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Title : **Bounding uncertainties around the conceptual representation of species in radiological assessment in the context of routine atmospheric release**

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Keywords :

Radiological risk assessment, non-human biota, reference organism, terrestrial, absorbed dose rate, atmospheric discharges

Highlight:

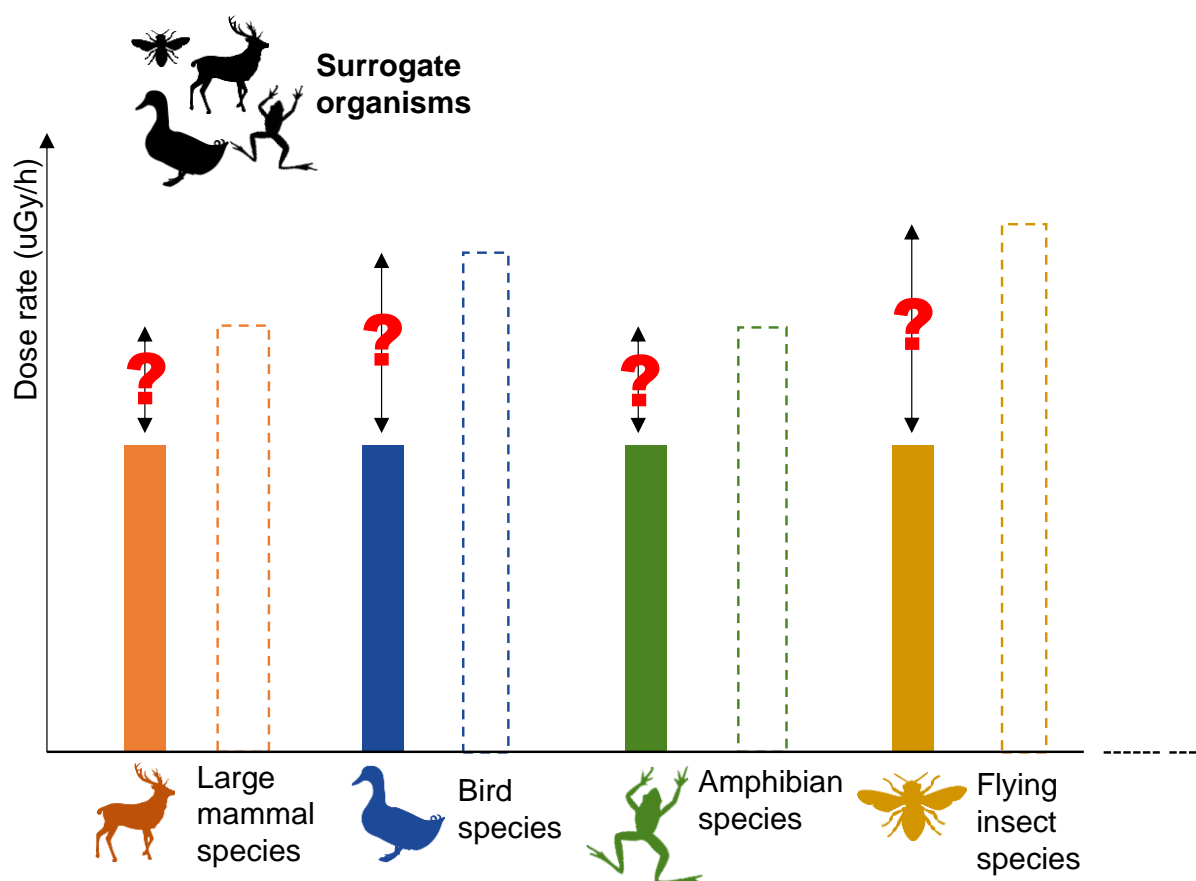
Radiological risk assessment is based on reference organisms

Assessments can be made with a limited number of organisms

Dose rate does not change linearly with size of organisms

Available knowledge demonstrates that use of reference organisms provides adequate level of protection

Graphical abstract:



Abstract

Wildlife protection has become of regulatory interest since the International Commission on Radiological Protection (ICRP) developed an approach to assess the level of radiological protection specifically for animals and plants. For the purpose of demonstrating compliance with regulation to protect the environment against routine authorized discharges from nuclear facilities, the wide variety of biota inhabiting an ecosystem needs to be condensed to a limited set of representative organisms, as proposed by the ICRP with a set of ‘reference animals and plants’ which can be considered representative of many other species. It is now recommended in the International Atomic Energy Agency (IAEA) Safety Standards, and internationally accepted, that the use of such a limited number of organisms to represent a pool of species is adequate for radiation protection purposes, particularly in planned exposure situations. Adding site-specific species to that set of surrogate species can respond to various interests, such as ensuring a site-specific context to the assessment that addresses stakeholder interests and can aid in stakeholder consultation and risk communication. Moreover, there is a need to question whether the use of the set of surrogate organisms is conservative enough to cover a wider range of biodiversity. Previous studies partially answered this question and this paper adds a range of test cases. A selection of hypothetical representations of possible site-specific species are assessed on the basis of possible variations in size (mass) and occupancy habits. Dose rates are evaluated to determine the greatest difference between hypothetical organisms and those for reference organisms, considering radionuclides potentially discharged in

atmospheric routine release from different nuclear facilities. Differences observed in the results between hypothetical and reference organisms were less than one order of magnitude in all cases, the difference being dependent on the radionuclides considered. These findings do not preclude the inclusion of site-specific species in environmental radiological assessments if it is considered necessary, but they provide reassurance that using reference organisms for radiological impact assessments in the case of routine atmospheric discharges is sufficient.

