Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Spatial variability of population exposure to cosmic radiation in Germany and sensitivity to environmental conditions

Eric Petermann

epetermann@bfs.de

Federal Office for Radiation Protection

Munehiko Kowatari

National Institutes for Quantum Science and Technology

Article

Keywords: Cosmic radiation, Population exposure, Effective dose, Spatial variability, PARMA, Environmental radiation

Posted Date: November 13th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11480348/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Spatial variability of population exposure to cosmic radiation in Germany and sensitivity to environmental conditions

Authors: Eric Petermann[1], Munehiko Kowatari[2]

1 – Federal Office for Radiation Protection (BfS), Berlin, Germany

2 - National Institutes for Quantum Science and Technology (QST), Department of Radiation Regulatory Science Research, Chiba, Japan

Corresponding author: Eric Petermann (epetermann@bfs.de)

Abstract:
Cosmic radiation contributes to natural background exposure worldwide, yet comparatively little is known about how exposure varies within national populations and how environmental conditions affect this variability. We estimated cosmic-radiation exposure across Germany with the PARMA model using a 250-m calculation grid that incorporated elevation, geographic position, residential population and spatially varying soil moisture. The population-weighted mean annual effective dose was 0.31 mSv, and variability across the population was relatively small (coefficient of variation 8%). Elevation was the main spatial determinant, with the highest exposures occurring in southern Germany and mountainous regions. Accounting for population distribution had little effect on the national mean, but differences from area-weighted estimates became more pronounced towards the upper end of the exposure distribution. Muons and neutrons contributed about 82% of the annual effective dose. Changes in solar activity altered the population-weighted mean dose by +3.0% to −5.9% relative to the reference conditions, whereas the effect of soil moisture on total dose was smaller. Estimated annual doses were also sensitive to assumptions about building shielding. The results indicate that fine-scale modelling adds little to national mean estimates but is more informative for local exposure patterns and higher-exposure population groups.

Keywords: Cosmic radiation; Population exposure; Effective dose; Spatial variability; PARMA; Environmental radiation.

1. Introduction

Cosmic radiation is a ubiquitous component of natural background radiation and contributes substantially to the external radiation exposure of the general population. In its recent report on public exposure to ionizing radiation, the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) estimated the global average cosmic dose to the public at 0.30 mSv per year, corresponding to roughly 10% of the mean global dose from natural background radiation (UNSCEAR) estimated the global average cosmic dose to the public at 0.30 mSv per year corresponding to roughly 10 % of the mean global dose due to natural background radiation that the general public receives [1]. At ground level, exposure originates from secondary particles produced by interactions of primary cosmic rays with the Earth's atmosphere, with the relative contribution of different particle components (neutrons, muons, protons, photons, electrons, positrons and others) varying with altitude and geomagnetic shielding, which varies geographically and is primarily related to geomagnetic latitude, with a smaller longitudinal component. While cosmic radiation exposure is generally lower at sea level, it increases markedly with elevation and may therefore show considerable spatial variation even within a single country. Geomagnetic shielding is generally stronger at lower latitudes, resulting in increasing cosmic-ray intensity towards higher geomagnetic latitudes at a given elevation. Soil moisture also affects the cosmic-ray dose rate through its influence on the neutron component, as hydrogen in soil water efficiently moderates neutrons and thereby reduces the near-surface neutron flux [2,3]. Consequently, population exposure reflects the combined spatial distribution of the radiation field and the population rather than ambient dose rates alone.

Global population exposure to cosmic radiation was investigated by Sato [4] who derived population-weighted estimates for 230 countries using the PHITS (Particle and Heavy Ion Transport Code System)-based Analytical Radiation Model in the Atmosphere (PARMA) in combination with gridded population

and elevation data at a spatial resolution of 2.5 arc-minutes (approximately 3–5 km over Germany). The resulting world population-weighted annual effective dose was 26 % lower than earlier UNSCEAR estimates [5] which relied on substantially coarser population and elevation data and a simpler approach based on altitude-dependent scaling factors. Cinelli et al. [6] subsequently provided a 1-km-grid assessment of cosmic-ray exposure across Europe and derived population-weighted national mean doses, although spatial variation in the underlying dose model was represented solely by elevation. The most recent UNSCEAR assessment [1] applied the same PARMA-based cosmic-ray flux model as Sato [4], combined with spatially resolved population and elevation data at 1-km resolution, but assumed a fixed soil-water content to derive population-weighted national mean doses.

Several national studies have also accounted for the spatial distribution of population exposure. In Switzerland, Rybach et al. [7] combined elevation-derived cosmic-radiation dose rates on a 2 × 2 km grid with population-density data, demonstrating that population-weighted exposure can differ from the spatial average because high-dose, high-elevation regions are not populated in proportion to their area. For Japan, Fujimoto and O'Brien [8] estimated cosmic-ray doses for all municipalities using the PLOTINUS model, accounting for latitude, longitude and altitude, but representing each municipality by the location and elevation of its city office; population-weighted national and prefectural doses were subsequently derived. Similarly, Chen et al. [9] applied PARMA to 1,506 Canadian communities covering approximately 85% of the Canadian population, using community-specific latitude, longitude and elevation as well as solar activity, but assuming a fixed soil-water content; the resulting estimates therefore characterized population exposure at discrete community locations rather than its continuous spatial variation in exposure across the population.

