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Considering the Environment When Applying the System of Radiological Protection:Part 1 Broadening the Reference Animals and Plants Approach and Related Derived Consideration Reference Levels

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**Considering the Environment When Applying the System of Radiological Protection: PART 1 Broadening the Reference Animals and Plants Approach and related Derived Consideration Reference Levels**

ICRP PUBLICATION XXX

Approved by the Commission in MMMMM 20XX

**Abstract**

**–** This publication broadens the Reference Animals and Plants (RAP) and Derived Consideration Reference Levels (DCRL) approach outlined in *Publication 108*. It introduces a methodology for establishing additional DCRLs at higher taxonomic levels to complement the existing DCRLs which are defined at the family level. A transparent, data-driven approach for assessing the effects of ionising radiation on non-human species in their natural environment is described. By integrating comprehensive radiation effects data, documented models, and considering the underlying assumptions, the methodology enhances transparency, reproducibility, and improves the ability of assessors to address complex environmental impact assessments.

The broadened RAP approach extends beyond the twelve RAP families defined in *Publication 108* by incorporating higher taxonomic levels such as class, phylum, and broad non-human species groups (vertebrates, invertebrates, and plants). This expansion improves the representativeness and applicability of the RAP approach in radiological environmental impact assessments. The approach applies two statistical models: the Acute-to-Chronic Transformation of Radiation Effects (ACTR) model, which extrapolates chronic effects from acute data, and the Endpoint Sensitivity Distribution (ESD) model, which synthesises chronic and acute effects data across taxonomic groups. The additional DCRLs are derived using the 5th percentile of the ESD, with a multi-criteria Extrapolation Factor (EF) applied to establish the lower boundary, and accounting for data gaps and uncertainties.

As simple guidance, the DCRLs (family) from *Publication 108* are the benchmarks recommended for environmental impact assessments. The additional DCRLs introduced in this publication provide complementary reference points, particularly in cases where dose rates approach or exceed DCRLFamily values. This broadened approach where benchmarks can be used in conjunction, is especially relevant for complex impact assessments, such as evaluations of large facilities, post-accident scenarios, and protected ecosystems. It also allows flexibility in applying different ESD percentiles to identify an acceptable level of protection in consultation with stakeholders or to incorporate site-specific data for refined assessments.

Irrespective of the DCRLs used, the guidance from *Publication 124* applies: the lower boundary of the relevant DCRL should be applied in planned exposure situations, while in existing exposure scenarios or post-accident long-term assessments, DCRLs help guide optimisation of radiological protection of non-human species. Additionally, in emergencies, at the time where the focus shifts to environmental recovery, the acute ESD models for classes or phyla, or broad species groups can support stakeholder discussions providing retrospective information on the likely ecological consequences of radiation exposure.

By broadening the RAP approach, this publication strengthens the scientific basis for environmental radiological protection, facilitates stakeholder engagement, and contributes to support decision-making in environmental impact assessments. The additional DCRLs at higher taxonomic levels introduced in this publication provide an important complement in complex cases as it offers the possibility of a more refined assessment and a transparent evaluation of the level of confidence. The methodology and underpinning data enable assessors to adapt their assessments to specific contexts, make informed judgments, and reduce uncertainties in evaluating radiation impact or risk to non-human species. Further guidance on the application of the DCRLs within the system of radiological protection will be provided as Part 2 in this series of publications ‘Considering the Environment When Applying the System of Radiological Protection Part 2: Integration within the system, including practical use of Derived Consideration Reference Levels’.

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*Keywords*:Reference Animals and Plants approach; Derived Consideration Reference Levels; Classes, Phyla and broad non-human species groups; Radiation effects on non-human species; Endpoint Sensitivity Distribution; Stakeholders; Environmental Radiological Protection

MAIN POINTS

* **This publication introduces and applies improved methodologies for establishing Derived Consideration Reference Levels (DCRL), as absorbed dose rates to assess the impact of ionising radiation on non-human species, and to guide proportionate and risk-informed actions to protect the environment.**
* **Comprehensive summaries of chronic and acute radiation effects data across species representing different taxonomic levels (class and phylum) or broad non-human species groups (vertebrates, invertebrates and plants) support the derivation of DCRLs using the** **Acute-to-Chronic Transformation of Radiation Effects (ACTR) and the Endpoint Sensitivity Distribution (ESD) models.**
* **DCRL for classes, phyla or broad groups are based on the 5th percentile of the corresponding ESD, along with a multi-criteria Extrapolation Factor to account for data gaps and uncertainties.**
* **The methodology, as applied in this publication, builds on the Reference Animals and Plants (RAP) approach outlined in *Publication 108,* incorporates an expanded data set for deriving the DCRLs, and is aligned with methodologies used to assess the impact of other types of hazards in the environment, thus supporting comprehensive environmental impact assessments and the justification of protective actions in a multi-contaminant context.**
* **The DCRLs derived using this methodology are broadly consistent with, and should be used in conjunction with, the DCRLs outlined in *Publication 108,* which continue to serve as references for environmental impact assessments, while DCRLs at higher taxonomic levels are complementary to support assessments in complex cases.**
* **For complex impact assessments, this expanded analysis allows further characterisation of radiation impacts across a broadened range of species and environments, also facilitating engagement with stakeholders in the optimisation of radiological protection of non-human species in their natural environment.**

# WHY THIS PUBLICATION?

1. With the publication of the 2007 General Recommendations (ICRP, 2007), the International Commission on Radiological Protection (ICRP) expanded its system of radiological protection beyond the original sole focus on protection of humans (see the 1977 and 1990 General Recommendations (ICRP, 1977; 1991)), to include explicit consideration of protection of the environment. The need to do so had already been recognised for some time, and had been driven by public interest, scientific developments, environmental legislation, and international ‘instruments’ such as the Rio Declaration in which emphasis was given to the link between the quality of the environment, societal development, and human well-being (United Nations, 1992).
2. In *Publication 91* (ICRP, 2003), the Commission proposed a framework for protection of non-human species from the harmful effects of ionising radiation, which was subsequently. adopted through inclusion in *Publication 103* (ICRP, 2007), in which environmental radiological protection (ERP[[1]](#footnote-2)) was recognised as a specific and distinct objective of radiological protection. The current Reference Animals and Plants (RAP) approach to ERP was outlined in detail in *Publication 108* (ICRP, 2008), followed by guidance for its application in *Publication 124* (ICRP, 2014). One of the aims of this approach was to, as far as possible, be consistent with the ICRP approach to human radiological protection as well as with existing frameworks for management of environmental risks from other hazardous substances (see, e.g. Larsson, 2016). Since the introduction of the RAP approach, the Commission has further developed and updated the ERP framework in *Publication 114* (ICRP, 2009), *Publication 136* (ICRP, 2017) and *Publication 148* (ICRP, 2021); these publications expand on key topics outlined in *Publication 108* and provide up-to-date information on environmental transfer parameters, dose coefficients, and radiation weighting factors, respectively.
3. While acknowledging the developments over the last decades, and beyond the perpetual desire to integrate the most recent knowledge, there are reasons to continue developing the ERP framework. Increasing societal awareness of the interconnectedness between human and ecosystem health, economy and society, alongside a growing emphasis on sustainability, may call for a broadened approach (Clement et al., 2021). A broadened approach could support a more transparent and scientifically robust implementation of environmental protection efforts, aligned with the United Nations Sustainable Development Goals (SDGs) (United Nations, 2015). In a context of exposure to a wide range of potentially co-occurring pollutants, another advantage of a broadened approach is to adopt a methodology consistent with those utilised in ecological risk assessments for other hazardous substances (e.g. chemicals), enabling an integrated assessment of the overall impact of human actions on the environment. This also provides an opportunity to transparently share all relevant information, assumptions, and judgements with stakeholders.
4. Ultimately, this publication seeks to promote a holistic and sustainable outcome when applying the principles of justification and optimisation, by using dose (rate) benchmarks that guide practical applications of the international system of radiological protection (Garnier-Laplace et al., 2024). In support of this goal, this publication introduces a methodology that addresses some of the challenges identified in the *Reference Animals and Plants* (RAP) approach described in *Publication 108* (ICRP, 2008) and *Publication 124* (ICRP, 2014), notably those related to representativeness and the diversity of wildlife, including the variability and gaps in exposure and effects data for non-human species.
5. Currently, twelve *Reference Animals and Plants* (RAP) serve as proxies for organisms in the natural environment, each RAP with its radiosensitivity-related numerical benchmark (Derived Consideration Reference Level, DCRL) expressed as dose rate bands extending one order of magnitude. This publication builds on and broadens the RAP/DCRL approach by using comprehensive data sets of radiation effects and introducing methodologies that reduce the reliance on expert judgement and provide ways to transparently assess uncertainties (Garnier-Laplace et al., 2024). Enhanced clarity, streamlined processes, and improved tools and guidelines are expected to assist assessors/implementers and other stakeholders in better understanding the impact of ionising radiation on the environment, as well as demonstrating radiological protection of non-human species in their natural environment, thereby supporting scientifically well-founded protective actions.

# BACKGROUND

## Setting the scene: key elements of the Commission’s approach to radiological protection of the environment

1. The ERP element of the ICRP’s system of radiological protection focuses on protection of non-human species[[2]](#footnote-3), in their natural environment, from harmful effects of ionising radiation. In the 2007 General Recommendations, *Publication 103* (ICRP, 2007), the Commission stated its objective for environmental radiological protection, along with a number of related protection targets: ‘*…preventing and reducing the frequency of deleterious radiation effects to a level where they would have negligible impact on the maintenance of biological diversity, the conservation of species, or the health and status of natural habitats, communities and ecosystems*.’
2. A series of publications describe the key elements of the ICRP’s approach to ERP. The first in the series, *Publication* *91* (ICRP, 2003), laid out a preliminary proposal for a framework for ERP, including ethical considerations, a proposal that was subsequently adopted and included in *Publication 103* (ICRP, 2007). *Publication 108* (ICRP, 2008) outlined the framework in detail; subsequently, *Publication 124* (ICRP, 2014) described how the framework could be applied in different exposure situations[[3]](#footnote-4). The overall aim is to be as consistent as reasonably possible with both the ICRP approach to human health protection and other existing frameworks for management of ecological impacts from other types of stressors e.g. chemicals (Pentreath et al., 2015; Larsson, 2016).
3. *Publication* *108* (ICRP, 2008) introduced the concept and use of twelve *Reference Animals and Plants* (RAP), referred to as the ‘RAP approach’ in this publication. The RAPs represent wild animals and plants in terrestrial, marine and freshwater ecosystems, and are defined as ‘*A hypothetical entity, with the assumed basic biological characteristics of a particular type of animal or plant, as described to the generality of the taxonomic level of family, with defined anatomical, physiological, and life-history properties, that can be used for the purposes of relating exposure to dose, and dose to effects, for that type of living organism*’(ICRP, 2008). To characterise those RAPs, relevant databases (e.g. environmental transfer parameters, and dose coefficients) have been generated to support assessments of radiation exposure and related effects, and to guide decision-making with regard to environmental protection. Since *Publication 108*, three supplementary publications have been issued to update the methodological and scientific basis on specific elements of the RAP approach:
   * *Publication* *114* (ICRP, 2009) set out the models and parameter values for estimating the exposure of RAPs.
   * *Publication* *136* (ICRP, 2017) further developed and extended the methodology to derive dose coefficients (DCs) for RAPs*;* the DCs listed in *Publication 136* supersede those originally listed in *Publication 108*.
   * *Publication 148* (ICRP, 2021) set out the recommended radiation weighting factors for RAPs, with particular emphasis on alpha radiation and low-energy beta radiation.
4. Assessing whether the protection targets, as defined in *Publication 103* (ICRP, 2007), are met requires a level of simplification in order to be manageable in practice (Real and Garnier-Laplace, 2020). The RAP/DCRL approach enables such simplification. Dose rates estimated for each RAP may be compared to associated *Derived Consideration Reference Levels* (DCRL) to consider whether impacts are likely and whether protective actions are necessary.
5. A DCRL is a ‘*band of dose rate within which there is likely to be some chance of deleterious effects of ionising radiation occurring to individuals of that type of Reference Animal or Plant (derived from a knowledge of defined expected biological effects for that type of organism) that, when considered together with other relevant information, can be used as a point of reference to optimise the level of effort expended on environmental protection, dependent upon the overall management objectives and the relevant exposure situation*.’ (ICRP Glossary - ICRPaedia). A DCRL is therefore a range of dose rates that can be used as benchmark for assessing radiological impact on non-human species. This approach may be used to demonstrate (for specific organisms, or in a general and conservative way in a screening approach) whether non-human species are adequately protected, and guides the level of effort expended on optimisation of protection in a manner that is proportionate to the level of risk.
6. The concept of *Representative Organisms*, introduced in *Publication 124*, may be considered when a more realistic assessment is needed. A representative organism is a particular species or group of organisms selected during a site-specific assessment. A representative organism may or may not correspond to a RAP, depending on the assessment purpose and its ecological context (ICRP, 2014).
7. The demonstration of protection of non-human species is generally targeted at the population level, although it can be adapted to assess whether species of wild animals and/or plants at risk (e.g. listed species, such as rare or endangered species) are protected at the individual level, using supporting data sets on exposure and effects specific to the species of interest. Because of differences in protection endpoints, exposure pathways and prevailing circumstances, domesticated species and veterinary patients are beyond the scope of this publication, although information presented may still be relevant. Indeed, the effects data summarised in this publication are likely to be useful in supporting guidance for the adequate protection of individual animals exposed in veterinary settings as explored in *Publication 153* (ICRP, 2022).

## Practicality of RAPs

1. A framework for assessing the risk to, or impact on, non-human species must include information on environmental transfer of radionuclides to non-human species of interest, the exposure and dose, and the dose-response relationship with suitable criteria to help judge the significance of the exposure. Establishing such linkages can be very challenging considering the diversity of organisms in the natural environment (Pentreath and Woodhead, 2001; Larsson, 2008). To address this challenge, the Commission developed the 12 RAPs (listed in Table 2.1), described at the taxonomical level of family. Family was chosen by the Commission as the highest taxonomical level within which anatomical, physiological, and life-history characteristics relevant to radiation effects are reasonably consistent. In *Publication 108* (ICRP, 2008), RAPs are proposed to broadly represent non-human species; RAPs are reference models, analogous to the reference person defined in *Publication 103* (ICRP, 2007).