1. Introduction

The International Commission on Radiological Protection (ICRP) and the International Atomic Energy Agency (IAEA) call for the explicit demonstration of environmental protection from radionuclides (RNs) discharged by facilities and activities using atomic energy and radiation sources for industrial processes [1,2]. To support that objective the ICRP has developed a protection framework for non-human biota [3]. This framework allows the creation of a standardized methodology [4,5], which can be implemented for environmental radiological impact assessments. It is not practical for an assessment to analyze all species and populations within an area of interest. International recommendations [4,5] advise that the diversity of wildlife can be adequately represented with a limited set of reference organisms, and standard assessment models associated with transfer parameters [6], dose coefficient [7], and reference levels [5]. The ICRP approach for biota risk assessment is based on a set of 12 ‘reference animals and plants’ (RAPs), which consist of *“a small set of hypothetical entities that are representative of animals and plants present in different environments (terrestrial, freshwater, marine) and which form the basis of a structured approach to the assessment of exposure to, and effects of, ionising radiation”* [5]. The number of such surrogate organisms (SOs) used in radiation risk assessment models varies across approaches. For example, the modelling approach developed by Argonne National Laboratory (RESRAD-BIOTA), considers four general organism categories: two for terrestrial ecosystems and two for marine and freshwater ecosystems. Alternatively, the Environmental Risks from Ionising Contaminants (ERICA) project, developed through the European Commission EURATOM Framework, proposes a wider range of reference organisms (ROs): 13 in each of terrestrial, marine, and freshwater ecosystems. Not all the potentially exposed actual organisms would be included in the mentioned sets of SOs (e.g. ROs or RAPs), but it is considered that they are still adequately represented [8]. However, in radiological risk assessments on fauna and flora for different purposes, it is not uncommon to find that site-specific organisms need to be considered in addition to the surrogate organisms (ROs or RAPs) [9–11]. The selection of specific organisms is primarily a function of the surrounding environment but may also take into account societal factors. For example, species of particular importance to culture may be chosen to increase confidence in assessments [10]. Furthermore, to demonstrate compliance with endangered

species or protected species regulations, additional sensitive species may be assessed. IAEA Safety Guide GSG-10 [4] indicates that, “*a generic approach may not be appropriate for the assessment of the impact on flora and fauna in particular circumstances, for example when dealing with protected species or endangered species. For these cases, a more specific assessment may be required.* “. Similarly, the DOE standard for evaluating radiation doses to aquatic and terrestrial biota [12], part 3.1.1, states “*Care must be taken by the user if the graded approach is applied in an evaluation of potential radiological impacts to endangered, threatened, rare ...*”. For some nations, the regulatory framework may also require that site-specific species have to be considered into account in the assessment and be supported by site-specific data [13]. Conservatively, umbrella species, keystone species, or focal species could be included in the list of organisms considered in the assessment [14]. The most exposed actual organisms and the most sensitive organisms can also be part of the analysis. In view of the low level of radiological risk related to routine releases from activities and facilities, it is generally not practical for an assessment to take into account all living species and populations within an area of interest. Some selection criteria are therefore necessary to identify a manageable number of organisms sufficient to address assessment objectives [9]. Despite of the wide range of geometric characteristics, habits, and habitats observed in the compendium of site-specific species and SOs, in numerous cases, no important differences were noted in the predicted dose rate (DR) [9–11]. These conclusions can be attributed to, the similarity of the transfer factors for the site-specific species and their corresponding surrogate organisms, the relatively small effect of the mass, habit, and habitats on the dose coefficients [15,16], and also to the assumptions on which the methodologies for calculating dose coefficients and transfer parameters for wildlife radiological assessments are based.

Nevertheless, the literature lacks conclusions on whether the use of only SOs in the assessments adequately protect the site-specific organisms. Working Group 3 of IAEA’s MODARIA II program (Modelling and Data for Radiological Impact Assessments) has conducted an analyses to address this issue. The objectives of this study were, to bound uncertainties around the conceptual representation of species in assessments in case of routine atmospheric releases. A selection of hypothetical representations of possible site-specific species are assessed on the basis of possible variations in size (mass) and occupancy habits. Maximal predicted dose rate differences between hypothetical organisms and its corresponding SO were estimated. Although transfer factors are important parameters in the dose rates estimation, this study did not focus on the influence of such parameter.

This analysis provides pragmatic information to risk assessors and regulators in the context of routine radiological risk assessment of wildlife.

2. Materials and methods

2.1 METHODOLOGY OVERVIEW

The workflow to assess the largest observed difference in predicted DR calculation between a site-specific organism and its corresponding SO is presented in Figure 1. First of all, hypothetical organisms with extreme shapes and sizes were created for each category of SO in order to produce maximum dose rate differences (step 1-a). Several groups of SO were considered from those included in the ERICA tool [17] and in the ICRP biota dose assessment approach [5]. Since the source term could not be precisely defined, a list of the radionuclides identified for different nuclear facilities (step 1-b) was selected. Due to the variability of the atmospheric release scenario, in order to be representative of the greatest number of deposition cases, several scenarios were considered. DRs were estimated for each hypothetical organism and for its corresponding SO for each deposit scenario (step 2) and then compared (step 3).

