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The role of risk communication in radon mapping, risk assessment and mitigation activities in Sardinia (Italy)

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Abstract. In 2014, the Sardinian Regional Department of Hygiene, Health and Social Security promoted the Regional Prevention Plan, which embraced the protection of the population from exposure to indoor pollutants, including radon gas. The programme foresaw: the drafting of "Guidance for the construction/renovation of buildings"; radon monitoring and mapping activities during a dedicated campaign based on geological surveying; a radon health impact assessment; community involvement and a radon risks communication campaign. The objectives of the programme were focused to protect Sardinian population from radon risk, with special reference to vulnerable and susceptible subjects, spread knowledge about risks and the opportunities to reduce them. Using a Health Impact Assessment procedure, the number of attributable deaths was estimated based on radon exposure levels, also visible as preventable events by implementing preventive actions. The purpose of this article is to illustrate the activities carried out, with specific reference to the use of communication to develop each action, to understand strengths and weaknesses and the lessons to be applied in Sardinia and other areas.

Monitoring and evaluation results indicate that the health of populations living in radon-exposed areas can be significantly improved by reducing exposure to radon and synergistic risk factors. It is essential to strengthen awareness-raising events using historical and acquired knowledge, and to monitor progress in order to reinforce further actions, as these schemes should be planned for the long term, with central coordination and continuous evaluation.

The case of radon risk management and communication in Sardinia offers a number of suggestions and lessons learned, both for the continuation of the work that is expected to be very intense in the coming years, and for the problems that may arise in other regions and countries affected by radon risk.

1 Introduction

Radon gas has long been known for its undesirable effects on health, both for workers and the general population. It has been studied, as a decay product of uranium and thorium, along with a range of radioactive substances since the early 1900s. The results of numerous studies were compiled until, in 1988, radon and its decay products were classified by the International Agency for Research on Cancer, IARC, of the World Health Organization, WHO, as human carcinogens for lung cancer, in Group 1 (IARC, 2001). The International Commission on Radiological Protection (ICRP) emphasised the magnitude of the public health problem and is-

sued specific recommendations on health risk and protection from radon in living and working environments (ICRP, 1993; Lecomte et al., 2014).

In Italy, a series of legislative measures have been applied that derive from the promulgation of European Union Directives, which according to current law must be adopted in each of the member states. There have been seven EURATOM Directives: 80/836, 84/466, 84/467, 89/618; 92/3, 96/29, 13/59. The last one was integrated into Italian legislation for the protection of workers (and therefore only concerns workplaces) in 2008 (Law n.81/2008) and updated for the protection of citizens in December 2020 (Law 101/2020); the implementation of the last law is in progress, including a National Plan and homogeneous rules for monitoring and for the definition of risk.

Further measures had dealt with the issue of radon risk for the general population. The Ministry of Health's National Prevention Plan for 2014–2018 (implemented at the regional level) with reference to the issue of indoor pollution, recommended to "promote good practices in the field of sustainability and eco-compatibility in the construction/renovation of buildings, also in relation to radon risk", proposing as a core indicator the "approval of guidelines to orient building regulations in an eco-compatible way". As a consequence, the Sardinian Regional Department of Hygiene, Health and Social Security promoted in 2014 a programme dedicated to protecting the population from exposure to radon gas as an indoor pollutant (Regional Prevention Plan 2014–2019, Deliberation of the Regional Council n.30/21 of 16 June 2015, Action P-8.2.4).

The programme included a number of different actions to monitor environment and health, to plan prevention activities and to spread information. The complex governance of those activities was supported by a network of competencies from different field of expertise and scientific background: public administrators, civil servants in public health, environment and building sectors, practitioners, experts in environmental monitoring, physics, geology, engineering, architecture, epidemiology, health policy, communication. The communication of scientific knowledge and its use for reporting and decisions in this context is clearly a priority: the basic need is to create a communication between professional communities with different norm and practices; but other necessity emerge organising the whole process, like identifying internal and external stakeholder and engage them according with the objectives, produce shared knowledge, transfer this knowledge to public administrators with different responsibility and to the general public. The process of science communication is then in place, and needs a specific support (Fishhoff, 2019). Risk communication represents a component of this effort: dealing with the radon risk meant organising extensive monitoring throughout Sardinia, informing a significant number of mayors and citizens to convince them to take measurements. This was done in order to build a knowledge base and define the areas at risk. Consequently, it was possible to plan prevention activities on which to base a risk communication campaign extended to the community and stakeholders. Further types of communication activities were also necessary for developing the process: internal communication within the group of experts, inclusive communication to inform and guide towards specific actions, external communication to inform a wider audience (Cori, 2016).

The case of radon risk communication management in Sardinia offers a number of suggestions and lessons learned, both for the continuation of the work that is expected to be very intense in the coming years, and to face the problems that may arise in other regions and countries affected by radon risk. The aim of this article is to illustrate the activities carried out, to understand what the strengths and weaknesses are and what lessons can be applied in this and other territories, specifically in the domain of communication, that is ancillary to the management of radon risk.

The recent publication of "The Potsdam radon communication manifesto", designed "to support states to prepare an effective and efficient communication strategy and to avoid the main pitfalls in radon communication" is a valuable reference to evaluate the work done and envisage the potential for progress and improvement (Bouder et al., 2020).

2 Radon risk communication

Radon risk communication is a topic that has raised interest in every situation where this risk exists, due to a number of contextual and element-specific data. It is possible to identify a consistent literature referred to radon communication, supporting the implementation of protection measures and public health programmes (Sandman et al., 1987; Weinstein et al., 1988; Vogeltanz-Holm and Schwartz, 2018; Bouder et al., 2020; Lacchia et al., 2020; Martell et al., 2021). Risk perception have been studied from multiple perspectives, and several approaches are useful to identify the reaction of people to risk information, that are strictly linked to their role and possibility to act. The context of radon risk communication can be defined as a typical case of "care communication", according to the definition of Lundgren and McMakin (2018), where the experts have acquired an accurate knowledge of the risk, but the risk itself is poorly known and understood by the general public and specifically by the exposed population. Moreover, radon risk experts explain that the problem of indoor air pollution from radon is relatively easy to resolve with mechanical solutions or devices that facilitate air circulation in the buildings.

