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Indoor radon concentration related to building type and foundation of dwellings – implications for radon risk prediction

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Summary

Indoor measurements of radon concentration have been carried out by our working group in more than 9000 dwellings in different regions of Germany. To investigate the statistical relationship between indoor radon, house type and building ground specifications, different multiple regression analyses of variance were performed. Besides the parameter “geographical position” as a major proxy for both region-specific geological properties and building characteristics, various house type and living style variables significantly contribute to the explained variance for both ground floor and basement radon concentrations. The radon transfer relation from soil gas to indoor air depends strongly on the above-mentioned parameters. Comparing the eastern and western part of Germany, the differences due to the building fabric of older houses lead to a substantial variation of the transfer factor, being in the eastern part up to twice as high as in the western part. For new dwellings, however, which are built according to the same standards, the transfer factors reach almost identical values. Risk prediction maps for radon in houses based on the German soil gas map and the regional distribution of radon transfer, indicating the probability to exceed certain indoor threshold values, can be designed to serve as tools for indoor radon prediction, especially in regions with no or only a few measurements of indoor radon.

Keywords: *indoor radon prediction, soil gas, house types, analysis of variance, radon transfer*

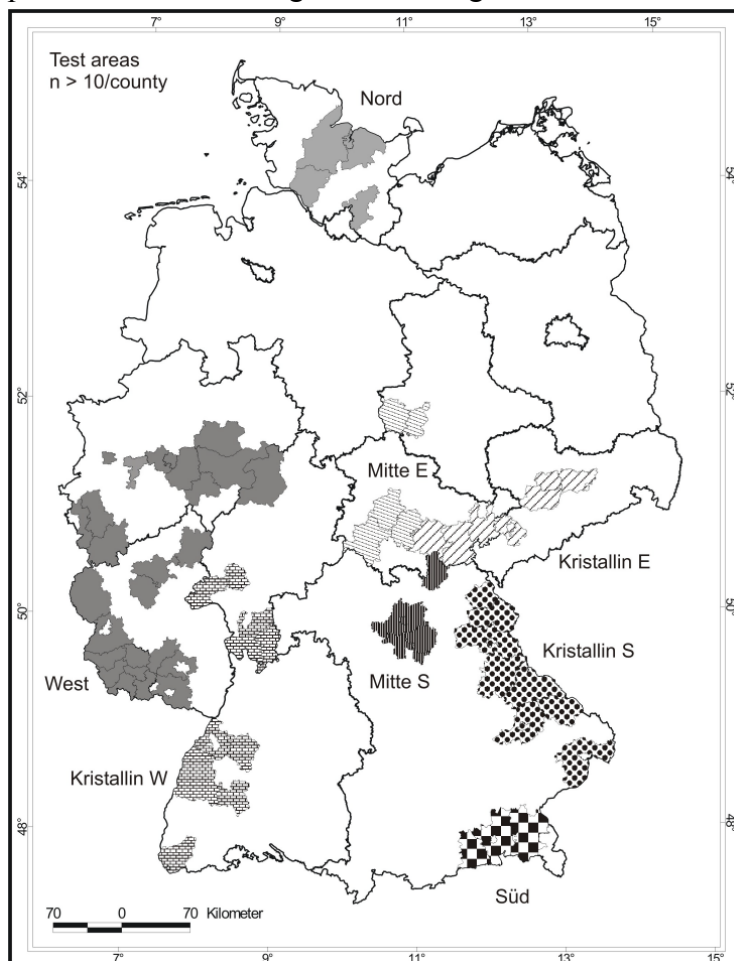
1. Introduction

The indoor radon concentrations in dwellings are influenced by many processes depending on parameters of the building ground and housing characteristics. Regional extrapolation of indoor radon levels, based on soil gas concentration of radon and constrained by geological units, is applied until now only in a few countries like Germany and Czech Republic. Despite

some common characteristics, house and foundation properties may differ considerably in the same community and often even in the same street. While our published contribution to this workshop (Kemski et. al., this workshop) deals with the geogenic parameters of the regional radon potential and their cartography, we present here the results of their combination with house and life style variables (e.g. foundation and construction type, sealing, building materials and age, ventilation).

2. Database

During the last ten years, indoor radon measurements in 9644 houses in different regions of Germany were carried out. They belong to a series of research projects financed by the federal ministry for environment and some state authorities. The test areas were chosen mainly because of geological criteria (e.g. rock type, tectonic aspects) and known “hot spots” with high radon concentrations. The measurements were conducted for a period of one year with track film detectors based on the German DIN 25706. In each house two detectors were placed – if possible one in a living room in the ground floor and one in the basement.