Table 2.1. Identification and description of the Reference Animals and Plants (RAPs) defined at the family level (herein referred to as RAPFamily) as introduced in *Publication 108* (ICRP, 2008).

|  |  |  |
| --- | --- | --- |
| RAP | Environment | Description |
| Deer | Terrestrial | A large terrestrial mammal |
| Rat | Terrestrial | A small terrestrial mammal |
| Duck | Aquatic | An aquatic bird |
| Frog | Aquatic | An amphibian |
| Trout | Aquatic | A freshwater fish |
| Flatfish | Aquatic | A marine fish |
| Bee | Terrestrial | A terrestrial insect |
| Crab | Aquatic | A marine crustacean |
| Earthworm | Terrestrial | A terrestrial annelid |
| Pine tree | Terrestrial | A large terrestrial plant |
| Wild grass | Terrestrial | A small terrestrial plant |
| Brown seaweed | Aquatic | A seaweed |

1. The ICRP’s targets of protection of non-human species are three-fold and focus on either individual species (‘*the conservation of species*’), multiple species (‘*the maintenance of biological diversity*’), or their assemblage (‘*the health and status of natural habitats, communities, and ecosystems*’). The biological endpoints of most relevance are, therefore, those that could lead to changes in population size or structure, e.g. those directly relevant to population demography, including mortality, morbidity, reproductive success, and genetic integrity of wild populations (ICRP, 2008), along with interactions of populations of species within communities and ecosystems.

## Rationale and benefits of a broadened RAP approach

1. Opportunities for improvements of the ERP framework were identified by the Commission in *Publication 108* (ICRP, 2008), which recognised the sparseness of exposure and effects data for non-human species. Although some extrapolation methods have been explored to reduce knowledge gaps in radionuclide transfer factors for various species, for example in *Publication 114* (ICRP, 2009), traceable methods beyond expert judgement to quantitatively address interspecies variation in radiosensitivity and reflect this variation in the DCRL derivation have been lacking.
2. This publication builds on *Publication 108* (ICRP, 2008) and broadens the RAP approach through provision of up-to-date data and methodological guidance on application of RAPs and DCRLs. It briefly recalls the principles and approaches adopted to evaluate the appropriateness of RAP-specific data regarding exposure of non-human species and dose estimates (via external and internal exposure pathways), and then focuses on biological effects, and the meta-analysis of effects data to improve the scientific rigour of the DCRLs. A methodology is introduced for meta-analysis of effects data, with consideration given to the data sources (type and quality) and their application to non-human species in their natural environment. The methodology can be applied to higher taxonomic levels such as class or phylum or to broad organism groups such as vertebrates, invertebrates and plants, in support of impact assessments.

## Objectives, methods and outcomes

1. Statistical extrapolation models were developed to quantify the range of radiosensitivity of population-relevant endpoints within a given taxonomic level. The current RAPs and DCRLs defined in *Publication 108* (ICRP, 2008), referred to as RAPFamily and DCRLFamily throughout this publication, can be used if the representativeness at the family level is appropriate. However, a broader representativeness, e.g. at the class level, may be more suitable in certain cases. For example, an assessment may need to consider a wider range of representative organisms. Additionally, the use of the broader set of effects data made available by associating species at higher taxonomic levels (e.g. class) is helpful when addressing data gaps (e.g. no chronic effects data exist for the bee RAPFamily but data exist for species belonging to the class of insects and other classes grouped into the broad group of invertebrates). As such, this publication also addresses a gap identified in *Publication 124* (ICRP, 2014), by providing more information to relate ‘*RAPs to Representative Organisms*.’
2. Applying statistical methods that are reproducible, transparent, and flexible means the level of effort dedicated to protection of non-human species can be more conveniently and rationally discussed between interested parties. In brief, the additional DCRLs provided with this publication (termed DCRLClass or Phylum related to RAPClass or Phylum) were developed using results from laboratory experiments that satisfied data quality checks necessary for the mathematical treatment, and which described population-relevant endpoints for environmental protection. DCRLClass or Phylum were then compared with (1) other laboratory results that had not been used in their derivation and (2) effects data from field studies in areas contaminated by radionuclides. This offers a scientifically defensible and transparent approach using effects data available at the taxonomic level of class or phylum (RAPClass or Phylum) and reduces the reliance on expert judgement. The proposed DCRLClass or Phylum are compared with previously published values (i.e. DCRLFamily in ICRP, 2008), and preliminary advice is provided on how assessors can implement these methods to obtain effect benchmarks. Further advice on the use of the DCRLs in general is being developed through ongoing activities of ICRP.
3. A series of electronic annexes (Excel files) summarise the effects on non-human species associated with: (1) acute exposure relevant to emergency exposure situations; and (2) chronic exposure relevant to planned and existing exposure situations or in the medium and long-term following an emergency. For each RAPClass or Phylum considered, the annexes provide all the data used to produce the numerical values contained within this publication, and list all the sources of the primary data.

## Structure of the publication

1. Section 3 sets out the rationale for broadening the current RAP approach, which is to increase the taxonomic level options beyond that of family to higher levels. It also gives an overview of the RAP-related data available and updated aspects of the methods applied in support of the estimation of dose, effect, and calculations to enable impact assessment to be undertaken.
2. Section 4 provides a review of the biological endpoints of interest following acute or chronic radiation exposure of non-human species. The method from Garnier-Laplace et al. (2010) that was used to reconstruct dose (rate) – effect relationships based on the FREDERICA database (Copplestone et al., 2008), is briefly summarised, along with the use of statistical inference models for the best use of such effects information. The methodology for establishing DCRLs utilises two models: the *Acute-to-Chronic Transformation of Radiation Effect* (ACTR) model that predicts chronic effects from acute effects data, and the *Endpoint Sensitivity Distribution* (ESD) model which provides comprehensive summaries of chronic and acute radiation effects across a range of taxonomic groups such as classes, phyla, or broader groups such as vertebrates, invertebrates and plants. Section 4 then provides values for DCRLClass or Phylum along with an evaluation of the uncertainties at taxonomic levels higher than the family, a comparison of the outcomes with the DCRLFamily described in *Publication 108* (ICRP, 2008), and elements for potential application of the broadened RAP approach.
3. Section 5 discusses the DCRL ranges through comparison with results of a literature review of recently published laboratory experiments and field data from sites contaminated by radionuclides, focusing on chronic exposures and non-human species groups for which the sparseness of data contributes most to the uncertainties. A discussion of important extrapolation issues, such as how to deal with propagation of effects from individual to population levels, ends this section. Section 6 concludes the publication with preliminary recommendations for the use of DCRLs, a summary of values and related uncertainties, and perspectives on how the ICRP framework for ERP might evolve.

# ELEMENTS OF the REFERENCE ANIMALS AND PLANTS APPROACH

## Practical use of RAPs: enhancing robustness and flexibility

1. Twelve Reference Animals and Plants (RAPs) were initially described in *Publication 108* (ICRP, 2008) (see Table 2.1) for use in radiological environmental impact assessments for non-human species. *Publication 108* describes the main biological and population features of the RAPs, highlighting the similarities and differences of the species within the family to which they belong. From the outset, it was recognised that RAPFamily represent a small number of species for which exposure and effects are not always available - for example, there are no data available in *Publication 108* for the Reference bee or the Reference frog. However, data exist for species of other families, and compiling and summarising effects data at the class level (or higher taxonomic levels) allows for broader data inclusion. Robust reviews on exposure data (e.g. IAEA, 2009; 2010; 2014a; Wood et al., 2013) and effects data (e.g. Real et al., 2004; Garnier-Laplace et al., 2006; Copplestone et al., 2008; UNSCEAR 2011) inform the work herein.
2. To enhance the applicability of the RAP, a broadened RAP definition, which leaves the taxonomic level flexible, could be formulated: ‘*Reference Animals and Plants are defined as hypothetical entities, with anatomical, physiological, and life-history properties defined at the required level of taxonomy to relate exposure to dose and to understand the effects at the population level*.’ This definition aims to ensure data appropriateness with regard to the taxonomic context and specific RAP or representative organism used in site-specific assessments. Specifically, it allows, in principle, the compilation and summarisation of effects data at any taxonomic level as long as the effects data meet the necessary quality standards for statistical treatment.
3. The DCRLs of *Publication* 108 (ICRP, 2008) were derived from effects data at the taxonomic level of family. Considering effects data at the higher taxonomic level of class or phylum increases the amount of data available to derive additional DCRLs using statistical inference models. Figure 3.1 shows the increase of effects data availability across taxonomic levels (family coloured orange), class, phylum in vertebrates (all coloured blue) as an example. Empty circles represent taxonomic groups where no data exist to inform the DCRLFamily (*Publication 108*) or where insufficient data are available to derive DCRLClass or Phylum (this publication). Full circles indicate groups with at least some data to inform the DCRLFamily (*Publication 108*) or with enough data to derive DCRLClass or Phylum (this publication). Effects data sets are organised per taxonomic levels, building up progressively from the top (family) to the bottom (broad group). It should be noted that the list of taxa depicted in the figure is driven by the set of RAPFamily and by the currently available effects data sets herein, and as such, is far from exhaustive. The broadened RAP approach described in this publication is based on *ca*. 5000 primary effects data in total, covering 135 and 30 species for external gamma exposure, acute and chronic conditions respectively.
4. The quality and quantity of the effects data set available in the FREDERICA database (Copplestone et al., 2008; IAEA, 2014d) allows a statistical (radio)sensitivity distribution to be established for population-relevant endpoints for eight (chronic data) and nine (acute data) classes or phyla (e.g. Garnier-Laplace et al., 2006; 2008; 2010), which provides the basis of the methodology supporting the broadened RAP approach. Grouping data of closely related classes into the next higher taxonomic[[4]](#footnote-5) level of phylum (e.g. ‘crustaceans’ includes data for two classes [*Branchiopoda* and *Malacostraca*]; see Table 3.1) is needed in some cases to allow for ESD model application. The broadened RAP approach also considers, as needed and appropriate, broad non-human species groups, such as vertebrates, invertebrates and plants, which are also frequently used as ‘wildlife groups’ in chemical risk assessments (EC, 2003; Garnier-Laplace et al., 2008) (Table 3.1). In theory, effects data at other taxonomic levels such as species or genus can be analysed using the statistical analyses underlying the broadened RAP approach, although the necessary, quality-controlled data sets are not often available.

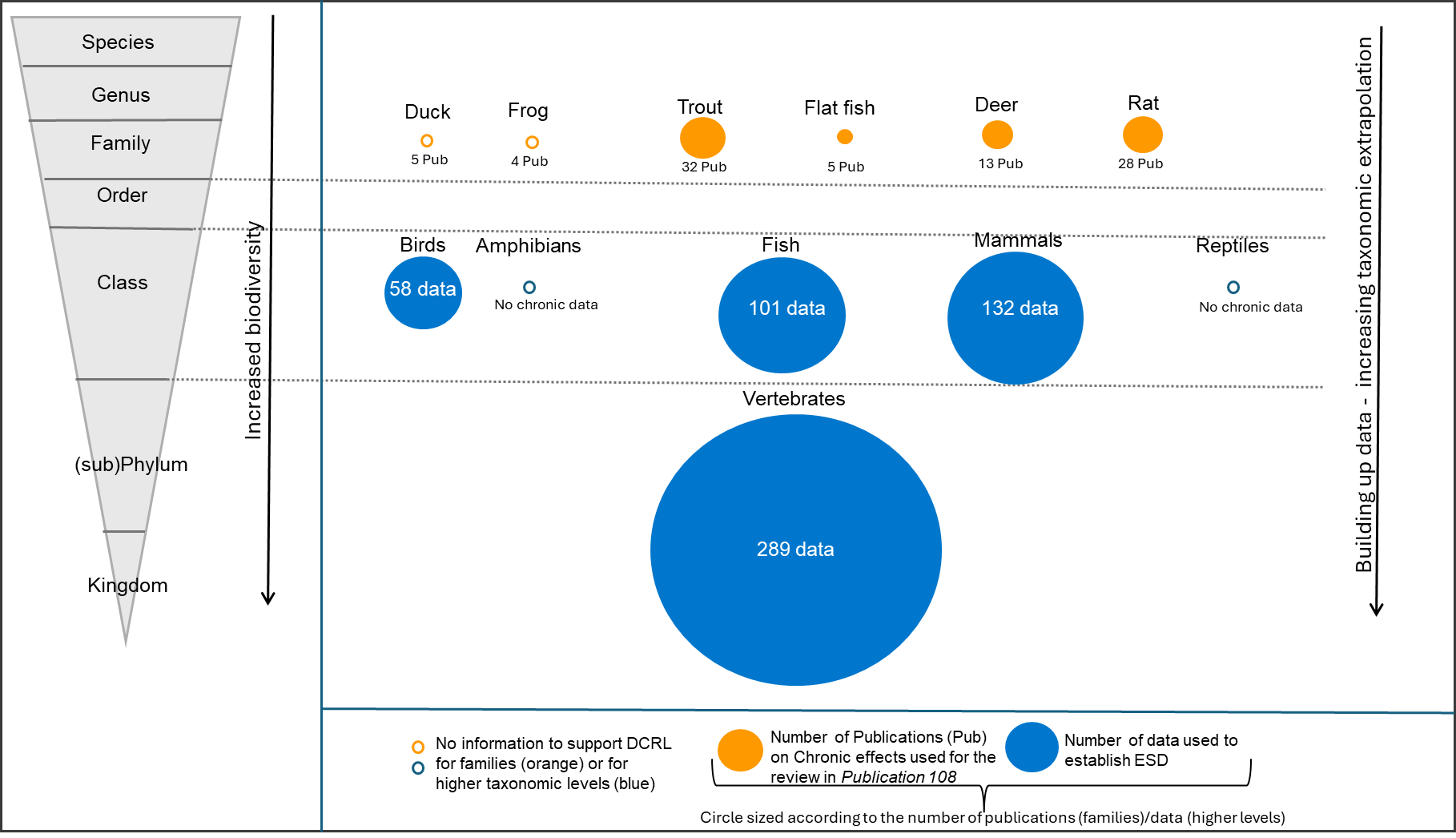


Fig.3.1. Illustration of how expanding the consideration of effects data from the family level (orange) to higher taxonomic levels (blue), such as class, phylum, or broad group, significantly increases the available data and supports the application of the statistical inference models proposed in this Publication. More details are provided in paragraph (25).

Table 3.1. List of common and scientific names of classes or phyla and broad non-human species groupings where taxonomic pooling of effects data is sufficient to build statistical (radio)sensitivity distributions and derive DCRLs. Note that the class *Insecta* is only documented with acute effects data. The third column lists the RAPFamily, as defined in *Publication 108* (ICRP, 2008).

|  |  |  |
| --- | --- | --- |
| RAPClass (or Phylum)  Common name | Scientific name  (class or phylum) | RAPFamily |
| Birds | *Aves*† | Duck |
| Fish | *Actinopterygii*† | Trout; Flatfish |
| Mammals | *Mammalia*† | Deer; Rat |
| Crustaceans\* | *Branchiopoda*†*, Malacostraca*† | Crab |
| Worms\* | Annelida\* (*Clitella*† and *Polychaeta*†) | Earthworm |
| Insects | *Insecta*† | *\_\_* |
| Conifers | *Pinopsida*† | Pine tree |
| Grasses and monocotsǂ | *Liliopsida*† | Wild grass |
| Shrubs, trees not coniferous, dicotsǂ | *Magnoliopsida*† | *\_\_* |
| Broad non-human species groups |  |  |
| Vertebrates |  | Frog§; Mammals; Fish; Birds |
| Invertebrates |  | Bee§; Earthworm; Crab |
| Plants |  | Brown seaweed§; Pine tree; Wild grass |

\*Phylum.