By reviewing a number of previous studies, the conclusion can be drawn that in general people's knowledge about radon is not accurate, both regarding the presence of risk and health effects, that it can be confusing and that "appear to reflect cognitive defence mechanisms by which individuals believe that *their* risk from radon are lower than the risks faced by others" (Vogeltanz-Holm and Schwartz, 2018). According to

the psychometric paradigm, people judge the riskiness of a hazard based on the combination of a number of (perceived) risk characteristics (Slovic et al., 2000). The element radon has by its very nature a number of factors to be taken into account in the perception of risk: it is an invisible, not observable, odourless gas that does not cause immediate health effects such as coughing, irritation or other; exposure is not voluntary and people not know whether they are exposed to the risk; the severity of the risk is not controllable; the risk is certain for the individual person, but is not understood; many people are exposed to the risk, but it must be measured at each individual location; the risk is new and unfamiliar, even if it is known to science. Several characteristics should contribute to increasing the level of perception and a systematic review suggests that public information materials about radon require revision, to improve knowledge and comprehension and stimulate public mobilisation (Vogeltanz-Holm and Schwartz, 2018). Today, several experiences of citizen involvement indicate that it is possible to implement public awareness activities and support the growth of competence and capacity to deal with problems such as radon pollution at home (Cori, 2016; Duranova et al., 2020).

By qathering as much information as possible about the specific context, the main aim of radon risk communication should be to disseminate information about the hazard and the means to limit and prevent it, being exhaustive and explaining the mechanisms of exposure, control and limitation. In the case of radon, communication assumes further relevance, urgency and necessity with regards to actors who can take action to identify and manage the risk.

3 Methodology

This article describes the activities carried out by different actors in Sardinia Region to implement the directives of the Regional Prevention Plan 2014–2019 regarding radon risk, from 2015 to 2019, when the results of the work carried out were presented at a public conference. Some additional elements concern on going and planned activities and how they are using the results of the work previously carried out to implement further communication and the prevention activities foreseen by the present Regional Prevention Plan 2020–2025, that also includes indoor air quality and radon risk. A specific and deeper analysis will be provided regarding the work done to identify radon risk areas based on geological data, due to the focus of the Journal publishing the present article. The communication activities will be specifically underlined in each phase of the activities illustrated.

The methods used for each activity, like radon monitoring and Health Impact Assessment are reported in the specific paragraphs (4.3, 4.4), in order to make it easier to understand each activity carried out.

4 Implementing a radon prevention programme supported by communication activities

The Sardinia Regional Prevention Plan 2014–2019 (Action P-8.2.4) included several activities, to be developed coordinately, simultaneously and with multiple competencies involved: the Regional Steering Committee was at the Department of Health, which allocated financial resources to the Sardinian Regional Health Protection Agency, ATS, and involved different actors coordinated in Working Groups for the different tasks: professional associations, the Sardinian Regional Agency for Environmental Protection, ARPAS; the Institute of Clinical Physiology of the National Research Council; the National Association of Italian Municipalities.[1]

The main activities are illustrated in this article, with a specific reference to the communication domain, that acquired a relevant role to be able to perform this complex program. The phases of the work are summarised in Table 1 below, indicating which type of communication was used in each phase. The planning phase started in 2016, the on-field radon monitoring covered two semesters, and the mapping and risk evaluation work was completed within the end of 2018.

- Activity A: Organising the dedicated working group and drafting the document "Guidance for the construction/renovation of buildings". The document was drafted during one year of activity by a dedicated Intersectoral Working Group and assumed by the regional administration in January 2019 (Sardinia Regional Government, 2019a).

- Activity B: The first phase of the ARPAS Radon Project consisted of knowledge building, examination of the territory, study of updated literature, geological mapping, and the choice of radon reference values. The collection of useful information was developed at the beginning, during four months. The length of the ARPAS Radon Project was two years.

- Activity C: Preparation of informative materials and legal binding sheets: description of the activity; materials to be used by the municipal technician in charge of the fieldwork; Inform consent; description of the dosimeter and its use; questionnaire to collect information about the building monitored; press release to start the activity; presentations for training activities. This was also an activity developed in the first two months of the project; the press conference presenting the ARPAS Radon Project took place in January 2017.

- Activity D: Two training courses for the municipal technician in charge of the fieldwork. This was specifically devoted to share the knowledge needed to perform an

[1] https://www.sardegnasalute.it/index.php?xsl=316&s=9&v=9&c=93932&na=1&n=10, (last access: 23 March 2022)

accurate monitoring activity, and to collect all the information needed to build a homogeneous information referred to each monitored place. In particular on: how to identify buildings to be measured; premises to be monitored; how to place the dosimeter. The completion of the questionnaires was also part of the training, due to the numerous information to collect. The training for municipal Radon Project officers was carried out by the various specialists involved in the project (physicists, geologists, environmental and health biologists), in two training sessions over two months. All the information and training materials, in Italian, are available on line.[3]

- Activity E: Radon monitoring in 142 Municipalities. ARPAS working group and support for monitoring and information gathering during the implementation. There were two monitoring campaigns, each lasting six months.

- Activity F: Additional campaign involving citizens with the "snowball" method, which was based on word of mouth and informal proposal of radon monitoring to friends, colleagues and acquaintances. This activity, in order to expand the number of monitored buildings, was developed in parallel with the previous one.

