ORIGINAL ARTICLE

A representative national indoor radon survey in Germany

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Abstract

***Background*:** Radon is a carcinogenic indoor pollutant, which can cause lung cancer. Therefore, radon protection was included in national legislations and radon protection activities are carried out in Europe.
***Objective*:** In Germany a nationwide survey to measure levels of indoor radon concentration in residential buildings was conducted.
***Design*:** The survey was designed to represent the population. The measurements were taken for 6,000 households all over Germany for 12 months, with two measurements in each household with track etch detectors. The distribution follows administrative units (401 districts). In a first step, participants were acquired through a nationwide mailing with randomly chosen addresses. In a second step, more participants were brought in by specific advertising campaigns in local media.
***Results*:** Results of approx. 6,500 households (= approx. 13,000 individual readings) were included in the study. The intention of a population-representative survey could not fully be accomplished, but the areal distribution of the participating households corresponded satisfactorily to the intended district-based distribution. The radon concentrations follow a log-normal distribution. The Germany-wide median is 44 Bq/m^3, the geometric mean 49 Bq/m^3, and the arithmetic mean is higher at 77 Bq/m^3.
***Discussion*:** The German reference level of 300 Bq/m^3 is exceeded in about 3.5% of all measurements. Higher values, mainly due to geology, occur in the eastern and southern part of Germany. Known dependencies on building characteristics are confirmed, such as increased values in older buildings or on lower floors.
***Conclusions*:** This survey can serve as a profound data basis for following radon studies in Germany and for an estimation of exposure of the population due to radon.

Keywords: *radon exposure*; *geology*; *mailing*; *radon map*; *building characteristics*; *representativity*; *radiation protection*

Radon is a radioactive noble gas, formed in soils and rocks, which can accumulate and be concentrated in buildings. Indoor radon is one of the leading causes of lung cancer after smoking (1, 2). The European Council directive 2013/59/EURATOM (3) includes requirements to protect the population against the dangers of radon exposure, which had to be implemented by the European members states. Germany published a new radiation protection act including radon protection (4) becoming effective in 2018. To effectively plan and implement radon protection measures, an evaluation of the radon exposure situation of the population in Germany is necessary. The German radon map (5) was based on a profound dataset on radon in soil gas measurements and several radon surveys were carried out in Germany. The database of indoor radon measurements available at the Federal Office for Radiation Protection (Bundesamt für Strahlenschutz, BfS) was heterogenic, with measurement data from different measurement methods, measurement durations, and not fully up-to-date regarding building characteristics, building style, and housing stock. Therefore, the BfS decided to carry out a new population representative indoor radon concentration survey with harmonised measurement methods. The study design and the results are discussed in this paper.

Before the study was started, a literature search was conducted for available population representative radon surveys in other countries. A lot of radon surveys were conducted for different purposes (e.g. radon mapping, identifying areas or buildings with high radon concentrations, evaluation of radon exposure, radon in specific buildings) already for a long time, and more frequently in the last years, mainly to fulfil the new legal requirements. A good overview of radon surveys in different countries in Europe is given in Pantelić et al. (6). In general, only few authors discuss the representativity of their survey

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(7–9) and only few countries report a population representative indoor radon survey (10–12). Carrying out a population representative indoor radon survey for Germany is not trivial and therefore ambitious. In the paper the challenges, drawbacks, possible bias, and the grade of reached representativity are discussed.

Materials and methods

Survey

The BfS announced a project to gather new indoor radon data for Germany in 2019. The aim was to perform a population representative indoor radon concentration survey of Germany. The measurement characteristics should be homogeneous, with a standardised measurement technique and measurement duration. The study should consist of 12,000 measurements in 6,000 dwellings to determine the annual mean radon concentration. The sample size was therefore already fixed in advance by BfS.

A relevant point in the design of the survey was the aim to be population representative. The sample should be drawn to best reflect the relevant characteristics of the population regarding indoor radon concentrations. A population-representative sample of dwellings could be drawn from a complete list of these relevant characteristics, which does not exist for entire Germany. It was also not possible to select a smaller area within Germany, which could be seen as representative for potential radon relevant characteristics such as geology and building factors, but also for other characteristics as age, gender, socioeconomic status, and settlement pattern. As a practicable solution for an extensive database for the sampling, a commercially available address register (Deutsche Post Direkt) was chosen. The address register also has some limitations concerning the completeness, such as being up-to-date and missing addresses due to objection of data usage. The selection of the sample (participants) for Germany was based on 401 administrative units (districts – 'Kreise, Landkreise, kreisfreie Städte') (13), to assure that the entire territory was taken into account.

The number of participants per administrative unit was calculated proportionally to the population in the unit. The overall aim was to have at least 12,000 indoor radon measurement results in 6,000 households at the end of the survey. Participants were recruited by postal mailing. The addressed households were offered a free-of-charge radon measurement within the survey. The sample was randomly selected from the address register without pre-filtering regarding building style, age of building, floor etc. With an expected participation rate of 5%, 120,000 letters were sent. But in total, only about 1,350 households were acquired by the random mailing, clearly less than what was needed. Therefore, the survey was advertised via (local) media, press releases, and via BfS, especially in the still under-represented administrative areas, to increase the number of participants. Known from experience, in such measurement campaigns the return rate is expected to be around 80% (20% loss), which also needs to be taken into account. The process to acquire a sufficient number of participants needed about 7 months. In total about 8,400 households participated in the campaign.

The administrative organisation of the survey and communication with the participants (e.g. registration, collecting building data) was mainly done via a specific website, following all necessary data-protection issues.

The measurements were carried out in two habitable rooms (e.g. living room, bedroom, dining room, children's room, working room) in each dwelling with track-etch detectors (SSNTD; closed detector with CR-39, chip size: 300 mm^2) for 1 year, according to DIN ISO 11665-4 (14). The influence of thoron is minimized based on the building type of the detector. The producer of the detectors regularly took part in the BfS intercomparison measurements of passive radon detectors. The detectors were sent and returned via postal mail, including a detailed instruction for placing the detectors (e.g. height in the room, distance from wall). The participation in the measurement campaign was free-of-charge. The 1-year measurements were carried out between July 2019 and April 2021.

For evaluation of potential relationship of the radon concentrations with building characteristics or living habits, data about the building and the measured rooms were collected. The questions were designed in a way so as to be answered easily and clearly by the participants and were answered directly by the participants via the website. Information about the following characteristics were collected: building type, year of construction, building style, number of apartments in the building, number of persons in the household, basement, basement access, connection of basement to the living area, tightness of the windows, ventilation, thermal retrofitting, radon remedial actions, floor, type of room, contact of the room with ground. Further questions included, if previous radon measurements were carried out in the household, the reason for participation and how the participant found out about the campaign (via mailing, press, etc.).

In the end, results were collected from 7,350 households, which corresponds to a return rate of about 87.5%.

Data analysis

The data (start and end date of measurement, building characteristics, living habits) and calculated radon activity concentration were collected in a database, harmonised, and checked for plausibility. Georeferencing of the building or apartment for spatial analysis was done via the postal address with a geocoding service of the Federal Agency for Cartography and Geodesy (15). Administrative

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units (federal state – 'Bundesland', districts) and geological units were assigned to each household with data from the Federal Statistical Office of Germany (13) and the geological map of Germany 1 : 250,000 (16). In addition, it was checked if a household is located within a radon precautionary area ('Radonvorsorgegebiet') (17). For further analysis only results with a measurement duration of 346–383 days (5% deviation of 1 year) are taken into account, which is valid for about 89% of the measurements. All measurements below 10 Bq/m³ were set to 10 (in the range of the detection limit, to avoid underestimation of these values). For most of the households two measurement results exist, and also the ones with only one result (due to the loss of a detector) are included. For the analysis no mean was calculated for the single households, but all measurements were used separately at room-level. In total 12,998 measurements in 6,499 households are taken into account for the analysis in this paper.

An extensive descriptive analysis was performed based on different administrative units (Germany, federal states, districts) and also displayed in maps as well as frequency distributions. The correlations of radon concentration with different building characteristics, geology, and additional data (e.g. type of recruitment, settlement structure) are discussed and shown in box-plots. A summary is reported in this paper and all details are given in the final report of the project (18).

Population representativity was the major aim of the survey and population weighted sampling was employed with a complete address list of Germany (see above). As the participation rate for this approach was too low, additional volunteers were selected through other channels (media, BfS, personal contacts). As the participants were asked about the way of recruitment, we can distinguish between the participants of the original random sampling (1,206 households, 'random sample') and the total sample, including volunteers recruited through other channels (6,499 households). The descriptive statistics and correlation analysis was done for both samples and results were compared.

In addition, to verify the representativity of the participating households, a comparison with available features (type of building, year of construction, number of apartments in the building, number of inhabitants) of census data was performed (19).

Results and discussion

Number and distribution of measurements

Figure 1 shows the spatial distribution of all households in Germany that were used for the assessment. The intention of the program was to achieve a population-weighted distribution of households over the entire area of the country. Accordingly, more households have to be investigated in more densely populated areas, and correspondingly fewer in less densely populated areas. Generally, this distribution could be achieved. In areas with bigger cities (e.g.: Berlin, Hamburg, Munich, Ruhr area, Rhine-Main area, Stuttgart) the sampling density is clearly higher than in predominantly rural regions (e.g.: parts of Lower Saxony, Mecklenburg-Western Pomerania, Brandenburg, Eifel-Hunsrück, south-eastern Bavaria). In underrepresented regions, a targeted follow-up search for households was conducted. In a few cases with a high number of participants a local clustering was the result (e.g.: Nuremberg area, Marburg, Osnabrück region).

