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Digital version of the European Atlas of natural radiation

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ABSTRACT

The European Atlas of Natural Radiation is a collection of maps displaying the levels of natural radioactivity caused by different sources. It has been developed and is being maintained by the Joint Research Centre (JRC) of the European Commission, in line with its mission, based on the Euratom Treaty: to collect, validate and report information on radioactivity levels in the environment of the EU Member States.

This work describes the first version of the European Atlas of Natural Radiation, available in digital format through a web portal, as well as the methodology and results for the maps already developed. So far the digital Atlas contains: an annual cosmic-ray dose map; a map of indoor radon concentration; maps of uranium, thorium and potassium concentration in soil and in bedrock; a terrestrial gamma dose rate map; and a map of soil permeability.

Through these maps, the public will be able to: familiarize itself with natural environmental radioactivity; be informed about the levels of natural radioactivity caused by different sources; have a more balanced view of the annual dose received by the European population, to which natural radioactivity is the largest contributor; and make direct comparisons between doses from natural sources of ionizing radiation and those from man-made (artificial) ones, hence, to better assess the latter.

Work will continue on the European Geogenic Radon Map and on estimating the annual dose that the public may receive from natural radioactivity, by combining all the information from the different maps. More maps could be added to the Atlas, such us radon in outdoor air and in water and concentration of radionuclides in water, even if these sources usually contribute less to the total exposure.

1. Introduction

The Joint Research Centre (JRC) of the European Commission decided to embark on a European Atlas of Natural Radiation (EANR) (De Cort et al., 2011), in line with its mission, based on the Euratom Treaty (EU, 2012), which is to collect, validate and report information on radioactivity levels in the environment. This Atlas is intended to familiarize the public with the natural radioactive environment, to give a more balanced view of the annual dose that it may receive from natural radioactivity and to provide reference material and generate harmonized data for the scientific community.

Natural ionizing radiation is considered to be the largest contributor to the collective effective dose received by the world population (UNSCEAR, 2008: Annex B). The human population is continuously exposed to ionizing radiation from several natural sources that can be classified in two broad categories: high-energy cosmic rays incident on the Earth's atmosphere and releasing secondary radiation (cosmic contribution); and radioactive nuclides generated during the formation of the Earth and still present in the Earth's crust (terrestrial contribution). Terrestrial radioactivity is mostly produced by uranium (^{238}U and ^{235}U) and thorium (^{232}Th) radioactive families together with potassium (^{4}K), which is a long-lived radioactive isotope of the element potassium. In most circumstances, radon (^{222}Rn), a noble gas produced in the radioactive decay of ^{238}U, is the major contributor to the total dose (UNSCEAR, 2008: Annex B, Table 12 and Fig. 36).

The Atlas is a collection of maps of Europe displaying the levels of natural radioactivity caused by different sources: from cosmic radiation to terrestrial radionuclides. As a first task, the JRC started to prepare a European Indoor Radon Map (EIRM), given its great radiological importance (WHO, 2009). Second, the JRC committed itself to map a variable which measures “what earth delivers” in terms of geogenic radon potential (RP), due to the heterogeneity of data sources across

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Europe and the need to develop models for estimating a harmonized quantity which adequately measures or classifies the RP. The European Geogenic Radon Map (EGRM) will also give the possibility to characterize areas for radon risk where indoor radon measurements are not available (Gruber et al., 2013a, 2013b; Bossew et al., 2015). A multivariate classification approach to estimate the geogenic radon potential has been developed and was proposed to the scientific community during the 12th International Workshop on the Geological Aspects of Radon Risk Mapping in September 2014 in Prague (https://remon.jrc.ec.europa.eu/About/Atlas-of-Natural-Radiation/Geogenic-radon/Geogenic-radon). In this context, multivariate estimation means to use information from several quantities which are physically related to radon, to assess a radon quantity of interest. Some countries, which have several input quantities available, have already been testing this approach (Miles and Appleton, 2005; Appleton and Miles, 2010; Szabó et al., 2014; Garcia-Talavera et al., 2013; Ielsch et al., 2017; Drolet et al., 2013, 2014). Although work on the geogenic radon map has been under way for several years, it has proven more complicated than thought initially. For these reasons, in our project we have decided to give priority to the development of those maps that should be part of the EANR but also be used as input parameters in the EGRM, such as the uranium map in soil or bedrock and terrestrial gamma dose rate.

Maps of uranium, thorium and potassium in soil, covering most European countries, have been created. In addition, a methodology was developed to estimate the terrestrial gamma dose rate using EURDEP data (https://remon.jrc.ec.europa.eu/About/Rad-Data-Exchange) (Bossew et al., 2017), and this map-s is now available. Maps of uranium, thorium and potassium concentration in bedrock are available for some countries. Moreover, the annual cosmic-ray dose map has been completed.

Finally, the first version of the European Atlas of Natural Radiation is available in digital format through a web portal (https://remon.jrc.ec.europa.eu/About/Atlas-of-Natural-Radiation), in which all the maps are collected and displayed with the related information.

This paper is structured as follows: Section 2 explains how the website has been designed and the map visualization tools used. In section 3 the different maps are described according to the general schema: a) Introduction, b) Materials and Methods, and c) Results and Discussion.

2. Web design and map visualization issues

2.1. Web design

The goal of the Radioactive Environmental Monitoring (REMon) web portal (https://remon.jrc.ec.europa.eu) is to provide a single point of access for up-to-date radiological information, allowing the general public to improve their understanding of environmental radioactivity. The portal offers geo-referenced data in the form of interactive maps, for general use, in an easy and straightforward manner. It contains a list of associated scientific publications and offers a number of interactive tools to the users.

The following data and services are currently available via the portal (Fig. 1):

- real-time monitoring information collected from automatic surveillance systems in most European countries by the European Radiological Data Exchange Platform (EURDEP). The map shows measurements of environmental radioactivity in the form of gamma dose rate averages and maxima for the last 24 h. These measurements originate from some 5500 monitoring sites operated by competent national authorities in most European countries and worldwide (so far 39 countries in total). Each station displays time series of averaged gamma dose rates for the last 30 days and last 24 h. Moreover, registered users can create custom maps, such as real-time gamma dose rates tracking for user's POI (points of interest).
- information about national radioactivity in Europe through the European Atlas of Natural Radiation (EANR), the topic of this paper.

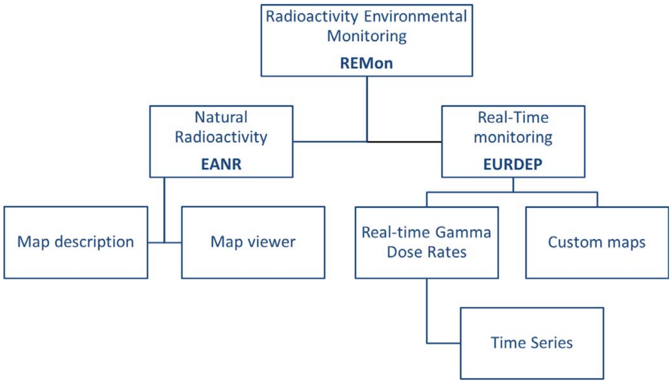


Fig. 1. Schema of the REMon website.

The portal offers a direct navigation through all main sections of the portal such as:

- general information about activities, e.g. Real-Time monitoring, Natural Radioactivity;
- maps and services, scientific publications;
- contact and other relevant information.

The entire web portal has been developed using a modern responsive design, in order to make all web pages automatically detect the visitor's screen size and orientation and change the layout accordingly. The map viewer has been developed using standard interactive mapping tools (https://remap.jrc.ec.europa.eu) in order to display complex radiological data in a simple, intuitive way.

2.2. Projection

The majority of maps reported in the Atlas have been developed using a 10 km × 10 km grid based on the old standard projection for the European Commission at the continental scale, viz. the GISCO-Lambert azimuthal equal-area coordinate reference system with spherical earth and centre of projection at 9° E and 48° N (hereafter referred to as GISCO-LAEA). The reason is historical: by the time the JRC had launched the first map, the European Indoor Radon Map, in 2006, several base maps had been developed before the European Commission decided in 2002 to adopt a new standard projection. This new standard is known as the European Terrestrial Reference System 1989 - Lambert azimuthal equal-area coordinate reference system with spherical earth and centre of projection at 10° E and 50° N (hereafter referred to as ETRS89-LAEA). Several radioecological maps had been developed in the old reference frame. More importantly, the European Soil properties thematic layers in raster format were available in the first version, still in the old GISCO-LAEA coordinate reference system (for the second version in ETRS89-LAEA, see Van Liedekerke et al., 2006). The intention was to overlay the indoor radon maps on these soil maps and study relationships. For further details on GISCO- vs. ETRS89-LAEA coordinate reference systems, see the EC and EuroGeographics report on map projections for Europe (Annoni et al., 2001).