- Activity G: Mapping of the Region. Collection of further material from previous monitoring campaigns, from years 1991–1997. Verification and control of radon measures by the ARPAS working group, and reporting for the formal definition of risk areas. The collection and processing of data, which began at the end of the first six-month instrumental monitoring and ended with the production of the final report, took place during 11 months of the ARPAS Radon Project.

- Activity H: The Health Impact Assessment and reporting were carried out during six months by the Institute of Clinical Physiology of the National Research Council, in collaboration with ARPAS. The final report was accepted by the Sardinia Regional Administration (Del. n. 7/49 del 12.02.2019).

- Activity I: Preparation of dissemination material. Information and dissemination.

4.1 Guidance for the construction/renovation of buildings

The drafting of "Guidance on sustainability and eco-compatibility in the construction/renovation of buildings in order to improve indoor air quality, also in relation to radon risk, to orientate building regulations in an eco-compatible way" was implemented through a Intersectoral Working Group (Determination of the Director General of Health no. 38/2016, no. 1370/2016, no. 1101/2017 and no. 1195/2017). The Intersectoral Working Group included representatives of: the Regional Departments of Health, Environmental Protection and Urban Planning; ATS (Prevention Departments); ARPAS; the National Association of Italian Municipalities; the Professional Associations of: Architects and Planners, Engineers, Geologists; the Department of Medical Sciences and Public Health of the University of Cagliari.

In 2016 the Intersectoral Working Group collected documentation (data, studies, guidelines, building regulations) on sustainability and eco-compatibility in the construction/renovation of buildings, with a specific reference to the radon risk, at regional, national and international level, in order to expand the knowledge framework on issues related to indoor air quality and on systems for reducing/abating indoor pollutant levels.

To develop this task, the communication activities were implemented mainly within the group, and in close connection with the scientific community working on the issues of indoor air quality, radon prevention, sustainable building. The document was drafted and officially acquired by the Sardinia Regional Government on January 2019 (Sardinia Regional Government, 2019a). The presentation and illustration of the document was done during meetings with the responsible institutions, workshops and training session dedicated to Regional civil servants and functionaries responsible in health, environment, construction and school sectors.

The practical application of the guidance document would only have been possible by mean of an accurate knowledge of the actual situation on the ground. In fact, the activity described below was in place and the knowledge acquired around building remediation and radon exposure prevention ready to be transferred to the responsible authorities and the community in general. A specific communication activity addressed to Public Authorities, the construction sector and Professional Associations was also planned as a follow up and described in the following pages.

4.2 Planning of the radon monitoring and mapping activity

The previous activity foresaw, among other actions, that "if more detailed information on the radon risk in the regional area is needed, a special agreement with ARPAS will be signed to classify the territory and identify the areas at risk". ATS has therefore established to instruct ARPAS to proceed with the "Classification of the regional territory of Sardinia with identification of radon risk areas". To this end, ARPAS prepared a Radon Project in 2016, performed field surveys, data processing, produced a final report and, in 2019, in collaboration with the Institute of Clinical Physiology of the National Research Council, a Health Impact Assessment and information materials for the general public.

The collection of data on radon risk started using the knowledge available to map the territory, on the basis of the administrative data and of the geological composition

Table 1. Activities developed under the Sardinia Region indoor radon prevention programme and related communication.

Activity	Content	Type of communication
Activity A	Preparation of "Guidance for the construction/renovation of buildings"	Internal communication
Activity B	Knowledge building.	Internal communication
Activity C	Preparation of informative materials and legal binding sheets	Information and risk communication
Activity D	Two training courses for fieldwork	Inclusive communication and risk communication
Activity E	Radon monitoring in 142 Municipalities	Inclusive communication and risk communication
Activity F	Additional radon monitoring campaign involving citizens	Inclusive communication and risk communication
Activity G	Mapping of the Regional risk radon areas.	Internal communication
Activity H	Health Impact Assessment and reporting.	Internal communication
Activity I	Preparation and distribution of dissemination material	Information, inclusive communication and risk communication

of the Sardinia Island. The data contained in the Geological Map of Sardinia, a representation including accurate details about a thousand different cartographic units, were structured by lithological units[2] to better meet the needs of the Radon Project. The result was the Lithological Map of Sardinia 1 : 25 000. The rocks of Sardinia were subdivided, on the basis of their origin, into three major classes: (A) magmatic rocks; (B) metamorphic rocks; (C) sedimentary rocks. These three main groups have been subdivided into eight typologies (level 1), within which the main lithologies present in Sardinia have been defined and reduced to 33 lithological units (level 2). Data on indoor radon were then referred to the two levels. The lithological map has proved to be of strategic importance in verifying the presence of radon in buildings and linking it to the type of rocks present in each area.

The Regional territory was divided into grids in order to obtain homogeneous average statistical values, which are homogeneous because they refer to one-dimensional regular grids with an equal number of measuring points. Finally, the administrative boundaries of individual municipalities served to easily identify the presence of urbanised areas.

The mapping activity resulted in the identification of 184 Municipalities, to be tested with 10 detection/measurement points each, in private buildings and schools; monitoring was performed only at the ground floors of each building, which are the most exposed to radon if it is present in the environment; ground floor is, as a consequence, the place where human exposure can be higher.

The reference levels for radon concentration that were chosen in the data processing are:

- the values of 100 and 300 $\mathrm{Bq\,m^{-3}}$ proposed by the WHO for dwellings (Zeeb and Shannoun, 2009), which recommends that countries should adopt a reference level of 100 $\mathrm{Bq\,m^{-3}}$ as far as possible, or in any case no higher than 300 $\mathrm{Bq\,m^{-3}}$;
- the value of 300 $\mathrm{Bq\,m^{-3}}$ indicated in Directive 59/2013/Euratom (not yet transposed when this monitoring was carried out) as the maximum value for the annual average radon concentration for both residential buildings and workplaces;
- the value of 500 $\mathrm{Bq\,m^{-3}}$, (indicated by Italian legislation as the action level for working environments, above which the employer must implement remedial action to reduce radon concentrations, unless he demonstrates that no worker is exposed to a dose exceeding 3 $\mathrm{mSv\,yr^{-1}}$). Excluded are kindergartens, nursery schools and compulsory schools for which, if the concentration exceeds 500 $\mathrm{Bq\,m^{-3}}$, remedial action must be taken without carrying out a dose assessment.