Despite these previous assessments, comparatively little attention has been given to the within-country distribution of cosmic-radiation exposure in populations and to how spatially varying environmental determinants translate into differences in population exposure. In particular, the extent to which population weighting and fine-scale spatial information affect the upper tail of the exposure distribution and subnational patterns, rather than national mean estimates alone, remains insufficiently characterized. Germany provides a suitable case study because elevation ranges from near sea level in the northern lowlands to more than 2,500 m in the Alps, while population density is highly heterogeneous. In particular, higher-elevation regions tend to be less densely populated, such that the spatial distribution of ambient dose does not directly translate into the distribution of population exposure. In addition to these spatial determinants, temporal solar modulation affects the galactic cosmic-ray flux, while soil moisture locally modifies the neutron component. Building attenuation and indoor occupancy further influence the translation of outdoor radiation fields into population dose estimates.

In this study, we characterize the spatial variability of cosmic-radiation exposure in the German population and investigate how population distribution and spatially varying environmental conditions shape national, subnational and upper-tail exposure. Using a 250-m calculation grid, we quantify the spatial distribution of effective dose rates from cosmic radiation, derive population-weighted estimates of the annual effective dose at national and municipal levels, and characterize the exposure distribution within the German population. We further quantify the contribution of individual cosmic-radiation components and evaluate the sensitivity of population exposure to solar activity, soil moisture and assumptions about building shielding. We also examine where population weighting and fine-scale spatial modelling add information beyond national mean exposure estimates.

2. Results

2.1. Cosmic dose distribution in the German population

The area-weighted unshielded cosmic dose rate across Germany had an area-weighted mean of 0.041 µSv/h and a median of 0.039 µSv/h. The interquartile range was 0.037–0.043 µSv/h, while the 95th and 99th percentiles were 0.049 and 0.056 µSv/h, respectively (Figure 1A). The coefficient of variation was approximately 12%. Lowest dose rates occurred in coastal regions of northern Germany, whereas the

highest values were found in the Alps. Overall, dose rates increased towards southern Germany despite the opposing geomagnetic latitude effect, which would tend to increase cosmic-ray intensity towards the north.

The population-weighted annual effective dose, accounting for indoor occupancy and reference building