A comprehensive ten-page questionnaire was used to collect information about construction characteristics and building ground properties (e.g. foundation, moisture insulation, building material, cracks and fissures). Geological units were attributed to the house locations based on the “*Geologische Karte der Bundesanstalt für Geowissenschaften und Rohstoffe, scale 1 : 200 000*” and clustered with respect to the geogenic radon potential. The German soil gas radon map (Kemski et. al, this workshop) was used to assign soil gas values spot-to-spot to the dwellings. For this study, all houses were grouped according to eight test areas with different geological settings (fig. 1).

Fig. 1. Representative test areas with different geological settings for comparison of soil gas and indoor measurements.

In the regions “Nord”, “West”, “Mitte S”, “Kristallin W”, “Kristallin S” and “Süd”, 56 counties with 7655 measured houses account for the old Federal Republic of Germany (western areas); whereas 12 counties in the regions “Mitte E” and “Kristallin E” with 1989 measured houses are situated in the former German Democratic Republic (eastern areas). The radon risk prediction was performed only for the southern part of Germany, where the measuring point density is high enough to support the spatial variability of the geological units.

3. Indoor radon related to housing characteristics

As shown in our first contribution to this workshop (fig. 18 in: Kemski et al, this workshop), the totality of measured values of radon concentration in soil gas and indoor air follow approximately a logarithmic normal distribution. Each of the clusters of the eight representative regions listed above follows again a similar distribution (fig. 2). The geometric means for the western areas comprise 35 to 64 Bq/m³ in the ground floor and 49 to 105 Bq/m³ in the basement (tab. 1). The two eastern areas exceed these values nearly by factor 2 (87 – 100 Bq/m³ in ground floor, 144 – 154 Bq/m³ in basement).