After this study and planning phase, radon monitoring activities with dedicated instruments begun, foreseeing two monitoring campaigns for a period of six months each. The survey was conducted using solid-state dosimeters with a CR39 plastic detector housed inside a radon-permeable container (holder), in 2 consecutive semesters (March–August 2017 and September 2017–March 2018) by positioning, based on the project objectives, the dosimeters in rooms on the ground floor of the sample buildings. The radon monitoring campaign required intensive and continuous communication activities throughout the fieldwork period. The National Association of Italian Municipalities supported the dissemination of information to the mayors and municipal technicians of the 184 selected cities by way of an electronic mail, while a web site was organised to show the main information, and to allow the download of useful sheets, training modules and administrative materials.[3]

Radon monitoring, as explained below, was supported by specific training, and the communication and comprehension dimensions were constantly taken into account. Upon completion of the measurements, the "Test Report" prepared by the ARPAS Laboratory of Environmental Radioactivity was sent to all the subjects who collaborated/participated in the Radon Project (private buildings and schools) indicating the annual average value of indoor radon concentration measured in the building during the period March 2017–March

[2]Sardinia Geoportal of the Region: https://www.sardegnageoportale.it/, (last access: 23 March 2022)

[3]http://www.sardegnaambiente.it/index.php?xsl=611&s=21&v=9&c=14552&es=4272&na=1&n=10, (last access: 23 March 2022)

2018. The data collected during the survey were treated confidentially and anonymously and only for the statistical purposes of the survey and in any case in compliance with Law 196/03 on the processing of personal data. For these reasons, the "Test Report" was delivered by the Municipality's Radon Project Contact Person in a closed and sealed envelope, with only the building code and address on the first page of the letter. The communication to the family pointed out that the concentration value found in the building had to be compared with the value of 300 Bq m^{-3}, which represented the reference level, as an annual average of the radon concentration in closed environments not to be exceeded, indicated by Directive 59/2013/Euratom (at that time not yet transposed by the national legislation on radon).With regard to the possible problems that radon can cause on one's health, it was pointed out that more information could be obtained from the relevant health authority; references for further knowledge were also provided.With regard to the possible problems that radon can cause on one's health, it was pointed out that more information could be obtained from the relevant health authority; references for further knowledge were also provided. Possible remedial actions were also communicated, summarising in a simple way the information contained in the documents produced by the Region ("Guidance for the construction/renovation of buildings").

The message texts were tested beforehand by means of targeted interviews with five different witnesses with a variety of skills and knowledge. However, it will be necessary to further verify the actual understanding of the messages conveyed, by means of a questionnaire and in-depth questionnaires, which are planned for a new phase of work in progress.

4.3 The radon mapping activity

The results of the monitoring campaign and the supporting activities are shown in Tables 2 and 3 below (Sardinia Regional Government, 2019b). Only two municipalities, out of a total of 184 initially selected, formally refused to carry out the monitoring activities and some partially carried out the required tasks. Further samplings were added during a second monitoring campaign. During the radon monitoring activity 390 samples were collected in schools, and helped to focus the efforts on the protection of students as vulnerable and susceptible groups and school personnel as workers (Larsson, 2014).

The Municipalities included in the Radon Project have been a total 208 in which 1837 buildings, with direct monitoring and the collection of radon measures. A radon map of the Region was produced, as shown in Table 2.

Two training courses (Activity D, Table 1) were held to inform municipal administrators and technical referents about the project, to support the request of monitoring radon levels in public and private buildings. In order to facilitate the participation, the courses were held in the largest cities in Sardinia. A total of 11 days was dedicated to the two training cycles and 148 municipalities participated, corresponding to 80 % of the municipalities involved. The number of participants is specified in Table 3.

The average concentration of indoor radon measured in the 208 municipalities, considering both measurements in private homes and schools, was 116 Bq m^{-3}, with the specific value indicated in Table 4 below.

The distribution of radon concentration values of buildings (Table 5) shows that the latter is lower than 300 Bq m^{-3} (maximum reference level indicated by Directive 59/2013/Euratom), for 93 % of sample buildings (equal to 1704 buildings), while 7 % of the sample (equal to 133 buildings) has values above 300 Bq m^{-3}. In particular, 4.2 % of the sample (equivalent to 78 buildings) has values between 300 and 500 Bq m^{-3}, and only 3 % of the sample (equivalent to 55 buildings) has values above 500 Bq m^{-3} (action level for workplaces provided by the Italia national law).

In order to obtain, from the indoor radon concentration values relative to the 208 municipalities of the regional sample, indoor radon concentration values for the entire regional territory (377 municipalities), two geostatistical techniques were applied, considered the most appropriate for the achievement of the objectives of the Radon Project. These techniques are a "kriging" method (Matheron, 1976) and a method of "lithogeostatistical processing – LGS" borrowed from the method proposed by Miles and Appleton (2005), which builds interpolations on the basis of a criterion based on the specific territorial contribution of lithologies. On the basis of these elaborations, the value of the probability of the exceedance of the reference level of 300 Bq m^{-3} has been estimated for each municipality in Sardinia.