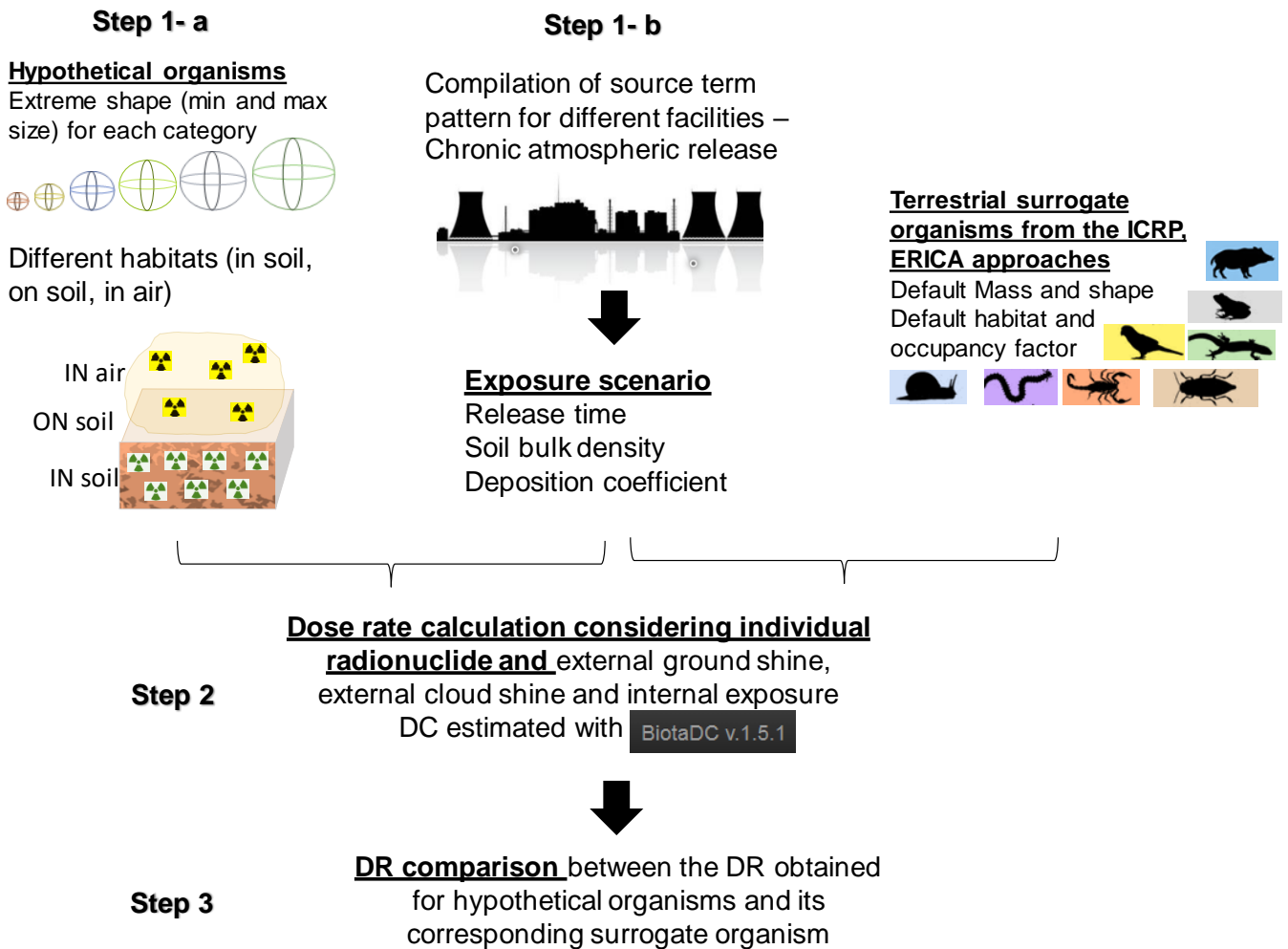


Fig.1. Schematic representation of workflow to estimate the maximal dose rate discrepancy between a site-specific specie and its corresponding surrogate organism

2.2 CREATION AND CHARACTERISTICS OF HYPOTHETICAL ORGANISMS (STEP 1-A)

2.2.1 Mass range for terrestrial hypothetical organisms

To cover a wide range of potential terrestrial organisms and account for the influence of mass on the dose coefficient (DC), hypothetical organisms were created with masses lower and higher than the thirteen corresponding SOs defined by default in the ERICA tool (version 1.3.1). It is not yet possible to define precisely accurate mass ranges of species belonging to the groups of surrogate organisms (ROs or RAPs) because (1) there is a lack of available information on the mass of some species (less certainty of parameters for insects than for mammals), (2) the mass of individuals within a species may vary widely, (3) new species are frequently discovered. . To ensure the analysis encompassed the variety of species around the world, masses (minimal mass and maximal mass) were established as a function of the range of mass of included organisms and, for practical reasons, as a function of the mass limits in the BiotaDC tool for calculating DC from the ICRP. Masses of the hypothetical organisms created were summarized in Table S1 in supplementary data and were compared to approximate mass ranges of several taxonomic groups (Fig. 2). For the thirteen groups of organisms considered, the mass range used in the creation of hypothetical organisms conservatively covered the mass ranges of real species for mammal, reptiles, bird, amphibian, mollusc-gastropod, and flora. For the arthropod-detritivorous, flying insect, and annelid, the masses of potential real species may be lower than the lowest mass limit considered in this study. In this case, the mass is set to 1 mg for internal and external exposure for occupancy on soil. For external exposure whilst in soil, the BiotaDC tool allows DC calculations for a narrow range of mass, between 1.7×10^{-4} - 6.6 kg.

The physical characteristics (masses and shapes) and habitat definition of the SOs corresponding to those of the ERICA ROs and the ICRP RAPs are summarized in Table S2. The main difference between the two approaches is the number of organisms considered.

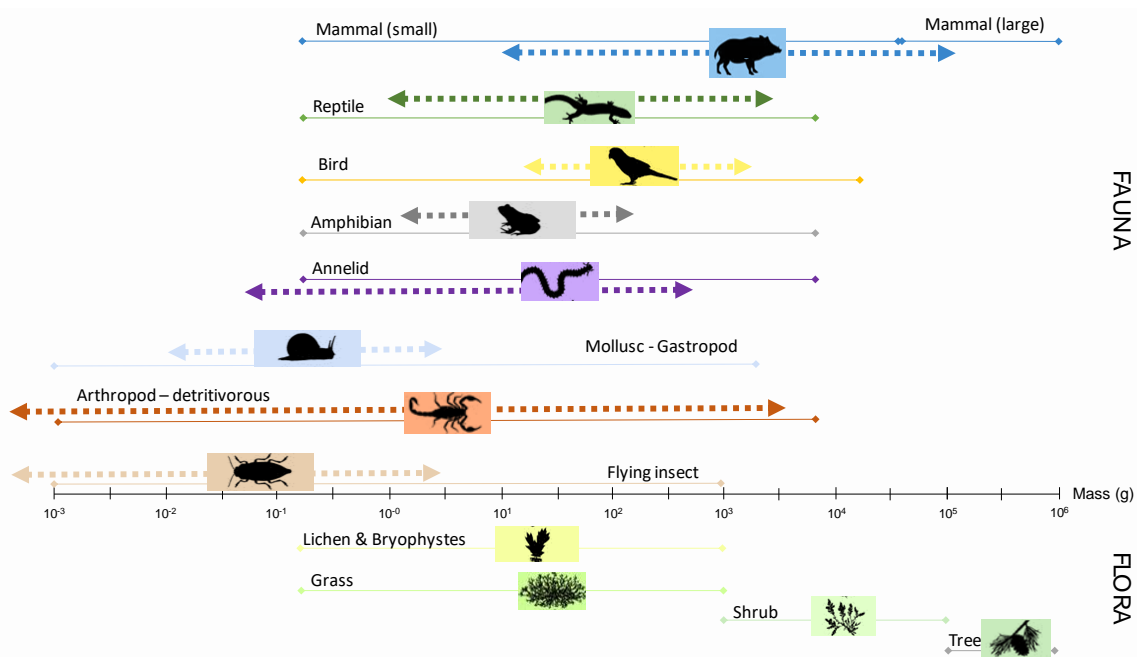


Fig. 2. Schematic representation of the mass range for the different organism categories. The dotted line represents the mass range of real species and the solid line represents the mass range considered for hypothetical organisms

2.2.2 Geometry definition for hypothetical organisms

For environmental dosimetry, the shape of the organisms is approximated by spheres and ellipsoids placed in a specific habitat (position in the media and occupancy factor) for the DC calculation. Depending on the geometries of the simulated organism, the shape of the organism can take any form between a sphere and a plane disk or even a line [18]. It would not be practical to consider all possible combinations of the ellipsoid dimensions defined by the 3 axes. For simplification and conservatism, the shape of the hypothetical organism was fixed to a spherical form. A realistic representation of the body shape and its internal structure as well as of the radiation geometry may be important when dosimetric endpoints are absorbed doses in particular organs or when exposure conditions suggest a highly anisotropic radiation exposure to a static or slowly moving organism. Additionally, BiotaDC can calculate an external DC for a wide range of masses but only for a spherical organism. Geometrical properties and masses of created hypothetical organisms are presented in Table S1.

