ORIGINAL ARTICLE

Radon levels in dwellings and workplaces: a comparison with data from some European countries

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Abstract

***Background*:** According to 2013 European Basic Safety Standards (EU BSS), legal and administrative consequences of having an area declared as radon priority area (RPA) concern workplaces (WP) and public buildings, as well as dwellings (DW). However, RPAs in many cases are defined as higher levels of indoor radon in DW. The reason is that most data are available for DW. So far, indoor radon data for WP (except for schools) and public buildings are scarce.

***Objective*:** The objective of this study was to compare indoor radon levels in DW and WP in a given area and to evaluate whether they have different distributions and different average levels.

***Design*:** Austria, Finland, Germany, and Italy provided indoor radon data on DW and WP.

Data related to WP were aggregated in the same grid, as already done for data on DW, to update the European Indoor Radon Map. Based on 10 km × 10 km grid cells, the same statistics are computed for both datasets. Thus, two structurally equal datasets for each country were generated to be statistically compared.

***Results and conclusions*:** Generally, there are numerous indoor radon data on DW than data on WP. Statistical analysis suggests that in all the countries, indoor radon levels – in terms of arithmetic mean (AM) of the natural logarithm-transformed data – in WP and DW are statistically different ($P < 0.05$), as well as from those referring to schools. The difference in distributions is neither attributable to the effect of geology nor to the effect of different sample sizes.

The correlation between aggregated data is positive in the sense that if the mean (over grid cells) radon concentration increases in DW, it increases in WP as well. Compared with DW, in all countries indoor radon levels in WP seem to be statistically different, but the results are not enough to draw final conclusions: on-purpose designed surveys could be a useful tool to better understand this phenomenon.

Keywords: *indoor radon; dwellings, workplaces; schools; statistical tests*

The European Basic Safety Standards (EU BSS) (1) provides a conceptual definition of 'radon priority area' (RPA) as an 'area where the radon concentration (as an annual average) in a significant number of buildings is expected to exceed the relevant national reference level' (Art. 103). Typically, this is interpreted as a greater occurrence of high radon concentrations in DW than average: to this end, many national surveys on radon levels in DW have been conducted since the 1980s (2).

Recently, a document was developed by a dedicated Working Party and subsequently adopted by the group of experts referred to in Article 31 of the Euratom Treaty, which deals with this topic as 'Delineation of areas with potentially high exposure to radon' (RP193 'Radon in workplaces [WP]')(3). RP193, indeed, provides a wider definition of 'areas', based on the fact that indoor 'radon concentrations in buildings can vary significantly depending on geogenic and anthropogenic factors'. Anthropogenic factors include the use of buildings, living habits, working conditions, and arrangements.

Defining a geographical area as RPA implies to introduce legal and administrative bindings: this is a delicate aspect. In the first place, the RPA identification leads to the adoption of provisions relevant to the protection from radon in WP and public buildings (EU BSS Art. 54)(3).

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Houses, WP, and public buildings, therefore, need to have the same distribution of indoor radon levels if the same RPAs are defined for all types of buildings. However, if the indoor radon levels at home are used for estimating RPAs, then their distribution should be representative also of that in WP and public buildings.

Previous indoor radon surveys pointed out a different distribution of indoor radon levels in DW and WP located at the same area and thus subject to the same geogenic radon influence. In some cases, WPs seem to have higher radon levels compared with DW (4, 5), whereas in other cases opposite conclusions were drawn (6). This can be a consequence of different construction styles, different occupation factors, intended use and different 'building physics' in terms of air circulation.

Moreover, under the term of 'WP' a great variety of situations are included, for example, from schools and public buildings up to warehouses, malls, etc. It is evident that, for instance, schools, shops, police stations, workshops, metro stations, industrial production halls, museums, etc., have different physical characteristics and little in common among each other, apart from being WP. A classification of WP according to radon characteristics is still missing.

For the abovementioned reasons, it is not clear how representative or adequate are RPAs derived from residential buildings and DW with respect to the distribution of radon in WP altogether or to a certain type of workplace.

In the framework of the EURAMET project MetroRADON (7), a study has been devoted to this topic. This work focuses on the analysis of data (radon annual activity concentrations in DW and WP) provided by Austria, Italy, Germany, and Finland. Its results and further elaboration are discussed in this article.

Materials and methods

Description of the datasets

Four indoor radon datasets (DW and WP) were built using data from past surveys: Table 1 provides an overview of national datasets with their main characteristics.

National data were collected considering their comparability in terms of:

1. Quantity of interest: radon (here denoted as ^{222}Rn) average over the period indicated in Table 1, which is not in all cases an estimate of the annual mean. In such instances, normalization was applied (see below) in Bq/m^3;
2. Duration of measurements: long-term (at least 3 months) measurements to evaluate the annual mean radon activity concentration;
3. Position: data referred only to rooms located at ground floor;
4. About WP datasets, there is a need to collect metadata on different types of WPs.

Nationally, available datasets consisted in radon annual (or estimated representative of the year) activity concentrations measured in DW and general WP (for Finland), or in different types of WP, such as public buildings, schools, and kindergartens (for Austria, Italy, and Germany). Moreover, Finnish databases covered the entire national territory, whereas in the case of Austria, Germany and Italy, the data were at the regional scale (Upper Austria and Saxony). At national level, collected data differed in some aspects, such as the order of magnitude of the numbers of collected data on DW versus WP (sample size): available data on DW are more numerous compared to those on WP.