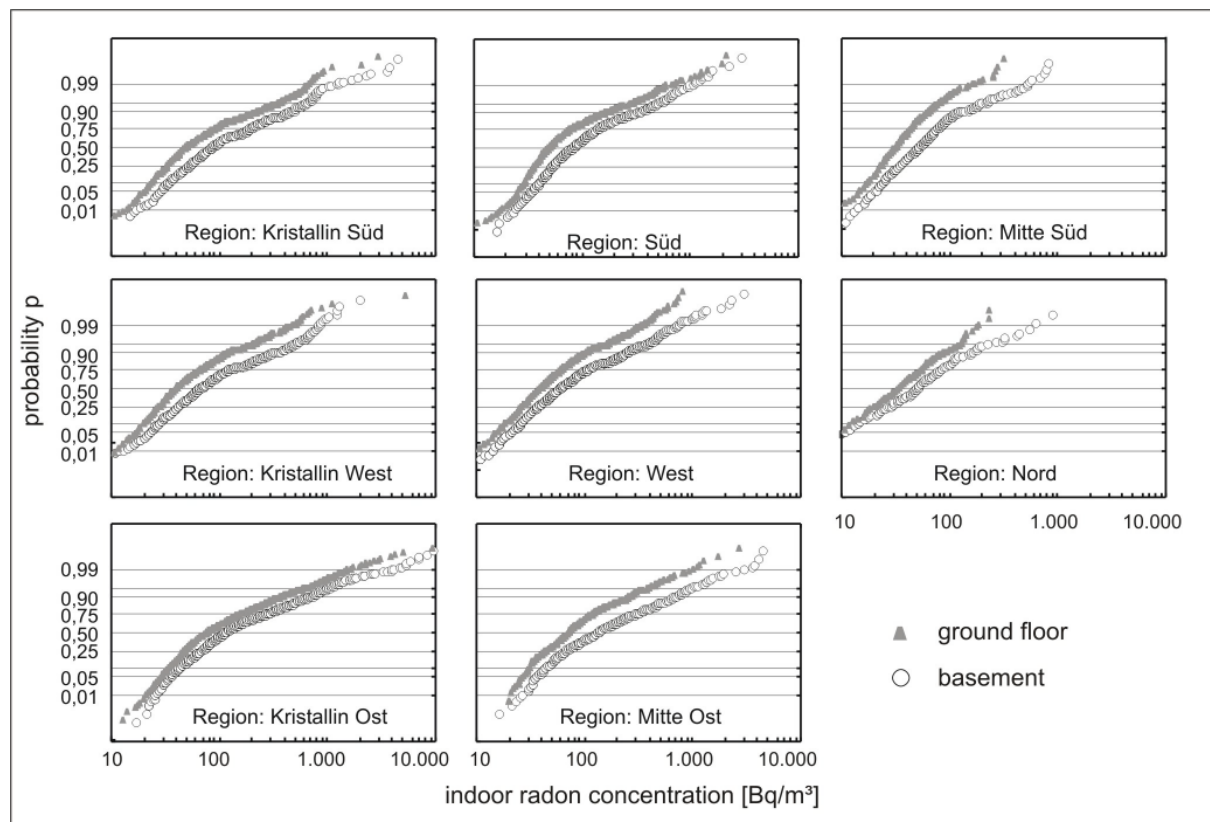


Fig. 2: Probability plots for radon concentrations in ground floor and basement of different regions

In several test areas, very high radon concentrations of more than 1000 Bq/m³ were found, the maximum value reaches more than 10 000 Bq/m³. 3.5 % of the rooms in ground floor and 9.0 % of the rooms in the basement hit the value of 400 Bq/m³.

ground floor					
region	geology	n	GM	GSD	Max
Nord	glacial sediments	219	36	2,2	240
West	palaeozoic, mesozoic sediments	2640	46	2,1	820
Kristallin West	granites	1221	50	2,2	5300
Mitte Süd	mesozoic sediments	716	35	1,7	330
Kristallin Süd	granites, metamorphic rocks	1074	66	2,5	2900
Süd	glacial sediments	1261	64	2,2	2200
Mitte Ost	volcanic rocks, sediments	446	87	2,3	2700
Kristallin Ost	granites, metamorphic rocks	1269	105	2,7	10000
<i>total</i>		<i>8846</i>	<i>57</i>	<i>2,4</i>	<i>10000</i>

basement					
region	geology	n	GM	GSD	Max
Nord	glacial sediments	177	49	2,6	900
West	palaeozoic, mesozoic sediments	2357	69	2,4	3000
Kristallin West	granites	1097	79	2,6	2000
Mitte Süd	mesozoic sediments	687	55	2,0	840
Kristallin Süd	granites, metamorphic rocks	951	105	2,6	4600
Süd	glacial sediments	1168	95	2,3	3100
Mitte Ost	volcanic rocks, sediments	422	154	2,8	4500
Kristallin Ost	granites, metamorphic rocks	1182	144	2,9	11000
<i>total</i>		<i>8041</i>	<i>88</i>	<i>2,6</i>	<i>11000</i>

Tab. 1: Geometric mean (GM), geometric standard deviation (GSD) and maximum values (Max) in Bq/m³; n = number of houses)

To explain the differences between regions on one hand and specific house types on the other, we performed a series of analyses of variance based on the questionnaire data, geological parameters and soil gas and indoor measurements. After some statistical tests, the raw data were clustered to categories summarising the major effects on radon indoor concentration. To give an example, the distribution of building materials in a house often is quite sophisticated. For one single wall in one single house, people use up to five different materials. Considering all other different substances contributing to a home, there would be a large list of materials with lots of places where they were build in. After sorting and testing different hypotheses, we found that the most important effects are the use of concrete and the use of quarried natural stones. As a result, the variable “building material” has three different categories: without concrete – with concrete – with natural stones.

Supplementary to the analysis of variance given in Kemski et al. (this workshop), we focus here on the distinctive features of different regions and are looking in detail for house characteristics and life habits. The variables in table 2, summarized with “environment”, are discussed in the above-mentioned contribution. As the comparison on regional scale requires a more detailed differentiation, the analysis presented here uses “counties” instead of “regions” as one of the predictor variables.