2.2.3 Habitat for hypothetical organisms

The diversity of flora and fauna with regard to habitats, behaviors, and exposure conditions creates a challenge for the development of dosimetric models for assessing exposure to biota from radioactivity in the environment. This range of diversity amongst biota increases the uncertainty for modelling

parameters used in dosimetric models. As a result, risk assessment for chronic releases typically adopts a conservative approach. In this analysis, hypothetical organisms were placed in the different habitats (IN soil or ON soil) with an occupancy factor of up to 100 %, depending on assumed behaviors. Habitat definition for hypothetical organisms are presented in Table S1.

2.3 RADIONUCLIDES CONSIDERED (STEP 1-B)

As the nature of the releases from different facilities can be diverse, an all-encompassing generic release scenario is impractical. Therefore, the maximal dose rate difference between hypothetical organisms and SOs was conservatively estimated by applying a unit activity concentration for each of several radionuclides. In the same manner used to account for the diversity of biota, the analysis evaluated multiple chronic release scenarios for a wide range of nuclear activities. Radionuclides were selected based on the work conducted in MODARIA I and II, IAEA safety reports series n°64 [19], of the Euratom commission [20] and current literature [9,11,21]. Distinctions were made between research centers, fuel fabrication facilities, nuclear power plants (NPPs), decommissioning activities for NPPs, waste disposal facilities, radiopharmaceutical facilities, and hospitals. NORM activities were also considered [22]. As an example, some radionuclides used in the assessment were sorted to different type of nuclear facilities as presented in Fig. 3. Finally, an initial group of 92 radionuclides was identified. Insufficient data on transfer factors was available for Au, Bi, Er, Fe, In, Ga, In, K, Lu, Mo, Na, Re, Sm, Tl, and Y; therefore, these elements have been excluded. Radon was not considered in this study as the dose estimation methodology, which is deserving of its own study [23], is very different. A total of 73 radionuclides were analyzed in this study including noble gases $^{85,85m,87,88}\text{Kr}$, $^{131m,133,133m,135,135m,137,138}\text{Xe}$, and ^{41}Ar and are presented in Table S3.



Fig.3 : Example of radionuclides released to the atmosphere for multiple nuclear facilities

2.4 PREDICTED DOSE RATE ESTIMATION (STEP 2)

The predicted absorbed dose rate (DR) for terrestrial organisms is the sum of three exposure components: internal absorbed dose rate, external absorbed dose rate from soil, and external absorbed dose rate from cloud immersion. Noble gases that are discharged with a relatively high activity concentration, Ar, Kr, and Xe, isotopes are not routinely included in wildlife assessments [24]. For practical purposes, it was assumed that Ar, Kr, and Xe do not contribute to internal dose rate for biota.

2.4.1 Dose coefficient models and dosimetric considerations

To account for the wide range of geometries for exposure pathways, internal and external DCs due to the cloud shine or soil shine were calculated using the ICRP's Biota-DC tool. The BiotaDC tool is an open-access web-based application (<http://biotadc.icrp.org>) that performs DC calculations for fauna and flora. Further information can be found in ICRP Publication 136 [7]. The dose coefficient calculation for the ICRP methodology assumes that any organism can be represented by a simple and homogeneous composition, and that the radionuclide is uniformly distributed throughout the volume of the source, whether external or internal [25,26]. The external exposure due to the in-, on- and above-soil exposure for the surrogate organisms or the hypothetical organisms was calculated by assuming a uniformly contaminated volume of soil, with a depth of 10 cm for on- and above-soil organisms, and 50 cm for in-soil organisms. This assumption is representative of aged contamination of soil following substantial

downward migration and activity redistribution [7]. The contribution of radioactive progeny to radiation exposure of non-human biota is commonly attributed to the parent radionuclide, subject to various assumptions. The most common approach is a simple and pragmatic method in which only part of the full decay chain is taken into account assuming full equilibrium between the parent radionuclide and its progeny. Criteria for truncation of decay chains are commonly based on the selection of an upper limit for physical half-life of a daughter to be accounted for in the given decay chain. To be consistent with the approach adopted in ICRP Publication 108 [3] as in the FASSET and ERICA projects [27,28] and in the ERICA tool [29], the decay chain was truncated at the first daughter nuclide with physical half-life greater than 10 days. Effects of radiation on living tissues depend on the type of radiation or, more precisely, on the density of ionization produced by the deposition of energy in the tissue, which is expressed via linear energy transfer. Thus in order to be consistent with the ERICA and ICRP approaches, radiation weighing factors for alpha radiation, low energy ($E_b < 10$ keV) electrons, and high-energy electrons and photons were set respectively to 10, 3 and 1 [17,30].

2.4.2 Transfer factor

The whole-body activity concentrations in biota were predicted directly from activity concentrations in environmental media using equilibrium CRs from the wildlife transfer database. The wildlife transfer database (WTD; www.wildlifetransferdatabase.org) [31,32] was established to collate CR values and was used by the IAEA and ICRP to develop reports on recommended transfer parameter values [6,33]. Version 1.3.1 of the ERICA Tool uses CRs from the December 2013 version of the WTD. The default CR values set in ERICA were developed using extrapolation approaches [34]. There is a set of rules that have been devised in order to fill in the data matrix [17]. In this version, CRs included in ERICA take into account the new transfer data from IAEA TRS 479 [33]. For internal activity concentration for the different surrogate and hypothetical organisms, the CR defined by default in version 1.3.1 of ERICA were considered. The CRs used in this study are summarized in Table S4 in the supplementary material.