Then the JRC considered how to manage all the maps, originally developed using the GISCO-LAEA spatial reference system into the ETRS89-LAEA projection for displaying the data (see all maps reported in this paper, thumbnails in the digital Atlas). Since for some data, such as indoor radon, the original sample point co-ordinates are not available but only spatial averages over the grid cells, it was decided to simply display the grid with its statistical values in the ETRS89-LAEA projection. This led to the current, compromise solution.

Instead the map viewer in the digital version of the Atlas uses Web Mercator projection. As described above, the data (based on ETRS89-LAEA L52 M^{10} grid for the majority of the maps) have simply been projected and displayed in the Web Mercator projection.

2.3. Other tools

Geostatistical analysis and data mapping have been performed using ArcGIS® (Esri) and Surfer® 11 (Golden Software, LLC) software.

With the goal to prepare all geospatial data, the Quantum GIS Geographic Information System software has been used (Open Source Geospatial Foundation Project, http://qgis.osgeo.org) while Geoserver, an open source server for sharing geospatial data (http://geoserver.org/), has been used for publishing all geospatial data using OGC (Open Geospatial Consortium) open standards.

3. Maps

So far the digital version of European Atlas of Natural Radiation consists of the followings maps:

- European annual cosmic-ray dose map
- European indoor radon concentration map
- European indoor radon - number of measurements
- European uranium concentration in soil map
- European thorium concentration in soil map
- European potassium concentration in soil map
- European terrestrial gamma dose rate map
- European uranium concentration in bedrock map
- European thorium concentration in bedrock map
- European potassium concentration in bedrock map
- European map of soil permeability

For each map, data have been collected, statistically analysed and mapped using the most appropriate methods available. They will be briefly described below. The classes chosen to display the data in the maps do not refer to any limit, reference, action level.

3.1. European annual cosmic-ray dose map

3.1.1. Introduction

The Earth is continually bombarded by high-energy cosmic-ray particles, and the worldwide average exposure to cosmic rays represents about 13% of the total annual effective dose received by the population. Therefore the assessment of cosmic-ray exposure at ground level is of great interest to better understand population exposure to ionizing radiation.

3.1.2. Materials and methods

The methodology used for developing the European Annual Cosmic-Ray Dose map has been extensively described in Cinelli et al. (2017b), and below we briefly report the main aspects:

- the values displayed depend only on elevation, and hence this map clearly reflects the elevation map;
- the dose has been assessed according to methods described in UNSCEAR (UNSCEAR, 2008: Volume 1, Annex B, Chap. 2);
- a global digital elevation model (DEM), called the GTOPO30 dataset (https://lta.cr.usgs.gov/GTOPO30), was used. This dataset was derived from several raster and vector sources of topographic information and is a raster georeferenced TIFF with a horizontal grid spacing of 30 arc seconds (approximately 1 km at the Equator);
- the accuracy of the simple and easy approach based only on elevation data has been confirmed by comparing the results with those obtained using other models.

Moreover, in Cinelli et al. (2017b) the annual cosmic-ray collective dose has been evaluated, and population-weighted average annual effective dose (per capita) due to cosmic ray has been estimated for each European country considered in the work.

3.1.3. Results and discussion

The European Annual Cosmic-Ray Dose map reports the annual effective dose that a person may receive from photons, direct ionizing and neutron components of cosmic radiation at ground level (Cinelli et al., 2017b; Tollefsen et al., 2016-01). This is the dose that a person may receive if she/he spends all the time at that elevation, considering 365 days per year and 24 h per day.

3.2. European indoor radon map

3.2.1. Introduction

The European Indoor Radon Map (EIRM) intends to show "means over 10 km × 10 km grid cells of long-term (ideally, mean annual) indoor radon concentration in ground-floor rooms of dwellings."

3.2.2. Materials and methods

The participants, counting national competent authorities, laboratories, universities etc., aggregate their raw data into cells over a 10 km × 10 km grid covering Europe. Defined by the JRC, this grid uses the GISCO-LAEA coordinate reference system. Exceptions have been made for Ireland and Malta which used their own 10 km × 10 km grids based on their national coordinate reference systems.

Specifically, data providers fill the cells with the following statistics calculated from their original data: the arithmetic mean (AM), standard deviation (SD), AM and SD of the ln-transformed data, median, minimum and maximum, as well as the number of original measurements in the cell. This procedure was agreed upon to ensure data protection, because the original data and their exact location are not given away, but remain at the national level, thus guaranteeing data privacy. The methods and procedures to collect and process the raw data have been further described in Dubois et al. (2010) and Tollefsen et al. (2011).

The choice of variable to be mapped can be seen as a compromise between an indoor radon map and a geogenic "radon potential" map. Moreover, restricting the data to annual mean radon concentration on ground-floor rooms means that data providers have to estimate this quantity, ideally from long-term measurements. Whenever measurements have been made over shorter periods, some intermediate modelling involving seasonal corrections may be necessary to estimate annual means. Admittedly, most people do not actually live on ground floors, especially in urban areas. In spite of its limitations, this approach was adopted simply because most data are available for this variable.

As a consequence, the statistics over the chosen quantity do not represent the ones of exposure. For that purpose, either data must result from a carefully design-based survey which reflects demographic reality (samples representative for population density and house and dwelling characteristics), or alternatively model-based correction to account for demographic representativeness must be performed. Since few national radon surveys are design-based, and demographic data with continental coverage have only recently become available (see e.g. Batista e Silva and Lavalle, 2013), neither the "design-based" nor the "model-based" approach could be chosen for generating a European radon exposure map; it must therefore be left to future efforts.

3.2.3. Results and discussion

As of August 2017, 32 European countries participate to the EIRM. More than 27,000 cells have been filled with data, based on more than 1,100,000 individual measurements in total (Table 1). As can be seen from Fig. 2, the number of measurements per cell and coverage of territory vary widely between countries and between regions of individual countries. The number of measurements per cell range from a

Table 1
Descriptive statistics for the dataset on which the EIRM is based, as of August 2017.

Number of non-empty cells	27,544
Total number of measurements	1,154,373
Measurements per cell, MED (MAD)	4 (4.4)
Min/Max number of measurements per cell	1/23,993
Cell mean, AM ± CV %	103.2 Bq/m^3 ± 139%
Cell median, MED (MADI)	60.0 (46.0) Bq/m^3
Percentage cell AM > 300 Bq/m^3	4.34%
Percentage cell AM > 100 Bq/m^3	34.3%
CV within cells, MED (MAD)	66.8 (34.0) %
GSD within cells, MED (MAD)	1.88 (0.68)

CV, coefficient of variation, where CV = SD/AM; MAD = MED(| x-MED(x) |).

single one up to a maximum of nearly 24,000 (for a cell in the UK). Still, there are many empty cells. The map thus mirrors the status of national surveys of indoor radon monitoring in Europe, at least up to the data released by national authorities to the JRC.

Large areas with high sampling density are found in e.g. the Czech Republic, Austria, Switzerland, North Italy, Belgium, the UK, South Finland and Luxembourg. The median number of measurements per cell equals 4, with a median absolute deviation (MAD) of 4.4 (Table 1). This heterogeneity of sampling density clearly influences the statistical uncertainty of the means as estimates of the expected concentration within a cell, as it does for the standard deviation and other statistics.

Fig. 3 shows the geographical distribution of arithmetic means over 10 km × 10 km cells. The map reveals a spatial trend in indoor radon concentrations across Europe and essentially reflects the underlying geology. Regions of high radon concentrations are found in the granite areas of the Bohemian Massif, the Iberian granite province, the Massif Central, the Fennoscandian Shield, Corsica, Cornwall and the Vosges Mountains, in the crystalline rocks of the Central Alps and karst rocks of the Swiss Jura and the Dinarides, the black shales in North Estonia and in certain volcanic structures in Central Italy.

The mean of all non-empty cells in all of Europe (for participating countries) is 103 Bq/m^3, while the median is 60 Bq/m^3. See Table 1 for descriptive statistics of the dataset which underlies the map. For all participating countries, more than 30% of the non-empty cells have an arithmetic mean above 100 Bq/m^3 and 4% of them above 300 Bq/m^3 (Table 1). The descriptive statistics for each country as well as the percentage of cells with AM above 100 and 300 Bq/m^3 are reported in the supplementary materials.