Analysis of variance								
Radon activity concentration in the indoor air (ground floor)								
		def.fr.	all regions (n = 8677)		West (n = 2591)		Kristallin West (n= 1164)	
			%	sig.lev.	%	sig.lev.	%	sig.lev.
natural environment	county	74/26/9	7,4	< 0.0001	1,0	< 0.0001	4,3	< 0.0001
	geology	6	3,0	< 0.0001	1,2	< 0.0001	1,2	0.005
	soil moisture	2	0,2	0.007				
	morphological situation	5			0,3	0.003		
	soil gas	7	0,4	< 0.0001			1,6	0.003
construction type	basement	3	15,3	< 0.0001	12,7	< 0.0001	12,3	< 0.0001
	construction type	5	3,0	< 0.0001	8,4	< 0.0001		
	building age	5	2,2	< 0.0001	0,6	0.017	1,9	< 0.0001
	building material	3	1,2	< 0.0001	1,3	0.0003		
	house type	6	0,8	< 0.0001	1,3	< 0.0001		
	moisture protection	2	0,4	< 0.0001	0,6	0.004		
	drainage layer	2					0,9	0.006
living habits	frequency of entrance	4	4,6	< 0.0001	8,0	< 0.0001	10,4	0.0005
	opening of windows	4	1,3	< 0.0001	1,8	< 0.0001	2,1	0.004
	opening of door	4	0,2	< 0.0001			0,6	0.02
	remaining variance		60,0		62,8		64,9	

Tab. 2: Multiple analysis of variance of indoor radon activity concentration (ground floor) for different regions

For living rooms in the ground floor, more than 15 % (12.7 % resp. 12.3 % in the regions) of the variance in radon concentration can be explained by the variable “existence of a basement” (fig.3). There are two aspects resulting from this effect. Most houses in flat areas of Germany, like in the northern quaternary lowlands, have a basement, which is at least partly below the ground and very seldom used as living room. Consequently, these rooms function as a radon buffer for the upper floors. The second aspect concerns buildings in low mountain ranges, which often are partly excavated in the slope of the hill. In such buildings the lowest floor is often inhabited, and the direct contact to the ground in the bottom and in one of the walls significantly increases the indoor radon risk.

The age of houses, which stands for different time-dependent building styles and likewise reflects the quality of the building fabric (fractures, sealing, weathering damages), explains 2.2% (0.6%, 1.9%) of the variability for ground floor rooms. The effect of the variable (fig. 3) is strongly region-specific. The two regions in the western part of Germany follow a common trend, which is clearly different to the other parts (southern and eastern). In the southern regions, the time period from 1930 to 1949, and in the eastern regions the period of the former GDR (1950 to 1990) show higher radon concentrations than the neighbouring time spans. For all regions, a positive trend to lower radon concentrations for younger houses is evident.

Concerning the construction type, prefabricated houses - mainly built by the use of concrete - show the lowest radon concentrations, while timbered houses, which mostly are of older age, show the highest values. Framed houses from wood differ significantly – this is due to the variation in building age and soil gas radon. For the region “West”, 75% of the framed houses are built after 1985 and only 25% of them have a soil gas radon concentration of more than 80 kBq/m³. For the region “Kristallin West”, 50 % of the houses are built before 1977 and 25 % have soil gas values of more than 230 kBq/m³. Again this is a strong argument to take care of regional differences even for houses, which are on a first sight very similar.

The life habits are mainly related to the air exchange rate in the rooms. The opening of doors and windows as well as the frequency of entrance into the rooms has the well-known significant influence on the mean indoor radon activity.