The distribution of the classes of indoor radon concentration values of the buildings was located in 26 lithological units involved (in 7 lithological Units out of the total 33 defined there are no buildings in which radon measurements have been made). The estimation of this distribution (Fig. 1) showed that:

- indoor radon data related to the buildings "Homes – Schools" on intrusive magmatic rocks show the highest values of indoor radon. They also show the highest values of geometric mean (GM) (>100 Bq m^{-3}) than the other lithologies, and there are many outliers with values >500 Bq m^{-3}. Among the magmatic intrusive lithologies, the highest GM concentrations (with values of 120–208 Bq m^{-3}) are present in buildings on monzogranites and granodiorites;

- indoor radon data related to buildings on effusive magmatic rocks, show values tending to be below 100 Bq m^{-3}, with a GM of 47 Bq m^{-3} and 37 Bq m^{-3} respectively in schools and homes;

- the data for buildings on parametamorphic rocks show that 50 % of the data are above 100 Bq m^{-3} with a GM

Table 2. Panel summary of radon measurements gathered during the Sardinia Regional Agency for Environmental Protection Radon Project.

OVERVIEW OF INVESTIGATIONS DONE IN 2017–2018	
ARPAS radon measurements	
Municipalities in the sample chosen by Radon Project providing complete information: questionnaire + dosimeter + evaluation of concentration (Activities C, D, E, Table 1)	142
Number of monitored buildings	1399
ARPAS further radon measurements (Activity F, Table 1)	
Volunteers participating to the additional campaign: questionnaire + dosimeter + evaluation of concentration	58
Number of monitored buildings	190
National radon campaign data (1991–1997) (Activity G, Table 1)	
Review of data provided by National sources (National Health Institute and National Agency for New Technologies, Energy and Sustainable Economic Development: questionnaire + dosimeter + evaluation of concentration	108
Number of monitored buildings	248
Total data available	
Total Municipalities	208
Total number of monitored buildings	1837

Note: Numbers shown for buildings and dosimeters are validated numbers only.

Table 3. Summary of training courses administered during the Sardinia Regional Agency for Environmental Protection Radon Project.

Province	Municipalities selected by Radon Project	Participants 1st course	% on selected Municipalities	Participants 2nd course	% on selected Municipalities	Total participants	% on selected Municipalities
Cagliari	32	19	59 %	8	25 %	27	84 %
Nuoro	32	16	50 %	10	31 %	26	81 %
Ogliastra	15	9	60 %	4	27 %	13	87 %
Oristano	30	19	63 %	2	7 %	21	70 %
Olbia Tempio	21	10	48 %	4	19 %	14	67 %
Carbonia Iglesias	10	10	100 %	0	0 %	10	100 %
Sassari	30	21	70 %	4	13 %	25	83 %
Villacidro	14	5	36 %	7	50 %	12	86 %
Total number	184	109	59 %	39	21 %	148	80 %

of 88 and 70 Bq m^{-3} respectively in schools and homes; in several buildings the values exceed 300 Bq m^{-3};

– indoor radon data related to buildings on sedimentary rocks present low GM values (70 and 49 Bq m^{-3} respectively in schools and homes), and there are still many values >300 Bq m^{-3}.

To complete the task, a classification of the regional territory with the identification of areas at risk was performed by ARPAS. Risk areas were defined as municipalities where the probability of exceeding the reference level of 300 Bq m^{-3} affects more than 30 % of the buildings. These areas involved 49 municipalities in Sardinia.

The following Fig. 2 represents the classification of the regional territory in relation to the probability of exceeding the reference level of 300 Bq m^{-3} in confined environments (indoor), both residential buildings and buildings used for working activities.

4.4 Assessment of lung cancer deaths attributable to radon exposure

An evaluation of radon impact on human health was carried out to quantify the number of deaths attributable to radon exposure, evaluated as proxy by the classification described above, as an indicator of priority interest for communication activities. The impact assessment by epidemiological approach, Health Impact Assessment, of radon exposure in Sardinia was developed on the basis of data collected during the radon monitoring campaign. The HIA was finalized for calculating the number of lung cancer deaths attributable (AD)

Table 4. Main representative values of radon concentrations in the lithological units and a general overview of indoor radon measures detected during the Sardinia Regional Agency for Environmental Protection Radon Project.

Main representative values of the radon concentration ($Bq\,m^{-3}$) in the lithological units (Levels 1 and 2)								
	Lithological Unit	Buildings (n)	Minimum	Maximum	AM	Average	GM	SD
a. igneous rocks	a1. intrusive	409	5.10	2.33	222.00	141.10	**139.20**	256.10
	a2. effusive	247	1.34	717.20	54.45	39.32	**38.22**	61.94
	a3. strand and bundles	5	32.55	1.85	531.90	208.60	**191.10**	763.40
b. metamorphic rocks	b1. parametamorphic	10	15.42	293.30	104.90	74.77	**78.73**	82.87
	b2. orthometamorphic	173	4.16	982.50	122.00	77.19	**73.22**	141.00
c. sedimentary rocks	c1. terrigen	809	3.35	4.38	85.48	54.10	**52.78**	180.00
	c2. carbonatic	173	3.02	502.30	78.65	55.95	**51.48**	87.45
	c3. volcanic-sedimentary	11	8.75	201.40	57.67	32.86	**34.76**	68.05
	Total	1837						
General overview of indoor radon measures		1837	1.00	4.38	116.00	63.00	65.00	193.00