Table 1 shows the number of households per federal states, which participated in the survey. In addition, the number of intended households is shown to fulfil spatial representativity and to cover for expected losses (see chapter 'Materials and Methods' for details). In Table 1, abbreviations are given for the federal states, which are used in the following discussions. In Fig. 3, the abbreviations are used in the map to provide the reader with a better geographical understanding. Some federal states have a slightly higher number of participants as intended (BE, NI, SL), some are medium (TH, HE, SN, BY), and two are clearly overrepresented (HB, HH). In others (BW, RP, SH, NW, ST) the intended number of participants could not be reached completely (up to maximum 15% difference). Only in MV and BB, the negative deviation from the intended number of participants was higher. In total, 12% more households were acquired than originally intended.

Descriptive statistics

In Table 2 the statistics of the measured indoor radon concentrations and number of households for the total sample are summarized. The arithmetic mean (77 Bq/m³) is considerably higher compared to the geometric mean (49 Bq/m³) and the median (44 Bq/m³), which also is a characteristic of a log normal distribution. The 95-percentile is 240 Bq/m³. A total of 18% of the measurements exceed 100 Bq/m³, 3.5% exceed 300 Bq/m³, and 0.34% exceed 1,000 Bq/m³. All statistical aggregates for the random sample (Table 3) are smaller than for the total sample. This indicates that the type of recruitment has a potential influence on the measured indoor radon concentrations.

The frequency distribution of the indoor radon concentration in Germany shows the known picture of a right-skewed or approximately log-normal distribution with an accumulation of values in the lower range of the distribution (Fig. 2).

Table 4 shows the statistics of the measured values in the federal states, which were used for the assessment.

The spatial pattern of the arithmetic mean for the federal states shows the highest concentration in Saxony and

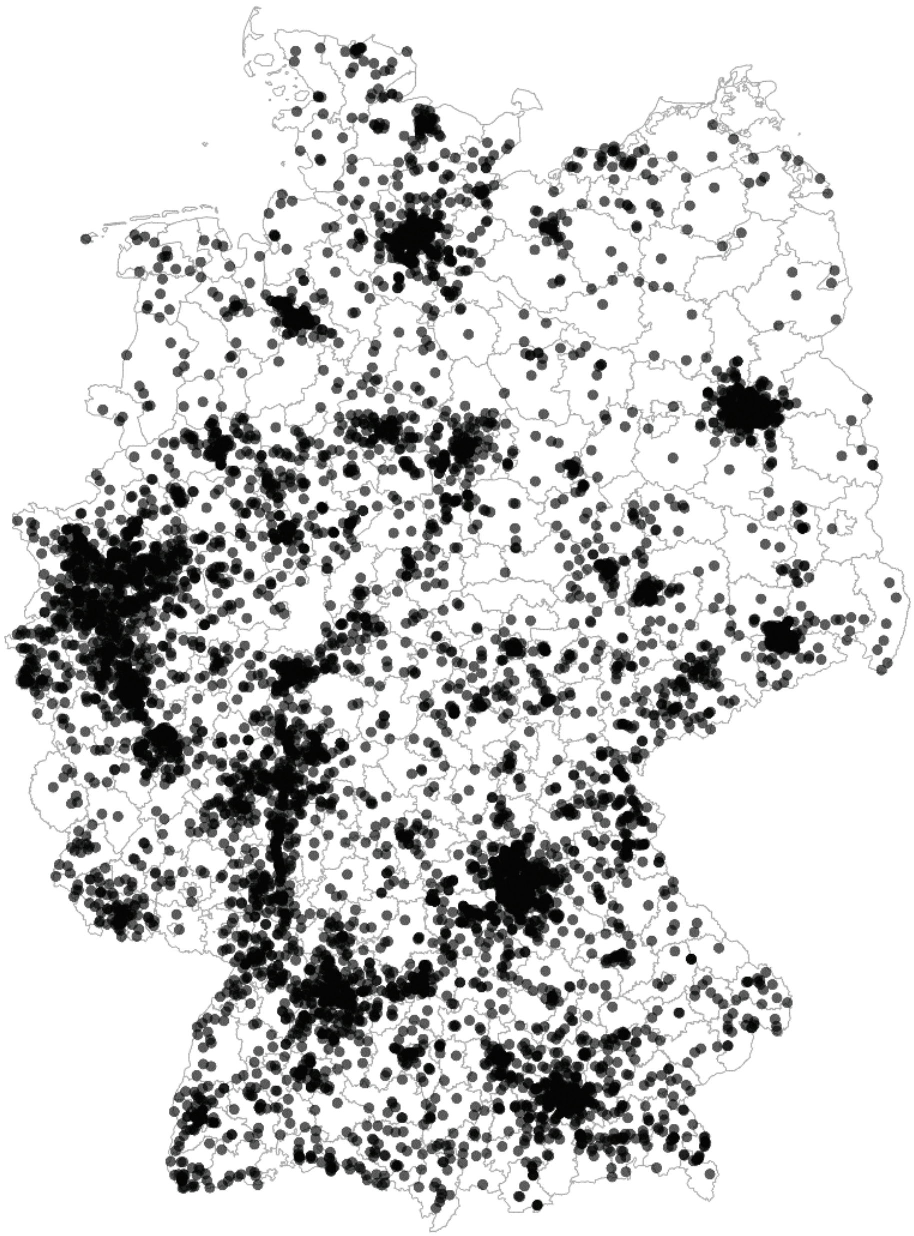

Fig. 1. Participating households (6,499 locations) in Germany (with district boundaries).

Thuringia (Fig. 3). With approximately 150 Bq/m^3 each, the values are clearly higher than in the other federal states. In Rhineland-Palatinate, Bavaria, Saxony-Anhalt, and Baden-Württemberg the mean values are between approximately 80 and 100 Bq/m^3, in Saarland and Hesse approximately 70 Bq/m^3, and in all other federal states between approximately 50 and 70 Bq/m^3. The lowest concentration with approximately 40 Bq/m^3 was observed in the smallest federal states (and simultaneously cities) in Berlin, Hamburg, and Bremen.

Generally, the indoor radon concentration in Germany is higher in the eastern and southern part of the country compared to the northern and western part. These systematic differences reflect the distribution of radon concentration in soil gas respective to the geogenic radon potential.

The observation of districts provides a more differentiated point of view (Fig. 3, right). In Saxony and Thuringia, the distribution is comparatively similar: high mean values can be observed in most of the districts or urban municipalities, especially in the Ore Mountains and the Thuringian Forest. In Rhineland-Palatinate, Bavaria, Saxony-Anhalt, and Baden-Württemberg the values vary to a much greater extent. In Bavaria, higher values are concentrated in the southern (foothills of the Alps) and south-eastern part of the state (Fichtelgebirge, Upper

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Table 1. Comparison of the number of households (participants) and intended number of households per federal state and in total (Germany)

Federal state	Abbr.	Intended number of participants (households)	Number of participants (households)
Baden-Württemberg	BW	999	957
Bavaria	BY	1,179	1,862
Berlin	BE	327	355
Brandenburg	BB	225	132
Bremen (Hanseatic City)	HB	61	211
Hamburg (Hanseatic City)	HH	166	395
Hesse	HE	564	661
Mecklenburg-Western Pomerania	MV	145	110
Lower Saxony	NI	717	739
North Rhine-Westphalia	NW	1,622	1,416
Rhineland-Palatinate	RP	368	345
Saarland	SL	90	92
Saxony	SN	369	467
Saxony-Anhalt	ST	202	171
Schleswig-Holstein	SH	262	245
Thuringia	TH	194	220
Total		7,490	8,378

Table 2. Descriptive statistics – Germany, total sample

AM	GM	Med	P95	*N* (households)	>100 (%)	>300 (%)	>1,000 (%)
77	49	44	240	6,499	18	3.5	0.34

AM: arithmetic mean; GM: geometric mean; Med: median; P95: 95-percentile (all units in Bq/m^3); *N* (households): number of households; >100 (%): percentage of measured values above 100 Bq/m^3; >300 (%): percentage of measured values above 300 Bq/m^3; >1,000 (%): percentage of measured values above 1,000 Bq/m^3.

Table 3. Descriptive statistics – Germany, only households with 'random' sampling

AM	GM	Med	P95	*N* (households)	>100 (%)	>300 (%)	>1,000 (%)
64	43	40	181	1,359	12	2.2	0.17

AM: arithmetic mean; GM: geometric mean; Med: median; P95: 95-percentile (all units in Bq/m^3); *N* (households): number of households; >100 (%): percentage of measured values above 100 Bq/m^3; >300 (%): percentage of measured values above 300 Bq/m^3; >1,000 (%): percentage of measured values above 1,000 Bq/m^3.