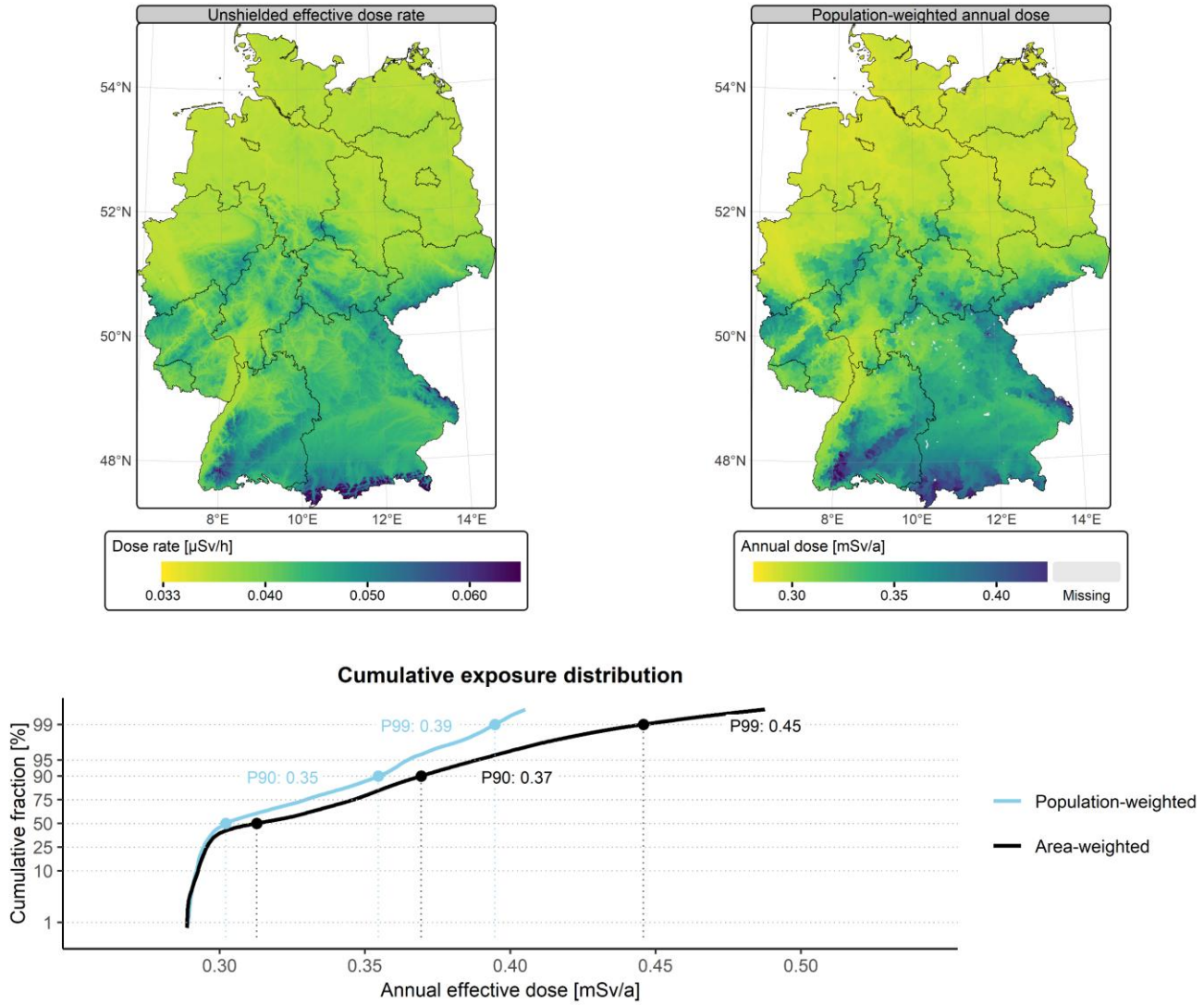


Figure 1: ***Spatial distribution and population exposure to cosmic radiation in Germany.*** *(A) Unshielded effective dose rate at 250 m spatial resolution. (B) Population-weighted mean annual effective dose by municipality, accounting for indoor occupancy and reference building shielding. (C) Cumulative distributions of annual effective dose at 250 m resolution using population weighting and area weighting. Markers indicate selected percentiles (P50, P90, and P99). For visualization, values exceeding the upper limits of the colour scales in panels A and B are assigned to the highest colour class.*

shielding, had a national mean of 0.31 mSv/a (Figure 1B). The interquartile range was 0.29–0.33 mSv/a, while the 95th and 99th percentiles were 0.37 and 0.40 mSv/a, respectively. Spatial variability within the German population was comparatively small, with a coefficient of variation of approximately 8%. The municipal pattern broadly followed the spatial distribution of the unshielded dose rate, although differences were most apparent in mountainous regions, where areas with the highest dose rates are generally sparsely populated. Municipal mean annual effective doses ranged from approximately 0.29 mSv/a in low-lying regions of northern Germany to 0.46 mSv/a in Balderschwang in the Alps, the highest-elevation municipality in Germany, with its settlement area located at approximately 1,000 m above sea level. Summary statistics for the German federal states are provided in Supplementary Table S1.

The population-weighted and area-weighted exposure distributions were similar around the median but increasingly diverged towards the upper tail (Figure 1C). The P90 was 0.34 mSv/a for the population-weighted distribution compared with 0.37 mSv/a for the area-weighted distribution, while the corresponding P99 values were 0.39 and 0.45 mSv/a. The area-weighted national mean was approximately 3% higher than the population-weighted mean. The mean elevation of populated locations was 199 m, compared with an area-weighted mean elevation of 260 m for Germany. At municipality level, differences were generally small in regions with limited topographic variability but exceeded 10% in some mountainous municipalities (Supplementary Figure S1).

Spatial resolution had only a minor influence on national population exposure estimates. Aggregating the model inputs from 250 m to 1 km produced virtually identical population-weighted mean doses and exposure distributions, with only small differences in the investigated percentiles. Hence, increasing the linear spatial resolution fourfold, equivalent to a 16-fold reduction in grid-cell area, did not materially alter national exposure statistics. Relative differences between both resolutions remained below 1 % for the population-weighted mean and all investigated percentiles up to P99.

2.2. Dose components

Muons were the dominant component of population exposure to cosmic radiation after accounting for component-specific shielding, contributing approximately 63% of the annual effective dose, followed by neutrons with approximately 19% (Figure 2A). Together, muons and neutrons accounted for about 82% of the total dose, whereas protons, photons, electrons, and positrons contributed approximately 18% in total. Contributions from heavier ions and other components were negligible (<0.1%). The relative contribution of individual components varied spatially across Germany. With increasing elevation, the relative contribution of muons decreased, whereas the contributions of neutrons, protons, and photons increased.