Again it should be emphasized that the cell mean (AM or median over cell means) is an estimate of the spatial mean of the quantity "long-term mean radon concentration in dwellings in ground-floor rooms", but neither (a) the mean over radon in ground-floor dwellings, nor (b) the mean over all dwellings, i.e. an estimate of exposure. For (a) one would have to calculate a weighted mean with population density by cells as weights; for (b) the distribution of dwellings over floors would have to be included as weight, together with a model which accounts for floor level. Since (a) population centres are preferentially located in valleys and flatlands, in many cases over quaternary geology which in most cases has lower radon potential, and (b) radon concentration decreases with floor level, on the average, demographically weighted mean radon concentrations and mean exposure are generally lower than the spatial mean of the quantity discussed here.

3.3. *U, Th and K in soil*

3.3.1. *Introduction*

Due to the important contribution of uranium, thorium and potassium radionuclides in the total annual effective dose received by the population both for external and internal exposure (UNSCEAR, 2008, Annex B), maps of these radionuclides in soil, covering most European countries, have been created. These maps can be used as input parameters for the EGRM, but also as stand-alone maps in the Atlas for the outline about natural radioactivity levels in Europe.

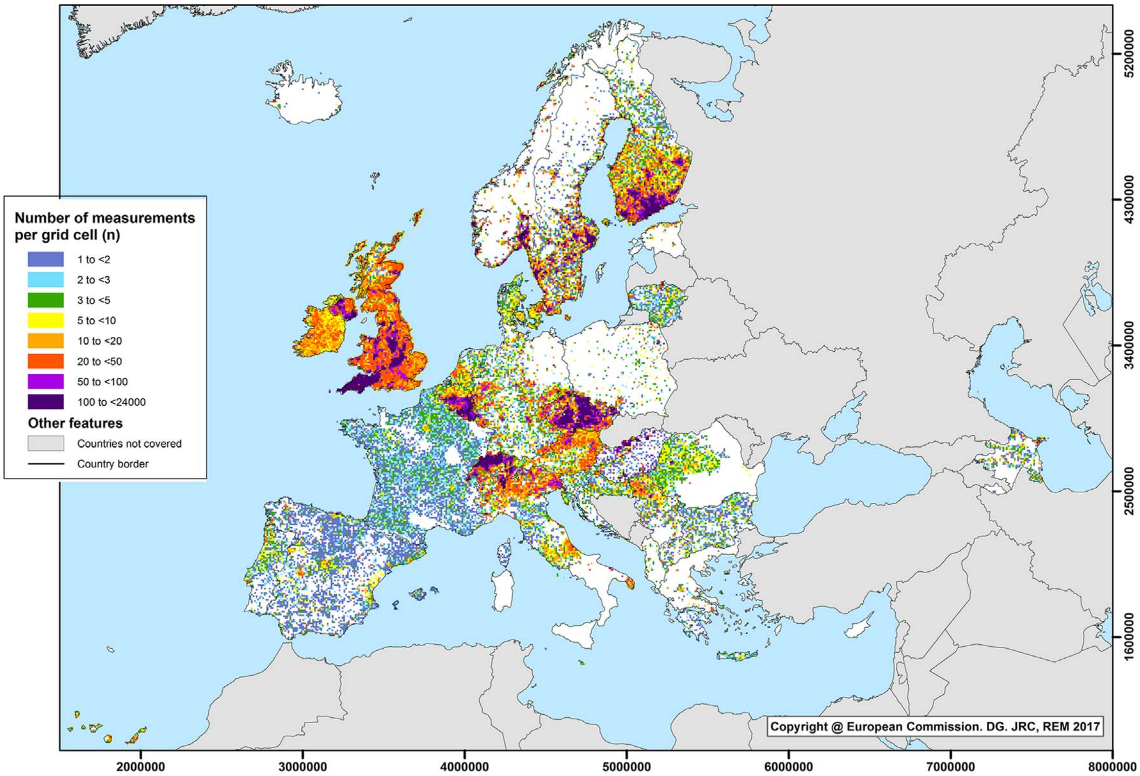


Fig. 2. Number of measurements per 10 km × 10 km cell of long-term radon concentration in ground-floor rooms of 32 European countries (ETRS89-LAEA frame). Latest update, August 2017. Source: European Commission, DG JRC (Tollefsen et al., 2010-03).

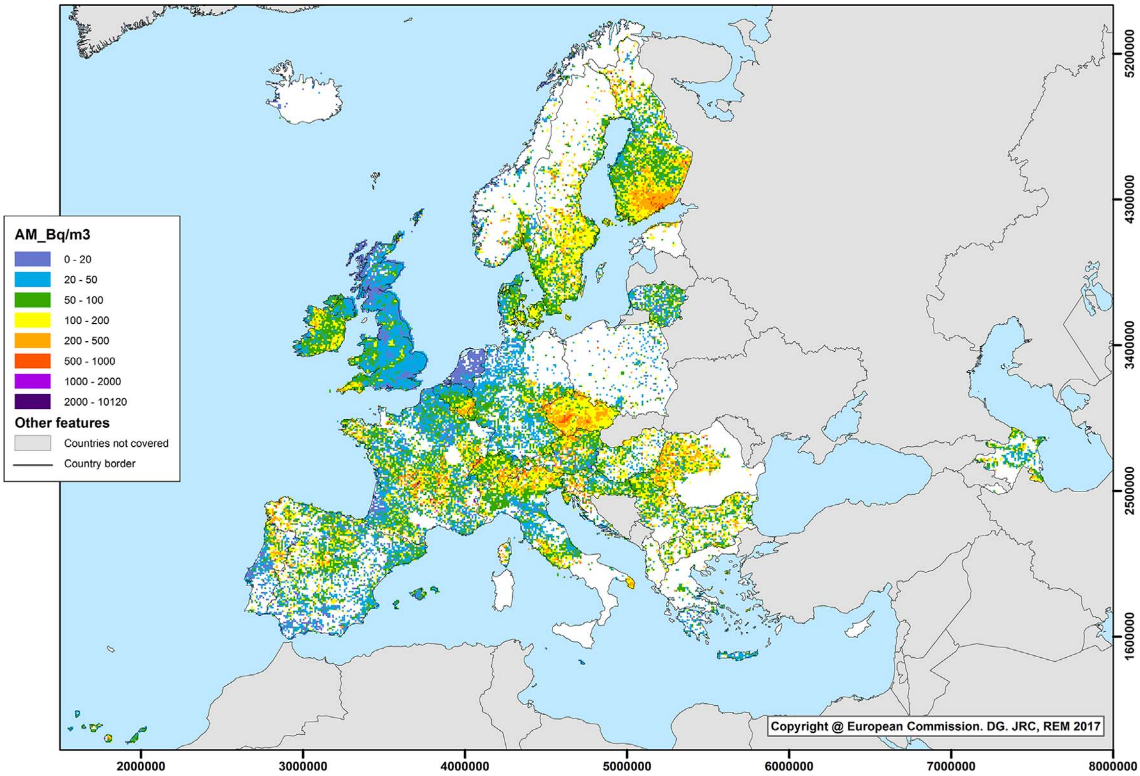


Fig. 3. Arithmetic means (AM) over 10 km × 10 km cells of long-term radon concentration in ground-floor rooms of 32 European countries (ETRS89-LAEA frame). Latest update, August 2017. (The cell mean is neither an estimate of the population exposure, nor of the risk.) Source: European Commission, DG JRC (Tollefsen et al., 2010-02).

3.3.2. Materials and methods

Databases. A research was carried out and identified two geochemical databases available for all the territory of Europe for mapping the uranium (U), thorium (Th) and potassium (K) concentration in soil.

FOREGS: the Geochemical Atlas of Europe, hereafter referred to as FOREGS, has about 1800 samples collected in Europe between 1997 and 2001, corresponding to a sampling density of about one sample per 4700 km^2. The European contribution to the programme has been carried out by government institutions from 26 countries under the auspices of the Forum of European Geological Surveys (FOREGS). Two different depth-related samples were taken at each site: a topsoil sample from 0 to 25 cm (excluding material from the organic layer where present), and a subsoil sample from a 25 cm thick section within a depth range of 50–200 cm (http://weppi.gtk.fi/publ/foregsatlas/article.php?id=10). The samples have been collected in forested and unused lands; greenland and pastures; and non-cultivated parts of agricultural land. U, Th and K have been measured using inductively coupled plasma mass spectrometry (ICP-MS).

GEMAS: the Geochemical Mapping of Agricultural and Grazing Land Soil project, hereafter referred to as GEMAS (Reimann et al., 2014a, b; http://gemas.geolba.ac.at/), involving 33 European countries, is a cooperation project between EuroGeoSurveys through its Geochemical Expert Group, and Eurometaux, the European Association of Metals. The GEMAS project collected samples of agricultural soil (Ap - horizon, 0-20 cm, regularly ploughed fields) and samples from land under permanent grass cover (Gr - grazing land soil, 0-10 cm). The sampling was completed in the beginning of 2009. The sampling density is about one sample per 2500 km^2 (about 3000 samples of Ap and 3000 of Gr for all of Europe). The determination of K was made by XRF. U and Th have been measured by ICP-MS with aqua regia extraction. The U and Th data have been corrected using the value of extractability of elements analysed by XRF, delivering true total concentrations, in an aqua regia extraction reported in Table 12.4 of Reimann et al. (2014a).