Palatinate, Bavarian Forest). In the other federal states, the areas with high indoor radon concentrations are smaller and locally distributed. But in most cases, the pattern follows geology with higher indoor radon concentrations in areas with a higher radon concentration in soil gas (e.g.: volcanic areas around Nohfelden and Kusel in Rhineland-Palatine, Harz mountains and surroundings in Saxony-Anhalt, eastern parts of the Rhenish Massif in North Rhine-Westphalia, southern parts of the Black Forest, or the Swabian Alb in Baden-Württemberg). In large parts of Germany, especially in the north (Lower Saxony, Brandenburg, Schleswig-Holstein, and Mecklenburg-Western Pomerania), the mean values in the districts are lower than 50 Bq/m^3 or in the range between 50 and 75 Bq/m^3.

For administrative purposes, the percentage of households exceeding a defined threshold value of indoor radon concentration is an important statistic. The spatial distribution of indoor radon concentration generally reflects the distribution of radon concentration in soil gas respective to the geogenic radon potential. Looking at the frequency of exceeding the existing reference level in Germany of 300 Bq/m^3 in the districts, this geologically caused pattern is visible (Fig. 4). In Saxony and Thuringia many; in Saxony-Anhalt, Bavaria, Baden-Württemberg, and Rhineland-Palatinate several districts show a high frequency of exceeding the reference level. These districts are found in most cases in areas with increased geogenic radon potential (e.g.: Ore Mountains, Thuringian Forest, Fichtelgebirge, Bavarian Forest, foothills of the Alps,

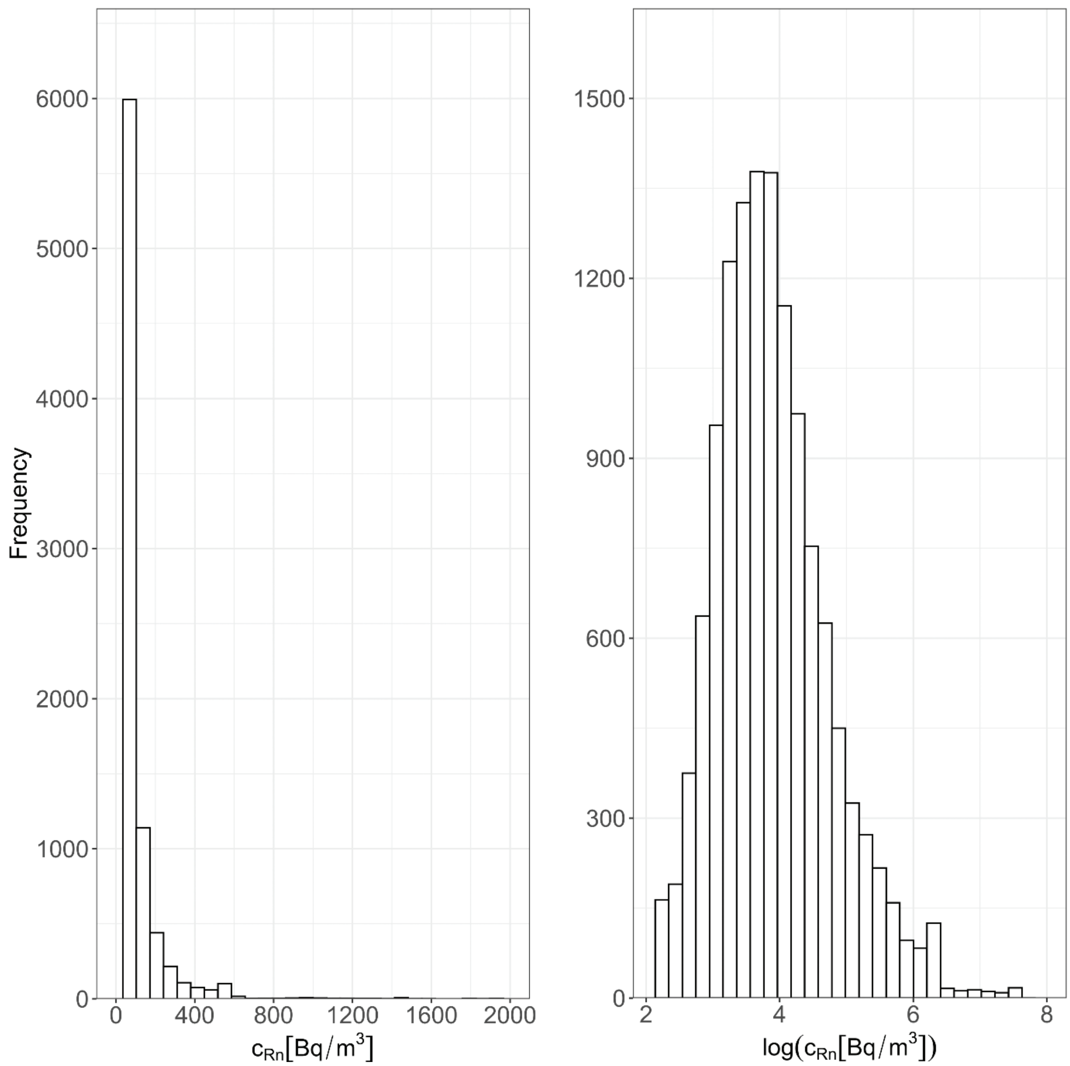

Fig. 2. Frequency distribution of indoor radon concentration (c_{Rn}, Bq/m³) in Germany (left: linear, right: logarithmic).

southern Black Forest). In the other federal states, only a few counties with a significant exceedance can be locally observed. In a large part of the districts, respectively urban municipalities, the percentage of values exceeding 300 Bq/m³ are lower than 0.5%. The value for the whole area of Germany is approximately 3.5%.

Correlations – geology

Since a long time, it is well-known that radon concentrations in soil gas as well as in buildings are generally correlated with geology. Here lithology (type of rock) and soil type are the main influencing parameters. For indoor radon concentration, of course, the type of construction and the existence of radon entry paths into the building are important too. All factors together determine how much radon can enter the building from the subsoil. Studies on this correlation have been carried out for several decades all over the world, for example Austria (20), Belgium (21), Czech Republic (22), Denmark (23), England (24), Germany (25–27), Norway (28), Switzerland (29), and the USA (30).

To assess the possible correlation between radon in indoor air and geology and for simplification, the geological units were divided according to rock genesis. Thus, the results for igneous and metamorphic rocks as well as sedimentary rocks and unconsolidated sediments were summarized in box-plots. The geological classification is based on the Geological Map of the Federal Republic of Germany on a scale of 1 : 250,000 (16). This map contains information on age (chronostratigraphy), composition (petrography), and formation of the rocks (petrogenesis) as well as information on the lithostratigraphy. The classification of the GÜK 250 was simplified by the BfS by summarizing similar or comparable geological units. As a result, 28 different geological units were defined. The locations of all investigated

Table 4. Descriptive statistics – federal states

Federal state	AM	GM	Med	P95	*N* (households)	>100 (%)	>300 (%)	>1,000 (%)
Baden-Württemberg	79	56	53	223	772	19	3.0	0.13
Bavaria	93	59	51	309	1,511	23	5.2	0.5
Berlin	38	29	28	88	268	4	0.4	0
Brandenburg	51	39	36	130	103	9	0.5	0
Bremen (Hanseatic City)	40	30	28	109	168	7	0.3	0
Hamburg (Hanseatic City)	39	29	27	110	287	7	0.3	0
Hesse	70	53	49	186	505	18	1.8	0
Mecklenburg-Western Pomerania	68	48	43	228	84	15	2.4	0
Lower Saxony	52	36	32	133	490	9	1.0	0.2
North Rhine-Westphalia	59	41	37	177	1,099	13	1.9	0.05
Rhineland-Palatinate	98	68	64	260	289	27	4.2	0.52
Saarland	72	54	52	172	71	19	2.1	0
Saxony	156	83	70	534	354	35	12.0	2.26
Saxony-Anhalt	81	58	52	241	134	24	3.7	0
Schleswig-Holstein	56	41	37	165	188	11	0.8	0
Thuringia	150	84	70	540	176	37	12.8	1.42

AM: arithmetic mean; GM: geometric mean; Med: median; P95: 95-percentile (all units in Bq/m^3); *N* (households): number of households; >100 (%): percentage of measured values above 100 Bq/m^3; >300 (%): percentage of measured values above 300 Bq/m^3; >1,000 (%): percentage of measured values above 1,000 Bq/m^3.

buildings and therefore of each individual measurement were assigned to a geological unit based on this classification.

The radon concentration for igneous and metamorphic rocks is summarized in Fig. 5. The highest values with a median of approximately 175 Bq/m^3 and a wide range of values (Q3 approximately 530 Bq/m^3; P95 approximately 1,250 Bq/m^3) are concentrated in areas with Upper Palaeozoic granites (ac mgt SaxRh). These rocks were found, for example, in the Ore Mountains, Fichtelgebirge, or Black Forest. The orthogneisses (ogn, median approximately 160 Bq/m^3) and the mica schists, phyllites, and mylonites (ms phy myl, median approximately 150 Bq/m^3) can be compared with the Upper Palaeozoic granites but show a smaller range. Both rock units are primarily found in eastern and north-eastern Bavaria and in the Ore Mountains. The volcanic rhyolites (ac mgt rhyo) have a significantly lower median value of approximately 70 Bq/m^3 than their plutonic equivalents (granites). The lowest values are found in the basic magmatites (bas mgt, median approximately 50 Bq/m^3). All other units show median values ranging between approximately 80 and 90 Bq/m^3.