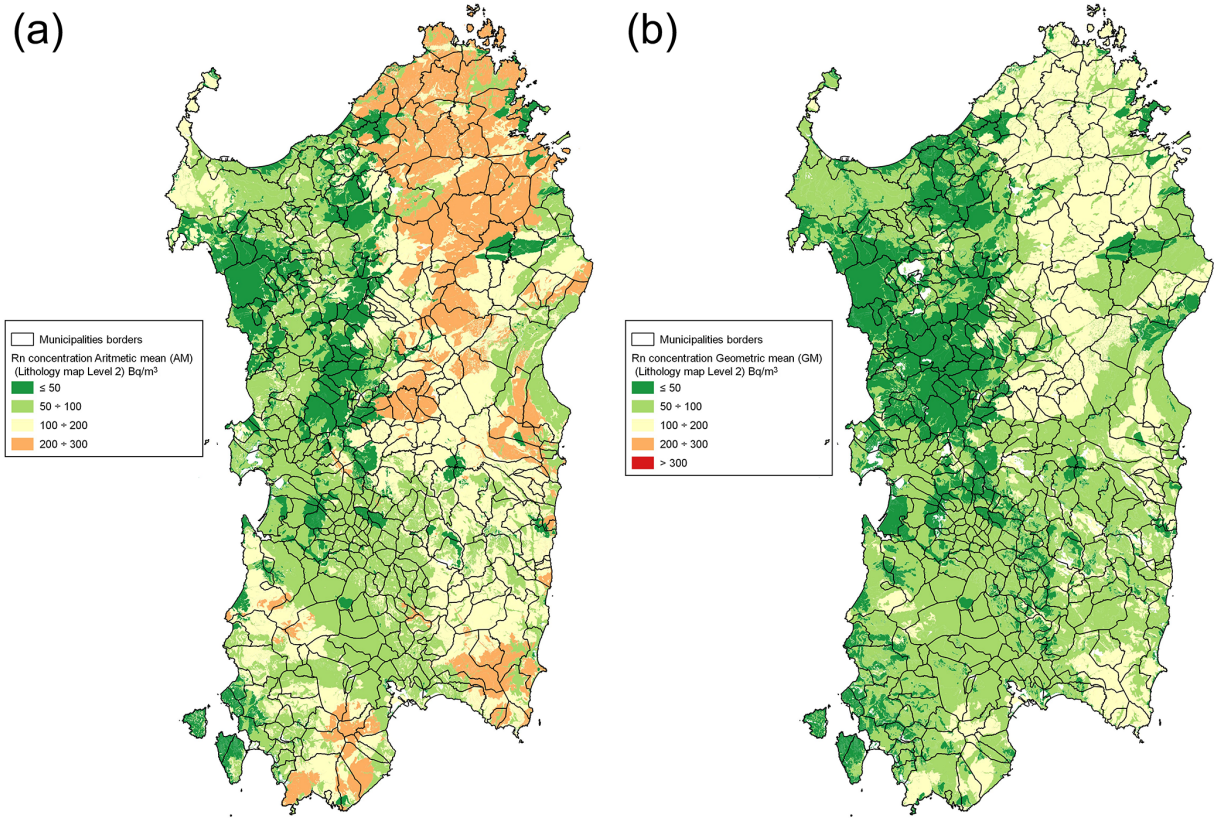

Figure 1. Arithmetic mean **(a)** and geometric mean **(b)** indoor radon concentration values in the Lithological Units based on the regional sample in Sardinia.

to exposure to radon concentration estimated on an annual basis, according to the following formula:

$$AD = LCD \times ERR \times RnC \quad (1)$$

where:

- LCD Lung Cancer Deaths expected per year in the study area = the product of the lung cancer mortality rate in the study area over the study period and the population living in the same period considered as potentially exposed.
- ERR Excess Relative Risk per Rn concentration unit ($1\,Bq\,m^{-3}$) = Relative Risk minus 1;
- RnC Radon concentration (average in the study area).

Mortality and population data were obtained from the Health Information System of the Region of Sardinia (primary

Table 5. Buildings and radon concentration detected during the Sardinia Regional Agency for Environmental Protection Radon Project.

Frequency of buildings (number) per class of radon concentration values (Bq m^{-3})		
Class values	N°	%
0–≤ 300	1704	92.8 %
>300–≤ 500	78	4.2 %
>500	55	3.0 %
Total	1837	100 %

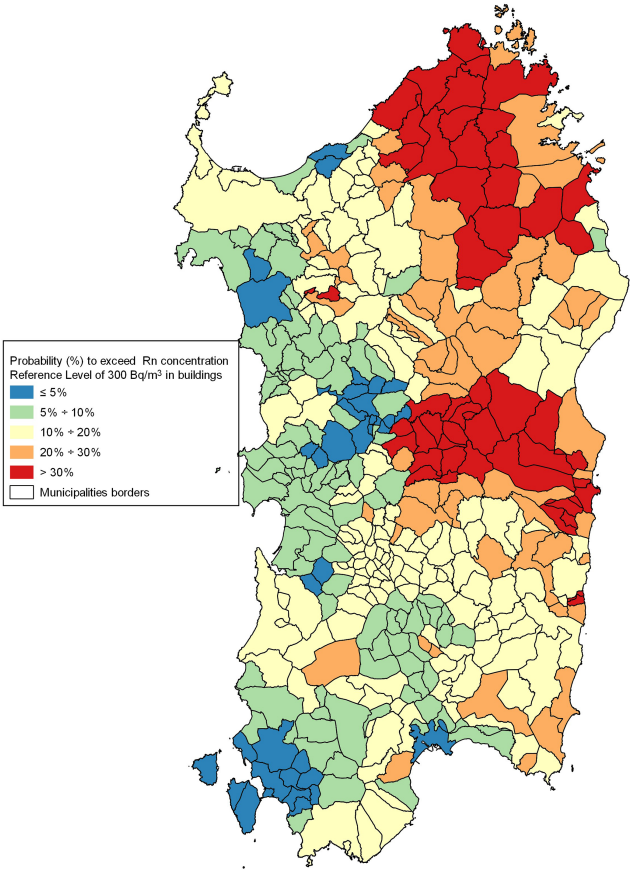

Figure 2. Classification of the regional territory of Sardinia and identification of radon risk areas.

source: ISTAT, The Central Institute of Statistics), radon concentration values from ARPAS' mapping, and the value of 1.16 per 100 Bq m^{-3} (1.0016 per 1 Bq m^{-3}) was used as Relative Risk (Darby et al., 2005).