2.4.3 Activity concentration in varying media and test scenarios

The basis of the study relies on the dose rate calculation and comparison between a surrogate organism and hypothetical organisms with extreme/bounded geometry placed in the same location and with the same exposure conditions. The air activity concentration for each radionuclide cited in Table S3 was set to $1 \text{ Bq}\cdot\text{m}^{-3}$. To remain consistent with ICRP and the ERICA approaches, the concentration in the surface layer of the soil was considered to be homogeneous down to a depth of 10 cm [7]. The equation used to estimate the annual average concentration in the surface layer of the soil is as follows:

Eq. 1

$$C_{m,i} = \frac{DD}{t-(t-1) \cdot \rho \cdot Z \cdot \lambda_{rad}} \cdot \frac{1 - e^{-(\lambda_{rad})(t-1)} - e^{-(\lambda_{rad})(t)}}{\lambda_{rad}}$$

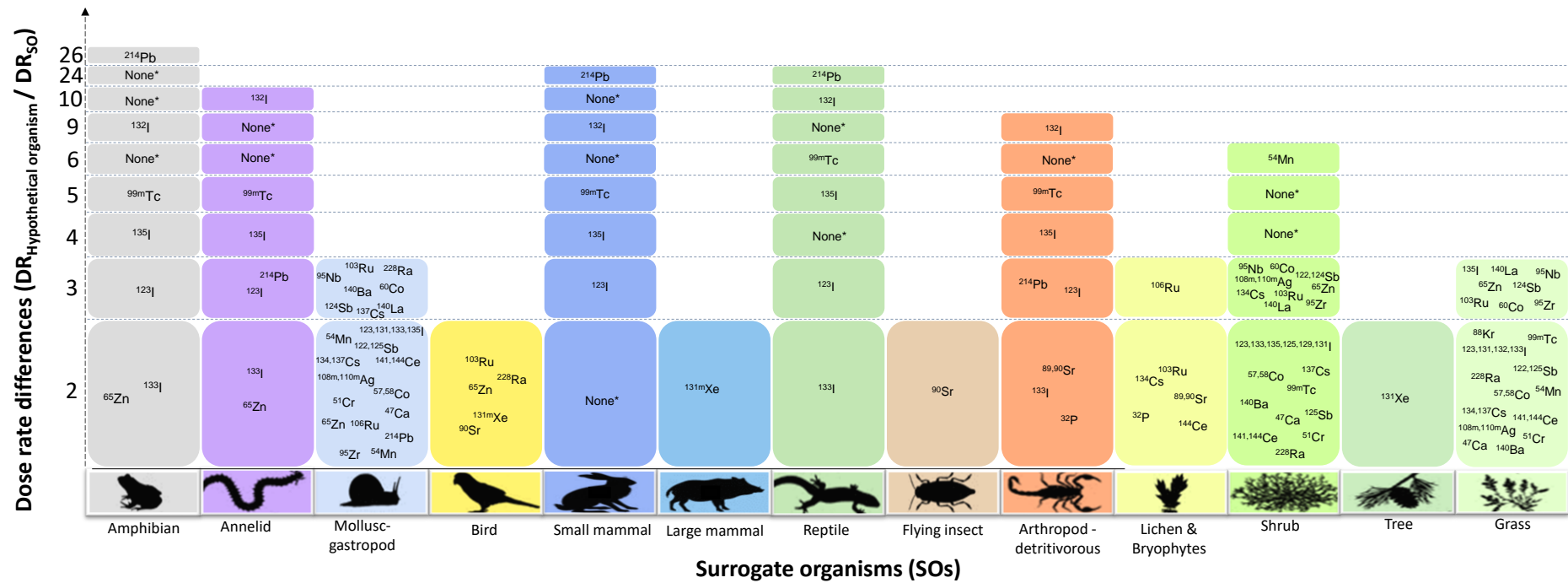
where $C_{m,i}$ represents the mean annual mass activity of the radionuclide in the soil (Bq/kg of soil) of the n^{th} year, DD represents the deposition rate (Bq·year/m²), t is the operating lifetime of the facility (years), ρ is the soil density (kg/m³), Z is the thickness of the surface layer of soil under consideration (m), and λ_{rad} corresponds to the radioactive decay constant (year⁻¹). The deposition rate was estimated by multiplying the air volume activity by the deposition rate. To represent the breadth of expected cases, several release scenarios were considered. According to the GSG-10 [4], for most facilities and activities, a radiological environmental impact assessment typically assumes a continuous and constant discharge during the operational period (e.g. 30 or 50 years). For this study, 30, 50, and 100 years were assumed, depending on the activity or facility type. A range of soil density and deposition rate were also tested. Soil density depends on soil type and the extent of soil compaction. For generic calculations, SRS 19 suggests a 1300 kg/m³ soil density for soils other than peat soil [35]. This study considered a wider range of soil densities; 1000, 1300, and 3000 kg/m³. The dry and wet deposition coefficients were identical regardless of the radionuclides considered and used by default in ERICA (assumption from SRS19) (500 m/d). A mean deposition velocity (DV) of 1000 m/d was assumed in SRS 19. The deposition velocity in this study was fixed to be 100, 500, or 1000 m/d. Effective loss due to lixiviation, washout, or root uptake was not considered. Ultimately, 27 cases were studied as presented in the matrix table in Table S5 in SI.

3. RESULTS

3.1 OBSERVABLE DR DISCREPANCY BETWEEN HYPOTHETICAL ORGANISMS AND SURROGATE ORGANISMS

Dose rates were calculated for 73 radionuclides including 12 noble gases for multiple deposition scenarios, and several hypothetical organisms (potential site-specific organism) in different media with varying extremes of shape and extremes occupancy habits in order to cover a wide range of existing cases. As each radionuclide was considered individually, the worst case is dependent not only on the deposition scenario, but also on the radionuclide considered. The most important discrepancies between the dose rate of a hypothetical organism and a surrogate organism for specific radionuclides are presented in Fig. 4. The greatest difference (ratio between DR-Hypothetical and DR –SO) between the predicted dose rate for hypothetical organisms and its corresponding SO (e.g. ROs or RAPs) was obtained for the “amphibian” group, with the most extreme difference of 26 due to exposure to ²¹⁴Pb. For terrestrial flora, the greatest DR difference is 6 due to ⁵⁴Mn exposure for the “shrub” organism. For the “bird”, “flying insect”, “large mammal” and “tree” groups, the greatest DR differences with hypothetical organisms were lower than a factor of 2, regardless of the size of the hypothetical organism or the RN listed in Table S3. Since not all radionuclides are necessarily released by all nuclear facilities and activities, the greatest