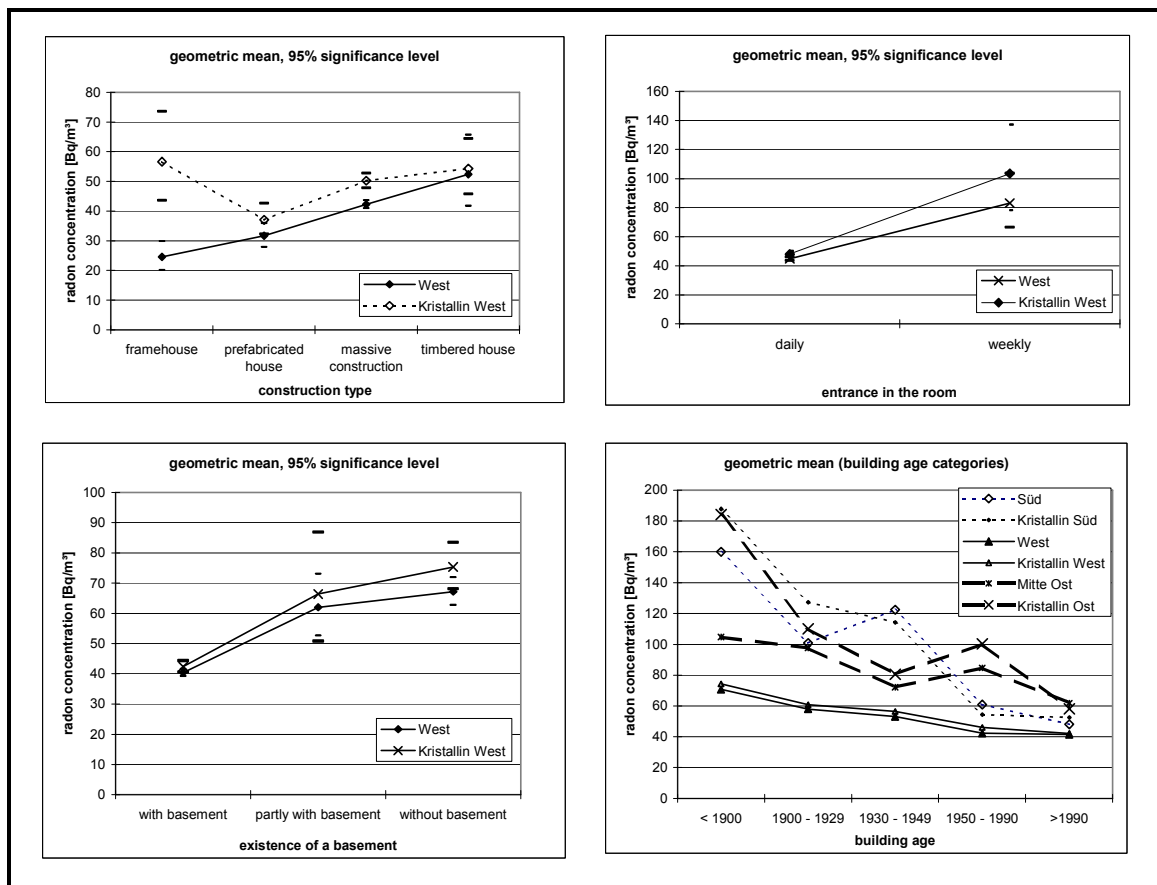
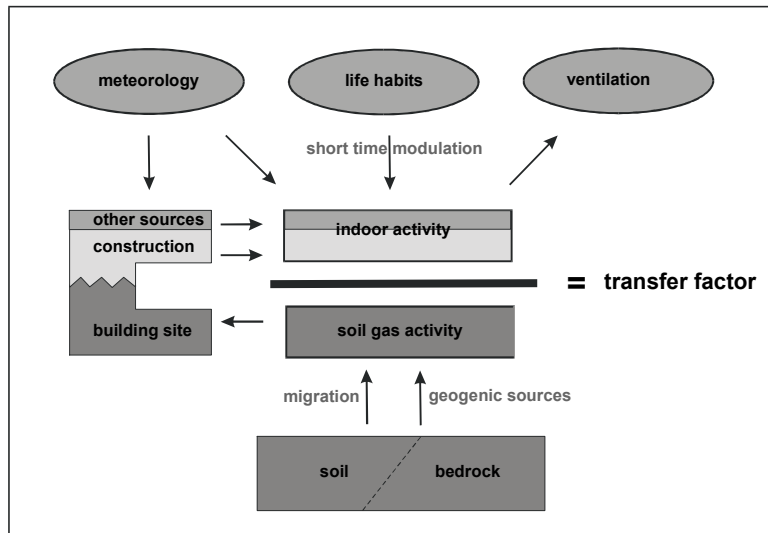


Fig. 3: Effects of different house and life style characteristics on indoor radon activity

After the reintegration of Germany in 1989, the average indoor radon in both parts of the country was found to be rather different, being about two times higher in eastern Germany, where also the proportion of houses exceeding 400 Bq/m³ is much higher. This is not necessarily due to a higher natural radon source, but is mainly caused by the low quality of construction of many old houses in the former German Democratic Republic. Regarding the houses built after 1990, the distributions of indoor radon concentration are nearly identical. Thus we know at least for Germany, that geogenic and constructive differences cause a variability, which complicates a uniform mapping of the “radon potential” all over the country. With respect to the open discussion on radon mapping, a representative database recording also house characteristics with “enough” measurements for different construction types and habitation structures - besides indoor and soil gas measurements - seems to be a fundamental requirement.