Data analysis, comparison and merging. Since the GEMAS samples were collected at 0-10 cm and 0-20 cm depth, the FOREGS Topsoil has been chosen as the reference group for FOREGS data. Observing the Q-Q plots (see supplementary materials), it has been assumed that both databases, FOREGS Topsoil data and GEMAS (Ap + Gr), can be described by the following distributions:

- Normal distribution for K_2O
- Lognormal distribution for Th and U.

To compare the two databases, first the ratio between the arithmetic mean and median of K_2O, natural logarithmic of U (hereafter ln-U) and of Th (hereafter ln-Th) has been calculated.

The comparison between the distributions of the two databases, FOREGS Topsoil and GEMAS (Ap + Gr), reported in Fig. 4, confirms the results of the ratios between the mean and median (Table 2); in details:

- K_2O: the mean and median are similar and also the distributions;
- ln-U: the comparison of the mean (0.92) is much better than the median (0.75). The distributions appear quite similar;
- ln-Th: the comparison of the mean (1.05) is better than the median (1.10). The distributions appear quite different.

Our purpose is to have a database (hence a map) that best represents the European soil. FOREGS Topsoil and GEMAS data in this respect are complementary because they taking into account different kinds of soil (Agricultural, Grazing and residual soil-undisturbed), collected at different locations with the same methodology. After testing the possibility to harmonize the databases, it was realised that the best solution was to merge the two databases without any correction-harmonization.

To check the spatial correlation of the merged database, Surfer® 11 software (Golden Software, LLC) has been used. Choosing the standardized estimator, experimental variograms have been computed for K_2O, ln-U and ln-Th of the merged database (Fig. 5).

The K_2O, ln-U and ln-Th have been interpolated using the Surfer® 11

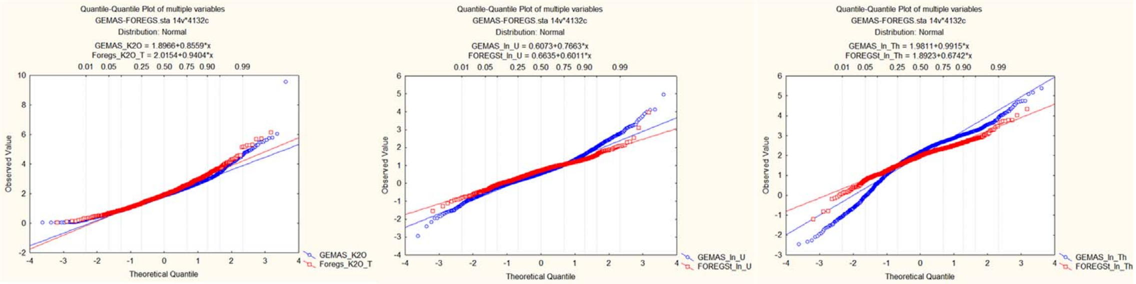


Fig. 4. Quantile-quantile plots of K_2O, ln-U and ln-Th of FOREGS Topsoil and GEMAS (Ap + Gr) databases considering a normal distribution.

Table 2
Ratio between the arithmetic mean and median of K_2O, ln-Th and ln-U of FOREGS Topsoil and GEMAS (Ap + Gr) databases.

	Arithmetic mean GEMAS/FOREGS	Median GEMAS/FOREGS
K_2O	0.94	0.96
ln-U	0.92	0.75
ln-Th	1.05	1.10

software (Golden Software, LLC) on the 10 km × 10 km GISCO-LAEA grid used for the indoor radon map, already described in sections 2 and 3.2. The smoothing interpolator that has been used is kriging (block type), applied to ln-U and ln-Th and not transformed data for K_2O, and using the variogram models reported in Fig. 5. Then the interpolated values for K_2O (Fig. 8) and the exponential for U and Th, i.e. the geometrical mean-GM (Figs. 6 and 7) have been displayed using ArcGIS® software (Esri, 2011) with the ETRS89-LAEA frame.

3.3.3. Results and discussion

Figs. 6 and 7 display respectively the geometrical means (GM) in mg/kg of the concentration of uranium and thorium in soil over 10 km × 10 km grid cells, while Fig. 8 displays the concentration in percent of K_2O. These maps have been estimated using FOREGS and GEMAS European databases.

From a rough visual analysis of the three maps we can notice a correlation between the three elements. Areas characterized by the highest values for all the considered elements are in central Italy, North-West Iberia, East Sweden, South Finland and Central France. Moreover we can notice a correspondence with the highest regions identified in the European Indoor Radon Map (Fig. 3). Further work has been planned to best study the correlation between the 3 elements and between U and indoor radon concentrations.

Countries having additional databases available at national level could decide to use their own data to develop the maps of Th, U and K_2O concentration in soil. Belgium was a favourable case for exploring the methodology of Th, U and K_2O mapping using several different databases available. A harmonized database was built by merging radiological (not airborne) and geochemical data. Using this harmonized database it was possible to calibrate the data from the airborne survey (Cinelli et al., 2017a, 2018).

So far Belgium, the Czech Republic and Estonia provided aggregated data from their national databases to be displayed in the maps of U, Th and K_2O concentration in soil and the associated references. The maps of U, Th and K_2O concentration in soil displaying the data from the countries mentioned above are reported in the digital version of the European Atlas of Natural Radiation (Tollefsen et al., 2016-04; Tollefsen et al., 2016-05; Tollefsen et al., 2016-06).

3.4. Terrestrial gamma dose rate

3.4.1. Introduction

Terrestrial gamma dose is another non-negligible contribution to total dose to humans from natural or enhanced-natural sources. Its origin is gamma emitting natural radionuclides which are ubiquitous in the environment, in particular in soil and rock.

Specifically, these are the primordial radionuclides ^{4}K and members of the ^{238}U and ^{232}Th series. Altogether there are about 35 primordial radionuclides, naturally occurring in the environment (among gamma radiators, except the mentioned ones, most known are members of the ^{235}U series and ^{138}La), but their contribution to dose is negligible, in comparison to the former.

Gamma dose rate above ground depends on source strength, i.e. radionuclide concentration in the ground, and attenuation by the ground, depending on chemical composition of soil or rock and humidity. In general, U and Th decay chains are not in equilibrium in the environment. This is owed to different chemical and physical properties of the decay products, which leads to chemical and physical fractionation in environmental media, mainly due to different solubility in water. ^{222}Rn and ^{220}Rn which belong to the ^{238}U and ^{232}Th chain, respectively, can migrate in the ground, depending on permeability. They can exhale into the atmosphere and gamma radiating Rn decay products can be precipitated back to the ground with precipitation. As a result of these geochemical processes, the sources of gamma radiation

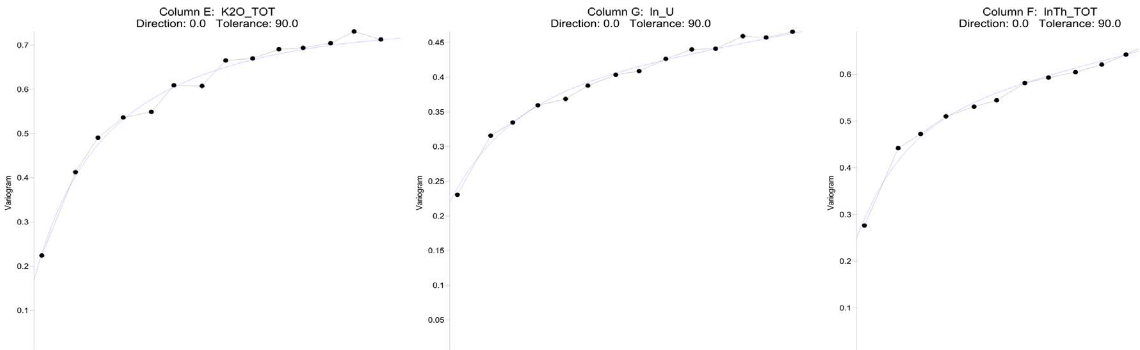


Fig. 5. Variograms (black line with points) and model (blue line) considering K_2O, ln-U and ln-Th data of the merged database. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