2.3. Sensitivity analysis

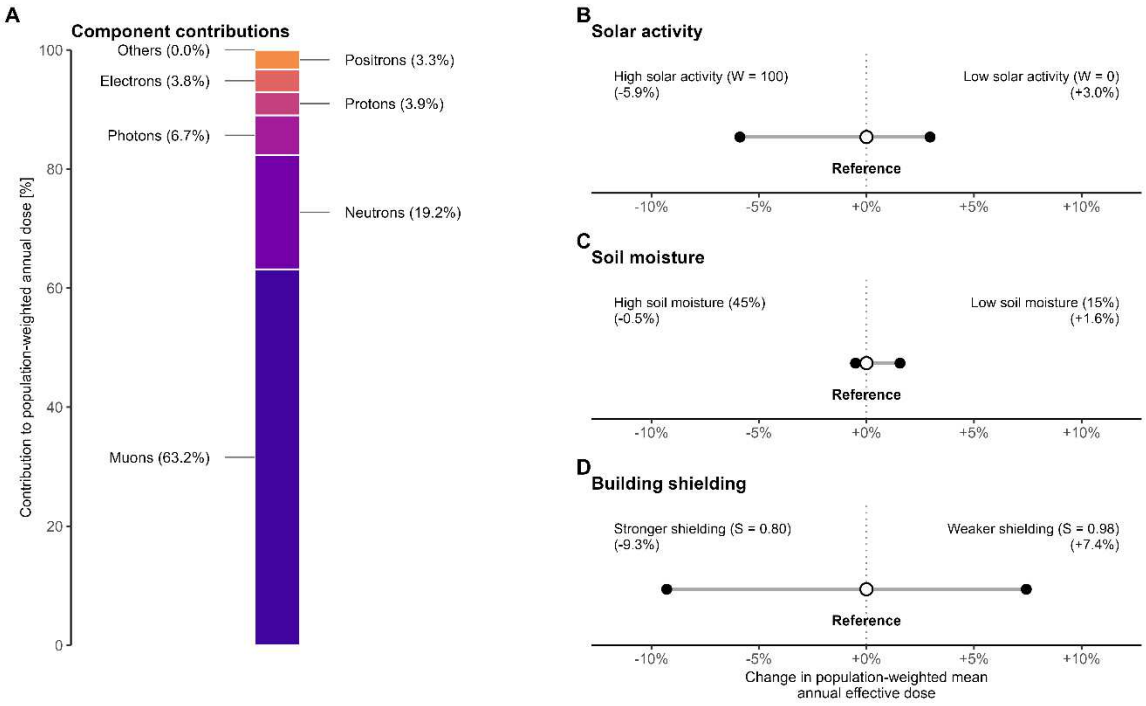


Figure 2: ***Contributions of cosmic-radiation components and sensitivity of population-weighted annual effective dose estimates in Germany.***
(A) Relative contributions of individual cosmic-radiation components considering component-specific shielding to the population-weighted annual effective dose under the reference conditions. (B–D) Relative changes in the population-weighted mean annual effective dose resulting from variations in (B) solar activity, (C) soil moisture, and (D) building shielding. Changes are expressed relative to the reference scenario defined by a solar modulation parameter of W = 50, spatially varying long-term mean soil moisture, and a building shielding factor of S = 0.90. Positive values indicate higher and negative values lower population-weighted annual effective dose compared with the reference scenario.

Solar activity had a moderate effect on the population-weighted annual effective dose (Figure 2B). Under the low solar activity scenario (W = 0), the estimated dose was 3.0% higher than under the reference scenario, whereas under the high solar activity scenario (W = 100) it was 5.9% lower. The influence of soil moisture on total annual effective dose was smaller (Figure 2C). Under the dry-soil scenario, the population-weighted dose was 1.6% higher than under the reference conditions, whereas under the wet-soil scenario it was 0.5% lower. Among the investigated parameters, assumptions on building shielding had the largest influence on the estimated annual effective dose (Figure 2D). Changing the indoor shielding factor from the reference value of 0.90 to 0.80 and 0.98 changed the population-weighted mean dose by approximately −9.3% and +7.4%, respectively. The three sensitivity analyses address conceptually different influences on the exposure estimates and were not defined on a common probabilistic or extremal scale. The solar-activity and soil-moisture scenarios represent selected low and high environmental conditions, whereas the shielding scenarios examine alternative values of an effective population-level parameter used to represent spatially heterogeneous indoor attenuation.

3. Discussion

This study characterizes the spatial variability of population exposure to cosmic radiation across Germany and shows that the ambient dose pattern is primarily governed by elevation, whereas population distribution determines how this spatial pattern translates into population exposure. Despite pronounced local elevation gradients in mountainous regions, overall variability within the German population was modest, with a coefficient of variation of approximately 8%. Dose rates generally increased towards southern Germany, although the geomagnetic latitude effect alone would favour somewhat higher cosmic-ray intensities towards the north. The southward increase therefore indicates that topographic variation outweighs the comparatively small geomagnetic gradient across Germany. Given the limited north–south extent of the country (47°N to 55°N), geomagnetic variation contributes

only modestly to the spatial exposure pattern. Further, the sensitivity analysis showed only a small influence of spatial variations in soil moisture on total dose. The resulting spatial variability in population exposure is comparatively small relative to other natural radiation sources in Germany. For example, coefficients of variation of approximately 164 % and 48 % can be derived from the results reported in Petermann et al. [10] and Petermann and Hoffmann [11] for indoor and outdoor radon, respectively. Compared with radon exposure, cosmic-radiation exposure is therefore much more homogeneous across the German population, although higher-exposure groups remain identifiable in mountainous regions. The spatial variability of the muon component was comparatively small, whereas neutrons and protons exhibited stronger relative spatial gradients (see Supplement Figure S2). Consequently, the radiation components contributing most strongly to local spatial contrasts are not identical to those dominating the national mean dose.

Differences between the 250-m and 1-km calculations were small for national summary statistics and the overall exposure distribution, indicating that a 1-km grid is sufficient for national-scale estimates under the present modelling framework. Finer resolution becomes more useful at local scales, particularly in mountainous areas where strong topographic gradients coincide with heterogeneous population distributions.

The population-weighted national mean annual effective dose of approximately 0.31 mSv/a corresponds to an unshielded annual dose of approximately 0.34 mSv/a and agrees closely with previous estimates for Germany. Sato [4] reported a population-weighted unshielded value of approximately 0.35 mSv/a, while the estimate of Cinelli et al. [6] corresponds to approximately 0.34 mSv/a after accounting for their occupancy and shielding assumptions. The close agreement suggests that finer spatial input data have little effect on the national mean, but mainly improve the representation of local exposure patterns and the population exposure distribution. The population-weighted annual effective dose of 0.31 mSv/a is also close to the current UNSCEAR estimate for the mean global population exposure to cosmic radiation. For broader international context, UNSCEAR [1] reported national population-weighted annual effective doses ranging from approximately 0.20 mSv/a in Singapore to 0.81 mSv/a in Bolivia.