†Class.

ǂSimply defined, dicots and monocots are plants whose seeds have two cotyledons (the leaves of the seed) and one cotyledon respectively.

§RAPFamily with no existing effects data.

## Basis for implementing the RAP approach

1. To assess the radiological impact on non-human species, it is necessary to be able to estimate an organism’s radiation exposure. Exposure of non-human species is normally expressed as an absorbed dose (or dose rate) in Gy (or µGy h-1), as relevant weighted with reference to the relative biological effectiveness (RBE). Weighting factors are given in *Publication 148* (ICRP, 2021) and can be used with Dose Coefficients (DC) provided in *Publication 136* (ICRP, 2021). Along with site-specific activity concentrations and concentration ratios that express the equilibrium between the concentration of a radionuclide in the whole body of the organism and the environmental media, assessors can then estimate dose (or dose rate) for a given organism. The estimated level of exposure is then compared with a dose criterion (e.g. the DCRL) for the relevant RAP. In *Publication 108* (ICRP, 2008), the Commission published the main elements of the RAP approach for radiological impact assessments. There are several assessment tools and methodologies, largely based upon the ICRP approach, which allow users to conduct an assessment of the impact of dose rate(s) for different (mainly planned and existing) exposure situations (e.g. Higley et al., 2003; USDoE, 2004; Beresford et al., 2008a, 2016, 2022; IAEA, 2009, 2010, 2014a,b, 2021; Beresford and Vives i Batlle, 2013; Brown et al., 2013, 2016, 2019; Copplestone et al. 2013; Yankovich et al., 2013, 2014; Vives i Batlle et al., 2016; ICRP, 2017; Skipperud et al., 2017; Beresford and Willey, 2019).
2. The consideration of natural background dose or dose rate was originally introduced to contextualise incremental doses or dose-rates calculated for non-human species. The Commission in its *Publication 108* (ICRP, 2008) stated that ‘*additional doses that were just fractions, or small multiples, of the normal background dose rates might be unlikely to be the cause of any environmental managerial concern,* …...’. Typical values are provided in Beresford et al. (2008b) for terrestrial organisms (maximum weighted dose rate ca. 6.1×10-1 µGy h-1; 40K generally dominates exposures) and in Hosseini et al. (2010) for aquatic organisms (mean weighted dose-rate ca. 2 µGy h-1, radionuclides mainly contributing to exposure being 40K, 210Po and 226Ra).

# COMPILATION AND SUMMARISATION OF EFFECTS OF IONISING RADIATION IN SUPPORT OF THE BROADENED RAP APPROACH

## Comparative analysis of radiosensitivity between species and endpoints

1. Non-human species exhibit a wide range of radiosensitivities (e.g. UNSCEAR, 2011). They may react to ionising radiation exposure according to a complex dynamic of responses expressed at different levels of biological and ecological organisation). Even though the primary mechanisms that cause radiation damage appear common to all living organisms, individual responses to radiation exposure vary significantly. Responses to radiation exposure depend on factors such as type of radiation, whether the exposure regime is acute or chronic, cell type affected, biological endpoint *(*e.g. reproduction being more sensitive than mortality), life stage (embryo, larval and/or juvenile stages are the most sensitive), and level of biological organisation. Responses also vary according to whether they are observed in *in vitro* single stressor studies or in actual ecosystems with seasonal conditions, and multiple stressors (UNSCEAR, 2011).
2. In this publication, primary data regarding dose and dose rate-effect relationships have been assembled consistently for quantitative meta-analysis. Effects data on non-human species were divided into two exposure types: acute exposure expressed as absorbed dose (Gy), mimicking the first hours or days in an emergency exposure situation; and chronic exposure expressed as absorbed dose rate (µGy h-1), for longer term and constant levels of exposure, i.e. in planned and existing exposure situations, as well in the weeks or months following an emergency. Effects data taken into account within the three population-relevant endpoints - reproduction, mortality and mortality-, included various biological responses such as growth, hatchability, tumour induction, etc. The mutation endpoint was excluded as mutations are stochastic events, not adapted to the approach used in this publication. Furthermore, there is a lack of knowledge on a potential link between mutational changes and alterations at the population level.
3. Finally, to ensure the robustness of any comparison of radiosensitivity between species and population-relevant biological endpoints, the meta-analysis was restricted to the more numerous experiments with external gamma or X-ray irradiation under conditions where dose and/or can be reliably controlled. Experiments considering internal exposure and/or high-LET radiation were excluded due to greater uncertainty in dose estimates. While this approach prioritises methodological consistency and data reliability, it is acknowledged that excluding certain data may omit potentially significant observations. However, additional data sources are considered later in this publication to provide a more comprehensive perspective.

## Update of effects data

1. The primary source of radiobiological data for non-human species is the FREDERICA database (https://frederica-online.org/mainpage.asp or ERICA Tool at tier 3- https://erica-tool.com/). The most recent significant update of FREDERICA was carried out by the Biota Effects Working Group within the IAEA Environmental Modelling for Radiation Safety Programme (EMRAS II), mainly by adding relevant data from the Russian literature (IAEA, 2014d). The database also contains the publications reviewed by ICRP in its *Publication 108* (ICRP, 2008). Information on the relationship between dose or dose rate, and type and magnitude of radiation-induced effects, was reviewed using the method described in detail by Garnier-Laplace et al. (2010) and summarised below, with a logic diagram outlined in Annex B. Additionally, a review and compilation of effects data from publications released between 2011 and 2022 (not in FREDERICA) was completed and used to assess the robustness of each derived DCRL (Section 5.1). Observed effects on non-human species from sites contaminated by radionuclides were also examined and reported for comparison with data from controlled conditions (Section 5.2).
2. As mentioned in Section 2.5, two statistical inference models inspired from the field of chemical ecotoxicity analysis and ecological risk assessment have been developed and applied in this publication: the ACTR model using knowledge of acute exposure effects to infer chronic effects, and the ESD model quantifying the radiosensitivity variation of endpoints and species within a given taxonomic group. Both require consistent data sets to be prepared prior to data processing.
3. For each effects data set extracted from a published article, selection criteria were applied and, if satisfied, a dose (rate) - effect relationship (i.e. dose-response curve) was constructed. From each chronic dose rate-effect relationship, the dose rate giving a 10 % change in observed effect in comparison with a control, the EDR10, was then estimated along with its standard error. A similar approach was applied for acute effects data and used for estimating the dose giving 50 % change in observed effect in comparison with a control, the ED50, along with the standard error. These percentages, 10% and 50%, for chronic and acute exposure respectively, correspond to critical ecotoxicity indicators conventionally used to assess and compare chemical ecotoxicity among species and endpoints (Garnier-Laplace et al., 2010; Beaugelin-Seiller et al., 2020), but can be varied dependent on the assessment context.
4. The two statistical inference models are presented in Annex C. Both the ACTR model and the ESD model are applied to sets of critical radiotoxicity indicators, i.e. ED50 or EDR10 (respectively, for acute or chronic exposure) for population-relevant endpoints, such as reproduction, morbidity or mortality, for all species of the same taxonomic class or phylum, or broad group.
5. The ACTR model aims at transforming observed data of acute radiotoxicity (ED50) into predicted data of chronic radiotoxicity (EDR10) for any given combination of species and endpoint. Its development and application enabled significant expansion of the data for chronic radiation effects by predicting chronic radiotoxicity values (EDR10) for species where only acute exposure data (ED50) exist.
6. Annexes in the form of Excel files for each RAPClass or Phylum and broad non-human species group, and each exposure type (i.e. acute or chronic) contain effects data for all species of the same class or phylum. Effects data address reproduction, morbidity and mortality, as general endpoints of interest. Reported data include radiotoxicity indicators – EDR10 or ED50 – estimated from dose (rate) - effect relationship on the basis of the data in the FREDERICA database which assembles publications up to 2010. Table 4.2 and Table 4.4 presented in chapter 4.5 show the number of effects data and species used per class or phylum, and per broad group, respectively. Some discussion of publications post 2010 is included in Section 5.

## Derivation of DCRLs for chronic exposure

1. In *Publication 108* (ICRP, 2008), the Commission established DCRLs (Figure 4.1) using expert judgement based on a review of studies related to radiation effects for the main types of endpoints (mortality, morbidity, reduced reproductive success, chromosomal damage and mutations). This approach was considered by the Commission to be ‘*the only pragmatic approach …/… to consider the existing database on effects in terms of bands of dose within which certain effects have been noted, or might be expected, and then to select a band to serve as what is termed a “derived consideration reference level” (DCRL)*’ (ICRP, 2008).
2. In this publication, the DCRLs for each RAPFamily remain those that were derived and published in *Publication 108* whereasDCRLs for RAPClass or Phylum or other broad groupswere derived using the methodology described herein.

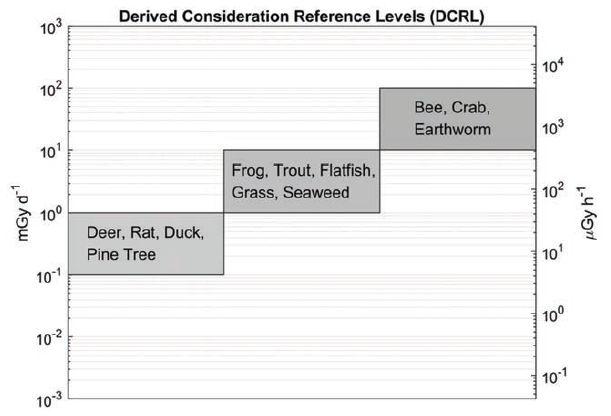


Fig. 4.1. Simplified representation of each RAPFamily and its related DCRLFamily as derived in *Publication 108* (ICRP, 2008). The ranges fall into three main groups of 0.1–1 mGy d-1 (or 4–40 µGy h-1) for deer, rat, duck, pine tree, 1–10 mGy d-1 (or 40–400 µGy h-1) for brown seaweed, flatfish, frog, wild grass, trout and 10–100 mGy d-1 (or 400–4000 µGy h-1) for bee, crab, earthworm – Note that this figure is from *Publication 148* (ICRP, 2021).

1. The methodology described above (ACTR and ESD models) provides a broadened approach to RAP representation, which can extend to higher taxonomic levels than family, such as class or phylum (RAPClass or Phylum) or broad non-human species groups, supplementing the DCRLFamily values. The proposed methodology is transparent as all of the data used are available, including the selected species and endpoints; specifically, these data are presented in the associated Microsoft Excel spreadsheets. The quantity and type of effect endpoints is known which allows an estimate of the uncertainty to be made using a semi-quantitative method. As a result, the broadened RAP approach described in this publication relies less on subjective decisions to determine the DCRL values. Figures 4.2a to 4.2h provide the basis to transparently derive DCRLs for chronic exposure for each RAPClass or Phylum (detailed in subsequent paragraphs). Each figure also indicates the location of DCRLFamily from *Publication 108* (ICRP, 2008).
2. As introduced above, the DCRLs are determined herein using a systematic derivation method. In the field of ecotoxicity of chemical substances and derivation of ecological benchmark criteria, when the statistical extrapolation method is implemented to derive a benchmark, such as a Predicted No Effect Concentration used for chemicals, the latter corresponds to the 5th percentile divided by an extrapolation factor (EF) from 1 to 5 according to the quality of the data set (EC, 2003, 2011). On this basis, the method selected here also uses the 5th percentile with a defined EF applied to account for remaining uncertainties related to the composition of the underlying data set. This allows to obtain the lower boundary (5th percentile divided by EF) and the upper boundary (best estimate of the 5th percentile) of the DCRL range, with all numbers rounded down to the nearest order of magnitude for simplicity. The approach proposed offers an optimised protection, noting that there will always be uncertainty and the need to ensure that an approach is not overly conservative which would lead to negative unintended consequences.

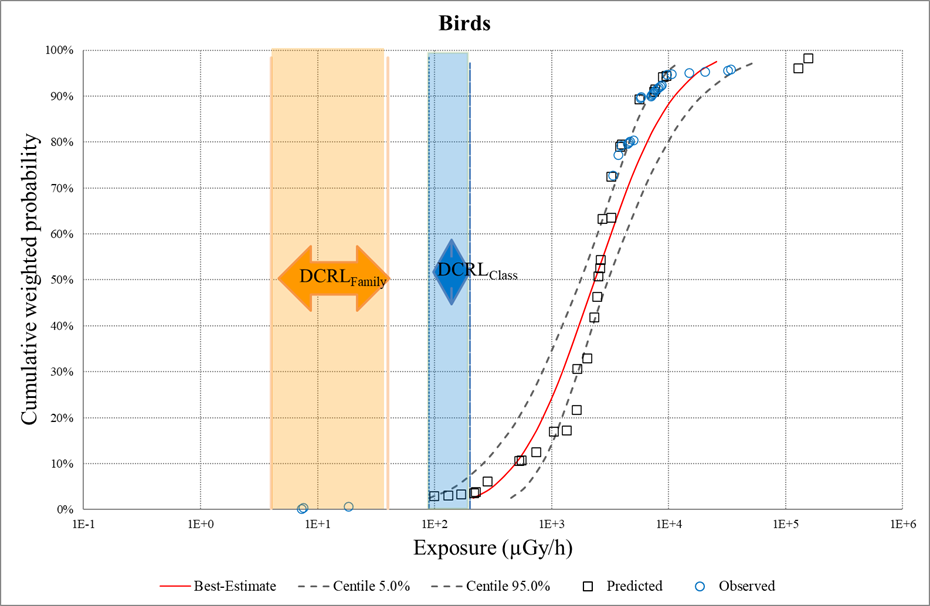


Fig.4.2a. Chronic Endpoints Sensitivity Distributions for Birds and related DRCLClass. (blue) DCRLFamily (orange) from *Publication 108* is also indicated.

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Description générée automatiquement

Fig.4.2b. Chronic Endpoints Sensitivity Distributions for Fish and related DRCLClass. (blue). DCRLFamily (orange) from *Publication 108* is also indicated.

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Fig.4.2c. Chronic Endpoints Sensitivity Distributions for Mammals and related DRCLClass (blue). DCRLFamily (orange) from *Publication 108* is also indicated.

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Fig.4.2d. Chronic Endpoints Sensitivity Distributions for Shrubs, Trees not coniferous, Dicots and related DRCLClass (blue). There is no corresponding DCRLFamily in *Publication 108*.

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Fig.4.2e. Chronic Endpoints Sensitivity Distributions for Grasses and Monocots and related DRCLClass (blue). DCRLFamily (orange) from *Publication 108* is also indicated.

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Description générée automatiquement

Fig.4.2f. Chronic Endpoints Sensitivity Distributions for Conifers and related DRCLClass (blue). DCRLFamily (orange) from *Publication 108* is also indicated.

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Description générée automatiquement

Fig.4.2g. Chronic Endpoints Sensitivity Distributions for Crustaceans and related DRCLClass (blue). DCRLFamily (orange) from *Publication 108* is also indicated.