Table 1. Description of datasets and their principal characteristic

Country	Dwellings (DW)		*N* cells	Workplaces (WP)		
	N samples	Duration of measurements		N samples	Duration of measurements	Type of WP
Austria	~7,000	6 months[1]	113	~1,200	3 months (SCH)	Adm.buil., SCH
				(1,000 adm.build. + 200 schools [SCH])	6 months[1] for adm. build.	
Finland	~162,000	60–70 days	373	~6,300	60–70 days	Many kinds of WP[3]
Germany	~2,000	4–12 months	48	~300	Annual sampling	Public building[2]
Italy	~14,700	Annual sampling	623	9,000	Annual sampling	Many kinds of WP
				(~2,400 WP + ~6,300 SCH- kindergartens [KG])		

[1]6 months: half-winter half-summer
[2]Public buildings (PBs) include administrative buildings (adm. build.), schools (SCH), and kindergartens (KG)
[3]No special WPs (*such as mines, waterworks, spas, etc.*) are included

The national databases were not homogenous in some methodological aspects, such as the duration and the period (season) of sampling: in Italy and in Germany, indeed, the sampling lasted 12 months, whereas in Finland only 60–70 days, and consequently the annual radon average was estimated applying a normalization factor. In Austria, 6 months measurements (half in winter and half in summer) were considered to be representative for the annual radon concentration.

As radon data are sensitive for data protection and privacy reasons, sharing information on accurately geo-referenced original data were not feasible. Consequently, WP and DW radon data were aggregated by the data owners into the same grid as for the European Indoor Radon Map (8, 9), based on 10 km × 10 km grid cells (defined by the same geographical coordinates, which refer, in this case, to a metric grid in LAEA projection). Grid cells with data only from either DW or WP have been eliminated from the analysis. Moreover, a minimum of two data per cell was set. With these assumptions, two comparable datasets were obtained for further statistical analysis.

On both aggregated radon data (DW and WP), descriptive statistics were computed: number of data in each grid cell, arithmetic mean (AM) of the natural logarithms (AM[ln]), standard deviation of the natural logarithms (SDL), median, minimum (min) and maximum (max).

Statistical analysis

For each country, data related to DW and WP have been paired when they refer to the same cell.

Before proceeding with any analysis, it was important to improve the quality of the data. To this end, an outlier detection analysis was performed. First, a bivariate test based on the Mahalanobis distance was applied to the paired data AM(ln)s. Subsequently, the Rosner's generalized extreme studentized deviate test (10) was performed on both the AM(ln)s individually in order to detect further outliers.

Statistical analysis on comparison of sample means was performed with the IBM SPSS software (11), whereas the linear regression analysis was carried out using the statistical software PAST (12, 13).

On data, a preliminary test of normality was carried out with the aim of establishing the type of test required in the comparison of sample means. In particular, the two most common normality tests, namely Shapiro–Wilk and Kolmogorov–Smirnov tests, were used. In both cases, $P < 0.05$ was considered to be statistically significant.

On national datasets, the AM(ln) data referring to DW and WP were compared to test the significance of mean value differences between the two groups.

As first comparison, a 'simple' test was implemented. Specifically, it was assumed to work with independent (or unpaired) samples. However, to eliminate the confounding contribution/effect of the soil, a matched-pairs test was carried out.

In both cases, whenever the two AM(ln)s variables were normally distributed, the well-known Student's (unpaired or paired two-sample) *t*-test was used. Conversely, when AM(ln)s were not normally distributed (the Shapiro–Wilk test or Kolmogorov–Smirnov test has a $P < 0.05$), then non-parametric Mann–Whitney (unpaired samples) and Wilcoxon (paired samples) tests were applied.

On each country's dataset exploratory statistics, for example, mean and quantiles, are computed and the distributions of AM(ln) for paired match samples of DW and WP were compared graphically using a box plot. Finally, to assess the possible effect because of the different number of data in DW and WP datasets, only sets of data weighted by the number of samples were analyzed. In particular, for each cell, the values of $AM(ln)_{DW}$ and $AM(ln)_{WP}$ were weighted by their own number of samples. The same data analysis scheme was also applied to subsets of the data to compare DW with specific WP, such as schools for Austria, Italy, and Germany.

Moreover, on each country's dataset, a correlation analysis was carried out. As parametric association model between Rn concentrations (RnC) in DW and WP a simple model was chosen:

$$RnC(WP) = b \cdot RnC(DW).$$

This assumption, which does not consider the presence of an intercept, appears to be the most plausible for physical reasons. As we are interested to find a *b* parameter, which optimally represents the symmetric association between the variables DW and WP, the use of a common regression is to avoid. Common linear regression (CLR), [1] in fact, is not symmetric because

$$b(X \mid Y) \neq \frac{1}{b(Y \mid X)},$$

where X is RnC (WP) and Y is RnC(DW).

To achieve reciprocal symmetry,[2] there are different options to explore, in this study we focalized on the following:

1. orthogonal (OR) or main axis (MA) regression (14–16)
2. reduced main axis (RMA) regression.

1. CLR estimates the conditional expectation $E(Y|X = x)$ where X and Y are DW and WP or reversely

2. $b(Y \mid X) \neq \frac{1}{b(X \mid Y)}$

Details about the regression model can be found in Appendix 1 and in Warton et al. (17)

Results of the application of the abovementioned regression options are described in the following paragraph.

Results and discussion

Datasets were built referring to radon concentration data in DW and WP for Austria, Finland, Germany, and Italy: in all the countries, DW and WP datasets differ in terms of the total number of samples and of distribution per cell. Looking at Fig. 1, the analysis of frequency distributions of samples per cell within all datasets (DW and WP) pointed out that in DW datasets the sample size is spread in many classes, from 10 samples per cell up to several hundred (as in the case of Finnish DW dataset). Conversely, in WP datasets, most of the data is in classes of 20 samples per unit (cell). To evaluate whether radon in DW and WP is differently behaving, on national DW and WP datasets, the AM(ln) was the parameter of interest. According to the literature, it was assumed that the radon in data within each cell is normally distributed (18, 19).

The box plot reported in Fig. 2 represents the AM(ln)s data distributions of DW and WP for Austria, Finland, Germany, and Italy. Looking at all box Plots, for Austria and Finland, radon levels in WP seem to be more scattered, in terms of a wider distribution and greater standard deviation compared with DW, as also shown in Table 2a. Similarly, radon median values in WP are lower for Austria and Finland but not for Germany: indeed, a very similar median value was found in Italy.

Similar conclusions concerning the dispersion of data can also be drawn looking at Table 2b when comparing DW with schools.