The values of the radon concentration for sedimentary rocks are summarized in Fig. 6. Due to the high affinity of uranium to organic material, a possible uranium (and later on of radium) enrichment in those sediments can occur (31–36). These higher radionuclide contents can result in higher radon concentration in soil gas above these rocks respectively in the weathered soils. Therefore, the rock classification distinguished between rocks with higher and lower organic content. But it has to be emphasized that about 75% of the location of the measuring sites are located above sedimentary rocks, which are classified as rocks without significant organic content (sed no org). These mainly comprise sandstones, siltstones, and mudstones, but also greywackes and marls. They are found often in the Rhenish Massif (Eifel, Hunsrück, Bergisches Land, Sauerland, Taunus). Only about 6% of the measured sites are found above sedimentary rocks with a higher organic content. These Old and Late Paleozoic rocks (sed org OPal, sed org LPal) like black shales and similar rocks are found in parts of Saxony and Thuringia or in the Sauerland. The Mesozoic sites with similar, but younger rocks (sed org Meso) are found mainly in southern Germany. Sites with rocks with significant organic contents (sed org OPal, sed org YPal, sed org Meso) are not characterized by increased indoor radon concentration. The median values are between approximately 60 and 100 Bq/m^3, the ranges are comparatively small (e.g.: P95 between approximately 380 and 480 Bq/m^3). The majority of sedimentary rocks (without organic content) shows the lowest values of all groups (median: approximately 50 Bq/m^3, P95: approximately 240 Bq/m^3). Clay shales and siltstones (clsh silt) as well as carbonates (lime) show similar average values (approximately 70 and approximately 60 Bq/m^3, respectively). In the case of the clay shales and siltstones, the P95 is significantly higher (approximately 540 compared to approximately 230 Bq/m^3).

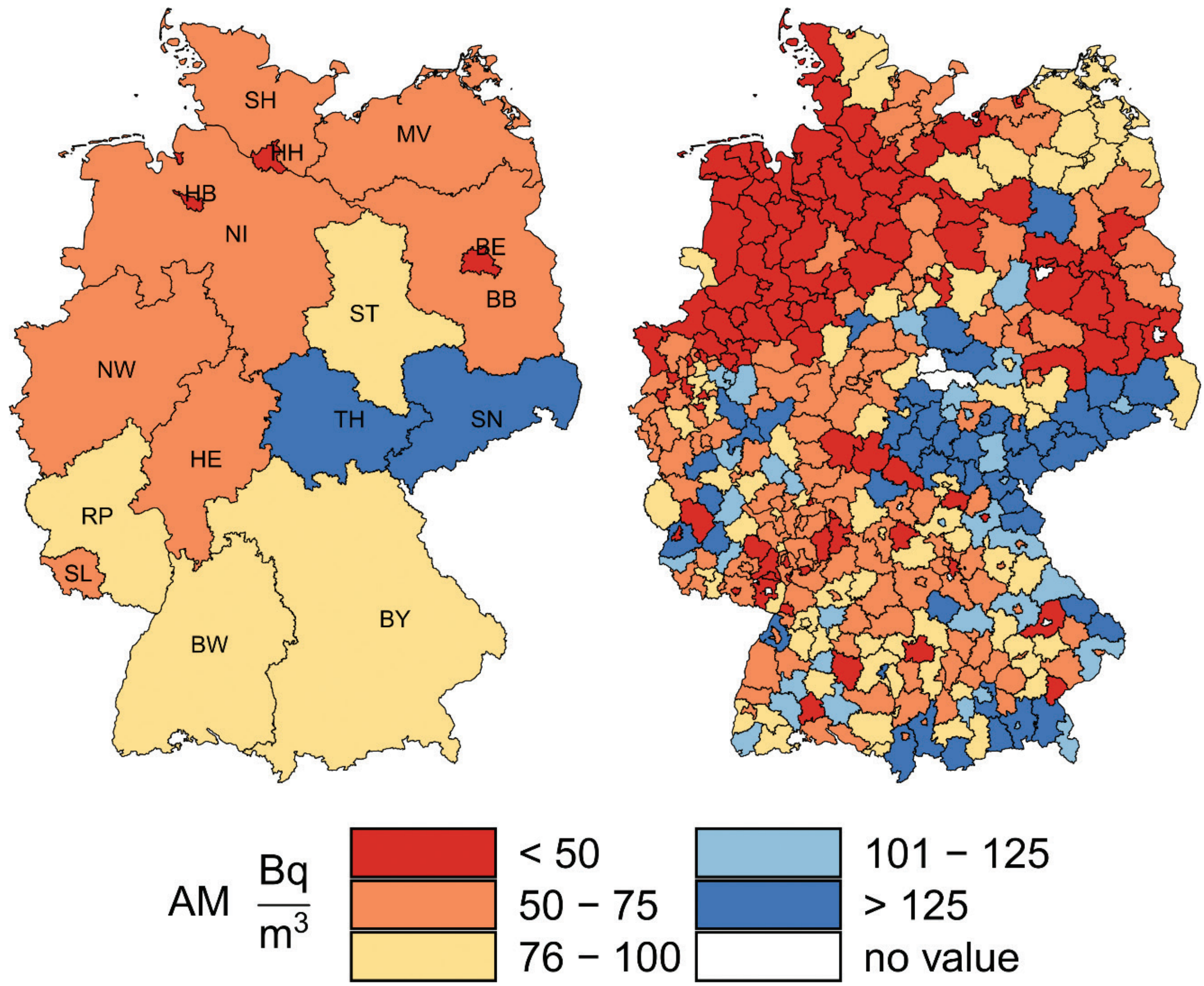

Fig. 3. Arithmetic mean (AM, in Bq/m³) in federal states (left) and districts (right); Abbreviations according to Table 1.

The values of the radon concentration for unconsolidated sediments are summarized in Fig. 7. Often, unconsolidated rocks can show a very heterogeneous structure or composition. In Germany, glacial deposits can differ significantly both in grain size and composition depending on the delivery area of the source material. Therefore, the northern German (delivery area: Scandinavia) and southern German glacial deposits (delivery area: Alpine region) are classified separately despite comparable ages. In principle, the composition of solifluction soils as well as floodplain deposits strongly depends on the composition of the primary material. Generally, differences in these basic materials can be reflected in the level of radon concentration in soil gas. Regarding the unconsolidated rocks, the differences between the different units are small. The median values of the indoor radon concentration range – independent of the classification – between approximately 30 Bq/m³ (mor N Präwei, glac dep N, mar sed, peat) and approximately 60 Bq/m³ (soli). The P95 values also trace these dependencies: approximately 130–160 Bq/m³ for the former groups and approximately 320 Bq/m³ for the solifluction soils. The lowest values are found in the anthropogenically influenced areas (anthr) with a median of approximately 25 Bq/m³.

Correlations – building characteristics

Besides geology, building characteristics can influence the indoor radon concentration. In the study, information about buildings characteristics was collected along with the measurements and correlations and non-correlations are also discussed in this chapter.

The year of construction has a well-known influence on indoor radon concentration. Several authors (29, 37–39) reported higher radon concentrations in older buildings. This trend is also discovered in this study (Fig. 8), even though not so clearly as in other countries (9). The mean