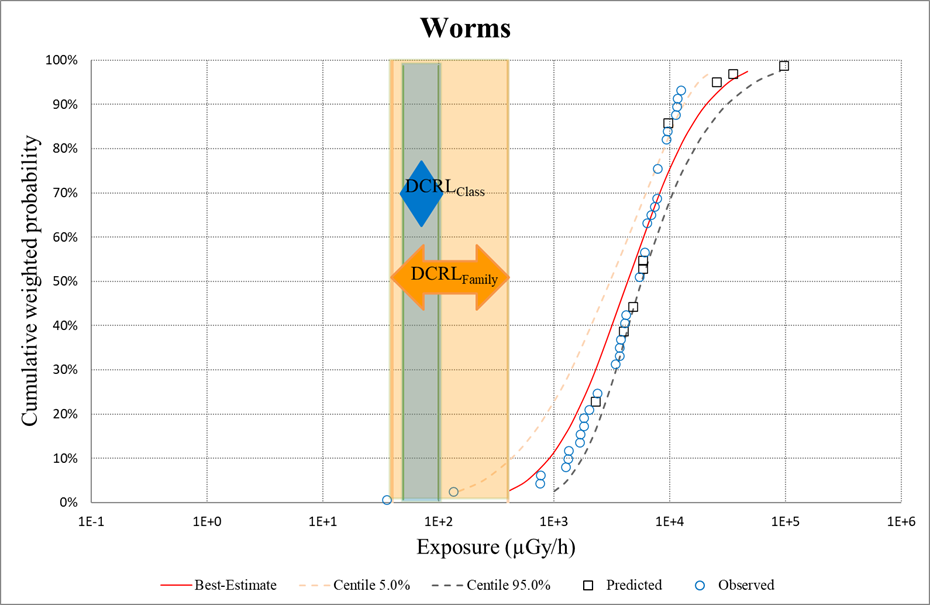


Fig.4.2h. Chronic Endpoints Sensitivity Distributions for Worms and related DRCLClass (blue). DCRLFamily (orange) from *Publication 108* is also indicated.

1. The EF value is determined according to a multi-criteria score, based on qualitative and quantitative features of the data set, which differs from one class or phylum to another. This EF approach is described in detail in Garnier-Laplace et al. (2006, 2010). The EF supports the level of confidence associated with the taxon-related DCRL. The criteria considered to determine the EF are listed in Table 4.1. Overall, this approach allows the uncertainties in the DCRL to be considered in a relative and semi-quantitative manner. An EF of 1 means that the underlying data set is of much higher quality and quantity than for an EF of 5, for example. As a result, in the latter case, more conservatism applies to the lower boundary value of the DCRL.

Table 4.1. Rules adopted to determine the Extrapolation Factor (EF) to be applied to the 5th percentile of any class (or phylum)-specific ESD for chronic exposure regime.

|  |  |  |  |
| --- | --- | --- | --- |
| Criterion\level of uncertainty | low uncertainty | intermediate uncertainty | high uncertainty |
| Individual score per criterion | 3 | 2 | 1 |
| #1. Total number of data | >100 | 50-100 | 0-50 |
| #2. Proportion of observed data in data set | 0.7 to 1 | 0.3-0.7 | 0-0.3 |
| #3. Proportion of reproductive endpoints | 0.7 to 1 | 0.3-0.7 | 0-0.3 |
| #4. Number of observed data below 5th out of total data | 0.7 to 1 | 0.3-0.7 | 0-0.3 |
| #5. Number of species | >10 | from 5 to 10 | <5 |
| TOTAL SCORE RANGE | 15 | 10 | 5 |
| EF RANGE\* | 1 | 3 | 5 |

\*The EF value can be determined for any Total Score value by using a linear transformation between the two ranges (EF=2/5\*Total Score+7), and then rounded up to the nearest integer for conservative purpose.

1. A score between 1 and 3 was applied to each descriptive criterion listed in Table 4.1, where 3 denotes the least uncertainty per individual item. Criteria contributing to the overall uncertainty were scored to justify the selection of an appropriate EF to define the lower boundary of DCRL. The adopted value for EF is then rounded up to the nearest whole integer. Table 4.2 presents the corresponding scores and EF per class or phylum for data sets describing chronic exposure conditions. Table 4.3 presents RAPFamily and RAPClass or Phylum and their DCRL attributes.

Table 4.2. RAPClass or Phylum data set features for chronic exposure conditions, application of the multi-criteria scoring, and final value obtained for the extrapolation factor.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| RAPClass or Phylum\* | #1† | #2† | #3† | #4† | #5† | Total score | Final EF |
| Birds | 58 | 0.43 | 0.79 | 0.1 (1/9) | 11 | 11 | 3 |
| Fish | 101 | 0.28 | 0.63 | 0.6 (2/3) | 12 | 11 | 3 |
| Mammals | 132 | 0.42 | 0.52 | 0.8 (4/5) | 7 | 12 | 3 |
| Crustaceans\* | 48 | 0.31 | 0.29 | 0 (0/0) | 10 | 9 | 4 |
| Worms\* | 41 | 0.73 | 0.78 | 1 (1/1) | 3 | 11 | 3 |
| Conifers | 41 | 0.20 | 0.22 | 0 (0/3) | 8 | 6 | 5 |
| Grasses and Monocots | 47 | 0.70 | 0.64 | 0 (0/1) | 7 | 9 | 4 |
| Shrubs, trees not coniferous and Dicots | 58 | 0.22 | 0.29 | 1 (4/4) | 12 | 10 | 3 |

\*RAPPhylum are marked with \*.

† #1 Total data points; #2 Proportion of observed data in data set; #3 Proportion of reproductive endpoints in data set; #4 Proportion of observed data below the 5th percentile (number of observed data below the 5th percentile divided by total number of data below the 5th percentile); #5 Number of species (see Table 4.1 for details).

1. To broaden the scope of DCRL beyond phylum, the previously described methodology has also been applied to other broad wildlife groups. This is needed because, for ecological risk assessments, it is sometimes necessary to refer to representative organisms (e.g. butterfly or salamander or viper) of other classes with no corresponding DCRL due to a lack of suitable effects data (e.g. class *Insecta* or class *Amphibia* or class *Reptilia*). Here the recommendation is to use a DCRL derived for broad non-human species groups, i.e. vertebrates, invertebrates or plants for initial screening of a radiological impact assessment, as appropriate. In such cases, the EF is set to a higher value of 10 to account for the additional uncertainty in whether the ESD for these broad groups is reflective of the missing class information (see Table 4.4).

Table 4.3. RAPClass or Phylum and their DCRL attributes - best estimate of the 5th percentile of the ESD, EF and bands for chronic exposure conditions (expressed in µGy h-1). The table also includes RAPFamily and DCRLFamily for comparison.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| RAPClass or Phylum\* | 5th percentile | EF | DCRLClass or Phylum† | RAPFamilyǂ | DCRLFamilyǂ |
| Birds | 313 | 3 | 100-300 | duck | 4-40 |
| Fish | 207 | 3 | 70-200 | trout; flat fish | 40-400 |
| Mammals | 60 | 3 | 20-60 | deer; rat | 4-40 |
| Crustaceans\* | 456 | 4 | 100-400 | crab | 400-4000 |
| Worms\* | 580 | 3 | 100-500 | earthworm | 400-4000 |
| Conifers | 379 | 5 | 70-300 | pine tree | 4-40 |
| Grasses and Monocots | 1020 | 4 | 200-1000 | wild grass | 40-400 |
| Shrubs, Trees not coniferous, Dicots | 664 | 3 | 200-600 | none | none |

\* RAPPhylum are marked with \*.

† DCRLClass or Phylum is the recommended range from the 5th percentile divided by the Extrapolation Factor to the best estimate of the 5th percentile. Both lower and upper boundaries are rounded down to the nearest ten, hundred or thousand as appropriate.

ǂ RAPFamily refers to RAPs as defined in *Publication 108* (ICRP, 2008). The DCRLFamily is the band derived by critical literature review and expert judgement in *Publication 108* (ICRP, 2008) for organisms of the RAPFamily type. In this Publication, although theoretically possible, none of these DCRL have been derived using the new methodology due to a lack of data at the family level.

Table 4.4. Broad non-human species group attributes and best estimate of the 5th percentile of the ESD, and bands for chronic exposure conditions applying an EF of 10 (expressed in µGy h-1).

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Broad group | RAPFamily | #1\* | #2\* | #3\* | #4\* | #5\* | 5th percentile | DRCLbroad group† |
| Vertebrates | deer; rat; duck; trout; flat fish; frog | 289 | 0.37 | 0.61 | 8/19 | 30 | 184 | 10-100 |
| Invertebrates | bee; crab; earthworm | 104 | 0.58 | 0.48 | 2/2 | 16 | 716 | 70-700 |
| Plants | pine tree; wild grass; brown seaweed | 147 | 0.37 | 0.39 | 3/8 | 28 | 688 | 60-600 |

\*#1 Total data points; #2 Proportion of observed data in data set; #3 Proportion of reproductive endpoints in data set; #4 Proportion of observed data below the 5th percentile (number of observed data below the 5th percentile divided by total number of data below the 5th percentile); #5 Number of species (see Table 4.1 for details).

†DCRL is the recommended range from the 5th percentile divided by an Extrapolation Factor of 10 to the best estimate of the 5th percentile. Both lower and upper boundaries are rounded down to the nearest ten, hundred, or thousand as appropriate.

## Endpoints Sensitivity Distributions for Acute Exposures

1. ESD can also be fitted for classes or phyla for acute exposures (Fig. 4.3). Acute ESD may be helpful in emergency exposure situations (e.g. in case of accidental exposure where wildlife may receive acute exposure). Such ESD may help communicate the type of potential effects on wildlife once dose estimates have been produced, and promote informed discussions with stakeholders. Qualitative and quantitative features of the acute ESD are described in Table 4.5 by class or phylum and in Table 4.6 by broad groups.
2. For illustrative purpose, the 5th percentile and the 50th percentile of the ESD (expressed in Gy) are reported in those tables. Any other percentile (corrected or not by an EF) of the acute ESD may be selected, dependent on assessment context.

Table 4.5. Overview of the quality of the data set per RAPClass or Phylum for acute exposure conditions. For illustrative purposes, the 5th percentile and the 50th percentile of the ESD (expressed in Gy) are reported.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| RAPClass or Phylum\* | Total data points | Proportion reproductive endpoints in the data set | Number of species | 5th – 50th percentiles of the ESD |
| Birds | 33 | 0.64 | 11 | 5.1-8.1 |
| Fish | 73 | 0.56 | 11 | 0.9-11 |
| Mammals | 76 | 0.71 | 4 | 0.6 -3.0 |
| Crustaceans\* | 33 | 0.39 | 7 | 2.2-57 |
| Worms\* | 24 | 0.29 | 2 | 3.1-56 |
| Insects | 82 | 0.17 | 23 | 3.7-70 |
| Conifers | 33 | 0.27 | 5 | 2.7-24 |
| Grasses and Monocots | 37 | 0.16 | 11 | 3.2-26 |
| Shrubs, Trees not coniferous, Dicots | 45 | 0.36 | 10 | 5.4-59 |

\* RAPPhylum are marked with \*.

Table 4.6. Broad non-human species group attributes informing assessments of effects of acute exposure to radiation. The same method was applied to enlarged data sets for vertebrates, invertebrates and plants, respectively. 5th and 50th percentiles (expressed in Gy) are indicated for illustrative purposes.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Broad group | RAPFamily | Total data points | Proportion reproductive endpoints in the data set | Number of species | 5th – 50th percentiles |
| Vertebrates | deer; rat; duck; trout; flat fish; frog | 191 | 0.65 | 27 | 0.3-5.3 |
| Invertebrates | bee; crab; earthworm | 186 | 0.30 | 42 | 5.3-130 |
| Plants | pine tree; wild grass; brown seaweed | 161 | 0.26 | 35 | 4.3-63 |

