets about quantities, which can serve as predictors (U concentration) or proxies (ADR) of the GRP, are available in many countries and on European level (2, 27).

Data harmonization

The harmonization of Rn data is partly possible by a detailed investigation of their methodologies and the development of model-based harmonization. For details, see (29).

Radon priority areas

The results showed that the main sources of inconsistency are underlying data and RPA definition, as well as the estimation methodology. For evaluating the cross-usage of RPA concepts, different mapping methods were compared. Applying a mapping method using data sets not designed for the specific requirements of the used mapping method is challenging. Different mapping methods often deliver the same results in RPA classification, depending on the definition of RPAs. The definition of thresholds is a key factor in delineation of RPAs and for harmonization purposes (15). For a detailed discussion about harmonization of radon mapping and RPA definition, see (9).

Measuring harmony

The quantification of the degree of methodological harmony has been raised during the AIRDOS project (3), which dealt with harmonizing European radiometric early warning systems.

In the project, the Shannon's information entropy, a measure of diversity that is commonly used in biodiversity studies has been proposed ((30); see also https://en.wikipedia.org/wiki/Entropy_(information_theory)). For a population whose members can belong to N distinct classes, each occurring with probability $p_i = n_i/n$ (n_i = cases in class i, n = total cases, and $i = 1, \ldots, N$), it is defined as

$$S := -\sum_{(i=1\ldots N)} p_i \ln(p_i)$$

We define the coefficient of harmony (%) by

$$\mathrm{H} := 100 \times (1 - S/S_{\max}),$$

where $S_{\max} = \ln N$ is the maximal possible entropy for the given N number of classes. Large diversity leads to low H coefficients. A disadvantage of the method is that the result depends on the definition of classes, which may be deliberate to some extent, in some cases.

For a selection of diverse methods of IRC measurement, which may be relevant with respect to Rn map harmonization, as found in the questionnaire carried out as part of Metro RADON ((27) Activity report 3.1.2; details are in (31)), harmony coefficients can be calculated (Table 1). The high degree of harmony for the measurement method, 63%, is due to preferential use of track etch (TE) detectors (CR-39 and other). On the other hand, while for measurement duration and season, the most populated class is '1 year' (22 of 56 in the questionnaire); the high number (20) of unclear or undefined responses to the questionnaire leads to a very low degree of harmony for this topic. The low harmony with respect to survey representativeness seems to be owed to the difficulty to assess and to achieve representativeness.

Possible top-down harmonization strategies

Model-based transformations

Inconsistency originating in *data* disharmony can be fixed relatively easily if the data and its metadata are well known. Metadata concern measurement methods and conditions during measurement and data specification (e.g. IRC in all floor levels or only ground floor). Data can be normalized to a common standard through models (see 10 and 32, annex 1 of that paper).

The matter is more complicated and, in general, not resolvable for aggregates, such as areal units in choropleth maps (see the MAUP section earlier).

The geogenic radon hazard index revisited

The GRHI was conceived as a tool to create a harmonized map of geogenic Rn (28). It can be understood as a generalization of the well-known GRP. The GRHI (and its proposed variants) is tailored to incorporate many predictors and to be estimated also in regions where soil-gas Rn concentrations and transport terms (k) are not available – as occurs for most of Europe. While the most promising variant of the GRHI appears to be a bottom-up one through a set of harmonized predictors over Europe (e.g. unified geological maps, etc.), a top-down variant is being discussed as well; it relies on regression of various types of regionally available continuous predictors and (re-) classification procedures for categorical predictors.

Harmonization of classed maps

Suppose the domain D consists of two 'countries', regions 1 and 2 (Fig. 5a–c). Each country delineates RPAs, using individual RPA definitions. This leads to the blue areas in region 1 as RPA1, and the red areas in region 2, RPA2 (Fig. 5a). Using definition 1 in region 2 leads to 'hypothetical' RPA1, dotted blue, and in analogy dotted red, the hypothetical RPA2, if definition 2 was applied in region 1. If the two regions are simply collated (Fig. 5b), the resulting RPAs (gray) are inconsistent because they are based on different definitions. Evidently, definition 2 is 'less strict'; thus, RPA2 are smaller than RPA1. However, the questionably defined or 'disputed' areas are actually small (yellow in Fig. 5c), while orange areas (RPA2) are RPAs according to both definitions, and the green areas (D – RPA1) are non-RPA according to both definitions; only the yellow ones, RPA1 – RPA2, are disputed. Hence, further discussion is necessary only in these areas. The harmonization task consists of establishing a rule, how the yellow areas shall be defined; the green and orange areas are non-RPA and RPA, respectively, undisputed between regions 1 and 2.