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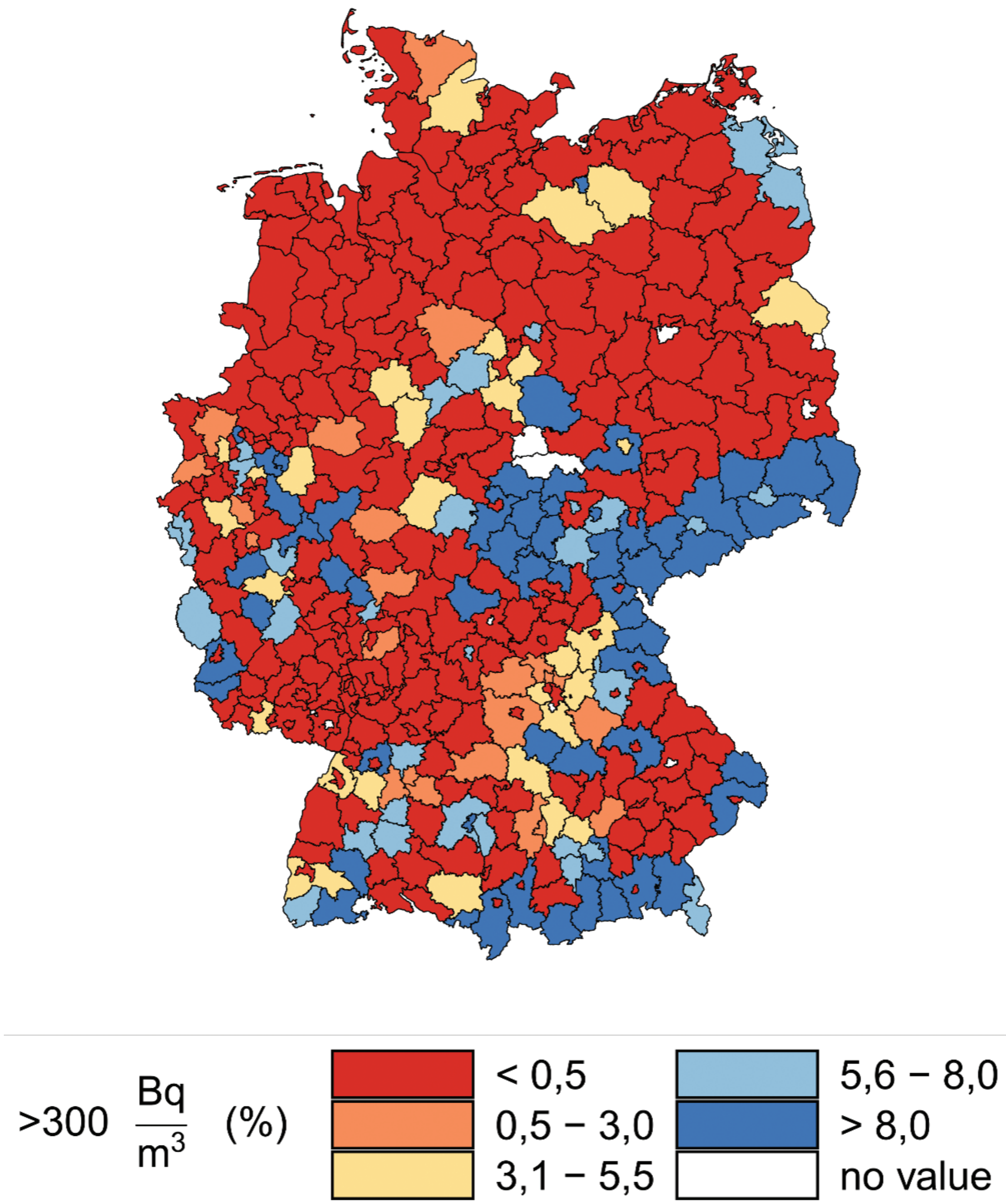

Fig. 4. Percentage (%) of households in a county with at least one measured value in an occupied room above 300 Bq/m³.

radon concentration in the newest buildings (after 2009) is 56 Bq/m³ which is almost half of the oldest ones (before 1919, 104 Bq/m³). A total of 31% of the measured buildings were built between 1949 and 1978. Figure 8 also compares the distribution of indoor radon concentrations with year of construction for the total sample (left) and for the random sampling (right). Both samples show the same trend, but as discussed before, the indoor radon concentration in the random sampling is in general a bit lower. Also, the number of measured buildings in the different building age groups follow the same distribution as in the total sample.

In general, the indoor radon concentration is higher in the basement or ground floor than in higher floors, as the main source for radon entry is the ground underneath or around the building (29, 40, 41). In a study in Austria, the factor if a room is in direct connection with the earth ('earthbound') has the highest impact on the indoor radon concentration (9, 42). Figure 9 shows the dependency of indoor radon concentration with floor levels (left) and also the higher radon concentration in rooms which are in direct connection with the earth (right). In this survey, 47% of the measurements were carried out in rooms on the ground floor and 19% in the basement and souterrain,

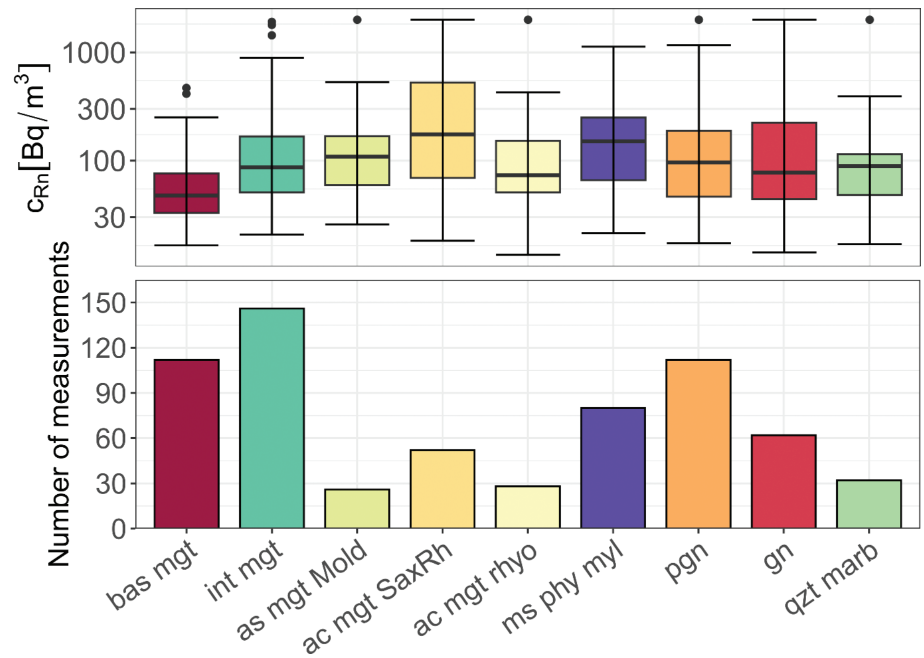

Fig. 5. Indoor radon concentration (c_{Rn}, Bq/m³) in different geological units – igneous and metamorphic rocks (bas mgt: basic magmatic rocks; int mgt: intermediate magmatic rocks; ac mgt Mold: acid magmatic rocks, granites of Moldanubikum; ac mgt Mgt SaxRh: acid magmatic rocks, granites of Saxothuringikum and Rhenohercynikum; ac mgt rhyo: acid magmatic rocks, rhyolithe; ms phy myl: mica shist, phyllite, mylonite; pgn: paragneiss; ogn: orthogneiss; gn: gneiss (undifferentiated); qzt marb: quarzite, marble).

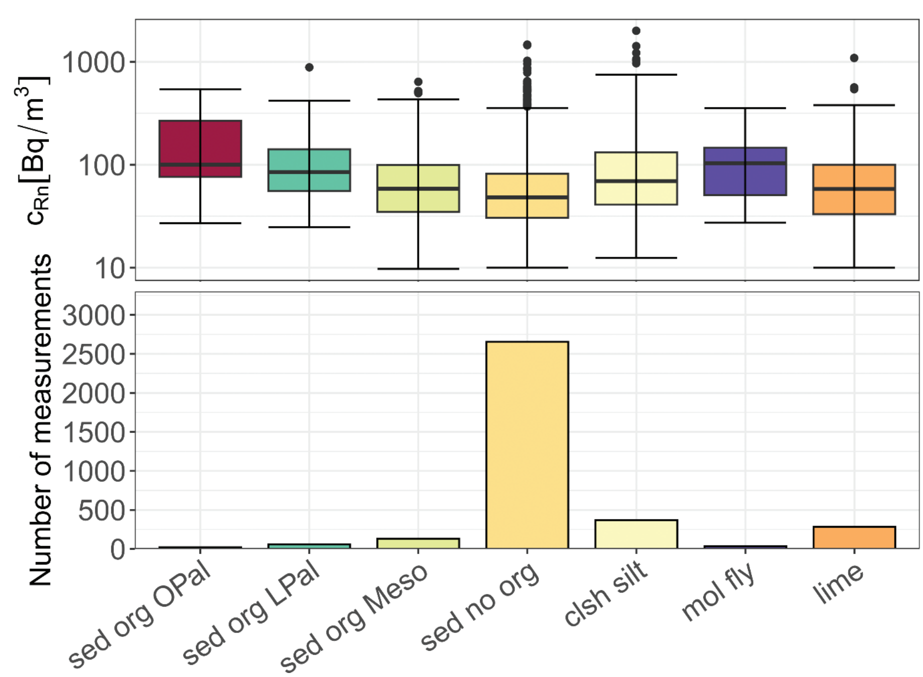

Fig. 6. Indoor radon concentration (c_{Rn}, Bq/m³) in different geological units – sedimentary rocks (sed org OPal: sedimentary and metamorphic rocks with higher organic content, Old Paleozoic to Precambrian; sed org LPal: sedimentary and metamorphic rocks with higher organic content, Late Paleozoic; sed org Meso: sedimentary rocks with higher organic content, Mesozoic; sed no org: sedimentary rocks without organic content; clsh silt: clay shale, siltstone; mol fly: molasse, flysch, conglomerate; lime: limestone, dolomite).