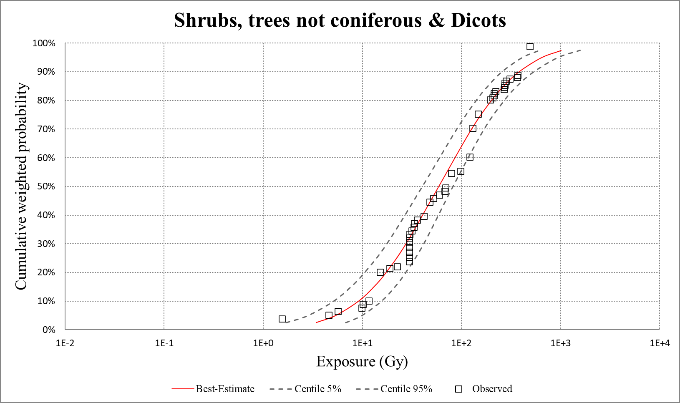
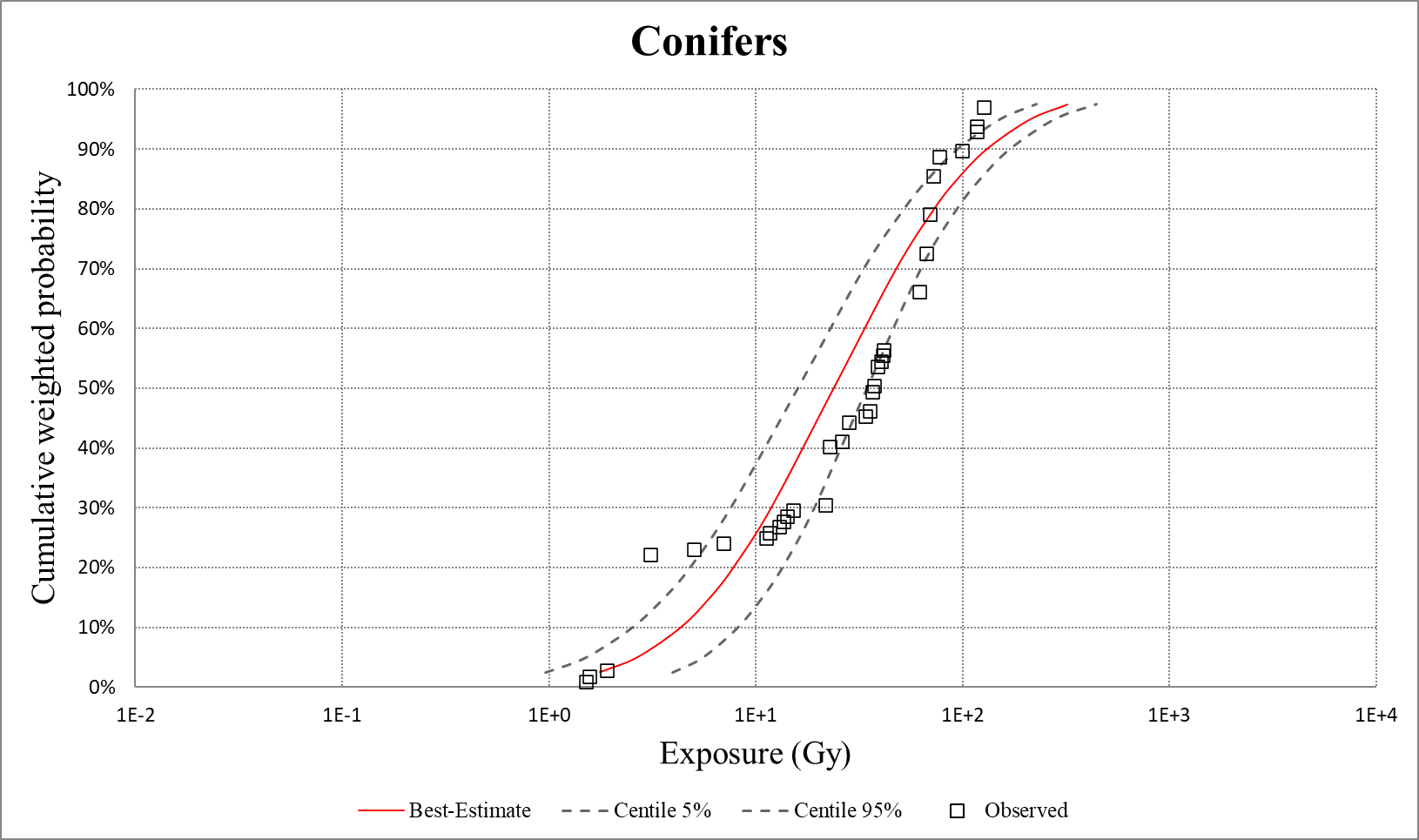
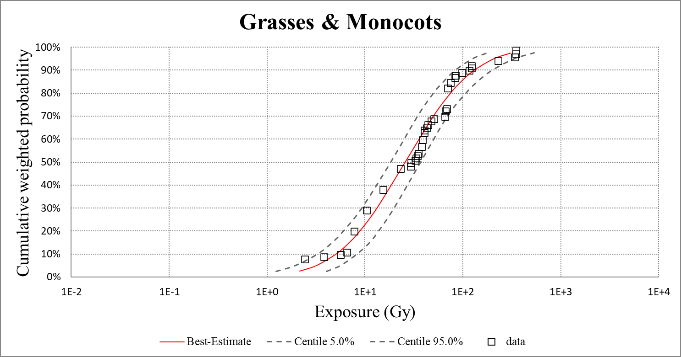
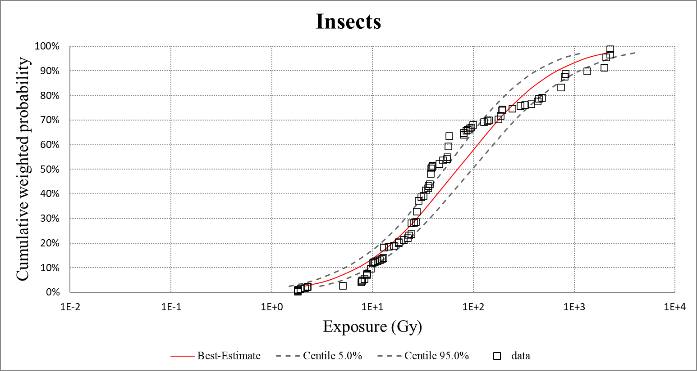
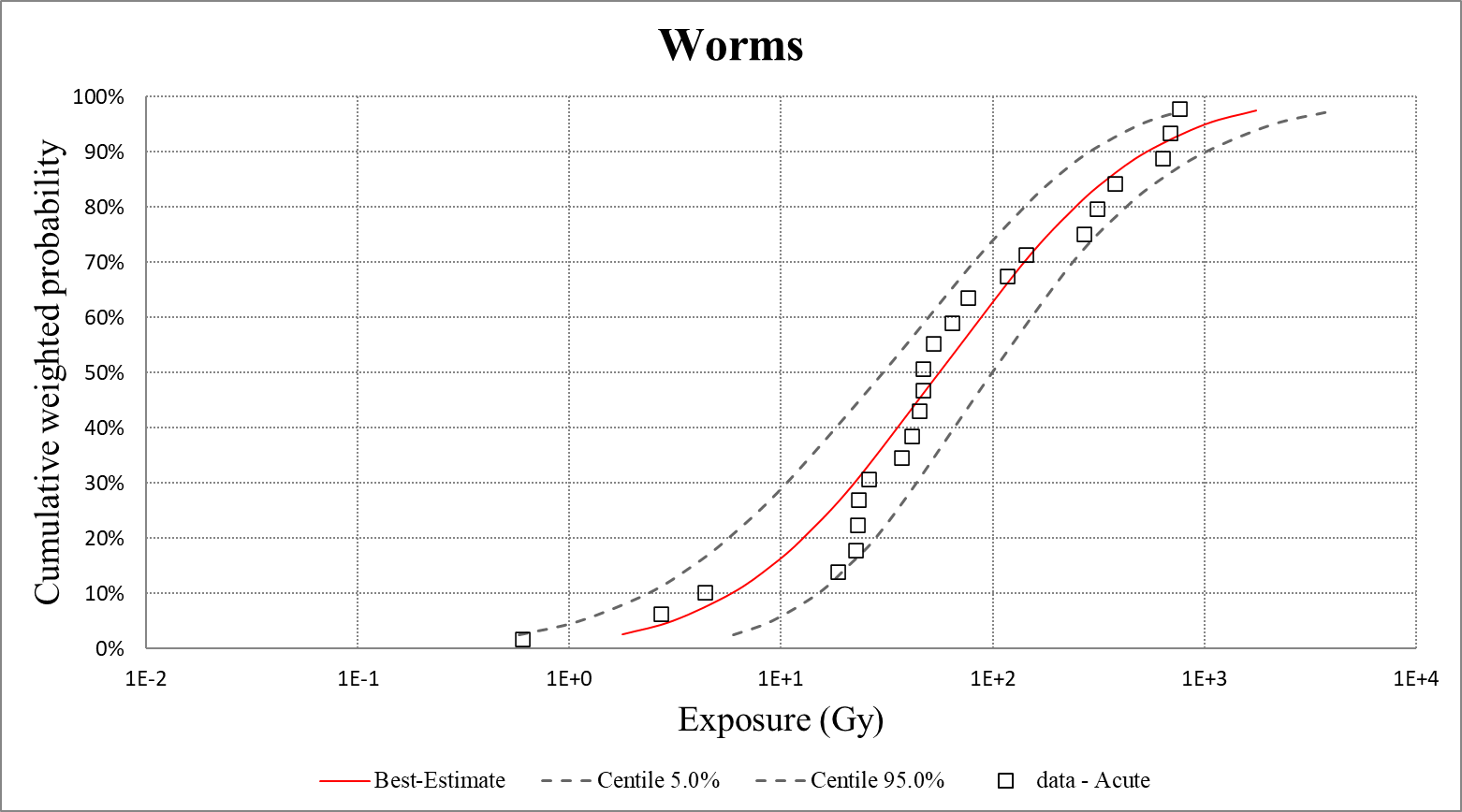
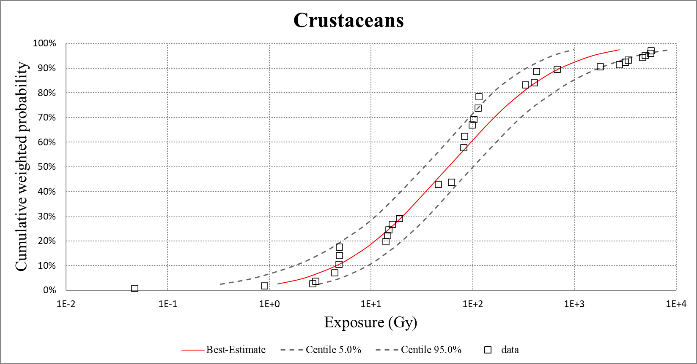
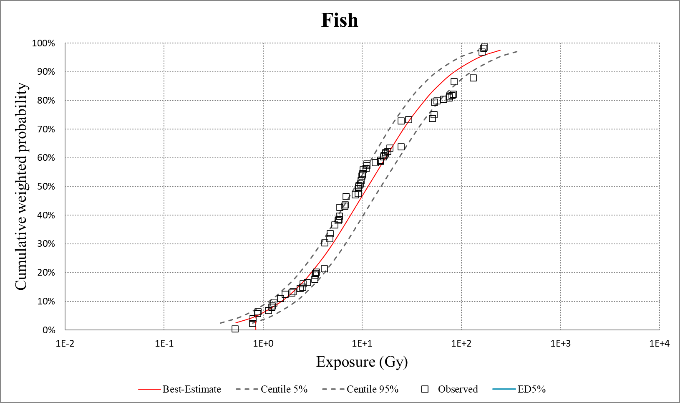
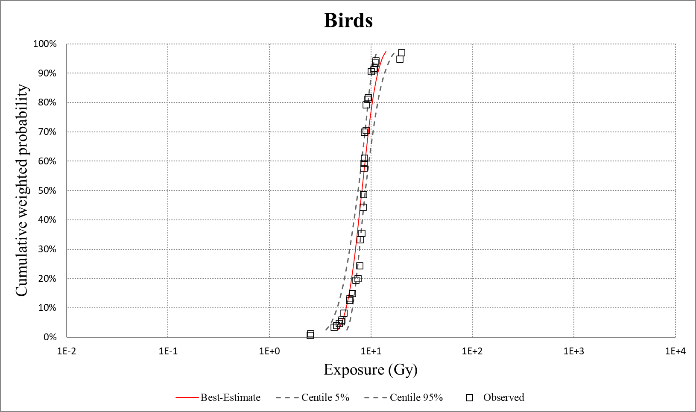
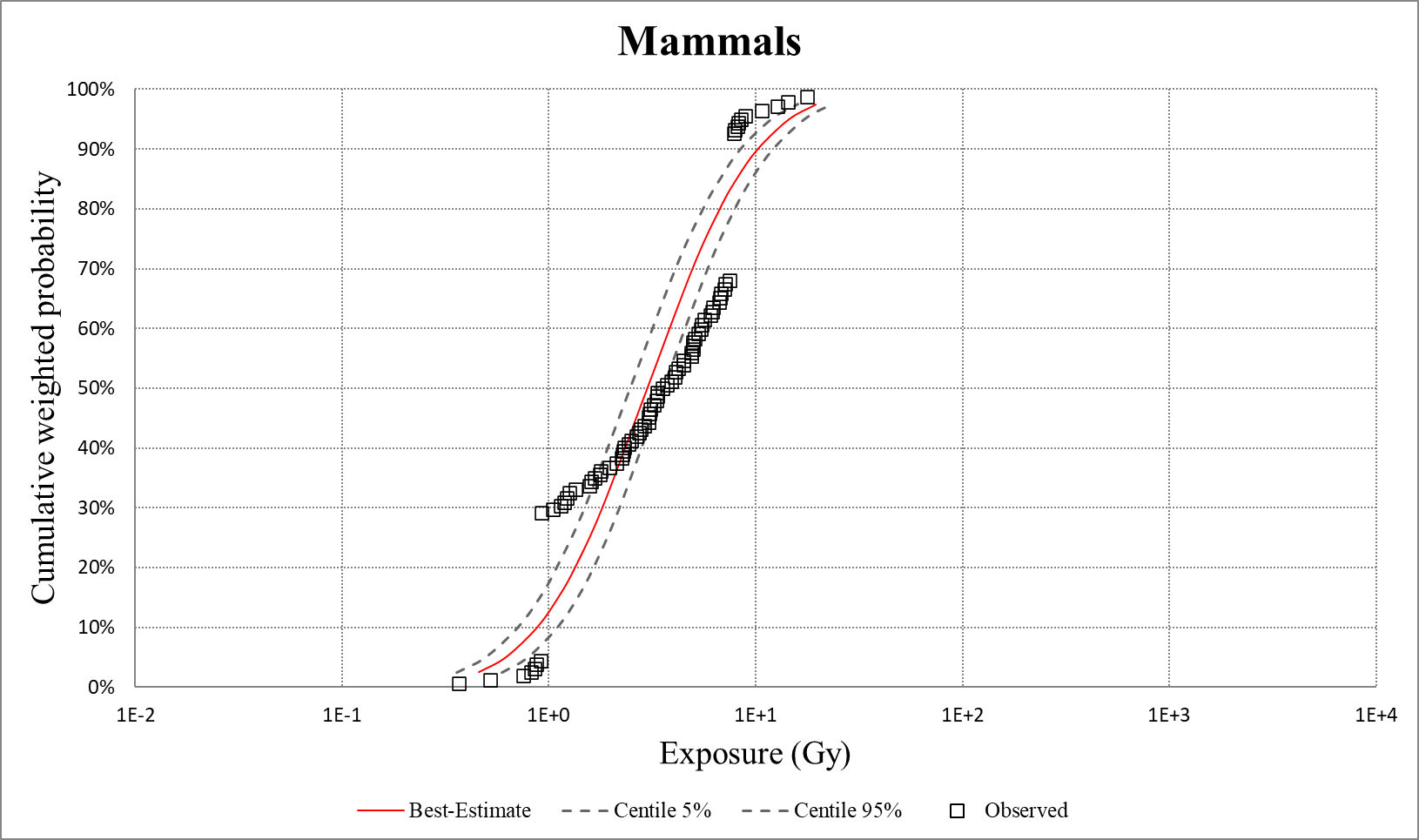


Fig.4.3. Acute Endpoints Sensitivity Distributions by class or phylum.

## Comparison of the outcomes of the proposed and existing approaches to derive DCRLs

1. Regardless of methodology used to derive the DCRLs, the original definition remains valid, i.e. ‘*a band of dose rate within which there is likely to be some chance of deleterious effects of ionising radiation occurring to individuals of that type of Reference Animal or Plant (derived from a knowledge of defined expected biological effects for that type of organism)*’. The differences introduced by the proposed methodology are, for any taxonomic group, to enable (i) the estimation of the level of radiation effects for any exposure level and (ii) the selection of a level of protection of organisms according to the percentile of the ESD chosen. The additional DCRLs, which are not intended to replace the DCRLs at family level but to supplement them, provided for a given class, phylum or broad non-human species group correspond to bands of absorbed dose rates (expressed in µGy h-1) for chronic exposures, within which there is likely to be 5% probability of having population-relevant deleterious effects for species of that taxonomic group (with deleterious effects defined as having more than 10% effect on endpoints such as morbidity, reproduction, or mortality).
2. Taxonomic classes or phyla with appropriate chronic effects data sets in terms of quality and quantity to implement the ESD, are shown in Table 4.7 and are as follows:

* Birds (class Aves), Fish (class *Actinopterygii*), Mammals (class *Mammalia*), and their grouping into the broad vertebrate group.
* Crustaceans (class *Branchiopoda* and class *Malacostraca*), Worms (class *Clitella* and class *Polychaeta*) and their grouping into the broad invertebrate group.
* Conifers (class *Pinopsida*), Shrubs, Trees not coniferous, and Dicots (class *Magnolopsida*), Grasses and Monocots (class *Liliopsida*), and their grouping into the broad plant group.