Main results of statistical analysis are summarized in Tables 3–6, in which the number of samples, number of cells, confidence interval, and P-values are reported.

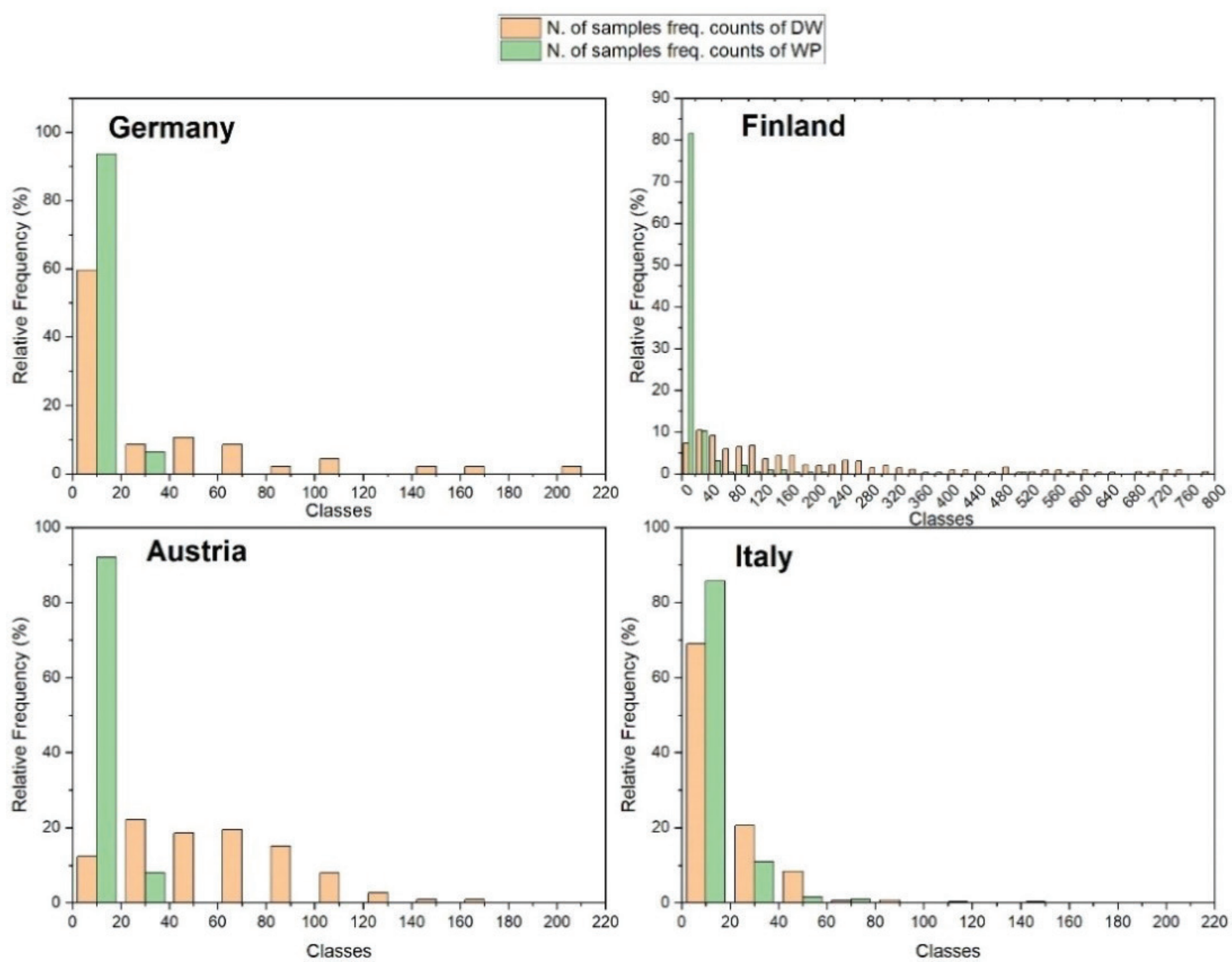

Fig. 1. Frequency distribution of sample sizes (DW and WP) per cell within each national dataset. Class dimension is the same for all dataset and equals to 20. Units of x-axis: Bq/m³.