Population weighting had only a modest effect on the national mean, which was approximately 3% lower than the corresponding area-weighted estimate. However, the difference increased towards the upper tail of the distribution. At P90, the area-weighted dose was 0.37 mSv/a compared with 0.34 mSv/a for the population-weighted distribution, while at P99 the difference increased to 0.45 versus 0.39 mSv/a (see Figure 1C). Population weighting is therefore of limited importance for the national mean, but becomes more relevant towards the upper tail because area-weighted statistics give disproportionate weight to high-dose, sparsely populated mountainous terrain.

The sensitivity analyses cover two different aspects of the exposure estimates. Solar activity and soil moisture represent temporal and environmental variability, whereas the building-shielding scenarios test assumptions about a poorly characterized population-level attenuation factor.

The solar-activity scenarios represent long-term modulation of galactic cosmic rays and do not include short-lived solar-particle events such as ground-level enhancements. Although such events can temporarily alter the secondary cosmic-ray field, their contribution to long-term population exposure at ground level is small and is more relevant at aviation altitudes. The approximately 11-year solar cycle is therefore the more relevant temporal variation for the present assessment.

The relatively small effect of soil moisture on total dose should not be interpreted as evidence that soil moisture has little influence on the neutron field itself. Increased hydrogen content reduces the near-surface neutron contribution through moderation and reduced neutron albedo. The DWD soil-moisture product represents an integrated value over the upper 60 cm of the soil profile, whereas the influence of soil water on the near-surface neutron field is depth dependent and weighted towards the upper soil layers. Neutron-transport studies indicate effective neutron sensing depths of approximately 10–30 cm under typical moist conditions, increasing to several decimetres under dry conditions [3,12]. The 0–60 cm DWD product therefore covers much of the relevant soil profile, although it does not capture the stronger weighting of near-surface moisture.

Seasonal snow cover was not explicitly considered. Because snow is rich in hydrogen, it may further reduce the near-surface neutron component locally, particularly in mountainous regions during winter [13], although its influence on the population-weighted national total dose is likely to be substantially smaller than its effect on the neutron component itself.

The building-shielding scenarios address a different aspect of the exposure assessment. Their numerical effect was larger than that of the selected solar-activity and soil-moisture scenarios, but the scenario ranges were not defined on a common uncertainty scale and should therefore not be compared directly. The sensitivity nevertheless shows that better population-representative information on building attenuation would improve annual exposure estimates.

Although individual indoor occupancy varies across the population, its influence on cosmic-radiation dose is limited by the relatively weak indoor attenuation. For the reference shielding factor of 0.90, even indoor occupancy fractions ranging from 0.5 to 1.0 would change annual dose estimates by only approximately +3.8 % to −1.6 % (equation 2) relative to the reference value of 0.85.

An important source of model uncertainty is the limited information available on cosmic-ray attenuation in the German building stock. Effective shielding depends on construction material, mass thickness, building geometry and floor level, and differs substantially among radiation components. The use of a uniform shielding factor of 0.90 therefore represents a population-level approximation rather than a building-specific exposure model. This simplification does not affect the spatial ranking of outdoor dose rates but may influence the absolute magnitude and inter-individual variability of estimated annual exposure. Future assessments could be improved by combining component-specific attenuation models with information on building type, construction material and floor-level occupancy.

Population weighting was based on residential population and therefore represents exposure at the place of residence rather than individual time–activity patterns. Daily mobility, workplace location, travel and temporary stays at higher elevations were not considered, and the estimates should therefore not be interpreted as individual personal doses. The resulting exposure misclassification cannot be quantified from the available data. A uniform indoor occupancy factor of 0.85 was also applied; while this is unlikely to materially affect national or municipal mean estimates, it may underestimate inter-individual variability.

The close agreement with previous PARMA-based estimates supports the internal consistency of the present calculations, but it does not constitute independent validation of the model. Direct validation of population-weighted effective dose is inherently difficult because the quantity integrates spatially varying radiation fields, indoor shielding and human time–activity patterns.

Spatially resolved cosmic-radiation estimates may be useful as background information for cumulative natural-radiation assessments and studies requiring regional exposure estimates. The relatively narrow national distribution also suggests that high-elevation populations, rather than broad regional differences, account for much of the upper exposure range.

Population exposure to cosmic radiation in Germany was comparatively homogeneous, with a mean annual effective dose of about 0.31 mSv and elevation as the main spatial determinant. Population weighting had little influence on the national mean, but became more relevant towards the upper end of the exposure distribution and in mountainous regions. The comparison between 250-m and 1-km calculations also shows that finer spatial resolution adds little to national summary statistics, while it remains useful for resolving local gradients and identifying higher-exposure population groups. Solar activity produced moderate changes in the estimated dose, whereas the influence of soil moisture on total dose was smaller. Building attenuation remains less well constrained and would benefit from more representative information for the German population. Taken together, the spatial detail needed for cosmic-radiation exposure assessment depends on the purpose of the analysis: national averages require relatively little fine-scale information, whereas local patterns and the upper tail of exposure benefit from finer spatial resolution.