1. For other classes not listed above (e.g. class *Amphibia*, class *Reptilia*), the recommendation is to use DCRL of the related broad group (here, vertebrates) for initial screening of a radiological impact assessment, as appropriate (e.g. consider the frog as a vertebrate; or a bee as invertebrate). In such cases, the EF is set to the higher value of 10 to account for the greater uncertainty given the lack of information for the missing class(es) in the data set.
2. Table 4.7 provides an overall comparison of the additional values (DCRLClass or Phylum or DCRL defined for broad groups) with the existing ones (DCRLFamily). The two sets of values are not directly comparable because they cover different ranges of diversity and sensitivity (species and endpoints) and are derived using two different approaches. Additionally, the quality and quantity of underlying effects data is used in the proposed methodology to determine an EF (from 1 to 5 for DCRLClass or Phylum; up to 10 for DCRL to account for uncertainty in situations where radiosensitivity of organisms of interest is insufficiently known at the level of class or phylum), whereas the bands of DCRLFamily were set using one order of magnitude.
3. Importantly, the two approaches used to determine DCRLs do not result in major differences to their values (Table 4.7 and Figs. 4.2a-h). The lower boundary of DCRLClass or Phylum or broad group values, are higher than the corresponding DCRLFamily values, except for bee/invertebrates (as there is no value for Insects), crab/Crustaceans and earthworm/Worms. This reflects reduced uncertainty and the use of more data to inform radiosensitivity. For the reference bee, crab and earthworm, the lower boundary of the DCRLClass or Phylum or broad group of invertebrates are lower by ca. one order of magnitude than those of the corresponding RAPFamily in *Publication 108*. This is because of the paucity (or lack of) data available to inform the DCRLFamily estimation. More effects data combined with the statistical analysis proposed in this publication, reduces uncertainty in the DCRLClass or Phylum or broad group of invertebrates.
4. A pragmatic conclusion from this comparison is that, for most groups, the differences in DCRLs, are minor (maximum of ca. one order of magnitude). This means that assessors may use them indifferently for screening impact assessments, particularly when related to planned exposure situations (as long as they explain their selection). For more complex assessments – such as a detailed radiation environmental impact assessment and/or in existing exposure situations, assessors might wish to complement their assessment using the DCRLClass or Phylum or broad groups. Such an approach allows for a more careful consideration of the appropriateness of the DCRLClass or Phylum or broad groups values based on their underlying effects data, as this can greatly reduce uncertainty.
5. An overall comparison of the methodological and scientific knowledge used in support of the set of DCRLFamily (*Publication 108*) and the additional DCRLClass or Phylum and DCRLs for broad groups (this publication) is detailed in Table 4.8, with additional discussion of uncertainties.

Table 4.7. Proposed DCRL related to RAPClass or Phylum (this publication) and RAPFamily (ICRP, 2008) with values expressed in µGy h-1. RAPFamily *in italics* indicates where there was no information to document the DCRLFamily range. RAPClass or Phylum *in italics* means that the EF applied to the 5th percentile was equal to 4 or 5 (high uncertainty), all others being scored at 3 (intermediate uncertainty). A higher EF of 10 (for higher uncertainty) was applied to obtain the lower end of broad group’s DCRL. The use of broad group’s DCRLs is recommended in situations where data on class or phylum do not exist.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| RAPFamily | DCRLFamily | C#† | RAPClass or Phylum\* | DCRLClass or Phylum | Broad groups |
| *duck* | 4-40 | < | Birds | 100-300 | Vertebrates |
| trout; flat fish | 40-400 | < | Fish | 70-200 | 10-100 |
| deer; rat | 4-40 | < | Mammals | 20-60 |  |
| *frog* | 40-400 | \_\_ | Amphibians | No data |  |
| *bee* | 400-4000 | \_\_ | Insects | No data | Invertebrates |
| *crab* | 400-4000 | *>* | *Crustaceans\** | 100-400 | 70-700 |
| earthworm | 400-4000 | > | Worms\* | 100-500 |  |
| *pine tree* | 4-40 | *<* | *Conifers* | 70-300 | Plants |
| *wild grass* | 40-400 | *<* | *Grasses and Monocots* | 200-1000 | 60-600 |
| none | \_\_ | \_\_ | Shrubs, Trees not coniferous, Dicots | 200-600 |  |
| brown seaweed | 40-400 | \_\_ | Brown Algae | No data |  |

\*Phylum.

†C# compares the lower boundary of the DCRLFamily with the one of DCRLClass or Phylum.

Table 4.8. Comparison of the methodological and scientific knowledge used in support of the set of DCRLFamily (*Publication 108*) and the additional DCRLClass or Phylum and DCRLs for broad groups (this publication). Some types of uncertainty are identified and quantified as far as possible, and limitations of the approaches are indicated.

| **Element of the RAP approach** | **RAP approach as defined in *Publication 108* (ICRP, 2008)** | **Broadened RAP approach as defined in this publication** |
| --- | --- | --- |
| Selection of effects data | **Experiments on the effects of radiation have varied widely in terms of species studied, modes of exposure (field or lab studies), external or internal exposure, acute (high dose rates over a short time period) or chronic (lower dose rates over a substantial period of the life(stage) of the organism under study), and biological endpoints measured**, leading to significant difficulty in combining study findings for the purpose of deriving dose-effect relationships. This diversity in experiments and conditions has resulted in broad and often overlapping conclusions in respective study findings.  **Publications supporting the literature review:**  249 (excluding state-of-the-art reviews) - FREDERICA (version in Copplestone et al., 2008). See Annex A of this publication.  **Limitation**: not all dose(rate)-effect relationships are quantified, and various types of exposures conditions are considered all together. | **Experiments under laboratory-controlled conditions, external gamma or X-ray irradiation, acute exposure and chronic exposure, with criteria applied to establish dose (rate) – effect relationships with reduced uncertainty for dose (rate) quantification. Only effects with demographic consequences on populations of species** were considered.  Primary source of data: FREDERICA updated in 2010 following the EMRAS programme.  **Publications to establish ESD:**  152 publications to extract chronic data sets: 52 (observed data) + 100 (predicted data). 121 publications to extract 159 acute data sets (observed data). See the supplementary excel files with all data and references.  Additionally, publications post-2010 from laboratory tests and from field studies were used to compare with the calculated DCRLs.  **Limitation**: knowledge where dose(rate)-effect relationships do not fit any of the models selected (log logistic or hormetic patterns – see the Excel Files for more information) was not considered (e.g. no effect values evidenced during experiments).  **Added value:** knowledge on acute exposure and dose-effect relationships now quantified and used to predict chronic effects data from acute effects data (via the ACTR model).  All dose(rate)-effects relationships are now expressed with the same critical radiotoxicity indicator, EDR10 and ED50 for chronic and acute exposure respectively. |
| Taxonomic level in support of the RAP approach | **Family** was suggested as the most suitable level of generalisation for types of animals and plants, as it was expected there would be the smallest variation in radiosensitivity among species and the best representativity in terms animals and plants in ecosystems (terrestrial, freshwater, marine).  As a result**, 12 RAPFamily, several of them with mainly inferred relationships between dose and effect, were proposed in support of the DCRLs.** | **Any taxonomic grouping** is appropriate provided there is sufficient quality-checked effects data for the species representing the taxonomic group to establish a statistical distribution of population relevant endpoints reflecting their radiosensitivities for chronic and acute exposures. For a given taxon, it is assumed that radiosensitivity variation is independent of the ecosystem.  As a result, **8 classes or phyla** have been identified which fit the criteria required to apply the new methodology. **3 broad groups** (vertebrates, invertebrates and plants) were also used to define DCRLs for species otherwise not covered. |

Table 4.8 (*continued*)

| **Element of the RAP approach** | **RAP approach as defined in *Publication 108* (ICRP, 2008)** | **Broadened RAP approach as defined in this publication** |
| --- | --- | --- |
| Methodology and assumptions to derive DCRLs | **Expert judgement based on careful analysis of available data and uncertainties from a literature review.**  **Limitation**: the range of each DCRL is fixed pragmatically at one order of magnitude and does not reflect the quality/quantity of existing data nor quantify the remaining uncertainties. 6 families have no effects data to support their DCRLs, which have been defined taking account of knowledge from other ranges of exposure and potential effects (background level, higher dose-rates). | **Statistical endpoints sensitivity distributions (ESD) established per taxon for chronic exposure** (data sets comprise observed data and predicted data from acute data using the acute-to-chronic transformation model).  **Limitation**: the range of DCRLs is fixed by selecting the best estimate of the 5th percentile of the ESD as the upper boundary of the DCRL; the lower boundary is obtained by dividing the 5th percentile by an Extrapolation Factor (EF) to account for the quality of the data set. Both lower and upper boundaries are rounded down to the nearest order of magnitude for simplicity.  The same approach was used for broad groups but with an EF of 10 as it is recommended for use in radiological impact assessments when knowledge for organisms of interest is very limited or unavailable.  **Added value:** the EF is defined as a multi-criteria score, reflecting the level of uncertainty associated with the underlying knowledge per class or phylum. Using a score ranging from 1 to 5, the uncertainty in the data sets was determined and then an EF applied accordingly.  Any interested party can reproduce the derivation of the DCRL values if the same supporting data sets are used.  It is also possible to apply the methodology using specific data sets more appropriate for the taxonomic/ecosystem circumstances being considered by the assessor and/or to decide on other choices/factors (e.g. select a different percentile of the ESD as the starting point to derive the DCRL). |

## Simple guidance on using DCRLFamily and higher taxonomic level DCRLs in conjunction

1. The DCRLs from *Publication 108* (ICRP, 2008) can continue to serve as references for any environmental impact assessment, with the proposed DCRLs at higher taxonomic levels used as a complement to support assessments in difficult cases. For initial screenings and planned exposure situations, DCRLFamily values are likely to be sufficient. But, if the observed or estimated exposure dose rates are close to (either below, within or above) the lower boundary of the DCRLFamily, the use of the DCRLClass or Phylum or the one for broad groups may provide more information within an assessment allowing a better estimate of the confidence in the assessment conclusions to be made.
2. In assessment cases involving, for example, large facilities, post-accident evaluations, specific protected ecosystems and/or species (or representative organisms), the proposed approach with a set of DCRLs at higher taxonomic levels offers the possibility of a more evidence-based assessment.
3. While higher taxonomic DCRLs (class, phylum, or broad group) can help in complex assessments such as those for existing exposure situations, assessors should carefully consider the underlying effects data and remaining uncertainties when selecting which values to apply. If necessary, the proposed approach enables the derivation of site-tailored DCRLs by using effects data specific to the assessment case (e.g. specific ecosystems or species) and/or by adopting a tailored level of protection (i.e. the percentile of the ESD used as the boundary of the DCRL) if this is a conclusion following discussion with stakeholders.
4. Irrespective of the set of DCRLs used as benchmarks in different types of assessments, *Publication 124* (ICRP, 2014) applies. It recommends that the lower boundary of the relevant DCRL should be used as the reference level for planned exposed situations. In other situations where chronic exposure is relevant, i.e. existing exposure situations or medium to long-term exposure (months, years) after an emergency, the DCRLs correspond to the exposure range to be targeted when applying optimisation of environmental radiological protection as a guide to the level of protection effort required.
5. In the acute stages of an emergency, the safety of humans and socio-economic considerations linked to for example widespread contamination are likely to be the initial priority. However, the focus can be expected to shift to broader environmental considerations including potential risks of exposure to populations of non-human species (wildlife) and conservation objectives, for example, as well as considering the risks and impacts of any protective or remedial actions. Here the acute ESD models per class, phylum or broad group could be useful retrospectively to support dialogue with stakeholders on any ecological impacts that may have occurred.
6. Further details are provided in Annex D and further advice and guidance on the application of the DCRLs for environmental radiological protection is under preparation (Part 2 in this series of publications).

# REVIEW OF THE ADDITIONAL DCRL VALUES RELATED TO THE BROADENED RAP APPROACH

1. As a result of their direct ecologically relevant link to the population dynamics of non-human species, radiation effects data on mortality, reproduction, and morbidity in animals and plants were the primary source of information applied in the stepwise approach described in section 4 for deriving Derived Consideration Reference Levels (DCRLs),using the proposed methodology in support of the broadened RAP approach. The data set used for such derivation was extracted from the most recent (2010) version of the quality-checked FREDERICA database and restricted to laboratory experiments of external gamma or X-ray radiation exposures, where dose or dose rate, and other factors, could be measured with accuracy and reproducibility. Since the completion of the database information in 2010, several papers (discussed in section 5.1), have been published that may be of interest in the context of the present publication, e.g. for checking the proposed DCRL by class, phylum or broad wildlife group values.
2. Radiation effects are much better documented for acute exposures. In the case of chronic exposures, the uncertainty is greater at low dose rates due to the scarcity of information. Although the empirical Acute-To-Chronic Transformation of Radiation Effects (ACTR) model used has allowed predicted data to be added to observed data in of the fitting of the Endpoint Sensitivity Distribution (ESD) models, the effects of chronic exposure remain a research priority to reduce the uncertainty associated with the 5th percentile of the ESD (which is key in determining DCRL boundaries).
3. Given these limitations, albeit addressed by the application of extrapolation factors to the 5th percentile of the chronic ESD to obtain the final range of DCRL, it is necessary to verify the appropriateness and relevance of these reference values by examining their positioning in relation to data that were not used for their derivation, i.e. data published since 2011.
4. This section aims to critically review the DCRLs derived using the new methodology based on (semi)-quantitative knowledge reported for laboratory experiments and field studies on sites contaminated by radionuclides. The remaining limitations and research needs are also analysed.

## Comparison with laboratory chronic effects data not used to derive the DCRLs

1. The literature review of laboratory studies focused on the effect of exposure to external X-ray or gamma radiation that comply with the selection rules of data for the DCRL derivation purpose. The publications found since 2011 are indicative of a shift with experiments deploying novel molecular or cellular tools. These tools help to study mechanisms of propagation from initial molecular events to potential adverse effects, including genetic and epigenetic effects induced by ionising radiation (e.g. Murat El Houdigui et al., 2019; Duarte et al., 2023). Such data are generally not adequate to determine benchmark criteria in support of radiological environmental impact assessments. In only some cases, those molecular biology approaches were applied in connection with observation of macroscopic endpoints (such as physiological or functional endpoints) in order to understand the underlying mechanisms.
2. Some papers were, however, usable to check whether the observed effects were consistent with or challenged the additional DCRLs. Hurem et al. (2018) observed a reduction by 31% of cumulative embryo production in zebrafish (*Danio rerio*) per week one month after exposure to 8700 µGy h-1. In another paper, no effect was observed on zebrafish hatching or embryo mortality at 1200 µGy h-1 (Gagnaire et al., 2021). These values are well above and hence not substantively challenging the DCRL for Fish (70-200 µGy h-1). In a third study, Maremonti et al. (2019) calculated an EDR10 of 31,300 (95%CI 15,900; 49,300) µGy h-1 for the number of offsprings in the worm *Caenorhabditis elegans*, which is also well above and hence not challenging the DCRL for Worms (100-500 µGy h-1). Similarly, for the Southern toad (*Anaxyrus terrestris*), no effect was observed on hatching or larvae mortality at 14,300 µGy h-1 by Stark et al. (2015), well higher than the vertebrate DCRL (10-100 µGy h-1). Finally, for bumblebees, Raines et al. (2020) reported that the colony queen production of *Bombus terrestris audax* was decreased by 46 % at 100 µGy h-1, which falls within the corresponding range for invertebrates DCRL of 70-700 µGy h‑1, and support this more conservative (lower) range than the one for bee where DCRLFamily is 400 to 4000 µGy h-1.