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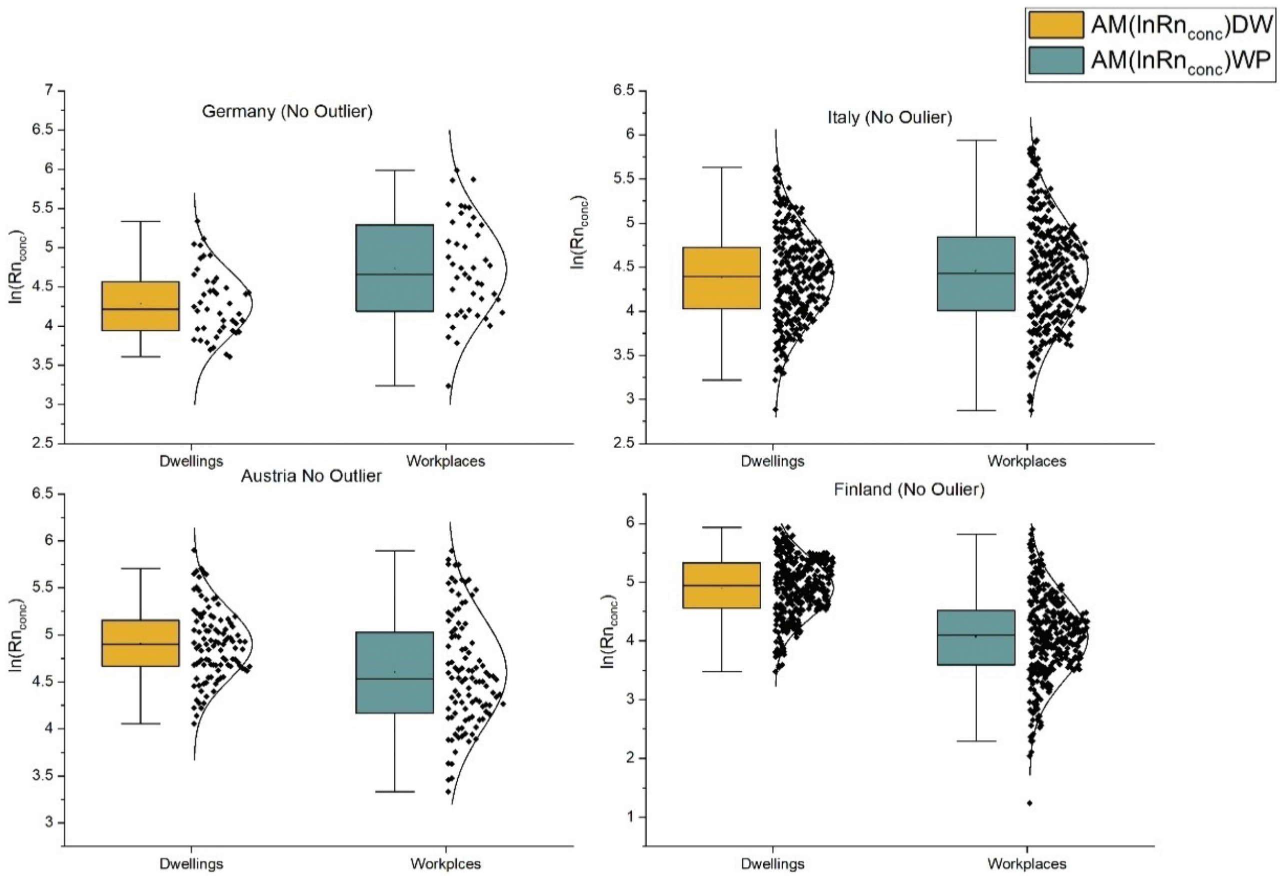

Fig. 2. Box Plot of AM(ln)s related to dwellings and 'general' workplaces (DW/WP): Austria, Finland, Germany, and Italy. Boxes: 25, 75% quantiles, median; whiskers: min-max.

Table 2a. Descriptive-weighted statistics (DW vs. WP)

Country	Type	*N.* Cells	*N.* samples[3]	AM(ln[x])[1]	SDL[2]	Min	Max	Range	Median
Austria	DW	107	6,462	4.89	0.36	4.05	5.90	1.85	4.88
	WP		1,141	4.60	0.54	3.34	5.89	2.55	4.54
Italy	DW	618	11,275	4.450	0.52	2.88	5.9	3.02	4.39
	WP		7,543	4.663	0.58	2.91	6.05	3.14	4.38
Finland	DW	367	160,717	5.11	0.40	3.47	5.93	1.74	5.15
	WP		5,950	4.21	0.47	1.24	7.27	2.75	4.24
Germany	DW	45	1,700	4.38	0.38	3.60	5.34	2.55	4.40
	WP		300	4.59	0.56	3.24	5.99	2.75	4.47

[1]AM(ln[x]) is the arithmetic mean of the logarithm.
[2]SDL = SD(ln x); SD is the standard deviation of the logarithm.
[3]Outliers are not included.

Table 3, which reports outcomes of weighted tests, shows that in all countries indoor radon levels in WP and DW are statistically different ($P < 0.05$), and this is not attributable to the effect of different sample size (see Table 2a for descriptive statistics).

However, it is well-known that the importance of the geology on indoor radon levels: to analyze this effect, the matched-pairs tests were carried out on national datasets. Table 4 reports the results of the statistical analysis on AM(ln) for paired match samples: data suggest that indoor radon levels in WP and DW are statistically different ($P < 0.05$).

In all countries, the different distribution of indoor radon levels in WP and DW seems not attributable to the effect of the geology nor to the effect of the sample size.

Table 2b. Descriptive-weighted statistics (DW vs. school)

Country	Type	N. cells	N. samples[3]	AM(ln[x])[1]	SDL[2]	Min	Max	Range	Median
Austria	DW	37	2,407	5.01	0.30	4.40	5.68	1.28	4.97
	WP		157	4.88	0.71	3.42	6.50	3.08	4.80
Italy	DW	493	9,428	4.45	0.50	2.88	6.25	3.37	4.46
	WP		5,110	4.38	0.54	2.91	6.29	3.38	4.38
Germany	DW	33	1,468	4.31	0.33	3.64	5.11	1.47	4.30
	WP		212	4.51	0.47	3.78	5.55	1.77	4.27

[1]AM(ln[x]) is the arithmetic mean of the logarithm.
[2]SDL = SD(ln x); SD is the standard deviation of the logarithm.
[3]Outliers are not included.

Table 3. Comparison on weighted data (DW vs. WP)

Country	Typology	N. samples	Interval1	P-value[2]	DW > WP
Austria	DW	6,462	(4.896; 5.039)	MW test[3] < 0.001	yes
	WP	1,141	(4.627; 4.842)		
Italy	DW	11,275	(4.532; 4.615)	MW test[3] < 0.001	yes
	WP	7,543	(4.497; 4.587)		
Finland	DW	160,717	(5.148; 5.231)	MW test[3] < 0.001	yes
	WP	5,950	(4.275; 4.373)		
Germany	DW	1,700	(4.335; 4.574)	MW test[3] < 0.001	no
	WP	300	(4.563; 4.896)		

[1]95% Cox confidence interval (20).
[2]When $P < 0.05$, the null hypothesis is rejected.
[3]MW test is Mann–Whitney U–test.

Table 4. Results of matched-pairs test (DW vs. WP)

Country	Typology	N. Cells	Interval[1]	P-value[2]	DW > WP
Austria	DW	107	(4.926; 5.078)	W[(4)]Test <0.001	yes
	WP		(4.645; 4.882)		
Italy	DW	618	(4.469; 4.557)	t-Student [3] 0.012	no
	WP		(4.545; 4.645)		
Finland	DW	367	(4.983; 5.093)	W[(4)]Test < 0.001	yes
	WP		(4.242; 4.403)		
Germany	DW	45	(4.252; 4.527)	t-Student [3] < 0.001	no
	WP		(4.723; 5.106)		

[1]95% Cox confidence interval (20).
[2]When $P < 0.05$ the null hypothesis is rejected.
[3]Matched-pairs *t*-test cannot be weighted.
[4]W test is Wilcoxon test.