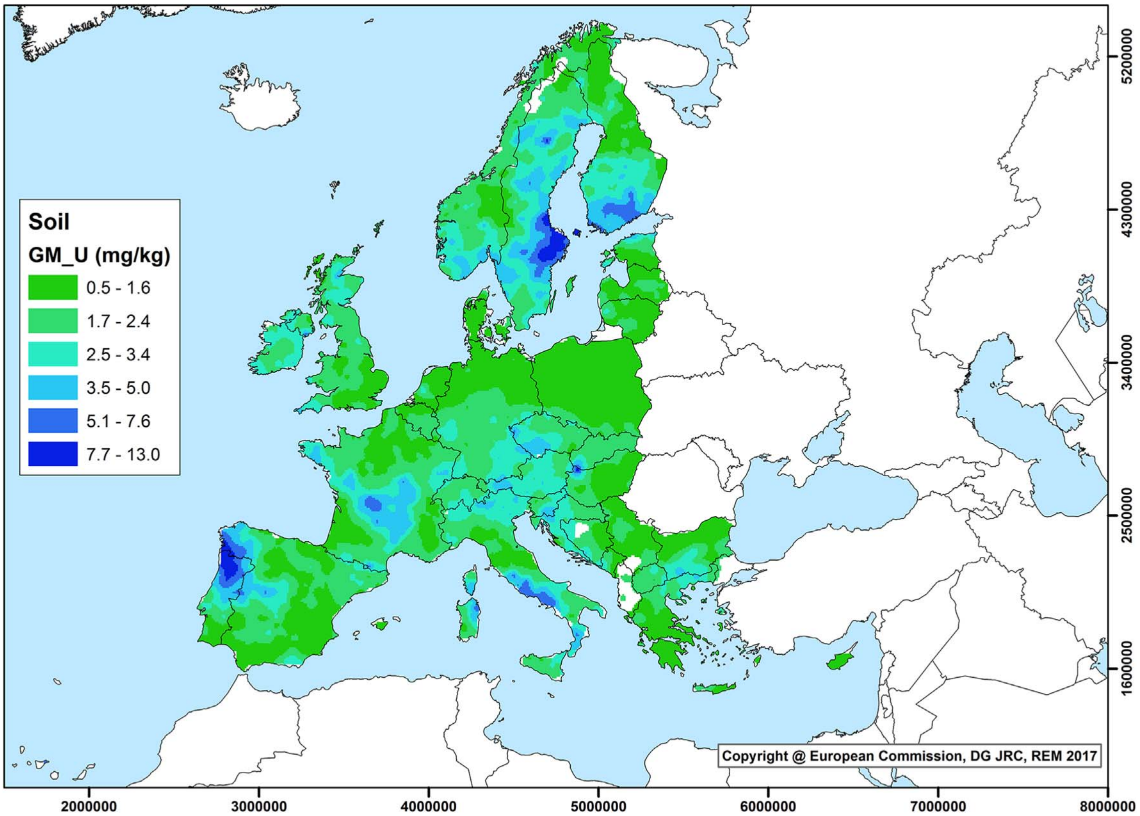


Fig. 6. Map of U (geometrical mean-GM) obtained by the kriging method on a 10 km × 10 km GISCO-LAEA grid using the merged database (ETRS89-LAEA frame).

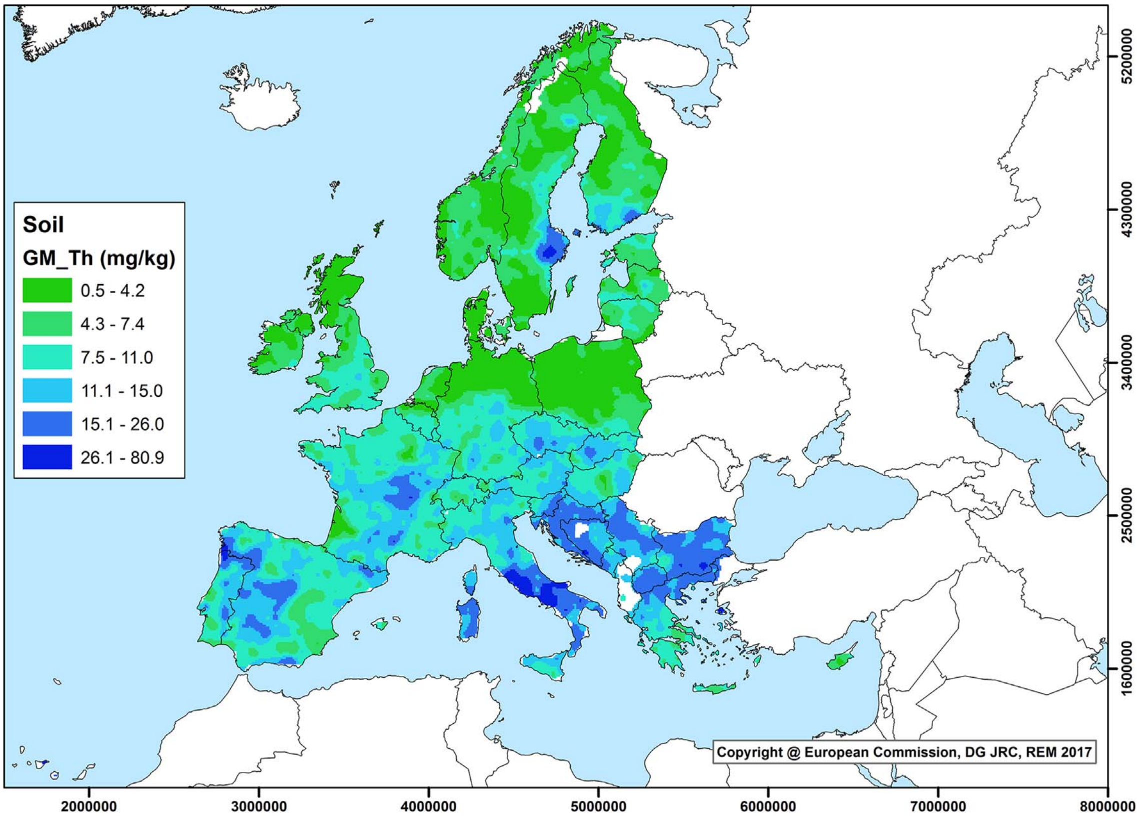


Fig. 7. Map of Th (geometrical mean-GM) obtained by the kriging method on a 10 km × 10 km GISCO-LAEA grid using the merged database (ETRS89-LAEA frame).

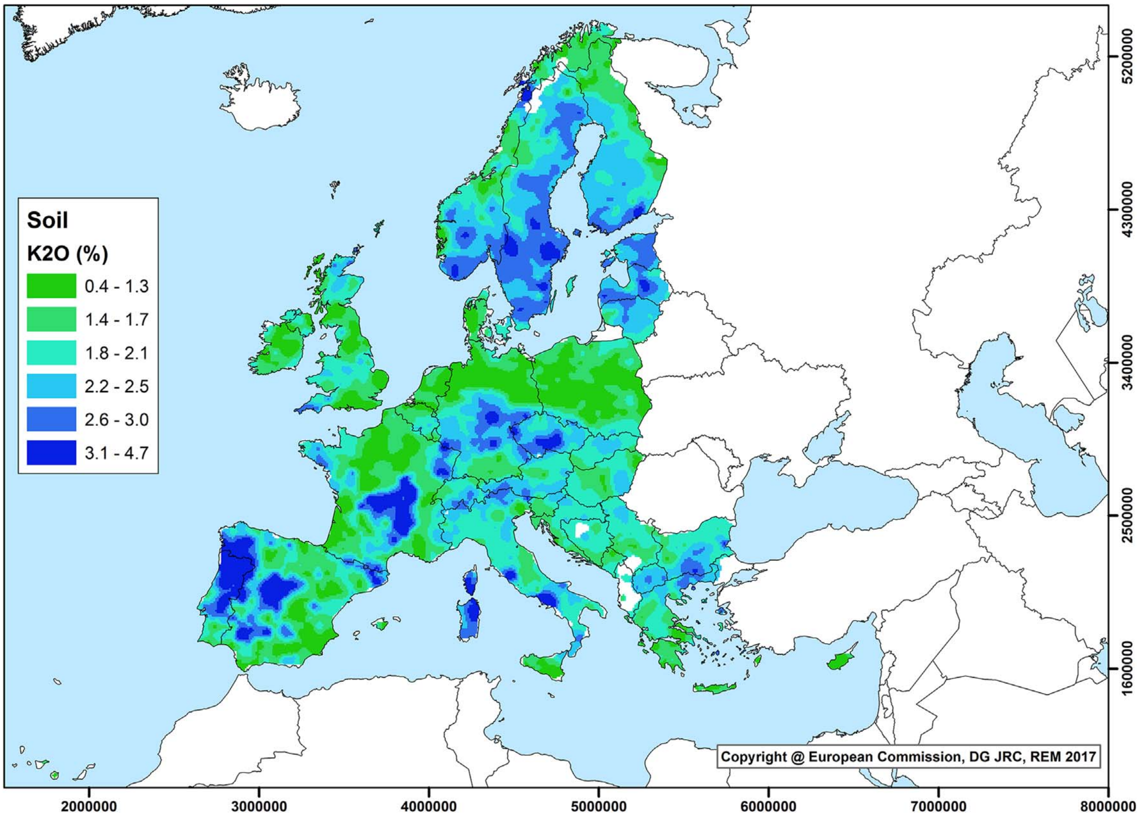


Fig. 8. Map of K_2O obtained by the kriging method on a 10 km × 10 km GISCO-LAEA grid using the merged database (ETRS89-LAEA frame).

are distributed differently from their parent nuclides.