The procedure consists of 1) defining a new rule whose 'strictness' lies between definitions 1 and 2, possibly including them and 2) the more difficult question is how to attribute an RPA status according to the new rule to the points of the disputed area. The matter is easy if the original data are available that underlie RPA1 and RPA2, but this is not the case in most instances. The problem is in its nature similar to the MAUP, discussed earlier.

Table 1. Degree of harmony for different issues in Rn measuring and mapping methodology

(Item in questionnaire), method	Classes	*H* (%)
(2.9), measurement location in dwellings	basement/ground floor/1st floor/different, other	34
(2.11), metadata available	yes/no	50
(2.13a), representativeness targeted	yes/no/unknown	16
(2.13b), degree of representativeness achieved	sufficient/not sufficient/no answer	10
(3.1), measurement method	TE/charcoal/electret/active/other	63
(3.1), duration and season	1 year/1–3 months, winter/6–9 months, incl. winter/unclear or undefined	9
(3.4), sensitivity to thoron; CR-39	yes/no/unknown	36
(3.4), sensitivity to thoron; LR-115	yes/no/unknown	16
(5.4c), raw indoor Rn data modeled	yes/no/unknown	10

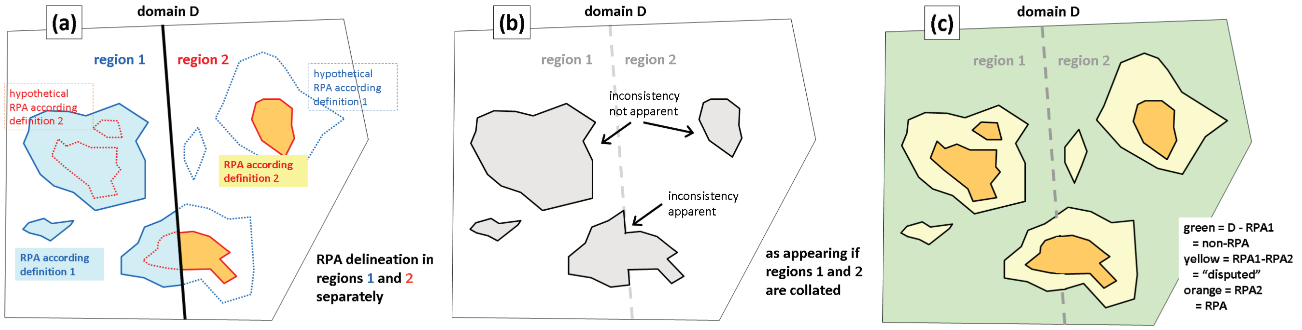

Fig. 5. Scheme, RPA disharmony, and identification of areas, where harmonization is necessary. (For details, see text.)

This paper does not intend to provide a solution, but further research may go along these thoughts. If *some* common database is available for both regions, such as a geological map or a map of U concentration in the ground, these could be exploited for the purpose, conditional to known RPA status in the green and red areas. If *no* common data are available, one may think about some fuzzy logic-type approach, which attributes a fractional status level between 0 (not-RPA) and 1 (RPA) to each point in the yellow zone, for example, according to some distance weighing scheme (cf. indicator kriging). A geostatistical approach is shown in (33).

Conclusions and outlook

A multitude of Rn maps has been generated on regional, national, and international scales. Notwithstanding their individual correctness, their appearance can be very different, thus complicating their comparability and interpretability. Reasons are 1) legal, political, and economic constraints pertaining to definition of the mapped quantity, sampling design, and mapping support, 2) availability of data (including predictor data, if applicable), 3) methodological choices of estimation algorithms, etc. The resulting 'disharmony' impairs usability by stakeholders and compromises credibility.

Specifically, disharmony can be traced to 1) inconsistencies on database and survey design level, 2) modeling methodology, and 3) mapping issues. Among these, the MAUP is a difficult problem to solve in top-down harmonization approaches. We propose research in that direction, as a support for a better joint interpretability of Rn maps. If, for Europe, harmonized joint maps are created, conflicts with national maps may arise. This is a problem that should be addressed more intensely in the future.

Harmonization can be achieved using bottom-up or top-down approaches. The desirable case is a bottom-up harmonization based on a unified sampling strategy, use of same covariables as predictors, usage of the same mapping method, consistent mapping support, and decision boundaries. This optimal situation is, however, hardly achievable on an international scale. To solve the problem of disharmonic maps, top-down harmonization approaches might be required. These approaches comprise model-based transformations (normalization to a standard situation) or harmonization of classed maps under consideration of the collocated predictors.

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