dose rate discrepancies for several examples of release footprint for several facilities and activities were sorted in Table 1. The greatest dose rate discrepancies presented in the Table 1 are related to the individual radionuclides considered in the potential spectrum of releases. For the NPPs, the potential maximum DR discrepancy between dose rate to a hypothetical organism and that to its corresponding SO is 9.8 when ^{132}I is the main contributor to the total DR for the “reptile” group. For the “bird”, “flying insect”, “large mammal” and “tree” group, regardless of the release scenario, the dose rate for a hypothetical organism would be the same as the corresponding SO with a factor lower than 2. For the research center source term used, the greatest dose rate discrepancy is observed for the lichen bryophytes and the “mollusc-gastropod” with a factor of 3, comparable to the order of magnitude for the decommissioning facility, fuel fabrication and reprocessing plant, and hospitals and radiopharmaceutical facilities. In the case of a pharmaceutical facility, the analysis has to be taken with caution. Indeed, for the 22 RNs considered as potentially released from such facilities, only 9 are considered due to the lack of CR values for the remaining RNs in the WDT or in TRS 479. Although TRS 479 specifies CR values for Fe, Lu, Mo, Na, Sm for flora organisms, it does not assign CR values to other organisms.



*None for no radionuclide in this range of dose rate difference

Fig. 4 : Highest dose rate (DR) differences calculated between the hypothetical organisms and the respective surrogate organisms (SOs) according to radionuclides

Table 1 : Highest dose rate (DR) differences calculated between the hypothetical organisms and the respective surrogate organisms (SOs) for several release profiles of different facilities. The radionuclides mentioned are those generating the maximum DR

Surrogate organism	NPP		Research center		Decommissioning		Fuel fabrication, reprocessing plants		Norm Facilities		Radiopharmaceutical facilities and Hospitals	
	Maximal DR _{created org./DR_{Ro}}	Considered RN	Maximal DR _{created org./DR_{Ro}}	Considered RN	Maximal DR _{created org./DR_{Ro}}	Considered RN	Maximal DR _{created org./DR_{Ro}}	Considered RN	Maximal DR _{created org./DR_{Ro}}	Considered RN	Maximal DR _{created org./DR_{Ro}}	Considered RN
Annelid	9.6	I-132	1.2	Sr-90	1.2	Ag-108m	1.2	Sr-90	3.1	Pb-214	5.4	Tc-99m
Bird	1.8	Ru-103	1.1	Cs-137	1.1	Ag-110m	1.1	Cs-134	1.7	Ra-228	1.1	I-123
Flying insects	1.5	Sr-90	1.5	Sr-90	1.1	Co-60	1.5	Sr-90	1.2	Pb-210	1.4	P-32
Mammal - large	1.3	Ce-141	1.3	Sb-125	1.1	Cs-137	1.3	Sb-125	1.2	Pb-214	1.3	Tc-99m
Mammal - small-burrowing	9.1	I-132	1.3	Cs-137	1.3	Cs-137	1.4	Cs-134	23.9	Pb-214	5.4	Tc-99m
Mollusc - gastropod	3.0	Zn-65	2.8	Co-60	2.8	Co-60	2.8	Co-60	2.6	Ra-228	2.4	Ca-47
Reptile	9.8	I-132	1.2	Cs-137	1.2	Ag-108m	1.2	Cs-134	26.1	Pb-214	5.6	Tc-99m
Amphibian	9.2	I-132	1.1	I-129	1.1	Ag-108m	1.1	I-129	9.3	Pb-214	5.3	Tc-99m
Arthropod - detritivorous	9.4	I-132	1.8	Sr-90	1.0	Cs-137	1.8	Sr-90	3.5	Pb-214	5.3	Tc-99m
Grasses & Herbs	4.0	Cm-243	2.7	Co-60	2.7	Co-60	2.7	Co-60	2.2	Ra-228	2.1	I-131
Lichen & Bryophytes	3.3	Ru-106	3.3	Ru-106	1.5	Cs-137	3.3	Ru-106	1.4	Ra-228	1.8	P-32
Tree	1.4	Ce-141	1.3	Sb-125	1.3	Co-60	1.3	Sb-125	1.3	Ra-228	1.3	Tc-99m
Shrub	4.9	Mn-54	2.7	Co-60	2.8	Ag-108m	2.7	Co-60	2.3	Ra-228	2.5	I-129

3.2 TYPE OF RADIATION AND EXPECTED DOSE RATE DISCREPANCY BETWEEN ORGANISMS

In most cases, the DR calculated for a SO and a site-specific organism is comparable, within a factor of 2. The similarity is particularly strong when the DR is dominated by an alpha emitter. Regardless of the species selected within the mass range considered for the hypothetical organism, the DR estimated will be the same as the SO. For short-range radiation emitters (alpha particles, alpha-recoil nuclei, and spontaneous fission fragments), it assumes that all the energy emitted is absorbed into the organisms for internal exposure. This simplification is based on the fact that α -particle energies range from 3-10 MeV and will penetrate tissue to a depth of 16 to 130 μm [36]. As the absorbed fraction is equal to 1, the DC value for alpha emitters is independent of organism size. Moreover, any contributions from alpha particles and electrons to external dose to terrestrial organisms are neglected because of their short range, and the inert layers (e.g. dead skin, fur, feather, shell, or bark) that cover radiosensitive tissues. These inert layers provide a barrier beyond which low penetrating radiation will not reach. As alpha emitters are considered only for internal exposure, the definition of the habitat has no influence on the dose rate value. This is also true for low beta emitters (<10 keV). Similar to alpha particles, for low beta emissions external exposure is not considered due to the short range and weak penetrating power of beta particles. Internal DC for beta particles is independent of the size of the organism. As an illustrative case, for ^3H , the low energy beta represents more than 65 % of the beta energy. In this case, the DC is quasi-independent on the size of the organism. Where the dose rate is dominated by the ^3H , the dose rate will be the same for any site-specific organism and its corresponding SO.