For these reasons, natural terrestrial gamma ray intensity above ground is not perfectly related with concentrations of parent nuclides. Furthermore, it is temporally variable, due to variable Rn progeny concentrations on or close to the ground surface, and due to temporally variable attenuation by humidity, snow cover and surface roughness, mainly owing to vegetation.

3.4.2. Materials and methods

In Europe, there is a large network of continuously operating monitors of ambient dose rate, whose purpose is to warn against nuclear emergencies. Detectors used are mostly Geiger-Müller and proportional counters which register gamma rays and cosmic muons. Increasingly, energy dispersive detectors are used (mostly based on $LaBr_3$ probes). The monitors are run by national authorities, but data transferred to the JRC, where they are stored and displayed almost real-time on a web site. For details, the reader is referred to site of the EURDEP system, https://eurdep.jrc.ec.europa.eu/Basic/Pages/Public/Home/Default.aspx.

Measured ambient dose rate ADR (or calculated from the spectrum, for spectrometric probes) consists of components originating from different sources: terrestrial radionuclides in and on the ground, Rn progeny in the atmosphere, cosmic rays and cosmogenic radionuclides such as ^{7}Be and ^{22}Na, airborne and deposited on the ground; additionally, anthropogenic radionuclides such as ^{137}Cs fallout from global fallout and from Chernobyl can still be measured easily all over Europe (the Fukushima accident did not contribute to an extent that could still be measured in Europe). In emergency situations, airborne anthropogenic gamma-radiating radionuclides and contamination of the detector case are additional contributions. While these do not contribute under routine conditions, another important component which contributes to the recorded count rate is the internal background of probes.

For the sake of completeness, anthropogenically enhanced natural sources shall be mentioned, essentially building and construction materials, landfills and mining and other industrial residues which can contain elevated concentrations of natural radionuclides and may locally contribute to ambient dose rate, depending on the positions of monitors.

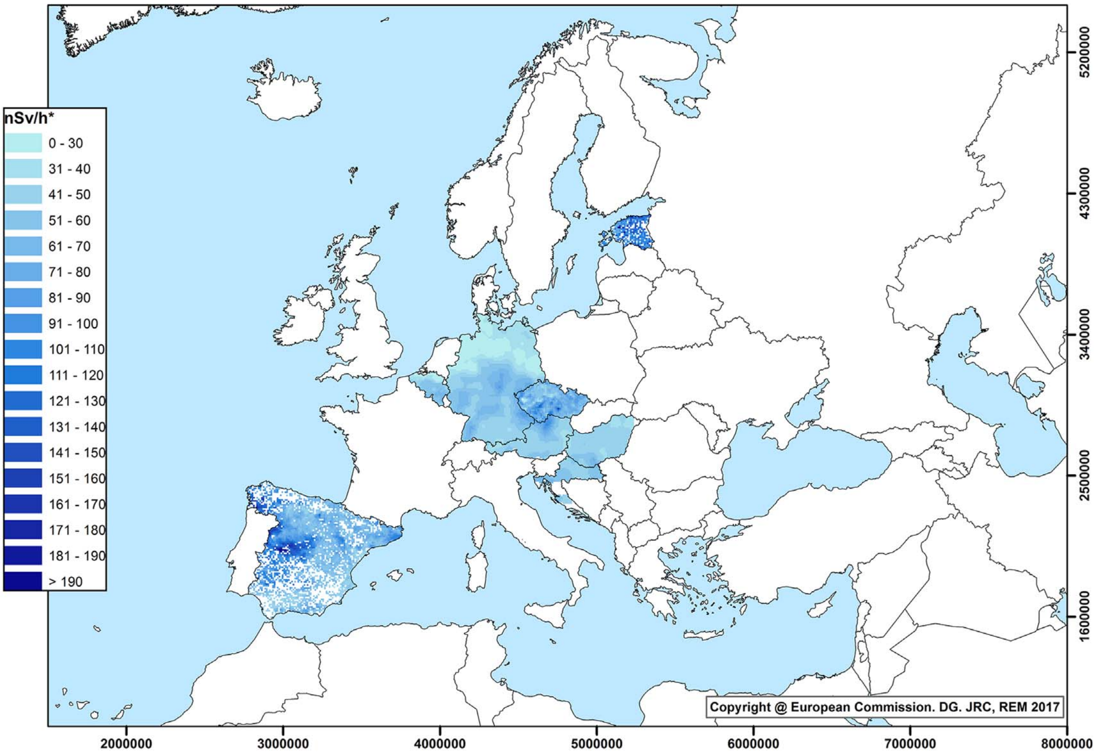
In order to identify the contribution from terrestrial natural gamma sources, one has to estimate the contributions of cosmic rays and anthropogenic fallout, and subtract the corresponding dose rates from the total one recorded by the monitor. The different contributions depend on source strengths and on the sensitivity of the probes against these components, as well as on local set-up and mounting of probes. All factors are often not known exactly, so that decomposition of the total recorded ADR in order to retrieve the terrestrial natural gamma component is not simple. (The matter is somewhat easier for spectrometric probes.)

In spite of large amounts of raw ADR data available in EURDEP, and of many years of efforts to understand in detail and to harmonize the differences between national systems, which is necessary for correct decomposition of the signals, sufficient information is available only for a few countries, namely Austria, Croatia, Germany and Hungary. For details, the reader is referred to the more extensive discussion in Bossew et al. (2017). Belgium, the Czech Republic, Estonia and Spain provided their ADR survey data, i.e. they have not been calculated from EURDEP. As a result, to date, the map of terrestrial ADR covers only a part of Europe.

In principle, however, the methodology has been established and could be applied to other countries once sufficient technical information becomes available.

3.4.3. Results and discussion

The map, Fig. 9, shows the gamma dose rate from terrestrial sources (natural plus ^{137}Cs fallout) to which a person is exposed if she/he spends all the time outdoors (Tollefsen et al., 2016-07). At this stage, ^{137}Cs fallout could not be separated, but in most locations contributes



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*nGy/h for Spain and Czech Republic

Fig. 9. European map of terrestrial gamma dose rate on a 10 km × 10 km GISCO-LAEA grid (ETRS89-LAEA frame). Latest update, March 2017. Source: European Commission, DG JRC (Tollefsen et al., 2016-07).

little (see Bossew et al., 2017). The data do not include the contribution of so-called Rn peaks, i.e. radiation of Rn progeny precipitated to the ground by precipitation. Dose rate generated this way can be quite high short-term (up to a few 100 nSv/h), but contributes only in the order 2-5% to annual terrestrial gamma dose.

The mapping support is formed by the same 10 km × 10 km cells as for the indoor radon map (see sections 2 and 3.2). In this figure, all countries have used nSv/h H*(10) as unit for ambient dose equivalent rate, except for Spain and the Czech Republic, which have used nGy/h for absorbed dose rate. The conversion factor between ambient dose equivalent rate and absorbed dose rate could be assumed to be approximately 1 (see EC, 2014).

3.5. U, Th and K in bedrock

3.5.1. Introduction

As noted in section 3.3, terrestrial radionuclides are ubiquitous in soil. Soil could be defined as the portion of the earth's surface consisting of disintegrated rock and humus. Therefore rock could be considered at the origin of the soil and source of the terrestrial radionuclides in the soil. Mapping the distribution of uranium, thorium and potassium terrestrial radionuclides in rock in addition to outline the level of natural radioactivity, could be interesting:

a) where the soil thickness is negligible because here the terrestrial gamma radiations are mostly due to the radionuclides in rock;
b) to study the mobility of radionuclides from parental material (rock) to soil;
c) to be used as input parameters for the European Geogenic Radon Map.