Table 5. Comparison of weighted data (DW vs. school)

Country	Typology	N. samples	N. cells	Interval[1]	P-value[2]	DW > WP
Austria	DW	2,407	37	(4.960; 5.156)	(Mann-Withney Test) 0.002	no
	School	157		(4.874; 5.385)		
Italy	DW	9,428	493	(4.516; 4.607)	(Mann-Withney Test) < 0.001	yes
	School	5,110		(4.469; 4.571)		
Germany	DW	1,468	33	(4.253; 4.486)	(Mann-Withney Test) < 0.001	no
	School	212		(4.446; 4.783)		

[1]95% Cox confidence interval (20).
[2]When $P < 0.05$ the null hypothesis is rejected.

The same analysis scheme was applied to compare radon data related to DW and a specific typology of WP: schools. The outcomes for Austria, Germany, and Italy are given in Table 5 and Table 6 whereas Table 2b reports descriptive statistics. In particular, the weighted test on data related to DW and schools showed that radon levels in schools and DW are statistically different ($P < 0.05$) in all the three countries (see Table 5). Conversely, the match-paired test highlighted that radon data in DW and schools are statistically different in Italy and Germany but not in Austria (see Table 6).

As shown in Table 2a and b, compared with DW, WP (and schools) data seem to be a little bit more scattered (cf. Standard deviations and ranges).

Nevertheless, although DW could be more suitable than WP to investigate radon distribution (less internal variability, etc.) in a given geographical area (mapping), at the same time, DW are not representative of 'all buildings'. Therefore, it could be appropriate to use the proper correction factors in the identification of RPAs or an integration in the sampling design of indoor radon surveys to account for the influence of different 'anthropogenic factors', as required in RP193 (3).

Outputs of the regression analysis for every national dataset (DW/WP) are reported in Table 7. Since there were no significant differences between slopes calculate by OR and RMA for an easy reading, only graphs related to RMA regression were reported (Fig. 3–6). Looking at the slopes of the fitted regression lines, it is possible to confirm a positive relation between AM (WP) and AM (DW) for all countries. To understand the strength and the direction of this relation, the value of the slope is a good indicator but it is important to understand whether the differences between these numbers are statistically different. As previously said, all symmetric regression models lead to a very similar conclusion, so, in order to compare slope values among countries, only data from RMA were used: results in terms of *P*-values as shown in Table 8. According to this table, slopes are not statistically

Table 6. Results of matched-pairs test[1] (DW vs. school)

Country	Typology	*N*. cells	Interval[2]	*P*-value[3]	DW > WP
Austria	DW	37	(4.979; 5.185)	(*t*-Student) 0.130	no
	School	37	(4.830; 5.402)		
Italy	DW	493	(4.453; 4.550)	(*t*-Student) 0.033	no
	School	493	(4.534; 4.646)		
Germany	DW	33	(4.177; 4.462)	(*t*-Student) <0.001	no
	School	33	(4.521; 4.877)		

[1]Matched-pairs *t*-test cannot be weighted.
[2]95% Cox confidence interval (20).
[3]When $P < 0.05$, the null hypothesis is rejected.

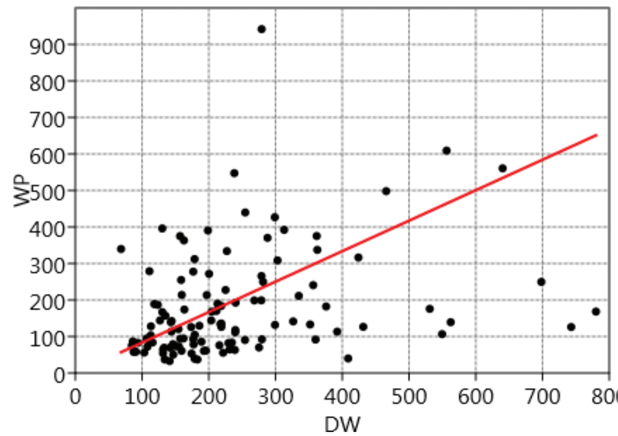

Fig. 3. Fitted RMA model between arithmetic mean (AM) in Bq/m^3 for workplaces (WP) on y axis and AM in Bq/m^3 for dwelling (DW) on x axis – Austria.

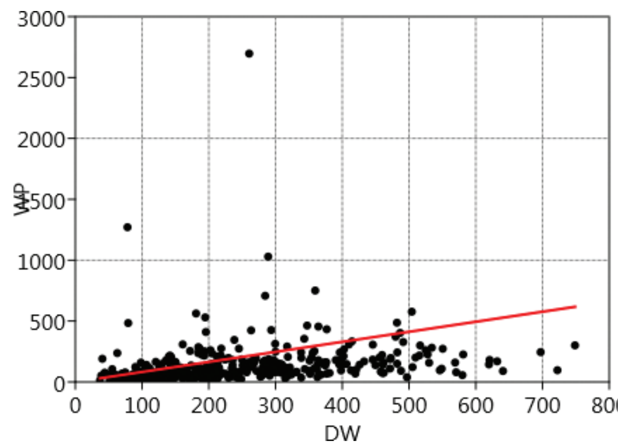

Fig. 4. A fitted RMA model between arithmetic mean (AM) in Bq/m^3 for workplaces (WP) on y axis and AM in Bq/m^3 for dwelling (DW) on x axis – Finland.