For $\beta+\gamma$ emitters (>10 keV), the DC value is influenced by the geometry, habitat definition, and type of exposure (internal or external) [16,18,36–39]. The effect of the organism's size definition on external exposure is opposite to that on internal exposure. For $\beta+\gamma$ internal irradiation (>10 keV), positive correlations were found between the DC value and the volume. Thus, the internal dose rates will be higher for larger species. For $\beta+\gamma$ emitters, which primarily contribute to the internal dose rate, the greater discrepancy corresponds to the hypothetical organism created with a higher mass than the surrogate organism. For $\beta+\gamma$ external irradiation (>10 keV), the dose conversion factors decrease with the size of the animal due to the increasing self-shielding effect from a larger size of an organism [16]. The differences in dose coefficients are more pronounced for low-energy emitters, because of the effect of self-shielding (ICRP, 2008). For $\beta+\gamma$ emitters that contribute primarily to an external exposure due to soil shine, the main discrepancy is estimated for organisms with a lower mass their corresponding SO. In all cases, the greatest dose rate discrepancy is within a factor of 3 for the fauna and a factor of 5 for the flora. For the case of the “shrub”, “grass”, “herbs” and the “mollusc-gastropod” groups, the DR discrepancies are higher by comparison than other groups of organisms. This is due to the consideration

of a different habitat for the hypothetical organism from the pre-defined habitat for the SO. Indeed, for those categories, hypothetical organisms were assumed to be living 100% in soil. For the shrub and grass groups, this corresponds to an organism constructed solely of a root system.

For $\beta+\gamma$ emitters that contribute predominantly to an external exposure due to cloud immersion, greater discrepancies between site-specific organisms and their corresponding SOs were observed. Those discrepancies are not linked to the effect of the size definition but primarily to the definition of the habitat. For example, organisms set IN soil by default (e.g. “arthropod”, “amphibian”, “reptile”, “small mammal”, “annelid” groups) in the ERICA or ICRP approaches are not considered as exposed to cloud immersion and this contributes to differences with hypothetical organisms. Except where the dose rate is mainly dominated by the cloud immersion pathway, the maximal DR difference reached a factor of 3 for fauna, confirming previous results [9]. Where a noble gas was the main contributor to the total DR, the dose rate difference between a hypothetical organism and the SO was expected to be within a factor of 2.

3.3 EFFECT OF DEPOSITION PARAMETERS, EXPOSURE PATHWAYS AND HABITAT DEFINITION

In order to be conservative, several deposition scenario cases were considered. The soil activity used in this study was a function of the soil density, the release time, and the deposition rate. For all the RNs considered, except for H, C, P, and S, the dose rate for internal and external exposure due to soil shine is dependent on the soil activity concentration. A modification of the deposition parameters and the soil characteristics may modify the contribution of the different pathways and thus the contribution of cloud immersion to the total dose rate. A high soil density and a low deposition rate were used to minimize soil activity concentration, giving more weight to the cloud immersion pathway in the total dose rate determination. For surrogate organisms that are mainly defined as living 100% in soil, a site-specific organism belonging to the same category living on soil is de facto exposed not only to internal and external exposure due to soil shine but also to cloud immersion. However, the cloud immersion pathway of exposure is not generally considered in risk assessment for biota and is not included in widely used tools such as the RESRAD-Biota modelling code or the ERICA tool in version 1.3.1 (but addressed in the version 2.0 released in October 2021), or in other published methodologies [7,24]. This exposure pathway is generally negligible. To be an important pathway, the internal and external exposure due to ground shine has to be minimal, which is possible when the activity concentration in soil is relatively low or comparable to the air activity concentration. However, this study shows that the cloud immersion pathway is relevant for some RNs: $^{123,132,133,135}\text{I}$, ^{140}La , ^{214}Pb , and $^{99\text{m}}\text{Tc}$, more generally for RNs with a shorter half-lives (<100 days) as illustrated in Fig. S1. Where habitat definition is concerned, the habitat

defined in the ERICA tool and by the ICRP approach was based on a configuration that results in maximum exposure to the organism. In order to test this hypothesis, a hypothetical organism is set in different media with a conservative assumption that it spends 100% of its time in that media. The configuration of habitat and habits for the surrogate organism is conservatively defined with some exceptions. When the total dose rate is primarily attributed to a $\beta+\gamma$ emitter, the more conservative approach sets this organism IN soil. The external dose coefficient for IN soil exposure is higher than the DC when an organism is set ON soil exposure. However, as indicated previously, the conservative habitat definition relies mostly on the nature of the predominant RN to the total dose rate. When the dose rate is dominated by RNs with half-lives of less than 100 days, organisms should be set ON soil instead of IN soil for those living both habitats, e.g. amphibian, mollusk-gastropod, small mammal, arthropod. In this particular case, the definition of the position in the air will influence the dose rate calculation. Generally, the greater the height, the higher the DC value as illustrated for several RNs in Fig. S2. However, the influence of the height in the DC value will remain insignificant. For the case of ^{132}I , a $\text{DC}_{\text{immersion}}$ discrepancy of less than a factor of 2 is expected for an organism of 1 kg set at 0.1 m and at a height of 100 m.

4. DISCUSSION

Hypothetical organisms were modelled in order to cover a wide range of site-specific species in terms of their masses. As illustrated in Fig. 2, the mass range covers several orders of magnitude of masses for the different categories, which in most cases encompasses the range of masses of real species. For the “arthropod”, there were more than 6 orders of magnitude between the smallest organism and the largest. For the “mollusc-gastropod”, “annelid”, “flying insect” and “arthropods” groups, the masses of the SOs were 3 orders of magnitude less than the upper limits of the mass range considered and inversely for the case of the “bird” and “reptile”. For the “large mammal” and for the “tree” organisms, masses of hypothetical organisms were of the same order of magnitude. As previously demonstrated, regardless of the size and the habitat of the SOs, the potential discrepancy between a site-specific organism and its corresponding SO will be less than a factor of 30 for the worst case scenario, for a single radionuclide, in the case of routine atmospheric releases. Previous studies to this analysis qualitatively demonstrated that the mass differences of an organism have relatively little impact on the dose rate value [7,9,13,16,40] but it was not shown quantitatively. It is clear from the present analysis that the impact of size (mass and/or geometry) on dose rate is not linear, with size differences of several orders of magnitude causing dose rate variations of only a fraction. In numerous situations, risk assessments in case of routine atmospheric releases, considered identical CR values for site-specific species and their corresponding SOs [9,11,41,42]. If a similar CR value is used, even when the site-specific species are configured with