4. Radon risk prediction

Long-term measurements of indoor radon concentration are now available in Germany for a total of about 25 000 houses, and there exists a radon soil gas map covering the whole area of



the country (Kemski et al., this workshop). Based on the regional distribution of both variables, the approach to predict indoor radon from soil gas radon can be tackled now. As dependency relation, the “transfer factor” ($tf = \text{radon in soil gas/indoor radon} [\text{‰}]$) was introduced in 2001 (Kemski et al. 2002)

Fig. 4: The “transfer factor”

It is in fact an apparent transfer factor, implying a distinct portion of uncertainty, because other sources of radon like the building material are coming into effect, especially in regions of low soil gas concentration. Processes like meteorological change, ventilation rate and life-style of the inhabitants overprint the influence of the soil-born primary source, particularly when the soil gas radon signal is low. It is higher at low soil gas concentrations, because there the effect of building material and other secondary sources is dominating the soil gas component. For each house, the soil gas value of the grid element in the German radon map was used to calculate the respective transfer factor. The factors mentioned here are based on the soil gas map issued 2004 (Kemski et al., 2005); they may change with the improvement of the map by additional measurements.

The distribution of transfer factors again is logarithmic normal, which is a demand for the calculation of threshold values in the upper tail of the distribution. The analysis of variance show similar results to the analysis of indoor radon concentration. Differences between the categorized groups (fig. 5) are evident. The regional variance follows mainly the east – west differentiation. In the western part of Germany, the transfer factors vary in a smaller range, following mainly the geology and the house construction. Looking only for young houses (< 1990, with basement, with concrete, without quarry stones), the transfer factors are quite the same in all regions (geometric mean between 0.6 and 0.7).