## Comparison with field data from sites contaminated by radionuclides

1. Several reviews have compiled and analysed the results of the field studies performed in the contaminated areas of Chornobyl and Fukushima (e.g. UNSCEAR, 2000, 2015; Geras'kin et al., 2008; Beresford and Copplestone, 2011; IAEA, 2015; Strand et al., 2017; Beresford et al., 2020; Real and Garnier-Laplace, 2020; IRSN, 2021; Takada and Schneider, 2023). To compare DCRLs with observed effects in field studies, these reviews were supplemented by a literature survey conducted in 2022, focusing on Fukushima and Chornobyl studies.
2. In the case of Fukushima studies, most were on molecular endpoints, with very few papers related to population-relevant endpoints. Regarding Chornobyl, studies were composed of molecular endpoints and population- or community-relevant endpoints (e.g. aquatic invertebrate diversity; soil decomposer activity). Several of these studies did not provide evidence of any significant effect (e.g. Bonzom et al., 2016; Fuller et al., 2022; Beresford et al., 2023) while some others concluded that there were significant effects of exposure to ionising radiation in the Fukushima and Chornobyl accident-impacted areas (e.g. Watanabe et al., 2015; Car et al., 2022).
3. Molecular endpoints are often used in field studies to shed light on toxicity mechanisms or as early warning biomarkers of adverse effects. Even if they are generally more sensitive than the population-relevant endpoints used to derive DCRLs, the long-term consequences of such molecular responses are still difficult to causally link to population level changes. In addition, the dose-response curves obtained using these molecular endpoints often are not linear due to feed-back loops in biological pathways. For those reasons, it is difficult to use these molecular endpoints for comparison to DCRLs and it is for the same reasons that those types of endpoints (e.g. mutations), were not included in the DCRL derivation in the new methodology.
4. Moreover, confounding factors may be contributing to uncertainties in field studies., leading to contradictory results. For example, on mammal abundance, a significant effect of ionising radiation was observed in Chornobyl by Møller and Mousseau (2013), whereas other long-term data showed no evidence of a negative influence of radiation exposure within the Chornobyl exclusion zone (Deryabina et al., 2015). To interpret the results obtained in field studies, it is necessary to consider whether confounding factors have been adequately considered, to attribute observed effects to exposure to ionising radiation. Several of the studies performed in Fukushima or Chornobyl affected areas (e.g. Møller and Mousseau, 2007) link biological responses with ambient dose rates. However, these may significantly underestimate the actual dose rates absorbed by organisms, particularly those moving through heterogeneously contaminated areas, and by overlooking the contribution of internal exposure. In addition to the dosimetric aspects, there is a wide variety of confounding factors, including geographic gene diversity, food availability, competition, human evacuation, presence of other pollutants than radionuclides, season and area in which samples have been collected, absence of adequate controls and/or indirect effects of ionising radiation, which can significantly influence the dose-effect relationships in field studies (Beresford et al., 2020; Real and Garnier-Laplace, 2020). Unless field studies are carefully designed to account for all confounding factors—a challenging and resource-intensive task—a direct comparison between the derived DCRL values and the observed negligible impact levels in contaminated areas remains difficult to establish.

## Extrapolation issues and research needs

1. As described in Section 2.1, the primary objective of environmental radiological protection and ecotoxicology is to protect non-human species at the population level. In the literature, many modelling approaches have been proposed to estimate effects of toxic stress at the population level. Depending on the goals of a given impact assessment, these approaches considered various endpoints providing different measures of potential ecological impacts relevant to different sets of conditions.
2. Mathematical population models known as Leslie matrices (Caswell, 2001) can be used to simulate risk at the population level, based on individual-based results from laboratory tests. This methodology, previously developed for chemical contaminants (Forbes and Calow, 2002; Hanson and Stark, 2012), combines available knowledge describing how population growth responds to changes in key biological functions (survival and reproduction), and how toxicity affects these biological functions. For ionising radiation, various dose rates can be calculated where population growth rate is reduced by 10 % and below 1 % (considered as resulting in a local extinction in the long-term). This approach has been used to compare the population growth rates with DCRLFamily (Lance et al., 2012; Alonzo et al., 2016).
3. One other line of investigation concerns the use of ecological models to generate dose effects predictions at the level of the population, based on the interaction of radiation with mathematically defined fecundity and repairing pools, in combination with ecosystem-level interactions such as migration, predation and competition for ecosystem resources. This type of model has been used in a historical contamination situation involving a population of field voles in the Chornobyl Red Forest, to compare predicted dose rates corresponding to various levels of impact or risk on population demography, with the DCRLFamily (Vives i Batlle et al., 2020). An advanced version of this model is being evaluated to assess the effect of radiation and chemical contaminants in a multi-stressor context (Vives i Batlle et al., 2022).
4. There are several other uncertainties that impact the comparison of DCRL to field data. As has been mentioned in section 5.2, the dosimetry in the field adds uncertainty in assessments of dose and dose rates and influence the understanding of the linkage of dose to biological impact. Dose reconstructions for (published) field-based data may have the potential to provide more robust dose-response relationships (Garnier-Laplace et al., 2015) than those achieved in the original studies.
5. Different life stages and the behaviour of animals will influence the doses received and the effects produced by ionising radiation (Stark et al., 2017). ODE modelling approaches that factorise multiple age classes (Vives i Batlle et al., 2010), and even highlight the effects of predator–prey dynamics, have been developed (Wilson et al., 2010). Considering the influence of such factors in the response of animals to ionising radiation will contribute to more realistic radiological impact or risk assessments.
6. Over the last decade, there has been a growing interest in studying multi- and transgenerational effects. Several papers have shown that these effects were linked not only to genetic but also to epigenetic factors (Horemans et al., 2019) and were associated to either an increase or a decrease in biological effects over generations (Sreetharan et al., 2023). The Commission considers that this topic is one of the research needs to support better understanding of radiation risk (Laurier et al., 2021).
7. Characterisation of the indirect effects of ionising radiation in the environment to determining when specific constituents of an ecosystem are disrupted resulting in imbalance, will contribute to better understanding of the consequences of radioactive contamination in the environment. Ecosystem-relevant endpoints include those that describe ecosystem structure and functions, and sometimes also, the services an ecosystem provides to humans and align to the wider protection goals of protecting natural resources (IAEA, 2014c). Quantifying ecosystem effects may, therefore, include measuring species composition, abundance, biodiversity, food web complexity and connectivity, habitat complexity (i.e. aspects of ecosystem structure) and production, decomposition, pollination, functional or trait diversity (i.e. ecosystem function). These various metrics could be used as integrative measures of the vulnerability or resilience of an ecosystem (Bradshaw, 2022).
8. Interaction with other stressors in the environment (natural or anthropogenic) could modify the effect of ionising radiation. Some methodologies have been proposed to try to understand the issue of multiple stressors in a context of radiological protection, by using models of concentration addition and independent action (Beaumelle et al., 2017; Salbu et al., 2019).
9. More studies are also needed to link radiation effects at the molecular (e.g. DNA damage) and cellular (e.g. oxidative stress) levels, with potential effects at higher levels of organisation (individual, population, community or ecosystem). Towards this, the application of Adverse Outcome Pathway (AOP) is a promising tool, which helps to identify gaps of knowledge by organising the scientific data in a systematic way, and to link toxic pathways at the subcellular level to a macroscopic endpoint such as reproduction (Tollefsen et al., 2022). Interestingly, the latest “omics” methodologies also provide suitable tools to highlight the most valuable molecular biomarkers. Indeed, large-scale molecular information can be quickly obtained through RNAseq or proteomics, even when working with organisms for which genome sequences are not currently available. This information can be used to elucidate the molecular modes of actions of contaminants and/or to develop sensitive methods for biomarker quantification (Gouveia et al., 2019). These tools could help determine the global toxicity of pollutants, helping in cross-species extrapolation. They can also provide weight of evidence information for molecular-initiating and key events in the AOP.

# CONCLUDING REMARKS

1. Building on the Reference Animals and Plants (RAP) and DCRL approach outlined in *Publication 108* (ICRP, 2008), this publication broadens the RAP approach by incorporating comprehensive data sets on chronic and acute radiation effects on non-human species. This has enabled the derivation of additional DCRLs at higher taxonomic levels, which complement the DCRLFamily already in use. Both sets of DCRLs, DCRLFamily and DCRL for classes or phyla or broad non-human species groups, are expressed as absorbed dose rates and can be used to assess the impact of ionising radiation on non-human species. The differences in DCRL values (families vs higher taxonomic groups) are of ca. one order of magnitude, meaning that assessors may use any of them for screening impact assessments provided they justify their choice.
2. DCRLs (family) from *Publication 108* (ICRP, 2008) are the benchmarks recommended for environmental impact assessments. The additional DCRLs at higher taxonomic levels introduced in this publication provide an important complement for assessing environmental impact in complex cases. They offer the possibility of more refined assessments along with a transparent evaluation of the level of confidence in the assessment conclusions.
3. For complex assessments (e.g. large facilities, post-accident situations, protected ecosystems and species), assessors should consider the underlying effects data and potential uncertainties when selecting which values to apply. The use of DCRLs at higher taxonomic levels can improve the representativeness of the real ecosystems under assessment, and as such reduce uncertainty. The approach also allows the derivation of site-specific DCRLs by using case-specific effects data or adjusting the level of protection (e.g. selecting a different percentile of the Endpoint Sensitivity Distribution (ESD) to derive the boundary of the DCRL).
4. Irrespective of the DCRLs used, the guidance from *Publication 124* (ICRP, 2014) applies: the lower boundary of the relevant DCRL should be applied in planned exposure situations, while in existing exposure scenarios or post-accident long-term assessments, DCRLs help determine the effort for protection of non-human species through optimisation.
5. For emergencies, as the focus shifts to environmental recovery, broader ecological risks—including potential wildlife impacts and conservation objectives—should be considered. In such cases, the acute ESD models for classes, phyla, or broad species groups can retrospectively inform stakeholder discussions on the ecological consequences of radiation exposure.
6. This publication strengthens environmental radiological protection by broadening the RAP approach and improving the scientific and methodological knowledge for benchmarks that may be used in environmental impact assessments. The integration of the proposed methodology along with the existing RAP family and related DCRLs will be examined further in the forthcoming publication on their application within the radiological protection system (Part 2 in this series of publications).

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1. PUBLICATIONS USED IN SUPPORT OF PUBLICATION 108, IN ITS ANNEX D. RADIATION EFFECTS IN REFERENCE ANIMALS AND PLANTS

Table A.1. Publications used in support of *Publication 108*, in its Annex D. Radiation effects in reference animals and plants. (Unless specified, the irradiation is with low LET (gamma or X-rays) and external.)