4. Methods

4.1. Data sources

For the spatially resolved dose calculations, three main input datasets were prepared on a common 250 m grid (Figure 3). Elevation was obtained from the digital elevation model of the German Federal Agency for Cartography and Geodesy (BKG) at 25 m resolution [14] and aggregated to 250 m by calculating the arithmetic mean elevation within each grid cell. Population data were derived from the *Haushalte-Einwohner-Bund* dataset [15], which provides building-level information including the number of inhabitants. These data were spatially aggregated by summing the number of inhabitants within each 250 m grid cell. Soil moisture was obtained from the German Weather Service (DWD) and represents mean conditions over the period 1991–2020 [16]. The original dataset provides mean monthly relative soil moisture as a percentage of usable field capacity over the reference period integrated over a depth of top 60 cm. This depth encompasses the range from which most soil-moisture-related effects on near-surface cosmic-ray neutrons are expected to originate. These values were converted to volumetric water content using regionalised data for field capacity and permanent wilting point provided by DWD as follows:

$$\theta = \theta_{WP} + \frac{SM}{100}(\theta_{FC} - \theta_{WP}) \quad \textit{(Equation 1)}$$

where θ denotes volumetric water content, θ_{FC} the volumetric water content at field capacity, θ_{WP} the volumetric water content at the permanent wilting point, and SM the relative soil moisture expressed as a percentage of usable field capacity. Latitude and longitude values were derived from the geolocation of 250 m cells midpoints.

4.2. Cosmic dose component calculation using PARMA

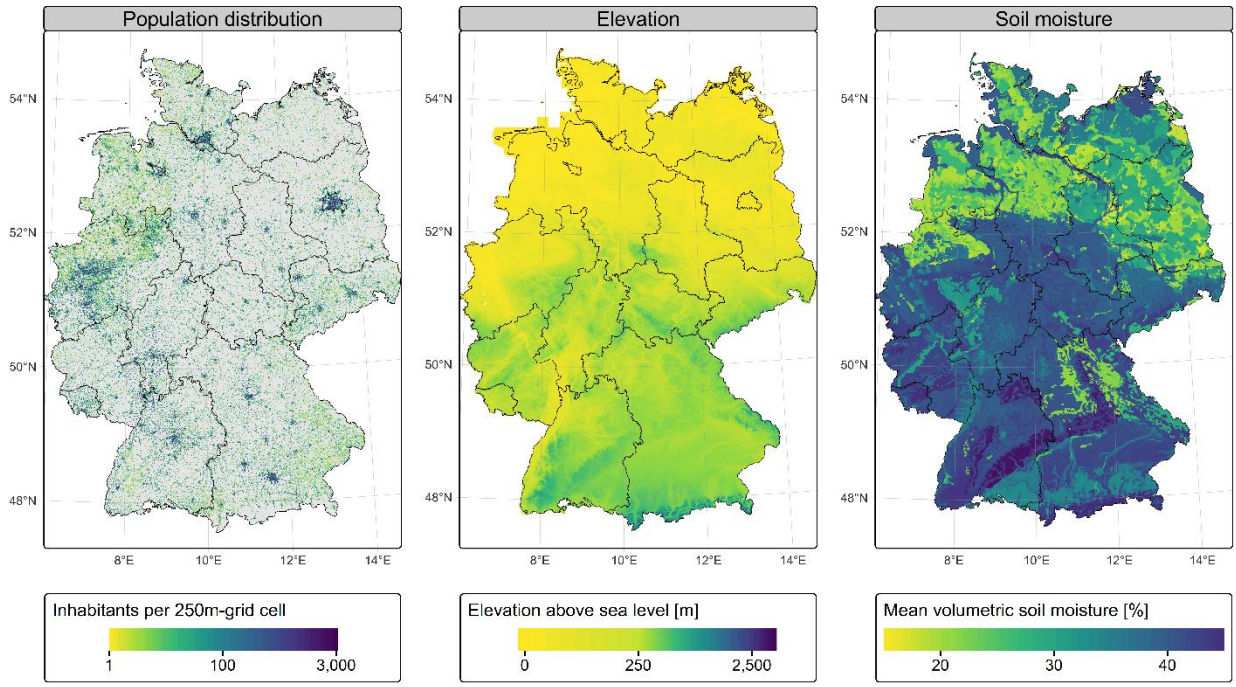


Figure 3: ***Spatial distribution of the main input variables used for the cosmic radiation dose calculations in Germany. (Left)*** *Population distribution, expressed as the number of inhabitants per 250 m grid cell and aggregated from building-level population data.* ***(Centre)*** *Mean elevation within each 250 m grid cell, derived from the 25 m digital elevation model of the German Federal Agency for Cartography and Geodesy (BKG).* ***(Right)*** *Mean volumetric soil moisture for the period 1991–2020, derived from German Weather Service (DWD) data. Multi-annual relative soil-moisture values given as percentage of usable field capacity were converted to volumetric water content using regionalised field-capacity and permanent-wilting-point data. All datasets were harmonised to the common 250 m modelling grid used for the dose calculations.*

The PHITS-based Analytical Radiation Model in the Atmosphere (PARMA) version 3.0, developed by Sato [2], was used to estimate terrestrial cosmic-ray fluxes throughout Germany. PARMA 3.0 provides energy spectra for neutrons, protons, ions with atomic numbers up to Z=28 (Ni), positive and negative muons, electrons, positrons, and photons. The model consists of analytical functions whose parameters were fitted to reproduce extensive air-shower simulations performed with the Particle and Heavy Ion Transport Code System (PHITS). The underlying PHITS simulations were evaluated against experimental measurements, while the ability of PARMA 3.0 to reproduce the simulated particle spectra was verified separately using coefficients of determination, which were close to unity for most particle types and somewhat lower for helium and heavier ions [2].