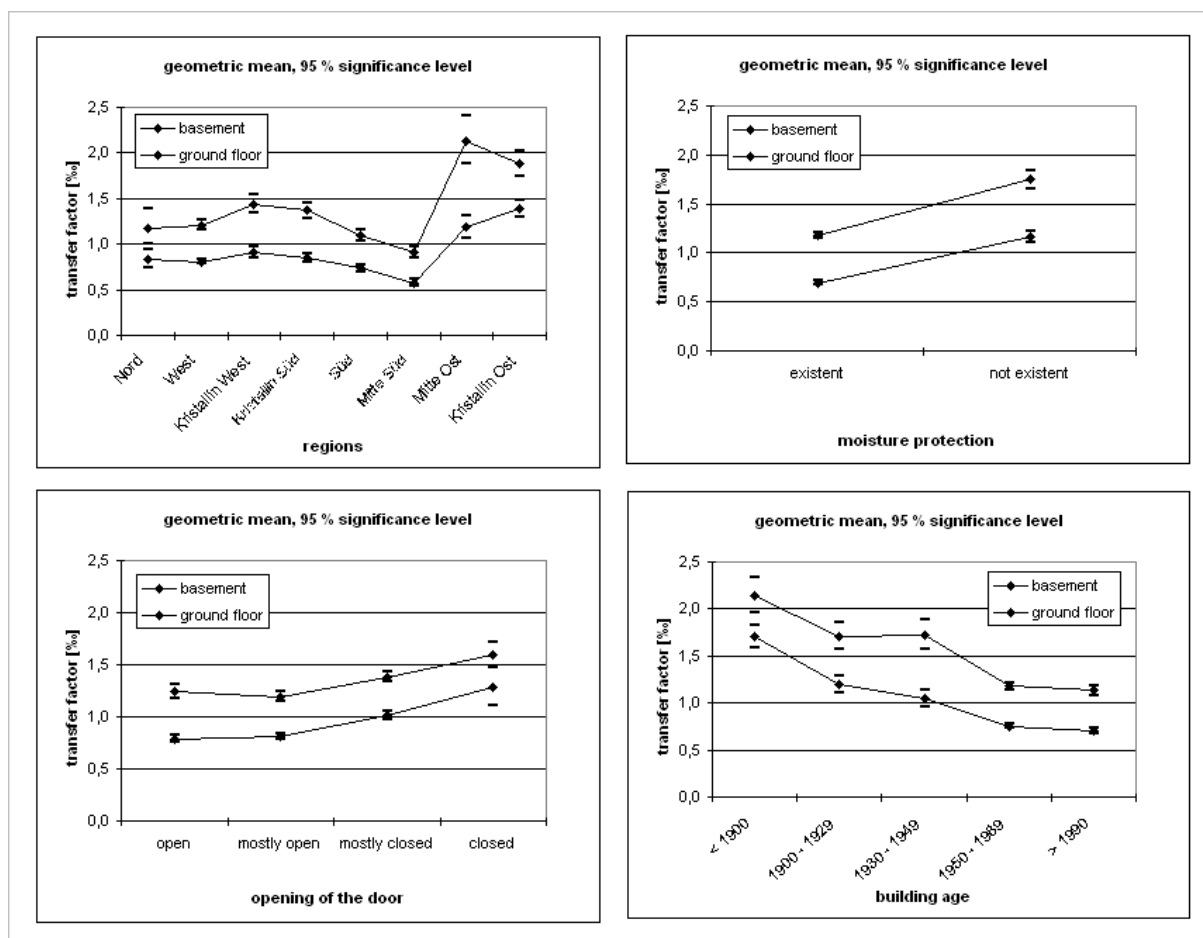


Fig. 5: Effects of categorized variables on the geometric mean of the transfer factor

Building age, existence of a basement and regional difference between the eastern and western county groups are the main variables regarding the specification of house types with different sensitivity for the radon problem. Tab. 3 shows the geometric mean and 90 percentile of the respective transfer factors. Situated on a building ground with the same geology and the same soil gas value - say 100 kBq/m^3 - we expect 10 % of houses exceeding 160 Bq/m^3 for house type A (west, basement, after 1990) and 10% exceeding 1120 Bq/m^3 for house type B (east, no basement, before 1950). This is a strong argument to account for specific regional characteristics of housing when mapping radon risk.

		built before 1950			built 1950 - 1990			built after 1990		
		n	GM	p90	n	GM	p90	n	GM	p90
West	with basement	781	0,9	3,2	3183	0,6	1,8	1264	0,6	1,6
	without basement	691	1,5	5,3	859	1,1	4,5	260	0,9	2,9
East	with basement	494	1,0	4,1	280	1,0	3,6	232	0,7	2,4
	without basement	533	2,4	11,2	88	2,7	20,6	82	1,2	5,9

Tab. 3: house type specific transfer factors[%] (soil gas – ground floor; n = number)

The above-mentioned facts indicate a general problem with the prediction of radon concentrations in houses. A high radon potential in the building ground leads not necessarily to indoor problems, especially in new buildings with appropriate insulation. On the other hand, a low radon potential does not exclude an increased radon risk for houses, where the living area is not sealed sufficiently against soil gas transfer. Based on the soil gas raster map of Germany and the spatial distribution of indoor radon measurements, we can calculate for each grid element with a given soil gas radon concentration the region-specific transfer factor, which is necessary to reach a specific indoor radon concentration. The proportion of values outranging this factor can be used to extrapolate the proportion of houses exceeding a certain threshold indoor radon level. We applied two different distributions of transfer factors – one for the western part and one for the eastern part. The approach uses the whole database, which means all types of houses, and we regard their distribution as representative for the specific area. The resulting map for the southern part of Germany (fig. 6), where we have a sufficient number of supporting data, is dominated by the described difference between east and west marked by the former national border. The highest percentages of houses exceeding the 100 Bq/m³ level exists in large parts of the “Erzgebirge” and the “Thüringer Wald”.