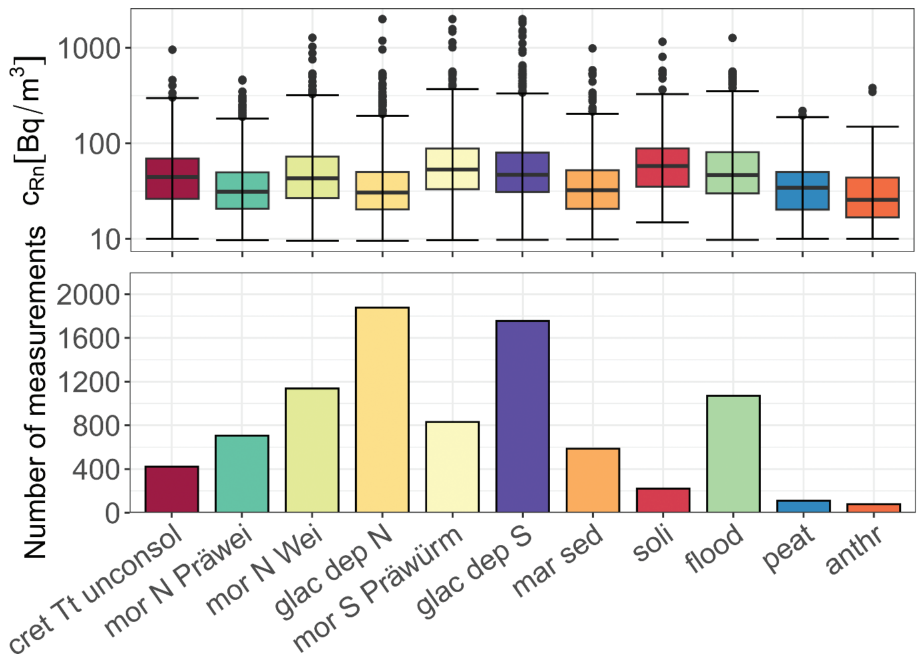

Fig. 7. Indoor radon concentration (c_{Rn}, Bq/m³) in different geological units – unconsolidated rocks (Cret Tt unconsol: unconsolidated rocks, basin sediments Cretaceous/Tertiary; mor N Präwei: ground/end moraines and loess, northern Germany Präweichsel; mor N Wei: ground/end moraines and loess, northern Germany Weichselian; glac dep N: (glaci)fluvial sands and gravels, northern Germany; mor S Präwürm: ground/end moraines and loess, southern Germany Präwürm; glac dep S: (glaci) fluvial sands and gravels, southern Germany; mar sed: recent marine sediments, aeolian sands; soli: solifluction soils; flood: floodplain deposits; peat: peat; anthr: anthropogenically influenced).

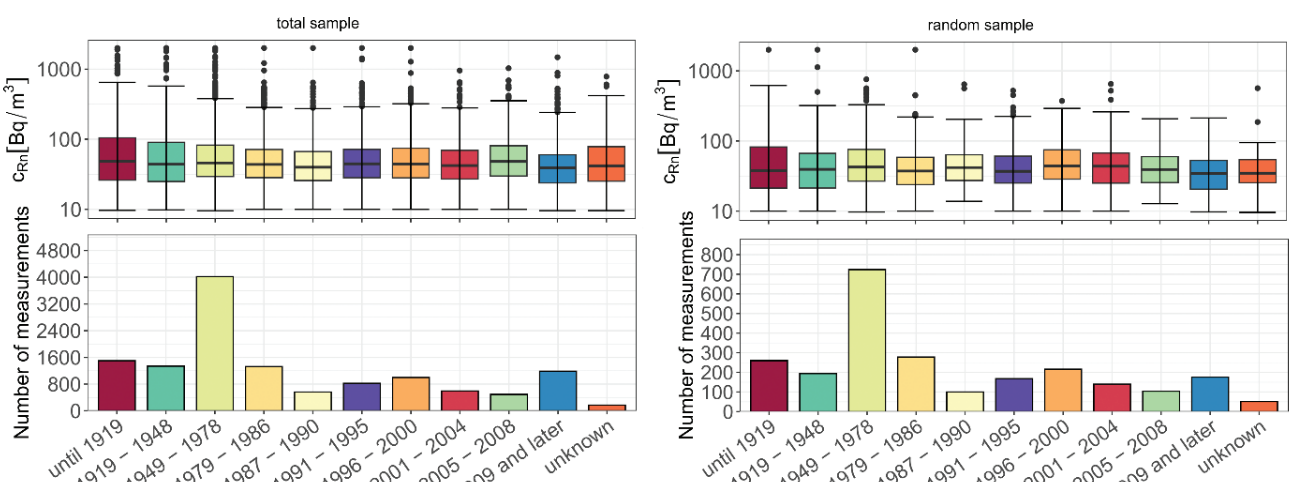

Fig. 8. Indoor radon concentration (c_{Rn}, Bq/m³) distributions and number of measurements in different classes of years of construction for total sample (left) and the random sample (right).

31% in first and second floor, and only 3% in rooms on higher floors. It was also noted that the radon concentration in buildings with more than three apartments is clearly lower than in buildings with only one apartment (single-family houses), which can be explained by the number of measurements in higher floors that usually show lower radon concentrations. In the survey, 60% of all measurements were carried out in single-family houses.

Figure 10 summarises distributions of the indoor radon concentrations based on other building characteristics. Higher radon concentrations were found in detached houses and semi-detached houses compared to row houses and other types of houses (Fig. 10e). In the survey 63% of the measurements were done in detached houses. Buildings with full basement showed lower radon concentrations than buildings that partly feature a basement, but

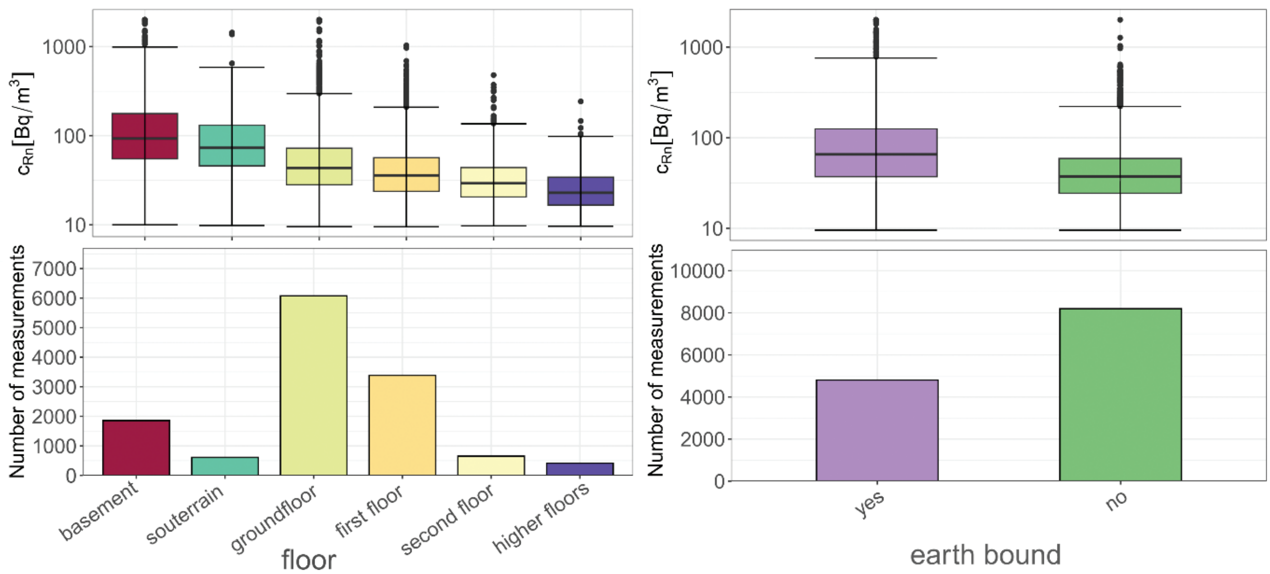

Fig. 9. Indoor radon concentration (c_{Rn}, Bq/m³) distributions and number of measurements in different floors (left) and if room is 'earthbound' (right), total sample.

surprisingly are in the same range than buildings with no basement (Fig. 10d).

So, in this study, existence of a basement has no clear influence on the indoor radon concentration, as discovered in other studies (9). Most of the measurements (70%) in this study were done in buildings with a full basement. In general, the tightness of the building envelope has an influence on the indoor radon concentration (37, 39). The tightness of windows is, in contrary to other building characteristics, not clearly defined and the answers possibly include a subjectivity of the participant. Nevertheless, the question was included in the questionnaire, as in previous studies patterns were detected (12). In this survey, no clear correlation of indoor radon concentration and window tightness was found (see Fig. 10b). This also confirms the results reported in the recent survey in Austria (9). Most of the measured buildings (74%) have no technical ventilation system, 19% have an exhaust fan in the kitchen or bathroom, and only 7% have a technical ventilation system for entire apartment or more rooms. Figure 10f shows that the indoor radon concentration in apartments with ventilation system is clearly lower. This is in line with results of other studies (39, 41). Also discussed in many studies from different countries is the potential increase of indoor radon concentration after thermal retrofitting, if only the tightness of the building envelop is increased, but the radon entry from the ground is not stopped (8, 37, 39, 43–46). In this study, the part of buildings with (40%) and without (47%) thermal retrofitting is comparable and slightly higher indoor radon concentrations are found in buildings with thermal retrofitting (Fig. 10c). It has to be noted, that the effect of higher indoor radon concentration and thermal retrofitting can be overlaid by the impact of year of construction of the building. Thermal retrofitting is more likely to occur in older buildings, which often have higher indoor radon concentrations because of other effects like building style, see also Figs. 9 and 10. Indoor radon concentration and the different types of rooms where the measurements were carried out show no clear correlations, except slightly higher radon concentrations in working rooms and slightly lower radon concentrations in bedrooms (Fig. 10a). This effect might be overlaid by the impact of floors, as more often bedrooms are located in the upper floors and working rooms in basements. In addition, working rooms might be used less frequently (e.g. not at the weekends) and therefore might be less ventilated.