3.5.2. Materials and methods

For mapping uranium, thorium and potassium concentration in bedrock in the European Atlas of Natural Radiation, a simple methodology on a country-by-country basis has been developed (Braga et al., 2015). In this, the main lithostratigraphic units have been identified at a scale of 1:1,000,000 (hereafter, geological units), using OneGeology-Europe data. The definition of the geological units has been supported by knowledge of petrology and mineralogy as well as relevant geological literature. Geochemical and radiological data of U, Th and K_2O concentration have been collected from scientific literature dealing with rock samples that belong to the different geological units defined above. These data have been used to estimate descriptive statistics parameters for U, Th and K_2O concentration in bedrock for each geological unit.

This methodology has been validated for Portugal by comparing literature data with those from a national survey of radiological data carried out by the Laboratory of Natural Radioactivity (LNR) at the University of Coimbra (manuscript in preparation). Overall, a reasonable agreement between the literature data, the LNR data and the Radiometric Map of Portugal are observed. Discrepancies between the databases seem to be contingent upon sample and analytical representativeness. Despite data limitations, the maps developed for U, Th and K_2O in bedrock provide useful information to the general public, and this may support additional research.

3.5.3. Results and discussion

The maps reported in Figs. 10–12 display the arithmetic mean, respectively, of the of U, Th and K_2O concentration in bedrock over geological units (Tollefsen et al., 2016-8; Tollefsen et al., 2016-9; Tollefsen et al., 2016-10). They can easily be improved if more data become available.

Even if the described methodology has been validated and it potentially allows mapping of all the European countries, it is highly time-consuming. For this reason, so far only 9 countries have been displayed in the maps: Austria, Belgium, Estonia, Hungary, Luxembourg, the

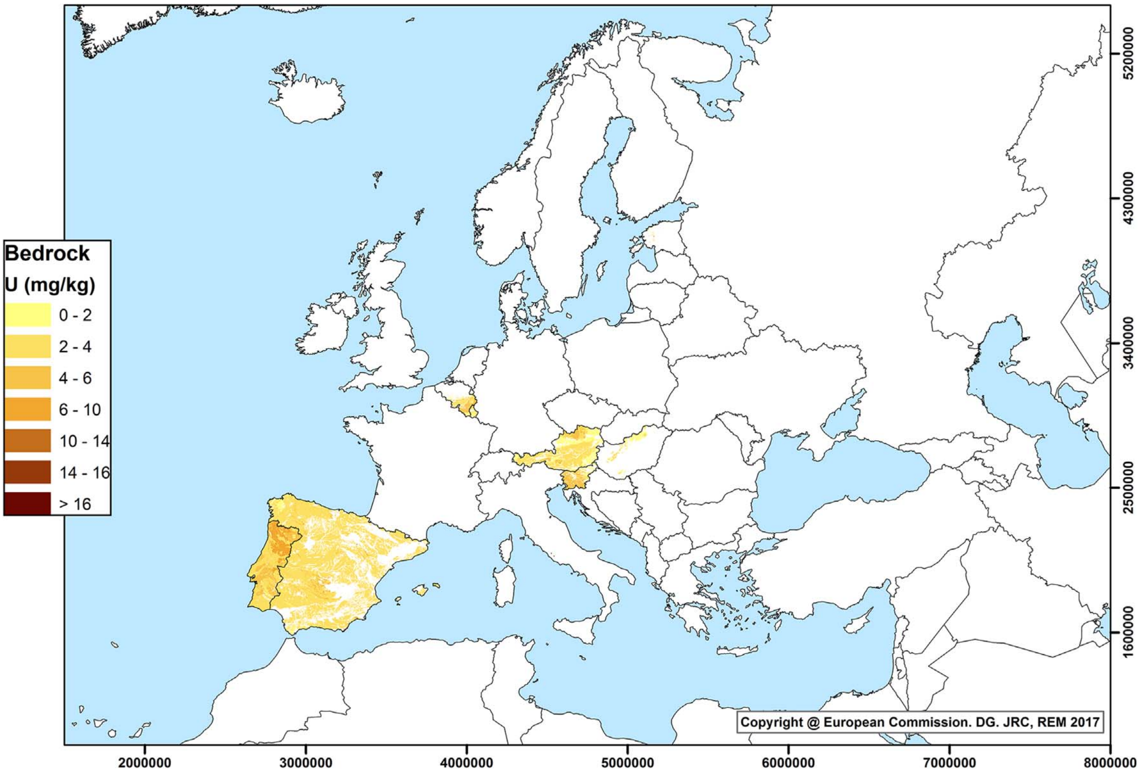

Fig. 10. Map of uranium concentration in bedrock (ETRS89-LAEA frame). Latest update, April 2017. Source: European Commission, DG JRC (Tollefsen et al., 2016-08).

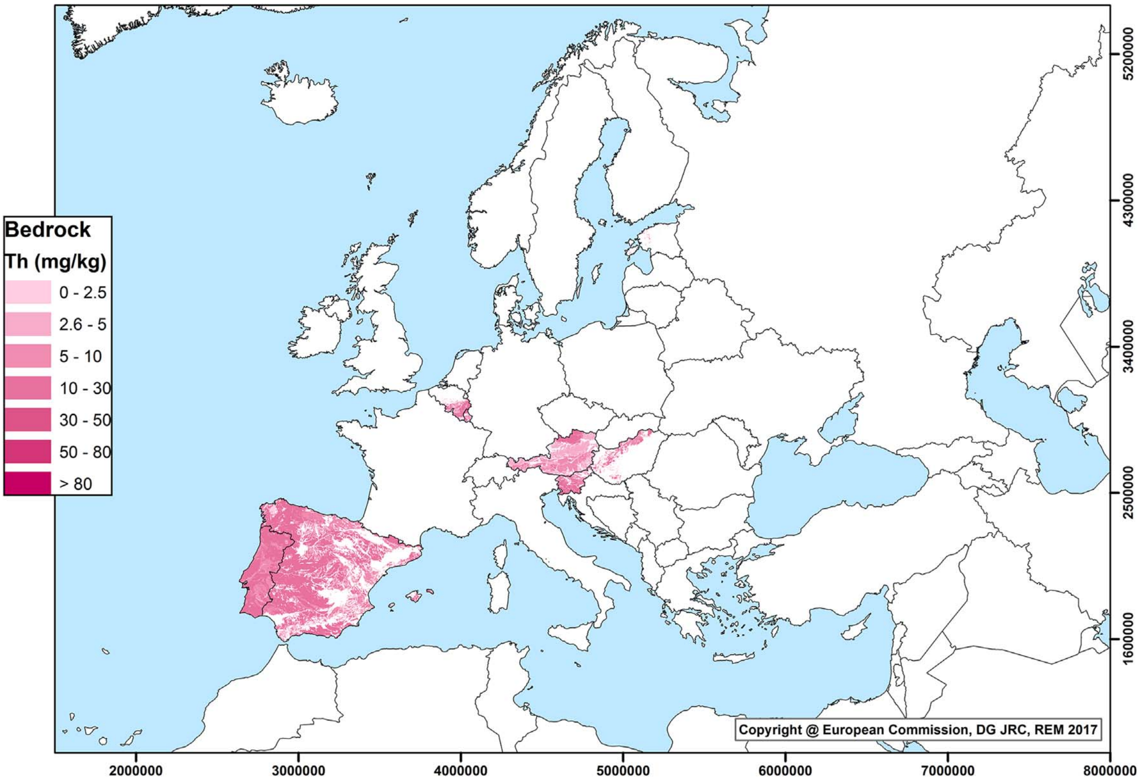

Fig. 11. Map of thorium concentration in bedrock (ETRS89-LAEA frame). Latest update, April 2017. Source: European Commission, DG JRC (Tollefsen et al., 2016-09).