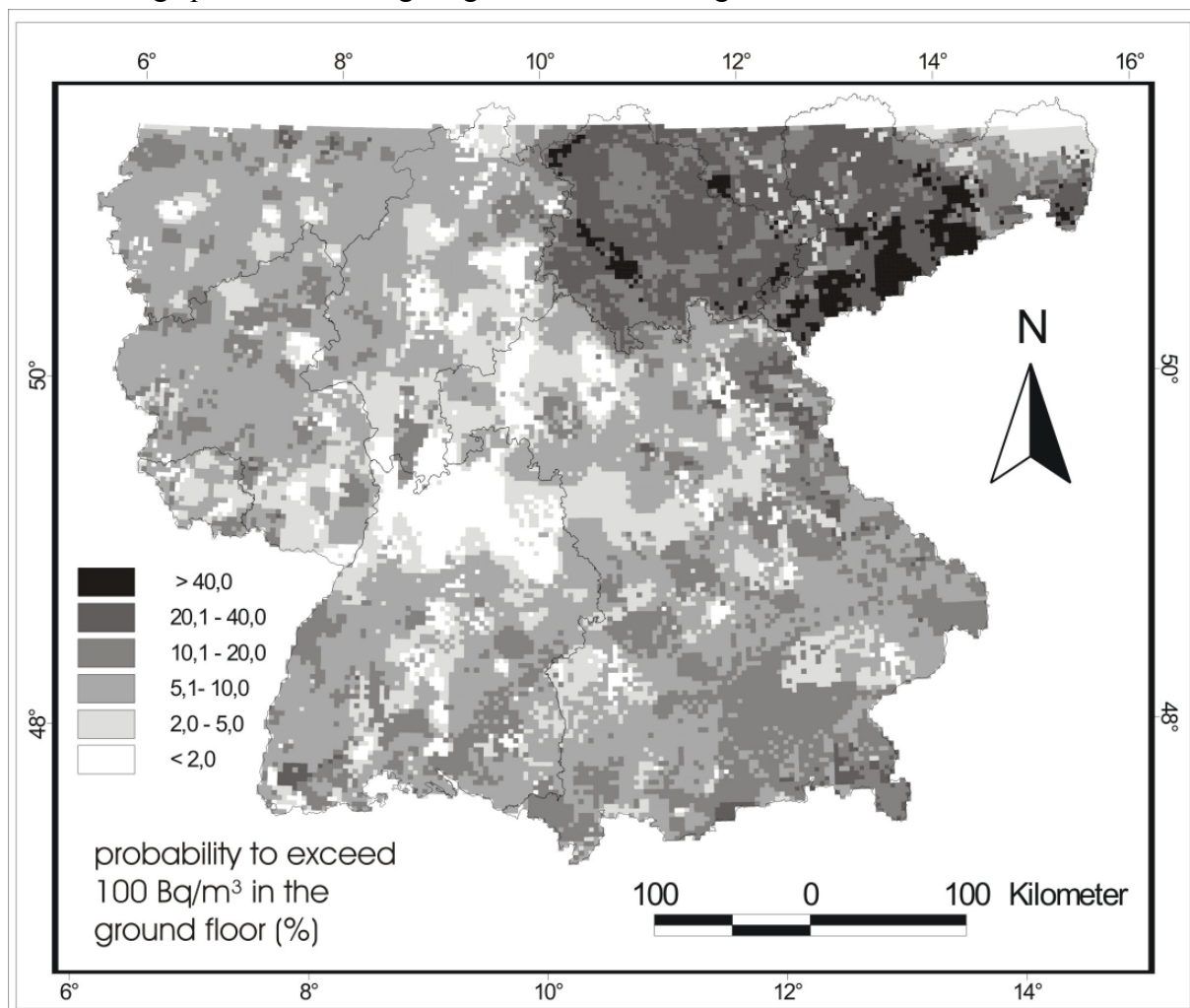


Fig.6: Interpolated map of the south part of Germany, indicating the probability to exceed 100 Bq/m³ in a ground floor room; prediction based on soil gas map and distribution of transfer factors

Here we expect more than 40 % of the houses with radon levels of more than 100 Bq/m³ in the ground floor. But also in the western part, in some areas in eastern Bavaria, in the Alps and in the Black Forest, more than 20% of houses reach this level. The benefit of such a map is quiet clear: confirmative indoor measurements could be planned with great efficiency. The map is also a good example for possible transnational maps, because there is no reason that the basic parameters used for the prediction are less comparable on a European level than in the presented study.

Matching the map with data from the house stock, it is possible to estimate the number of houses exceeding a given indoor level. Due to an incomplete database in the northern part of Germany, the following data are a first estimation. For the 100 Bq/m³ level we get about 1.6 million houses nationwide and for the 200 Bq/m³ threshold there are 0.6 million houses. In the high levels of radon risk we may found about 30 000 houses reaching more than 1000 Bq/m³. For a house stock of about 16 million, this means about 0.2 % of houses in Germany, which have a strong need to be mitigated in the next years.

5. Conclusions

The discussion on radon mapping in Europe is ongoing. There are many arguments for one or the other approach. In Germany, perhaps unlike in several other countries, the geologically based mapping leads to very effective tool for the prediction of indoor radon risk. This was achieved by a careful geoscientific elaboration of stratigraphic, lithological and methodological aspects of radon in the soil gas and due to the collection of detailed information about the house characteristics. Mapping based only on indoor measurements requires a large number of data and is only as reliable as the information about the house characteristics. Mapping based on geology requests the same effort considering the acquisition of house characteristics, but needs less measurements and may give a prediction for areas, where still no measurements exist. Therefore our vote counts for a combined method considering geological aspects and indoor data.

6. Literature

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