Table 7. Estimates of the OR and RMA regression model coefficients (DW/WP)

Country	*N*. cells	Slope±SE[1]		Interval[2]	
		OR[3]	RMA[4]	OR[3]	RMA[4]
Austria	113	0.791 ± 0.058	0.834 ± 0.05	0.555–0.968	0.650–0.988
Finland	373	0.728 ± 0.042	0.825 ± 0.034	0.119–0.956	0.525–1.076
Germany	48	1.288 ± 0.099	1.249 ± 0.087	0.899–1.498	0.940–1.427
Italy	623	1.033 ± 0.025	1.028 ± 0.022	0.934–1.122	0.942–1.105
All	1,157	0.865 ± 0.023	0.904 ± 0.019	0.693–0.848	0.759–0.885

[1]Standard error
[2]95% confidence level
[3]Orthogonal regression
[4]Reduced main axis regression

different ($P > 0.05$) for the pair Austria / Finland and Italy / Germany, but there are for the other pairs. Comparison of all four countries leads to $p = 3.7 \cdot 10^{-11}$, that is, the slopes are different.

This finding can also be visualized through statistical plots (see Fig. 7) of the normalized difference between DW and WP. It is apparent that the association between radon concentrations in DW and WP is

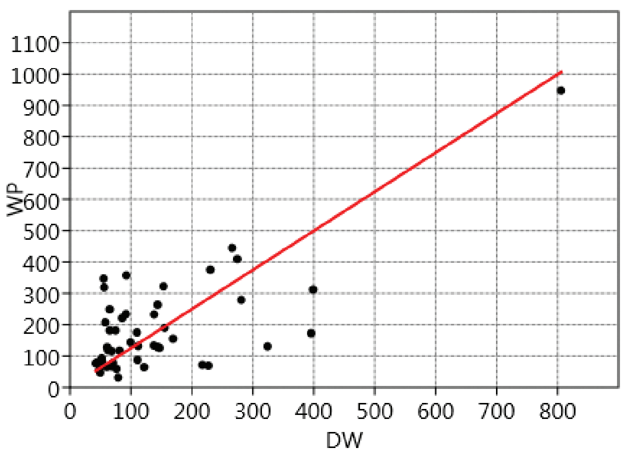

Fig. 5. A fitted RMA model between arithmetic mean (AM) in Bq/m³ for workplaces (WP) on y axis and arithmetic mean (AM) in Bq/m³ for dwelling (DW) on x axis – Germany.

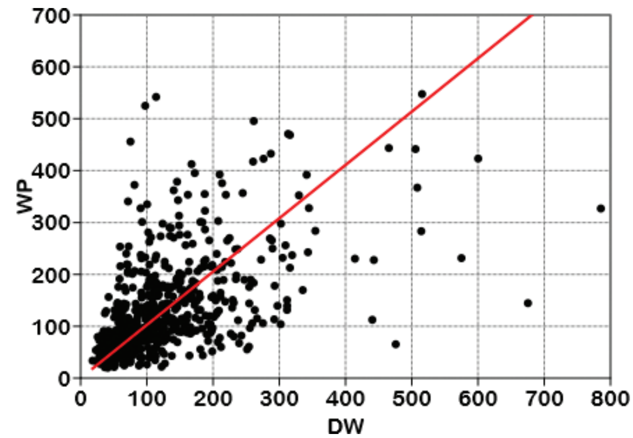

Fig. 6. A fitted RMA model between arithmetic mean (AM) in Bq/m³ for workplaces WP) on y axis and arithmetic mean (AM) in Bq/m³ for dwelling (DW) on x axis – Italy.

Table 8. *P*-values to the hypothesis that RMA slopes between countries are equal

Country	Austria	Finland	Germany	Italy
Austria		0.87	$P < 0.05$	$P < 0.05$
Finland	0.87		$P < 0.05$	$P < 0.05$
Germany	$P < 0.05$	$P < 0.05$		$P < 0.05$
Italy	$P < 0.05$	$P < 0.05$	$P < 0.05$	

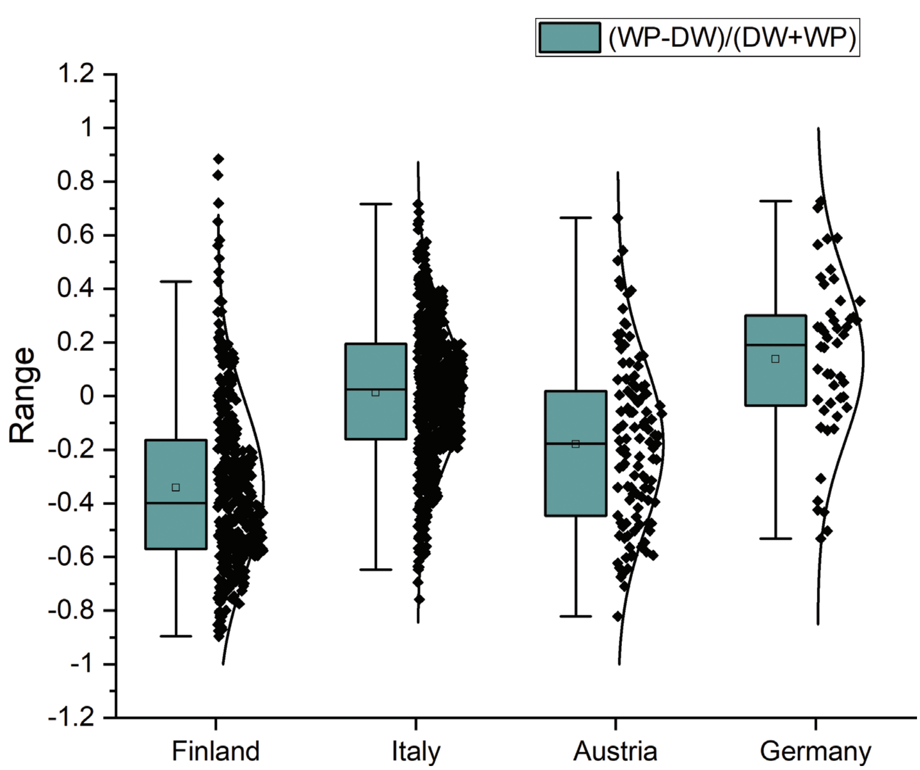

Fig. 7. Box plots of q = (WP – DW)/(DW + WP) calculated from AM related to Austria, Finland, Germany, and Italy. Boxes: 25, 75% quantiles, median; whiskers: min-max.