In the whole region (1 653 144 inhabitants), with a lung cancer mortality rate of 50.3 per 100 000[4] and an estimated average concentration of 116 Bq m^{-3}, radon-attributable cases were 130 out of 832 total expected LCD(attributable fraction 15.6 %); in the highest risk area, including 49 municipalities (129 287 inhabitants), with a lung cancer mortality rate of 42.5 per 100 000[3] and an estimated average concentration of 202 Bq m^{-3}, radon attributable deaths were 13 out of 55 total expected LCD (attributable fraction 23.6 %).

Due to the higher incidence of lung cancer among men compared to women, and an excess of male smokers compared to women, the cases annually attributable to radon exposure were much higher among males: 104 out of 130 at regional level and 10 out of 13 in the area of the 49 municipalities. Smoking, the primary causal factor of lung cancer, is an important confounding factor in the study of the association between radon and lung cancer. In fact, it is associated with radon exposure (smoking is tipically more prevalent in large cities where radon concentrations are generally lower), and is a cause of lung cancer independently of radon exposure, so smoking is usually a negative confounding factor (underestimation of risk). A strong synergy between radon exposure and cigarette smoking has been documented, so that the absolute risk of lung cancer remains about 24 times higher among smokers than among non-smokers as radon concentrations increase (Darby et al., 2005, 2006).

In the area of the 49 municipalities, of the 13 deaths attributable to radon, it was estimated that 9 are among smokers, 3 among ex-smokers and only 1 among never-smokers.

The assessment of mortality impact of radon exposure was developed by the Institute of Clinical Physiology of the National Research Council, Environmental Epidemiology Department. Material, methods and the results were presented and discussed in a working group with experts from ATS, ARPAS and the Regional Department of Hygiene, Health and Social Welfare. Six guided discussions of the working group were held to present the results and to draft the final report; four training sessions during six months and communication activities were held for the wider community of experts involved in radon management.

4.5 Community involvement

The communication of results, based on a dedicated plan, involved multiple stakeholders including: civil servants in the field of health and the environment; public administrators; health professionals committed to spread knowledge about radon-free buildings. An *ad-hoc* booklet for wide distribution was produced to complete the program, including a simple description of radon risk in indoor environments, explaining the interaction with smoking, the monitoring work done in Sardinia, with the risk areas identified, and the indications for measurement and remediation. The booklet collected the information produced during all the phases of the regional programme, simplified and explained taking into account the risk communication principles and suggestions (Slovic, 2012; Hevey, 2017; Vogeltanz-Holm and Schwartz, 2018). This instrument for information and awareness raising

[4]Data Sardinia Region 2007–2015, source: The Italian National Institute of Statistics, ISTAT.

was launched in October 2019, during a public conference in Nuoro, one of the provincial capitals in Sardinia Region, of a province that is widely affected by the problem of indoor radon. During the conference, representatives of the whole cycle of actions done on radon presented their work and the perspectives.

As a follow-up of the work developed the main activities were: a dialogue with the institutions responsible for specific remediation activities, in particular municipalities and schools, based on direct contact and distribution of information via direct messages; an exchange of information with the stakeholders involved in the working groups; a further program of activities for the new Regional Prevention Plan 2021–2025, that is planning a prosecution of the scientific activities and a reinforcement of action addressed to the general public.

A regional plan for school building renovation, called Iscol@, is proceeding in Sardinia, and the responsible personnel was instructed around the knowledge acquired during the radon monitoring campaign, and the indications for building renovation included in the Guidance Document produced by the Region.

5 Discussion, lessons learned and perspectives

To summarize the results of radon activities in Sardinia Region in terms of communication, an intense activity has been carried out, connecting different scientific competencies, civil servants and functionaries, professional bodies and regulatory agencies. This has meant setting up tools for exchange and dialogue between different knowledge, languages and working practices. By having common objectives, such as producing a guiding document, carrying out assessments of areas at risk, and assessing the risk to the population and the most exposed groups, this co-production work has had positive results. The documents produced have become part of the knowledge base of the Region in its various departments; they have been used to prepare specific legislation on radon, for training activities and for the preparation of a simplified brochure aimed at the non-expert communities.

The interinstitutional dialogue, guaranteed by the coordination of the Regional Department of Hygiene, Health and Social Welfare, Directorate-General for Health, allowed the implementation of a complex set of activities, and the possibility to cover the issue of radon from its identification by the experts in environmental sciences, to the prevention measures developed by the health experts, to the remediation activities, in charge of the construction and public work sectors.

The activities involving Municipalities have been addressed to technical personnel and administrators, and also citizens participated in the monitoring on field. This entailed networking and awareness raising activities, dedicate training. After the first phase, ARPAS' experts further mobilized people interested in radon monitoring, enlarging the number of buildings monitored.

The main lesson learnt from this experience is the need of a dedicated coordination and funds, with clear timeline and objectives. The public attention can be mobilized offering the possibility to monitor dwellings and to provide specific information about the property, together with the indications for remediation in case of radon presence.

Examining the results of the radon monitoring campaign, a dedicated activity must be devoted to identify the geological composition of rocks in interested areas, because they can be predictive of a presence of radon. A specific attention must be also dedicated to the monitoring of schools: a susceptible population from 5 to 18 years old students is in fact attending public schools, together with teachers and other school workers, who need to be protected according to the rules for workplaces.

The specific assessment for the Sardinia Region of the radon impact on lung cancer mortality gave the possibility to provide relevant data to fine tune prevention campaigns and communication activities. In particular, the linkage between radon exposure and smoke have been identified as a crucial issue.

The work done after the drafting of guidelines for limiting radon as indoor pollutant, after the monitoring campaign and the mortality impact assessment was a scientific communication among experts (seminars and training), and an effort to transfer the scientific information in simple terms for the non-expert public.