Correlations – others

Most of the measurements (41%) in the survey were carried out in two person households, about 20% in three or four person households each, only a few in one and more person households. No clear correlation was found comparing the indoor radon concentrations, but one-person households show slightly lower results than the others.

As discussed in the Materials and Methods chapter, the random sampling did not result in enough participants. So, more participants were recruited via other channels, and that information was collected in the questionnaire. A total of 19% of the households were randomly selected (mailing), most of the households learned about the measurement campaign through the media (46%), 17% through the BfS website (Fig. 11). The indoor radon concentration in the randomly sampled households is slightly lower (see also chapter 'Descriptive

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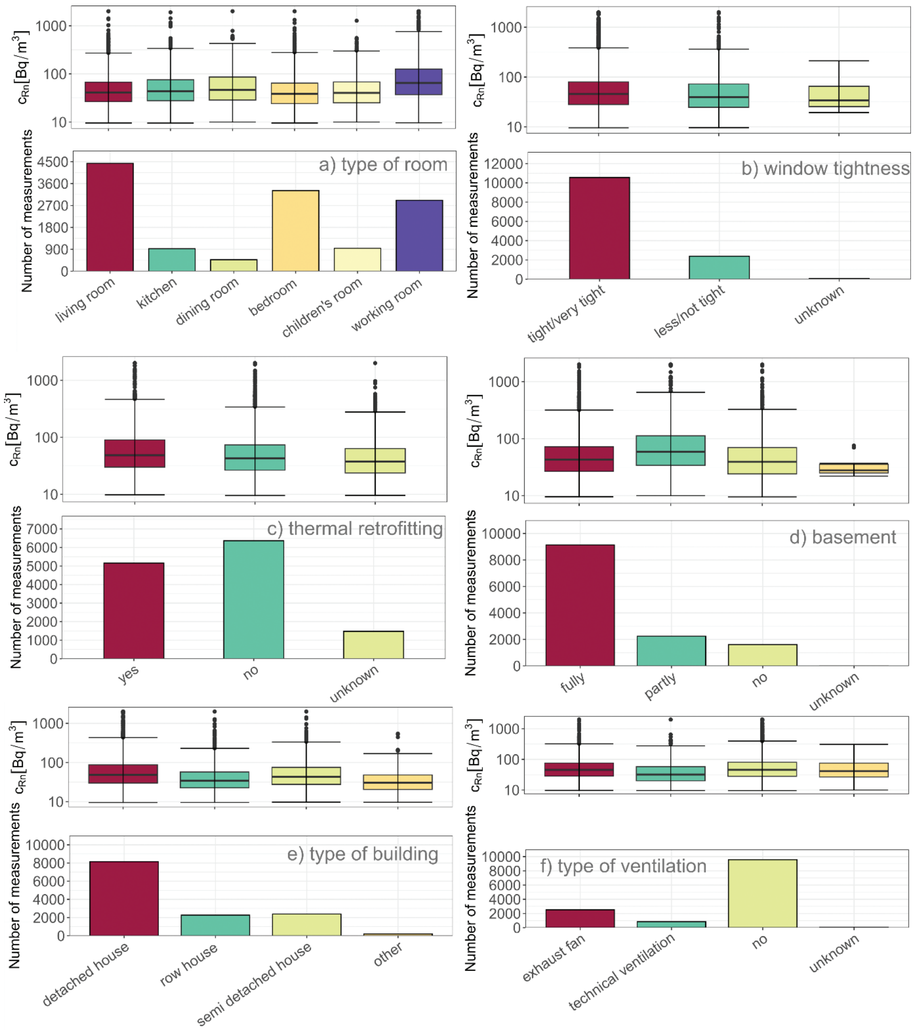

Fig. 10. Indoor radon concentration (c_{Rn}, Bq/m³) distributions and number of measurements with different building characteristics – type of room (a), window tightness (b), thermal retrofitting (c), basement (d), type of building (e) and type of ventilation (f); total sample.

Statistics'), the households which were recruited via the BfS or the website of the measurement service company, which carried out the survey, are slightly higher. This is explainable, as more likely people who have an idea about a potential higher radon risk, for example because of the geological area or the building they live in, registered actively via the websites for radon measurements. In general, the impact of how the household was acquired on the radon concentration is small, which can be taken into account in future planning of surveys. Also, the reason for the participation was asked. The ones who indicated that they expect higher radon concentrations in their homes (only 5%), had higher radon concentrations (AM: 139 Bq/m³, median: 70 Bq/m³) compared to the largest group (69%), who just wanted to know the radon concentration in their home (AM: 77 Bq/m³, median: 45 Bq/m³) or had a general interest in the topic (26%, AM: 64 Bq/m³, median: 40 Bq/m³).

The indoor radon concentration was also analysed regarding population density. A classification by the Statistisches Bundesamt (13) was applied to characterise administrative units according to their population density – city ('kreisfreie Großstadt'), urban area ('städtischer Kreis'), dense rural area ('ländlicher Kreis, verdichtet'), rural area ('ländlicher Kreis'). Most of the measurements in the study were done in the urban area (39%) and cities (30%), 17% in dense, and 13% in rural areas (Fig. 12). The indoor radon concentrations are lower in the cities and tend to be higher in the rural areas. This effect is explainable based on different building styles, floor distribution, and location of the apartments and living habits in the cities.

A clearly higher indoor radon concentration distribution (AM: 192 Bq/m³, median: 105 Bq/m³) is found in the measured households in delineated radon precautionary areas (17) compared to non-radon preventive areas (AM:

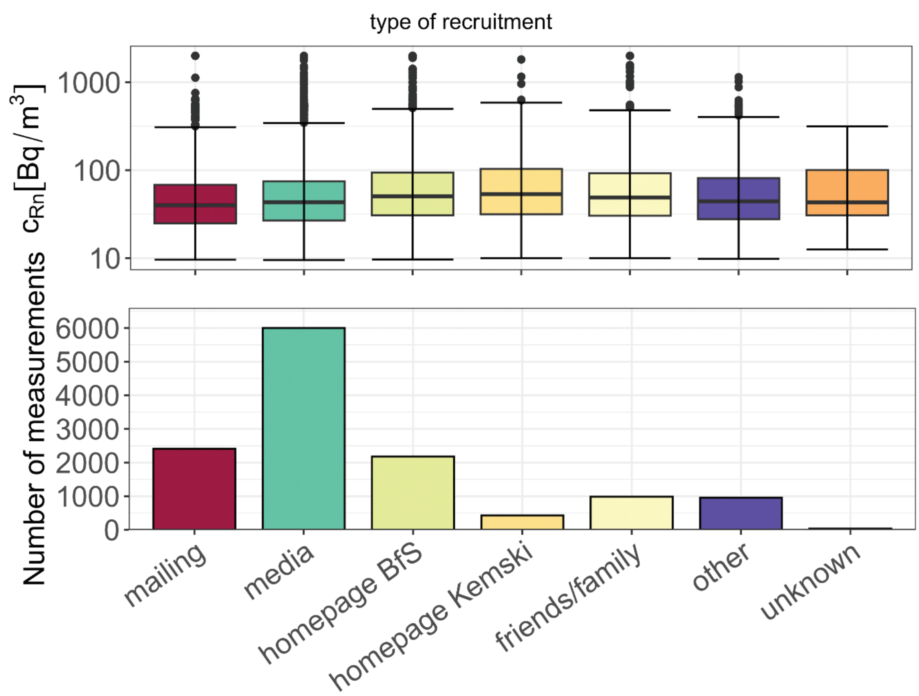

Fig. 11. Indoor radon concentration (c_{Rn}, Bq/m³) distributions and number of measurements and different ways of recruitment for participation, total sample.

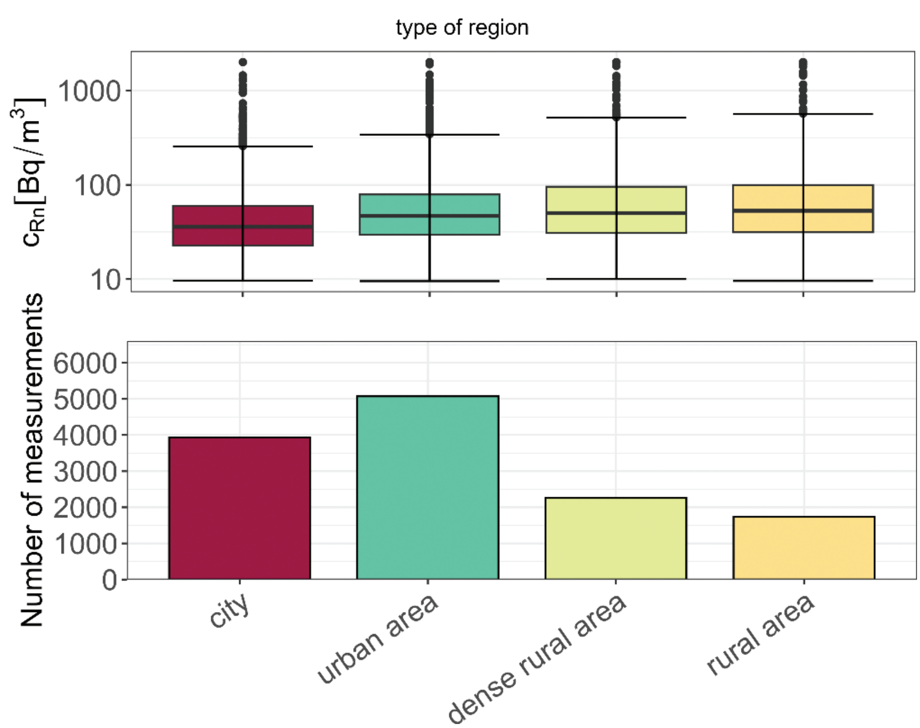

Fig. 12. Indoor radon concentration (c_{Rn}, Bq/m³) distributions and number of measurements with population density (four classes), total sample.