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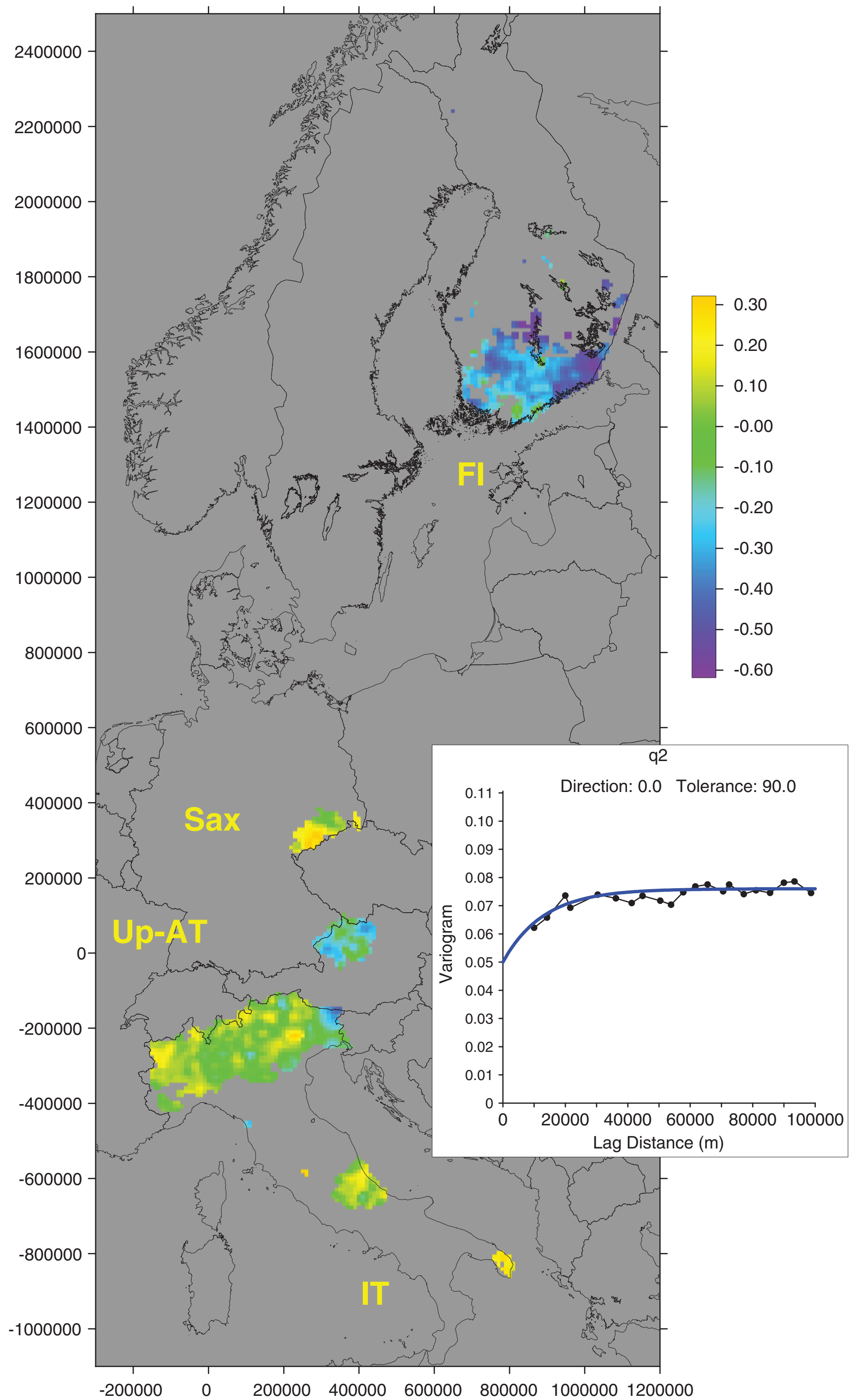

Fig. 8. Geographical pattern of the quantity (WP – DW)/(DW + WP). Inset: Variogram. Coordinates: LAEA (m). IT = Italy, Up-AT = Austria, SAX = Germany, FI = Finland.

different: in Austria and Finland, on the one hand (DW > WP in tendency), and in Italy and Germany, on the other hand (DW < WP), as also reported in Table 4.

Geographical trend of the association

The geographical distribution of the quantity q, estimated with ordinary kriging based on the shown variogram with Surfer v.8 software, is shown in Fig.8.

q = (WP – DW)/(DW + WP),

where WP and DW are the AM of radon concentrations in workplace and dwelling, respectively.

There is very little autocorrelation, as can be concluded from the variogram. While there are differences between the four areas, as discussed in the previous section, trends within the areas may exist; however, this cannot be convincingly proved given the data. Altogether, the analysis of section seems to be qualitatively confirmed. From the grid underlying in Fig. 8, spatial mean values of the ratios q can be calculated. The contrast between Austria/Finland and Italy/Germany (Fig. 9) is similar to the one found previously (Fig. 7). The statistics for grid data and data of cells (original data set) are provided in Table 9.

Summary and conclusion

A study was carried out on indoor radon data from Austria, Italy, Finland, and Germany. The datasets consist of indoor radon data (as annual average concentration at ground floor) on DW and WP. This study aimed to evaluate whether the distributions of radon in DW and WP were statistically different.