PARMA 3.0 has additionally been validated against measured cosmic-ray dose rates. Sato [4] reported agreement with measurements from 24 locations covering wide ranges of altitude and geomagnetic cut-off rigidity, with most calculated dose rates within approximately 10% of observations and a mean calculated-to-experimental ratio of 0.977. The model also accounts for variations in ground albedo neutron flux caused by differences in soil-water content and is implemented in the freely available EXPACS software.

The terrestrial cosmic-ray spectra calculated by PARMA depend primarily on atmospheric depth d (g/cm²), vertical geomagnetic cut-off rigidity r_c (GV), and the solar modulation index W. Atmospheric depth is derived from elevation according to the US Standard Atmosphere 1976, while r_c is determined from geographic position using a global geomagnetic cut-off rigidity map with an underlying geomagnetic database with approximately 1° spacing. For the reference calculations, a solar modulation index of $W = 50$ was used to represent approximately average solar modulation conditions. Spatially varying volumetric soil-water content was additionally supplied for each grid cell to account for its influence on the ground-level neutron component.

For each 250-m grid cell, latitude, longitude, elevation and soil-water content (soil moisture) were combined with the reference solar-modulation condition to calculate component-specific outdoor effective dose rates. Effective dose rates were derived from the calculated particle fluences using fluence-to-effective-dose conversion coefficients for isotropic irradiation according to the International Commission on Radiological Protection (ICRP) Publication 116 [17]. The resulting component-specific effective dose rates (µSv/h) formed the basis for the subsequent spatial aggregation and population-exposure calculations.

4.3. Postprocessing of spatial data

Calculated grid-cell-based effective dose rates were aggregated to the desired spatial unit of interest, including municipalities and the national level, by calculating population-weighted mean dose rates using the number of inhabitants in each 250 m grid cell as weights. Hourly effective dose rates [µSv/h] were converted to annual effective doses [mSv/a] by multiplication with 24 h/d and 365 d/a and conversion from µSv to mSv. For population exposure estimates, indoor and outdoor occupancy were additionally considered by applying the respective occupancy fractions and shielding assumptions before spatial aggregation. For comparison, area-weighted statistics were calculated by assigning equal weight to each grid cell. Municipality-level results were obtained by spatially intersecting the modelling grid with administrative boundaries and calculating population-weighted mean doses within each municipality. At the national level, summary statistics included the mean, selected percentiles, and cumulative exposure distributions.

4.4. Assumptions on shielding factor, occupancy and solar activity

Cosmic-ray dose rates indoors are generally lower than those outdoors because building materials attenuate part of the incoming cosmic radiation. The magnitude of this reduction depends on building characteristics, including material composition and mass thickness, and differs among radiation components; in particular, muons are much more penetrating and are therefore less effectively attenuated than other components. In the absence of sufficiently detailed and spatially representative information on building-specific shielding in Germany, a uniform indoor shielding factor of ~0.9

(corresponding to an effective wall thickness of 30 g/cm²) was applied to the total cosmic-ray dose, following Sato [4] and UNSCEAR [1] who proposed this value as a global average. For the estimation of component-specific contributions to annual effective dose, component-dependent shielding factors corresponding approximately to an effective mass thickness of 30 g cm⁻² were applied: 0.98 for muons and 0.80 for neutrons, protons, photons, electrons, and positrons, following Sato [4]. These component-specific shielding factors were used only to estimate the relative component contributions and were not applied to the reference total-dose calculation.

An indoor occupancy fraction of 0.85 and a corresponding outdoor fraction of 0.15 were adopted based on information from the German Environment Agency (2024, personal communication), consistent with the approach used by Petermann and Hoffmann [11] for public exposure estimation to outdoor radon in the German population. A solar modulation index of $W = 50$ was adopted following Sato [4], who used this value as an approximate mean solar modulation condition for the period after 2000.

4.5. Annual dose calculation

Annual effective doses [mSv/a] were derived from the calculated outdoor dose rates by accounting for indoor and outdoor occupancy and attenuation by building materials. For each administrative unit of interest, the population-weighted unshielded outdoor dose rate $\dot{E}$ [µSv/h] was combined with an indoor occupancy fraction $t_{in} = 0.85$, an outdoor occupancy fraction $t_{out} = 0.15$, and an indoor shielding factor $S = 0.9$. The annual effective dose E_{annual} was calculated as

$$E_{annual} = \dot{E}\ (t_{in}S + t_{out})\ * 24 * 365/1000 \quad \textit{(Equation 2)}$$

where division by 1000 converts µSv to mSv. Under the reference assumptions, the combined occupancy–shielding factor is $0.85 * 0.9 + 0.15 = 0.915$. Thus, the annual dose corresponds to 91.5% of the hypothetical annual dose obtained under continuous unshielded outdoor exposure.

4.6. Sensitivity analysis

A sensitivity analysis was performed to assess the influence of solar activity, soil moisture, and building shielding on the estimated annual effective dose. All model inputs were kept identical to the reference scenario and only the parameter under investigation was varied.

The reference scenario was defined by a solar modulation index of $W = 50$, an indoor building shielding factor $S = 0.90$, and spatially varying long-term mean soil moisture (Figure 3). To evaluate the influence of solar modulation, calculations were repeated for $W = 0$, representing very low solar activity conditions, and $W = 100$, representing substantially higher solar activity. The corresponding dates used in the PARMA calculations were 20 October 2009 and 2 May 2004, respectively. Because $W = 100$ does not represent the upper limit of the solar modulation index, these scenarios are referred to as low and high solar activity conditions, rather than solar minimum and maximum.