The specific lessons learnt in this context is a positive outcome of the scientific work developed, and the need to increase the participation of non-experts in producing further information material and more interactive instruments, to increase awareness and engage citizen in radon monitoring and remediation. To develop this action a dedicated financial effort should be addressed to provide monitoring facilities and advise on remediation to citizens in risk areas (Martell et al., 2021).

The perspectives include a renovated effort to continue the scientific work and the awareness raising campaign, considering the implementation of the recent law in Italy, that envisage a further identification of risk areas, also in Sardinia. The Law 101/2020 in fact include the definition of risk areas as municipalities where the probability of exceeding the reference level of 300 $\mathrm{Bq\,m^{-3}}$ affects more than 15 % of the buildings. The areas defined today cover municipalities where this probability is more than 30 %. This means that the number of municipalities will sharply increase, reaching the number of 162. As a consequence, all the activities will be planned addressing the newly identified risk areas.

6 Conclusions

Taking up each recommendation of the "The Potsdam radon communication manifesto" (Bouder et al., 2020) we can conclude with the following considerations, based on the development of work presented in the previous pages.

1. Governments and radon risk communicators need to convey science-based communication programs. The Region of Sardinia has promoted a plan to collect scientifically robust evidence and convey it to the public with multidisciplinary work by dedicated experts, as recommended.

2. Radon must be re-framed, from "a natural radioactive gas" to "indoor air pollution". From the outset the issue of radon has been framed as an indoor pollutant, which must be limited in work and living places, as recommended.

3. Policy-makers must take the lead and engage with experts and other stakeholders. The governance of the radon risk has been assumed by the Region's health authorities with a dedicated plan, involving scientific expertise (as indicated in point 1 of the Manifesto) and engaging subjects such as the Regional Environmental Agency and the National Research Council, in support of the Regional Health Service's prevention structures. The monitoring of activities and the involvement of regional managers has been constant, as indicated in the Manifesto.

4. Communications need to be inclusive, coherent and consistent. Communication has been discussed and simplified so that it is understandable to all and inclusive, as recommended, although efforts should be extended to broaden the audience of informed and sensitized citizens and associations. See in particular chap. 4.3, where the information dissemination is explained. As pointed out, a further analysis of the actual understanding of the messages conveyed is planned, by means of a questionnaire and in-depth questionnaires.

5. Communication needs to be sustained over time. Training planning activities and public consultation tables are underway and will continue over time in order to keep the focus and to be able to verify the results achieved, as recommended and introduced in a new program for future activities related to radon risk in Sardinia Region, in the framework of the updated Regional Prevention Plan.

6. Interactive tools may enhance communication. The recommendation to use interactive and modern tools has been considered and is part of the future planning of activities. This notwithstanding, we must say that this is a very weak point for the work developed in Sardinia Region. In fact, the Manifesto states that "Maps tend to draw people's attention and are therefore popular. To be effective these tools need to be truly interactive and offer the relevant level of accuracy to support well-informed decisions. Poorly designed tools may confuse or mislead people and as such should be discouraged. For instance, maps that highlight an entire region as a "high risk" or "low risk" area are misleading because the risks are not equally distributed across an area". The maps defined until now for the Sardinia Region indicate only the borders of municipalities, and are poor in sustaining a real comprehension of the radon risk.

7. Dedicated training programmes must be developed. Training has been taken care of from the beginning and is part of the activities that will be maintained over time, both for officials responsible for managing the radon problem, and for administrators, school teachers, citizens and associations.

8. Support social sciences and humanities research in the radon field. Support for research in the field is part of the activities carried out, but needs be strengthened and integrated with the work done in Italy and internationally, to identify and fill knowledge gaps, integrating the various fields of expertise with the social sciences and humanities as recommended. The objectives of the Sardinia Regional Prevention Plan 2014–2018 were focused to: protect Sardinian population from indoor radon risk, with special reference to vulnerable and susceptible subjects, particularly radon exposed smokers; spread knowledge about risks; inform about the opportunities to reduce risks. Those objectives and priorities have been confirmed in the new Prevention Plan 2021–2025. Future activities will include further dissemination of information to a wider audience, using multimedia tools, questionnaires and interviews, and a review of international literature on communication and radon risk perception to fine tune the instruments produced.

The results of numerous scientific studies indicate that the health of populations living in radon-exposed areas can be significantly improved by reducing exposure to radon and synergistic risk factors. It is essential to strengthen awareness-raising activities using historical and acquired knowledge and to monitor progress in order to reinforce further action, as these activities should be planned for the long term. The number of deaths attributable to differential exposures to radon can be interpreted as avoidable deaths and consequently concentrations should be lowered through proven interventions on existing and new buildings. The impact data estimated in Sardinia, in agreement with those of the literature, reinforce the indication for promoting wide-ranging precautionary actions, aimed at preventing other risk factors recognized as causal for lung cancer, first and foremost to-

bacco smoking, the most powerful factor synergistic with radon, in addition to industrial and vehicular air pollution.

Appendix A: Acronyms

ARPAS: Sardinian Regional Agency for Environmental Protection.
ATS: Sardinian Regional Health Protection Agency.
GM: Geometric Mean.
LCD: Lung Cancer Deaths.
WHO: World Health Organization.

Code availability. The indoor radon concentration values in the areas not covered by measurements were estimated by means of the Lito-Geo-Statistical (LGS) method, developed by ARPAS, https://doi.org/10.5281/zenodo.6424872 (Locci, 2022).

Data availability. The data collected and processed during the study are available upon request to the corresponding author.

Author contributions. LC drafted this manuscript, revised it and presented to the Journal; FB performed the radon health impact Assessment and drafted this manuscript; MC, ID and ES developed the monitoring activities carried out by ARPAS and drafted the manuscript; GS and PN coordinated the working groups, workshops, seminars, training activities and drafted the manuscript; NL, AS and MT supervised the radon activities at the regional level, and revised the manuscript; EB contributed to the final revision and restyling of the manuscript; OC contributed to the final revision of the manuscript.

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