very different physical characteristics, the estimated dose rate between the site-specific species and its corresponding SOs will be minimal (see Fig.3). The most significant influence in the variability of predicted dose rates when comparing site-specific species versus SOs was attributed to the choice of CR values [43–45]. CRs are aggregated parameters that should take into account all the exposure pathways (ingestion, inhalation, prey-predator relationship, trophic level) which lead to the estimation of radionuclide transfer to biota assuming equilibrium conditions. The range of the value of the CR can cover several orders of magnitude [31]. The main difficulty is that a relevant CR adapted to the studied site may create a more significant discrepancy between the surrogate organism and the site-specific organism, as demonstrated by Torudd et Saetre [10] and thus could be an important source of uncertainty. However, for endangered species or protected species, it may be impossible to determine such transfer factors due to the fact that regulations strongly limit the capture or destruction of protected species. Generally, transfer factors are not well known even for “classical species”. In this exercise, the CR values used were those proposed by the ERICA tool (version 1.3.1). Data on transfer parameters may change over time (due to the methodology considered, data collection, new data available, new interpolation methodology). A change in the CR value modifies the contribution of the defined pathways and thus may induce different maximal estimated discrepancy between the predicted dose rate for a hypothetical site-specific organism and a SO in comparison with those previously observed. In order to evaluate the influence of a CR modification, several calculations were performed by modifying the CR value using the 5th and the 95th value of the probability distribution functions defined in the ERICA tool for each CR. Values and distribution types (normal, lognormal, etc.) for each RN are presented in Table S6. The most significant dose rate discrepancies per organism for each category are presented in Fig. 5 and by RN in Table S7.

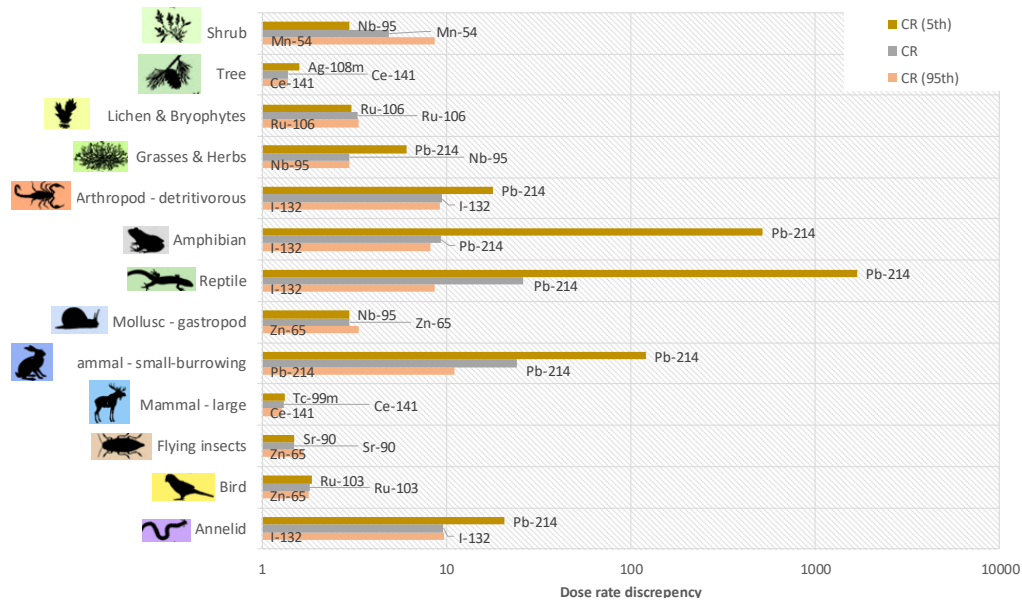


Fig. 5 : Highest dose rate (DR) differences calculated between the hypothetical organisms and the respective surrogate organisms estimating from two scenarios : CR fixed at the 5th value and CR fixed at the 95th value

An increase of the CR value will lead to an increase of the internal exposure pathway and inversely. The DC increases with the size of the organism for internal irradiation from high-energy β and γ . If the CR decreases, external exposure from ground shine or cloud immersion becomes more relevant. For external exposure to high-energy β and γ the CR value decreases with increasing size due to self-shielding. The most important dose rate difference between a site-specific organism and the RO can be found for a smaller organism. As illustrated in Fig. 5, a modification of the CR can markedly increase the estimated dose rate discrepancy when ^{214}Pb is the primary contributor to the total dose rate and the CR is smaller than the original used. Except in the case where ^{214}Pb is the primary contributor, a modification of the CR value to the 5th or the 95th of the CR value from the defined probability distribution function does not significantly affect the previous conclusion. Apart from the case of ^{214}Pb , the maximum discrepancies are not greater than a factor of 11 regardless of the RN and the categories of the organisms considered.

5. CONCLUSION

The protection of habitat quality for a diverse range of non-human species can be demonstrated by using surrogate species to represent the diversity of traits from a larger species pool. The constructed surrogate species for assessment of risk from ionizing radiation may differ in specific characteristics from representative organisms, but the approach presented in this analysis aims to reach the same objective, to demonstrate global protection using a limited number of organisms. Results demonstrate that the dose rate does not change linearly with the size of the species and has little effect on the results of risk

assessment. Habitat definition will lead to more significant dose rate discrepancies, depending upon the nature of the release and radionuclide half-lives (i.e. short-lived RNs). The main problem in dosimetry is the level of uncertainty introduced by the extrapolation of internal radionuclide activity concentration from its concentration in the external medium. It's recognized that the CR values contribute most to variability in predicted dose rates. However, where the CR used for the surrogate organism is also used for a site-specific organism belonging to the same category, the dose rate discrepancy for the worst case would be within one order of magnitude. The use of surrogate organisms resulted in a conservative estimate of the absorbed dose rates and confirms previous results. In several cases, for atmospheric chronic discharges, the main contribution to the total dose rate is from ^3H and ^{14}C , particularly for routine releases from NPPs. The CRs of these two radionuclides have the characteristic of being independent of both size and the type of habitat. In this case, the dose rate will be equivalent for a site-specific species and its corresponding surrogate organism.

Although these findings do not preclude the consideration of site-specific species in an environmental radiological assessment, they provide evidence that in general a limited set of representative organisms is adequate to meet the objective of risk assessment. As this study only covers the terrestrial compartment, an interesting future investigation would be to perform this methodology on other compartments such as freshwater and marine water ecosystem.

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