77 Bq/m³, median: 44 Bq/m³). This confirms the delineation of those areas for higher radon potential. But only 82 of the measured households (0.6%) were located in those areas.

Representativity

To evaluate the representativity of the measured households, some available features were compared visually with the data of the last census of 2011 (19). The census data represent the status of buildings about 10 years before the survey, but beside the year of construction, no big difference is expected. In general, the distribution of the measured households is reflecting the distribution of the census data in a satisfying way, with some exceptions and clear deviations. Figure 13 shows the comparison of the distributions of the census data versus the survey data (measured households) for the four analysed features – type of building (Fig. 13a), number of apartments in the building (Fig. 13b), year of construction (Fig. 13c), number of persons in the household (Fig. 13d). For the type of building, the measured sample can be considered to be representative of the buildings in Germany, the deviation is only a few percentages per group (Fig. 13a). A similar picture shows the number of apartments in the building (Fig. 13b). In contrary, clear deviations between the survey sample and the census data are seen in the year of construction – few buildings with the construction years

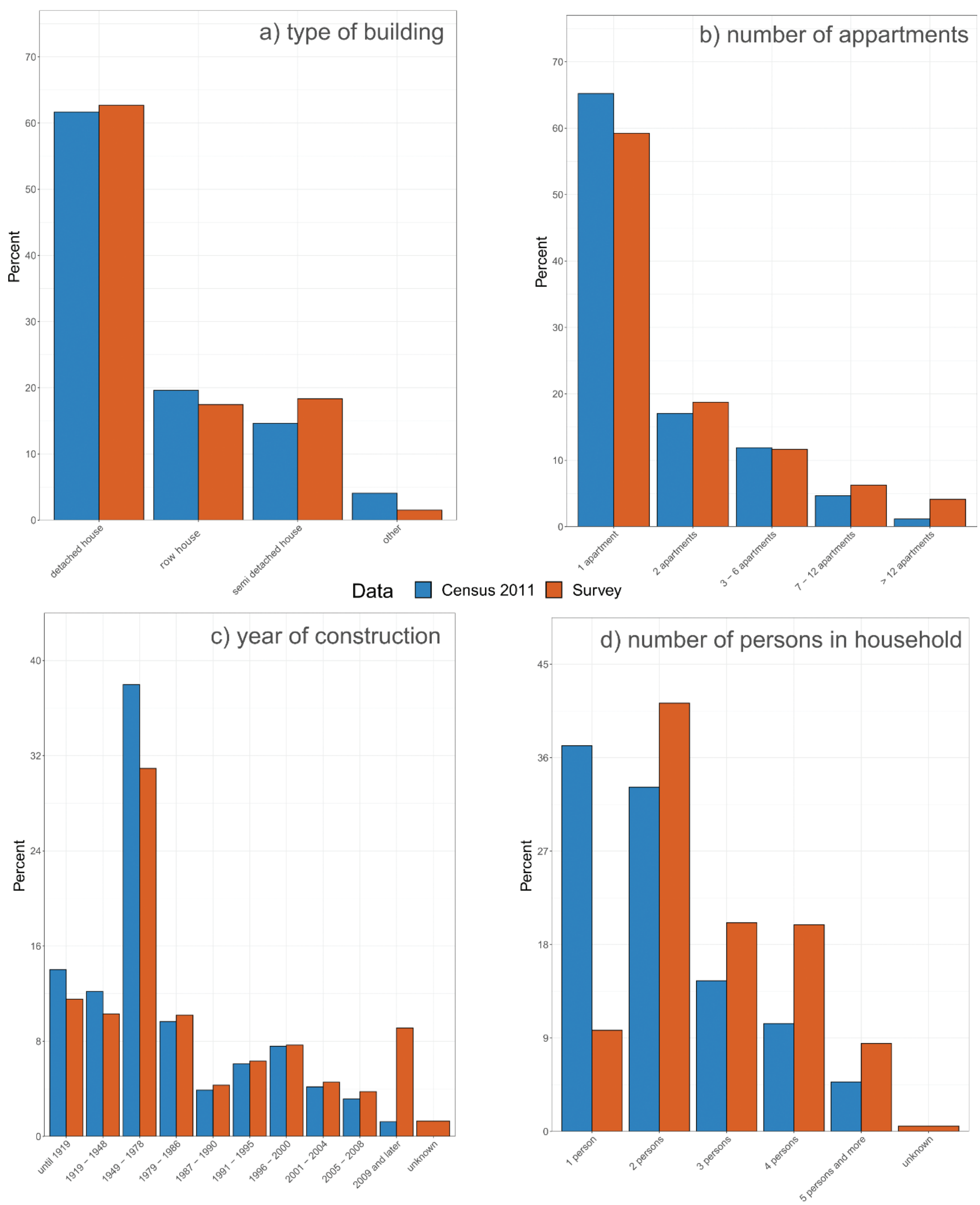

Fig. 13. Comparison of distribution of measured households (survey data) with census data (Statistisches Bundesamt, 2023) for different features (distribution in %) – type of building (a), number of apartments (b), year of construction (c), and number of persons in the household (d).

1949–1978 were measured and too much of the newest buildings (Fig. 13c). An explanation for the latter fact is that the census data end in the year 2011, whereas a lot of buildings were measured within the survey with a construction year after 2011. Also, a clear deviation was found in number of persons in the households – much less one-person households were measured compared to the census data, all other groups were over-represented (Fig. 13d). The reason could be that parents are more interested in the radon topic, to protect their families. This evaluation is based on the data for entire Germany, regional differences in the representativity in the level of federal states and districts were detected, for example type of buildings in cities versus rural areas or year of construction in different regions.

Summary and conclusion

A nationwide measurement campaign was conducted to determine the indoor radon concentration of residential buildings. For the measurements, standardized protocol track etch detectors in accordance with DIN ISO 11 665-4 with an exposure time of 12 months have been used. The distribution and collection of the measuring devices was done exclusively by post. In each building, two detectors should be placed in habitable rooms, regardless of the floor. For each household, information on the building and the measured rooms was also requested. The measurements have been free of charge for the participants.

The measurements took place throughout the entire country. The distribution was population-weighted and has followed administrative units (401 districts). In a first step, participants were recruited through a nationwide mailing with randomly chosen addresses, completed by participants included through specific advertising of the campaign in local media.

In the end, the results of approx. 6,500 households (= approx. 13,000 individual measurements) were included in a comprehensive descriptive statistical evaluation. The areal distribution of the households was corresponding satisfactorily to the previously desired district-based distribution. The measured values follow a log-normal distribution. The Germany-wide median was 44 Bq/m^3, the geometric mean was 49 Bq/m^3. The arithmetic mean was higher at 77 Bq/m^3. The 95-percentile was 240 Bq/m^3. In addition, the exceedance frequencies of radon concentrations above 100, 300, and 1,000 Bq/m^3 were calculated. These were approx. 18, 3.5, and 0.34%, respectively.

It is known that there are regional differences in the level of radon concentration in indoor air, essentially caused by varying radon source strength in the subsoil. This variability could also be shown in this campaign. The highest average values and exceedance frequencies were observed in Saxony and Thuringia with widespread higher radon concentration in soil gas. However, higher values were also observed in Rhineland-Palatinate and Bavaria. An analysis at the district level provides a more differentiated picture in all federal states. Regions with higher source strength in the subsurface are also clearly visible on a small-scale basis.

In addition, possible dependencies of the radon concentration in indoor air on parameters such as geology, building type, construction method, building age, basement, and floor were also considered. Known dependencies were confirmed, such as increased values in areas with granites in the subsoil, in older buildings, or on lower floors.

Finally, the representativity of the measurement campaign was assessed, based on data from the last German census in 2011 (type of building, age of construction, number of persons in the household, number of housing units in the building). The comparison of the two data sets generally showed a satisfactory agreement with just minor differences in certain classes of the considered parameters (e.g.: age of building 1949–1978, single-person household). The dataset of the measuring campaign is therefore in general considered representative for these parameters.

Despite these matches, a complete population-based representativity in the study could not be achieved. So, as a general problem in Germany a nationwide and accessible register of all inhabitants for randomly choosing participants does not exist. In addition, people with an interest in environmental and health issues are likely to participate disproportionately in such measurement campaigns. This may result in a bias with regard to socio-economic factors.

Nevertheless, this survey can serve as a profound data basis for following radon studies and radon work in Germany (the calculation of exposition due to radon, the pattern of radon hazard, information campaigns). The BfS used these data for generating a map of radon in dwellings in Germany (47).

Conflict of interest and funding

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