Sensitivity to soil moisture was assessed by replacing the spatially varying reference soil-moisture field with two spatially uniform scenarios representing comparatively dry and wet conditions. Volumetric soil-moisture contents of 15% and 45% were used for the low- and high-moisture scenarios, respectively. All other model parameters were unchanged. These calculations were intended to quantify the influence of soil water content on the ground-level neutron component and, consequently, on total cosmic-ray dose.

Sensitivity to building shielding was assessed by varying the indoor shielding factor around the reference value of $S = 0.90$. Because spatially representative data on building-specific shielding properties, such as material composition and effective mass thickness, are not available for Germany, additional scenarios were defined based on the range reported by Sato [4]. Shielding factors of $S = 0.80$ and $S = 0.98$ were used to represent stronger and weaker building attenuation, respectively.

4.7. Use of AI tools

During the preparation of this manuscript, the authors used ChatGPT (version 5.6 Sol, OpenAI) to assist with language editing, R coding, manuscript structure and clarity. All AI-assisted outputs were reviewed and verified by the authors, who take full responsibility for the scientific content.

Data availability

The processed data underlying the results of this study, including the reference 250-m cosmic-radiation dose grid, municipality-level exposure estimates and sensitivity-analysis results, together with the main R scripts used for data aggregation and visualization, are available through Zenodo at https://zenodo.org/records/23592852. Primary geospatial input data were obtained from the respective data providers described in the Methods section and are not redistributed because they remain subject to their original licensing conditions.

Conflict of Interest Statement

The authors declare that they have no competing interests.

Acknowledgements

The authors have no specific acknowledgements to declare. This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

References

1 UNSCEAR. Sources, Effects and Risks of Ionizing Radiation. Volume II: Scientific Annex B. UNSCEAR 2024 Report. (United Nations, New York, 2025).

2 Sato, T. Analytical Model for Estimating Terrestrial Cosmic Ray Fluxes Nearly Anytime and Anywhere in the World: Extension of PARMA/EXPACS. *PLoS One* **10**, e0144679, doi:10.1371/journal.pone.0144679 (2015).

3 Zreda, M., Desilets, D., Ferré, T. P. A. & Scott, R. L. Measuring soil moisture content non-invasively at intermediate spatial scale using cosmic-ray neutrons. *Geophysical Research Letters* **35**, doi:10.1029/2008gl035655 (2008).

4 Sato, T. Evaluation of World Population-Weighted Effective Dose due to Cosmic Ray Exposure. *Sci Rep* **6**, 33932, doi:10.1038/srep33932 (2016).

5 UNSCEAR. UNSCEAR 2000 Report. 89 (UN,, New York, 2000).

6 Cinelli, G. *et al.* European annual cosmic-ray dose: estimation of population exposure. *Journal of Maps* **13**, 812-821, doi:10.1080/17445647.2017.1384934 (2017).

7 Rybach, L., Bächler, D., Bucher, B. & Schwarz, G. Radiation doses of Swiss population from external sources. *Journal of Environmental Radioactivity* **62**, 277-286, doi:https://doi.org/10.1016/S0265-931X(01)00169-2 (2002).

8 Fujimoto, K. & O'Brien, K. Estimation of Dose Due to Cosmic Rays in Japan. *Japanese Journal of Health Physics* **37**, 325-334, doi:10.5453/jhps.37.325 (2002).

9 Chen, J., Timmins, R., Verdecchia, K. & Sato, T. An estimation of Canadian population exposure to cosmic rays. *Radiat Environ Biophys* **48**, 317-322, doi:10.1007/s00411-009-0226-z (2009).

10 Petermann, E. *et al.* Development of a High-Resolution Indoor Radon Map Using a New Machine Learning-Based Probabilistic Model and German Radon Survey Data. *Environmental Health Perspectives* **132**, 097009, doi:doi:10.1289/EHP14171 (2024).

11 Petermann, E. & Hoffmann, B. Mapping the exposure to outdoor radon in the German population. *Journal of Environmental Radioactivity* **281**, 107583, doi:https://doi.org/10.1016/j.jenvrad.2024.107583 (2025).

12 Franz, T. E. *et al.* Measurement depth of the cosmic ray soil moisture probe affected by hydrogen from various sources. *Water Resources Research* **48**, doi:10.1029/2012wr011871 (2012).

13 Rühm, W., Ackermann, U., Pioch, C. & Mares, V. Spectral neutron flux oscillations of cosmic radiation on the Earth's surface. *Journal of Geophysical Research: Space Physics* **117**, doi:10.1029/2012ja017524 (2012).

14 BKG - Federal Agency for Cartography and Geodesy. (Frankfurt am Main, Germany, 2018).

15 BKG - Federal Agency for Cartography and Geodesy. (Frankfurt am Main, Germany, 2022).

16 DWD - Deutscher Wetterdienst. in *DWD Climate Data Center (CDC)* (2020).

17 ICRP. ICRP Publication 116: Conversion Coefficients for Radiological Protection Quantities for External Radiation Exposures. Report No. 0146-6453, 1-257 (SAGE Publications, 2010).

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryMaterial.docx