Indoor radon data on WP were aggregated in the same grid as already done for the data related to DW in the

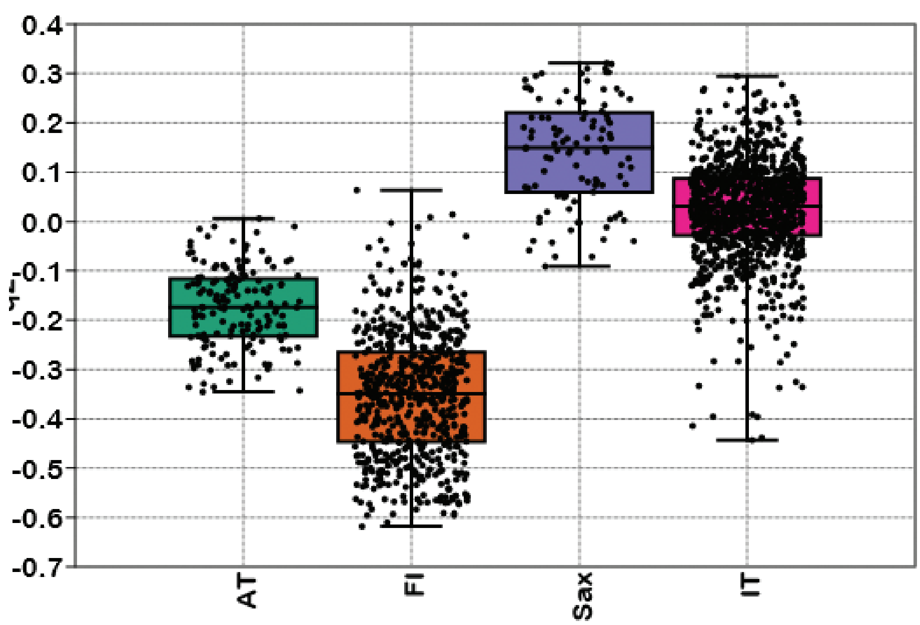

Fig. 9. Box plots of q = (WP – DW)/(DW + WP) calculated from AM of grid data related to Austria (AT), Finland (FI), Germany (Sax), and Italy (IT). Boxes: 25, 75% quantiles, median; whiskers: min-max.

Table 9. Statistics calculated for the quantity q = (WP – DW)/(WP + DW) from the grid underlying Fig. 8 compared with the statistics on dataset

Country	Data/Grid	*N*[1]	Arithmetic mean (AM)[2]	Standard error (SE)[3]	Standard deviation (SD)[4]	Median
Austria	**Data**	113	–0.180	0.029	0.312	–0.178
	Grid	156	–0.174	0.006	0.080	–0.174
Finland	**Data**	373	–0.342	0.016	0.313	–0.399
	Grid	606	–0.351	0.005	0.126	–0.349
Germany	**Data**	48	0.138	0.044	0.304	0.191
	Grid	102	0.141	0.011	0.108	0.150
Italy	**Data**	623	0.013	0.011	0.264	0.025
	Grid	1,005	0.024	0.003	0.101	0.031

[1]*N* grid is the number of grid cells on which the quantity has been estimated. *N* data is the number of cells that represent data in dataset.

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European Indoor Radon Map (10 km × 10 km grid cells). Thus, two structurally equal datasets for each country were generated to be statistically compared.

The results of statistical analysis suggest that in all the countries the associations between radon concentrations at WP and in DW are different in different regions. Even the directions of the associations, DW > WP or DW < WP, are different. The different distribution is neither attributable to the effect of geology nor to the effect of different sample sizes. The available data do not allow a final conclusion about the reason of the finding: further investigation is still needed to explain these inconsistencies between the results: on-purpose designed surveys could be a useful tool to better understand this phenomenon. A possible reason could be the compositions of the 'workplace' sets: indeed, different types of WP have different radon characteristics.

Even if DW could be more suitable than WP to investigate radon distribution in a given geographical area, it is worth noting that they do not represent 'all buildings', due to the influence of different anthropogenic factors.

The application of different regression models to evaluate the relationship between the two variables showed that in all countries, cell means of indoor radon levels in DW and in WP seem to have a statistically significant positive correlation. At the same time, the analysis confirms that DW and WP have different Rn characteristics, in general.

Conflict of interest and funding

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Authors' contribution

Conceptualization, R.T., G.C. P.B.; data curation, R.T., F.L., G.C.; formal analysis, R.T. F.L., G.C., P.B., G.B., M.G., E.S.; interpretation, R:T, F.L., V.G., G.C., P.B., O.H, F.S., G.B., M.G., E.S ; data acquisition, VG, O.H., T.H., F.S: ; writing—original draft, R.T, F.L., G.C.; writing—review & editing, R.T., F.L., G.C., P.B.; English revision, G.B., P.B. All authors have read and agreed to the published version of the manuscript.

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Appendix 1. Regression model

Orthogonal (OR) or main axis (MA) regression:
Starting from a linear regression:

$$y = b \cdot x.$$

In orthogonal (MA) regression, the residual are equals to:

$$r = \frac{y - bx}{\sqrt{1 + b^2}}.$$

In the logic of least-square (LSQ) optimization, the Σ of residues² are minimizes. For common linear regression (CLR), not symmetric, the solution is as follows:

$$b(Y|X) = \frac{Sxy}{Sx^2},$$

where

$$Sxy = \sum_{i=1}^{n} x_i \cdot y_i \text{ and } Sx^2 = \sum_{i=1}^{n} x^2.$$

Since this type of regression is not symmetric:

$$b(X|Y) \neq \frac{1}{b(Y|X)}.$$

For OR, the slope can be written as follows:

$$b(OR) = \frac{Sy^2 - Sx^2 + \sqrt{\left(Sy^2 - S2^2\right)^2 + 4\left(Sxy\right)^2}}{2Sxy}.$$

It is easy to demonstrate that

$$b(OR; X|Y) = \frac{1}{b(OR; Y|X)},$$

that is, the slope is reciprocal symmetric against exchange of X and Y, contrary to common regression.

Reduced main axis (RMA) regression:
Here, the slope is simply the geometrical mean of the conditional slopes Y|X and X|Y:

$$b(RMA) = GM\left[b(Y \mid X), \, {}^{1}\!/\!{}_{b(X \mid Y)}\right] = \sqrt{\frac{Sy2}{Sx2}}.$$

Also, in this case $b(RMA; X|Y) = \dfrac{1}{b(RMA; Y|X)}$