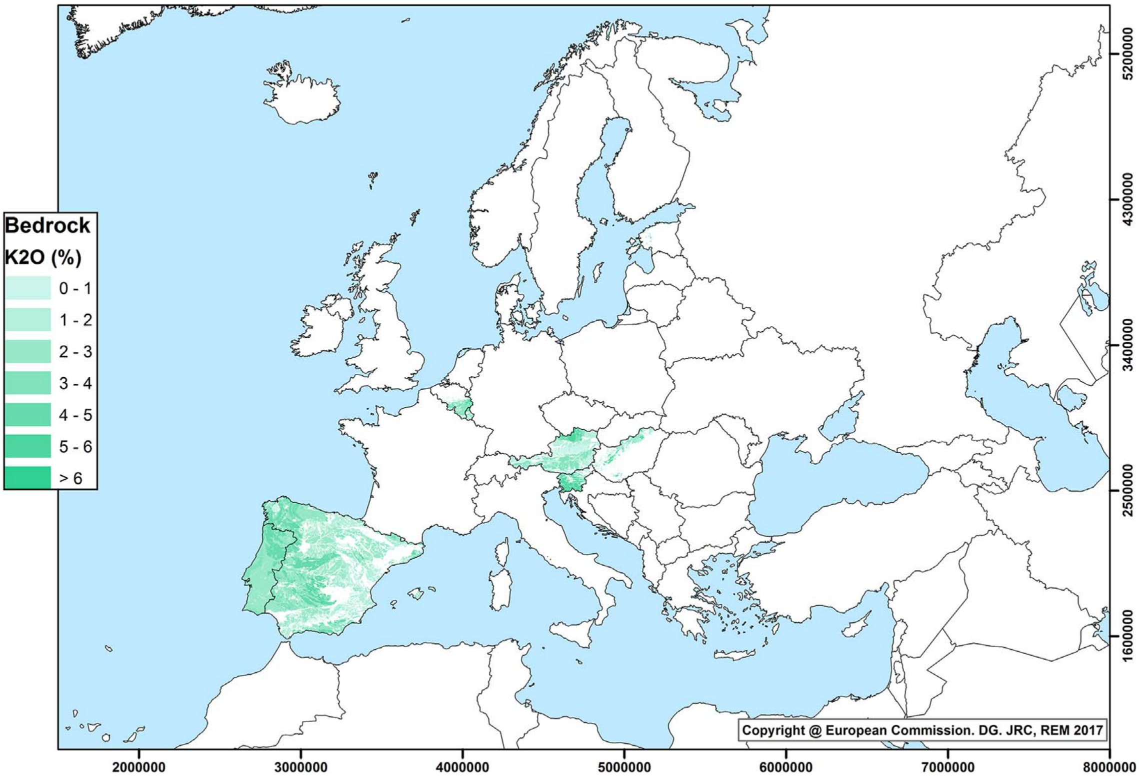

Fig. 12. Map of potassium concentration in bedrock (ETRS89-LAEA frame). Latest update, April 2017. Source: European Commission, DG JRC (Tollefsen et al., 2016-10).

Netherlands, Portugal, Slovenia and Spain.

3.6. European map of soil permeability

3.6.1. Introduction

The gas permeability of soil and rocks is one of the most important factors influencing the radon flux to the surface and potentially into buildings. Therefore it is an important parameter in the determination of radon risk classification and identification of radon priority areas. The radon potential, defined by Neznal (Neznal et al., 2004; Barnet et al., 2008), is a combination of Rn concentration in soil and soil permeability.

3.6.2. Materials and methods

The permeability of soil and rocks for gases could be determined by direct in situ permeability measurements or using the weight percentage of fine fraction ($< 63\,\mu m$) in the chosen soil samples (Barnet et al., 2008). Following the latter approach soils with the weight percentage of the fine fraction < 15% were designated as high permeable soils, in the range 15–65% as medium permeable and in the case of the fine fraction above 65% as low permeable ones (Barnet et al., 2008). The main disadvantage is given by the fact that other factors influencing the permeability are not taken into account (soil moisture, density, effective porosity etc.).

At the European level, maps of topsoil physical properties are available (Ballabio et al., 2016) with a resolution of 500 m, and in detailed maps of clay (< 0.002 mm), silt (0.002–0.05 mm), sand (0.05–2.0 mm) and coarse material (> 2 mm). These maps have been developed using information from LUCAS topsoil database, composed by data from about 20,000 topsoil samples (Tóth et al., 2013).

The fine fraction ($< 63\,\mu m$) has been estimated using LUCAS data summing the clay (%), silt (%) and the 5% of sand. This latter value has been estimated considering that the very sand fine fraction (0.05–0.1 mm) is the 20% of sand and then the 26% of the very sand fine fraction is to be in the range (0.05–0.063 mm) (Panagos et al., 2014). The raster calculation tool in ArcGIS® (Esri, 2011) has been used to estimate the percentage of fine fraction from clay, silt and sand maps (Ballabio et al., 2016).

3.6.3. Results and discussion

The European map of soil permeability in Fig. 13 (Tollefsen et al., 2016-11) displays the percentage of topsoil fine fraction ($< 63\,\mu m$) at 500 m resolution. In some countries the national permeability map has been compared with the European one based on the soil fine fraction and national experts told us that the results are almost acceptable (A. Ferreira, personal communication, February 2015; I. Barnet, personal communication, February 2015).

4. Conclusions

A printed version of the European Atlas of Natural Radiation has been planned, and for this scope exhaustive material will be prepared to explain the maps in detail.

Thanks to the availability of the Atlas (online and printed) the public will have a tool to:

- familiarize itself with natural environmental radioactivity;
- be informed about the levels of natural radioactivity caused by different sources;
- have a more balanced view of the annual dose received by the world population, to which natural radioactivity is the largest contributor;
- make direct comparisons between doses from natural sources of ionizing radiation and those from man-made (artificial), hence to better understand the latter.

Moreover the REM group of JRC will have the possibility to:

- develop the European Geogenic Radon Map using uranium concentration in bedrock and in soil, indoor radon, terrestrial gamma dose rate and soil permeability maps as input parameters;

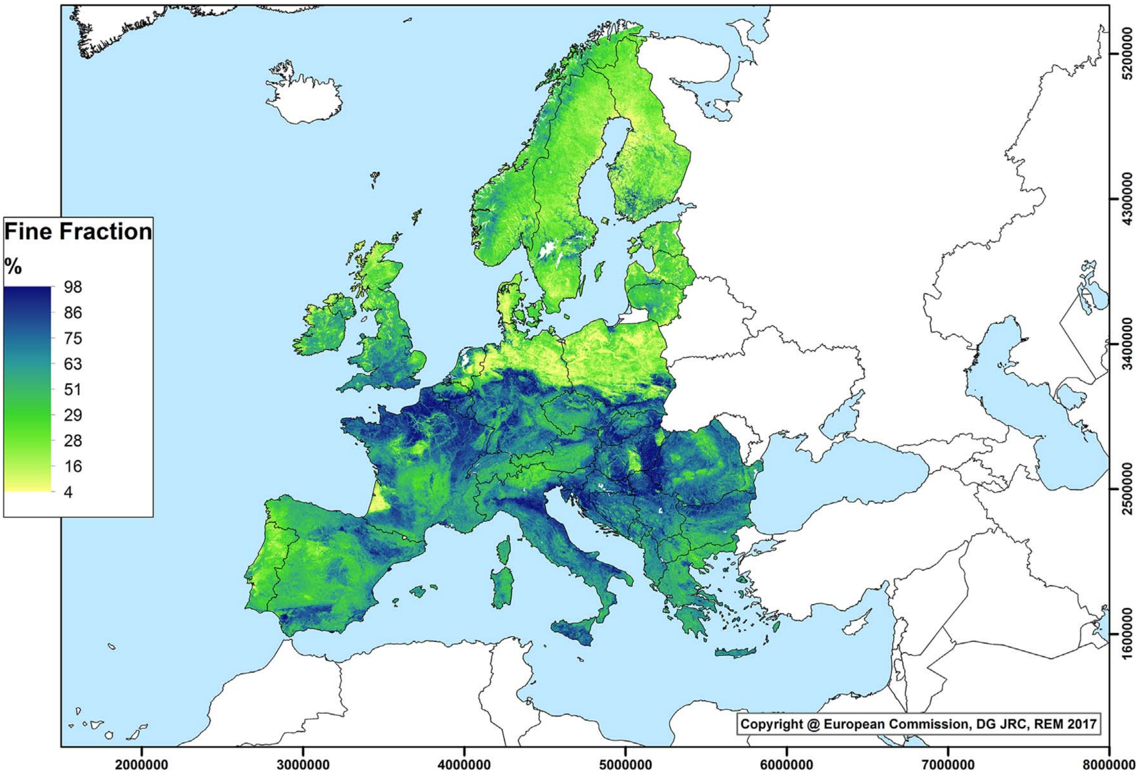

Fig. 13. Map of permeability displaying the percentage of soil fine fraction (ETRS89-LAEA frame). Latest update, April 2017. Source: European Commission, DG JRC (Tollefsen et al., 2016-11).

- estimate the annual dose that the public may receive from natural radioactivity by combining all maps.

The JRC will continue to work on all the maps by collecting data from new participants to the project and from established participants as they complement or improve their data, and will publish updated versions of the maps from time to time. Whereas some countries have finished their surveys years ago, there are those which have recently extended their previous pilot studies into national or complementary ones.

Work will also continue on the European Geogenic Radon Map and on the estimation of the annual dose that the public may receive from natural radioactivity, combining all the information from the different maps. Still more maps could be added to the Atlas, such us outdoor radon and radon in water and concentration of radionuclides in water, even if these sources give a smaller contribution to the exposure.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvrad.2018.02.008.

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