| **RAP** | **Mortality** | **Reproductive capacity** | **Morbidity** |
| --- | --- | --- | --- |
| Reference Deer (large mammals) | **Acute**  LD50  Cattle, sheep, goat, pig, donkey, horse, dog (Bond et al., 1965; UNSCEAR, 1996)  Donkey (Rust et al., 1954; Trum et al., 1959)  Pig (Mandel et al., 1980)  Dog (Beagle dog) (Andersen and Rosenblatt, 1969; Benjamin et al., 1998)  **Chronic**  Reindeer (Klevezal and Sokolov, 1999)  European elk (*Alces alces L*.) and Roe deer (*Capreolus pygargus*) (Kryshev, 1997; Sazykina and Kryshev, 2006)  Dogs (Beagle dogs)   * External irradiation (Carnes and Fritz, 1991, 1993; Grigoriev, 1989) * Internal exposure: Pu-238 (Weller et al., 1995; Muggenburg et al., 1996; Park et al., 1997); Sr-90 (Raabe et al., 1981) | **Acute**  Bulls, number of germ cells in the seminiferous tubules (Erickson et al., 1972)  Beagle dogs, germ cell depletion and sterility (BEIR III, 1980)  Cattle, monkey and sheep, in-utero irradiation, externally detectable malformations (Commission on Radiological Protection, 1989)  **Chronic**  Pig embryos, gonadal weight in offspring (Erickson and Martin, 1976)  Pigs (irradiated between days 0 and 108 of gestation), dead piglets or dead foetuses (Erickson and Martin, 1984)  Pigs (irradiated during gestation), number of germ cells (UNSCEAR, 1986) | NO DATA |
| Reference Rat (small mammals) | **Acute**  LD50  Rats (Vriesendorp and van Bekkum, 1984)  Rabbit, hamster, mice (Bond et al., 1965)  Mouse embryos (Gasinska et al., 1985)  Life shortening (acute or fractionated):  Mice (Sasaki, 1991; Oghiso and Yamada, 2003)  Post-natal mortality  Mice embryos (Covelli et al., 1988; Hande et al., 1990)  **Chronic**  Life shortening  Rats(French et al., 1974; Korytny et al., 1996)  Mice (Mole and Thomas, 1961; Spalding et al., 1964; Upton et al., 1967; Thomson and Grahn, 1989; Tanaka et al., 2003)  Survival  Mice (Grahn et al., 1978)  ***Internal exposure***  Rats   * Inhaled Pu-239 and Pm-147; life span and mortality (Scott et al., 1990) * Sr-90, ingested, lifespan (Korytny et al., 1996) | **Acute**  Rats (irradiated on different days of gestation or post-conception), number of germ cells, spermatogonia, testis weight (Erickson and Martin, 1972, 1973; Coffigny and Pasquier, 1976; Pinon-Lataillade et al., 1985; Canfi et al., 1990), size of ovaries, follicles and corpora lutea (Ershoff, 1960)  Rats (irradiated at different gestation stages), fecundity (Ershoff, 1960; Coppenger and Brown, 1967; Brent, 1971; UNSCEAR, 1977, 1986; Freud et al., 1990; Mazaud et al., 2002)  Adult mice, LD50 of late type A, intermediate, early type B spermatogonia, spermatozoa and spermatids, testis weight (Oakberg, 1957; Gasinska, 1985; Gasinska et al., 1987)  Mice (irradiated in different stages of gestation, and ages) number of implantation sites, embryos survival, late post-implantation death, pre-implantation death, and malformed foetuses (Friedberg et al., 1973; Di Majo et al., 1981; Pampfer and Streffer, 1988; Hande et al., 1990; Muller and Streffer, 1990; Rutledge et al., 1992; Jacquet et al., 1995; Friedberg et al., 1998; Muller et al., 1999)  Mice, malformation induction (Rugh and Grupp, 1961; Brent, 1971; UNSCEAR, 1986; Solomon et al., 1994)  **Chronic**  Male rats, number of A1 spermatogonia (Erickson, 1978).  Rats (irradiated during gestation), number of germ cells in males and females (Erickson and Martin, 1976; UNSCEAR, 1986)  Mice, stage 1 oocytes (Oakberg, 1962) and fertility (Stadler and Gowen, 1964)  Mice fecundity and fertility (Rönnbäck, 1965, 1983; Searle et al., 1980; Leonard et al., 1985)  **Internal irradiation.** Tritiated water or food:  Rats, primary oocytes (Pietrzak-Flis and Wasilewska-Gomulka, 1984; UNSCEAR, 1996)  Rats, fecundity, testis weight and sperm content; ovary weight, pre-implantation death, resorptions (Cahill and Yuile, 1970; Laskey et al., 1973; Laskey and Bursian, 1976)  Mouse fertility and fecundity (Rönnbäck, 1965; Ilyenko and Krapivko, 1993)  **Field studies**  Chornobyl: Mice, reproductive organs (Shevchenko et al., 1991)  Rock Valley (Nevada), dessert rats, multiplication rate per generation (French et al., 1974) | **Acute**  Young rat, body weight (Inouye and Kameyama, 1986; Canfi et al., 1990)  Rat embryos, body weight (Norten et al., 1991; Reyners et al., 1992; Solomon et al., 1994; Zaman et al., 1997) growth rates (Jensh and Brent, 1988), brain/bodyweight ratio (Uma Devi et al., 1999)  Rats (in-utero irradiated), embryo weight and length (Coppenger and Brown, 1967)  Rats (irradiated during organogenesis), learning capacity (Bornhausen et al., 1982)  **Chronic**  Adult mice, body weight (Caratero et al., 1998).  Adult rats, growth rate and body weight (Pinon-Lataillade et al., 1985)  **Tritium**  Pregnant mice, food labyrinth, learning and memory, and loco motor tests (very high uncertainty) (Wang and Zhou, 1995) |
| Reference Duck (birds) | **Acute**  LD50  3-4 day-old chicks (Stearner and Christian, 1972)  Domestic poultry (Bell et al.,1971)  Eggs of black-headed gull and domestic chicken (Phillips and Coggle, 1988)  Wild birds (Mellinger and Schultz, 1975) | **Acute**  Tree swallows (7-8 days of development) hatching, fledging success and growth (Zach and Mayoh, 1986a)  Young wild birds (tree swallow, eastern bluebird, and house wren), mortality during the nesting period (Zach and Mayoh, 1986b)  **Chronic**  Several bird species (American robin, brown headed cowbird, red-eyed vireo, hermit thrush, ovenbird, common flicker), hatching success (Buech, 1976).  Chicken embryos (Barred Rock), male and female sterility (Mraz and Woody, 1972)  Tree swallows, breeding success (clutch size, hatching success, fledging number, incubation time, and nestling time) (Zach and Mayoh, 1982)  **Field study** **Kyshtym (Sr-90):** baby starlings (*Sturnus vulgaris*) weight of chicks, reproduction of flycatchers in man-made nests (Sazykina and Kryshev, 2006) | **Acute**  Tree swallows, growth, development time (Zach and Mayoh, 1984)  Wild birds (tree swallow, eastern bluebird, and house wren), growth, primary feather length and foot length (Zach and Mayoh, 1986a)  Domestic 2-day-old fowl, growth rate (Brisbin, 1969)  **Chornobyl**  Ducks *(Anser anser L., Anas boschas L.)*, pathological changes in liver, kidney, lungs, or spleen (Suvorova et al., 1993) |
| Reference Frog (amphibians) | **Acute**  LD50  Frog at different life stages (*Limnodynastes tasmaniensis*) (Panter, 1986)  Toad (adults, juveniles and tadpoles) (Landreth et al., 1974)  Dusky salamander, mudpuppy, ‘congo eels’, rough skinned newts (Sparrow et al., 1970)  Frogs and salamanders (Cosgrove, 1965; Turner  et al., 1967; Conger and Clinton, 1973)  **Chronic**  Frog tadpoles (*Scaphiopus holbrooki*, *Bufo terrestris*, and *Rana catesbeiana*), survival to metamosphosis (Stark, 2006) | **Acute**  Paternal exposure of toads, survival of offspring, abnormalities in live offspring (Blair, 1960)  **Chronic**  Frog tadpoles (*S. holbrooki*, *B. terrestris*, and *R. catesbeiana*), hatching success of eggs (Stark, 2006)  **Chornobyl:**  Male brown frogs (*Rana arvalis*), fertility (Cherdantsev et al., 1993)  **Kyshtym accident (Sr-90)**  Brown frogs (*R. arvalis*), reproductive success and morphological abnormalities (Pyastolova et al., 1996) | **Chronic**  Frog tadpoles (*S. holbrooki, B. terrestris*, and *R. catesbeiana*), body mass, body length, or body index (g/mm) at metamorphosis, age at metamorphosis (Stark, 2006) |
| Reference Trout (freshwater fish) | **Acute**  LD50 or mortality  Silver salmon embryos (Bonham and Welander,1963)  Chinook salmon embryos (Welander et al., 1948; Wadley and Welander, 1971)  Rainbow trout embryos *(Salmo gairdnerii)* (Welander et al., 1971)  Rainbow trout fry (*Salmo irrideus*) (Kobayashi and Hirata, 1957)  **Chronic**  *Survival*   * Chinook and Coho embryos (*Oncorhynchus tshawytscha* and *Oncorhynchus kisutch)* (Donaldson and Bonham, 1964) * Silver salmon 5 days post-fertilization (*O. kisutch*) (Bonham and Welander, 1963) * Guppy embryos (*Poecilia reticulata*) (Woodhead, 1977) * Mosquito fish (*Gambusia affinis*) (Cosgrove and Blaylock, 1973)   *Influence of temperature in the radiation-induced mortality:* Medaka fish (*Oryzias latipes*) (Egami, 1970); Goldfish (*Carassius auratus*) (Hyodo, 1965a,b)  Beta irradiation: roach, survival (Fedorova, 1964)  *Internal irradiation:* Sr-90, salmon mortality (*Salmo salar*) (Fedorova et al.,1962) | **Acute**  Rainbow trout eyed embryos (*S. gairdnerii*), fecundity and growth (Welander et al., 1971).  Irradiation of both parents of rainbow trout (*S. irrideus*), cumulative mortality of eggs and fry (Foster et al., 1949)  Silver salmon (*O. kisutch*) (5 days post fertilisation), hatching success (Bonham and Welander, 1963)  Rainbow trout (late in embryonic development), sterility (Konno, 1980).  4-month-old rainbow trout fry, incidence of necrotic cells in the developing testes, ovary weight (Niiyama, 1957; Kobayashi and Mogami, 1958)  Rainbow trout sperm (*S. gairdnerii*), fertilisation rate of eggs, embryos survival, abnormal embryos (McGregor and Newcombe, 1972a,b; Newcombe and McGregor, 1972, 1973)  Male and female medaka (*O. latipes*), number of deformed and dead embryos, oocyte maturation, male fertility, eggs hatchability (Egami, 1955; Konno and Egami, 1966; Egami et al., 1967, 1983; Egami and Hyodo-Taguchi, 1969; Michibata, 1976)  Female medaka, oocyte maturation (ovarian growth) (Egami, 1955; Egami and Hyodo-Taguchi, 1965)  Medaka embryos (3 days post fertilisation), gonads development (Shimada and Egami, 1982)  3-day-old medaka fry, cell death and ovarian regeneration (Hamaguchi, 1976)  Medaka ovary or whole-body irradiation, egg-laying activity (Egami and Hyodo-Taguchi, 1965)  Female medaka (mated with unirradiated males), hatching success (i.e. increased induction of dominant lethal mutations); Irradiated males mated with unirradiated females showed a greater reduction in hatching success (Egami et al., 1983; Shima and Shimada, 1991)  Medaka (irradiated during embryonic and early postnatal development), gonadosomatic indices in males or females (Egami and Hama-Furukawa, 1981)  **Chronic**  Chinook and Coho salmon embryos (*O. tsawytscha* and *O. kisutch*), reduced relative fecundity, ratio of eggs weight to body weight in the 1st generation) (Hershberger et al., 1978; Woodhead, 1984)  Chinook salmon, retardation of gonadal differentiation (Bonham and Donaldson, 1972).  Salmon, number of primary sex cells in embryos (Kasatkina et al., 1973)  Artificially incubated rainbow trout roe (*S. irideus Gibbans*), early death of fore larvae (no dose–response relationship) (Lyapin et al., 1971)  **Tritium or gamma rays**  Medaka embryos, fertility and fecundity (Etoh and Hyodo-Taguchi, 1983; Hyodo- Taguchi and Etoh, 1985, 1986)  Medaka embryos, hatching rate, larval survival, incidence of vertebral anomalies (Hyodo-Taguchi and Etoh, 1993).  **Internal exposure**  Sr-90/Y-90. Brown trout eggs (*Salmo trutta*), hatch rate, fry size, abnormal embryos (Brown and Templeton, 1964; Templeton, 1970)  Ce-144. Salmon, hatching (Kasatkina et al., 1973)  Tritiated water. Adult medaka males, nº of spermatogonia (Hyodo-Taguchi and Egami, 1977; Hyodo-Taguchi et al., 1982) | **Acute**  Rainbow trout fry (*S. irideus*), feeding activity (Kobayashi and Hirata, 1957)  Medaka embryos (*O. latipes*), effects on developing brain (apoptotic cells, histological abnormalities) (Yasuda et al., 2006)  Paternal irradiation of guppy (*P. reticulata*), spinal deformities in F1 and F2 generations (Schroder, 1969)  **Chronic**  Chinook and Coho salmon embryos (*O. tshawytscha* and *O. kisutch*), growth, number of vertebrae and truncated operculae (Donaldson and Bonham, 1964)  Rainbow trout embryos (*Oncorhynchus mykiss*), immune response (Knowles, 1992)  in Coho salmon parr, growth and opercular defects (Donaldson and Bonham, 1964)  **Tritium:** Rainbow trout (*Oncorhynchus mykiss*), immune response (Strand et al., 1973, 1977, 1982)  **Tritiated water:** Guppy developing embryos (P*. reticulata*), body weight (Erickson, 1973)  **Beta radiation:** Carp, concentration of lipoperoxides in liver and muscle (Storozhuk and Shekhanova, 1977), overall response to infection (Shleifer and Shekhanova, 1980).  **Mixed radiation:** Pike, growth (Pitkyanen, 1978) |
| Reference Flatfish (marine fish) | **Acute**  LD50  Plaice (*Pleuronectes platessa*) (Ward et al., 1970)  Juvenile and pot-larval marine fish (6 species: *Micropogon undulatus, Fundulus heteroclitus, Mugil cephalus, Paralichthys lethostigma, Lagodon rhomboides, and Eucinostomus spp.*) (White and Angelovic, 1966)  Flatfish (*P. lethostigma*) (White and Angelovic, 1966)  Sharks (*Triakis scyllia and Heterodontus japonicus)* (Egami et al., 1984) | Male plaice (*P. platessa*), gonadosomatic index, testes weight (Brown and Templeton, 1964; Templeton, 1970) | Radiation + temperature and salinity (a 33 factorial experimental design) pinfish (*L. rhomboides*) irradiated at the post-larval/juvenile stage, eight body dimensions and weight (Engel et al., 1966; White and Angelovic, 1966, 1968) |
| Reference Bee (insects) | **Acute**  Abstracts in IDIDAS (International Database on Insect Disinfestation and Sterilization):  Survival after irradiation in metamorphic stages: black carpet beetles (*Trogoderma glabrum* and *Attagenus piceus*), lesser grain borers (*Rhyzopertha dominica F*.), confused flour beetles (*Tribolium confusum Jacquelin duVal*), rice weevils (*Sitophilus oryzae L*.), Cigarette beetles *(Lasioderma serricorne F.*), beetle (*Dermestes maculatus*) (Tilton et al., 1966a,b). | **Acute**  IDIDAS: reproductive sterilisation of arthropods (more than 2750 references. In total, 309 species, from 196 genera, 84 families, nine insect orders, and two arachnid orders have been studied (http://www-ididas.iaea.org/idi das/)  Drone honeybee pupae and 4-day-old queens (*Apis mellifera adansonii hybrids*), viability of the F1 worker progeny (no dose–effect relationship)  Drone honeybee pupae (*Apis mellifera adansonii hybrids*) crossed with non-irradiated queens, viability of the F1 worker progeny (no dose–effect relationship); 4-day-old queens, progeny viability; in both experiments, few F2 abnormal drones (Sakamoto and Takahashi, 1981)  Wasps (*Dahlbominus fuscipennis*), the population failed to reach the third generation (Riordan, 1964)  Wasps, number of disintegrating oocytes in females and offspring numbers (Baldwin, 1968)  Bark beetle population studies, egg hatch, larval mortality, pupae mortality (Smith, 1970) | NO DATA |
| Reference Crab (large marine crustaceans) | **Acute**  LD50  Blue crabs (*Callinectes sapidus*) (Engel, 1967, 1973).  Post-juvenile grass shrimp (*Palaemonetes pugio*) (Ress, 1962)  Survival of fiddler crabs (Engel, 1973) | No data are available on crabs or any large crustaceans.  **Acute**  Amphipods (*Gammarus duebeni*), fertility and fecundity (Hoppenheit, 1972)  Calanoid copepods (*Diaptomus clavipes*), eggs hatching (Bardill et al., 1977) | **Chronic?** (768, 1752, 6960mGy/day; no info on duration of exposure) Juvenile blue crabs (*C. sapidus*), moulting frequency and growth rate (Engel, 1967; Engel et al., 1971) |
| Reference Earthworm (annelids) | **Acute**  LD50: Earthworms (*Lumbricus terrestres* and *Eisenia foetida)* (Reichle et al., 1972; Heffner et al., 1973)  **Filed data:** population density of earthworms in a birch forest plot (Krivolutsky, 1987) | **Acute**  *E. foetida*, hatchability of cocoons and eggs, number of testicular cells (Suzuki and Egami, 1983), number of cocoons/tank (Hingston et al., 2004).  **Chronic**  *E. fetida* irradiated 2 generations (F0 and F1), reproductive capacity of adult F0, sexual maturation of F1 hatchlings, atrophic male reproductive organs in F0, hatchability of cocoons in F1, total number of F2 individuals produced per adult F1 (Hertel-Aas et al., 2007)  **Field study** (Sr-90, Cs-137, Zr-95/Nb-95, Ru-106, Pu-239, and Ra-226)**:** populations soil invertebrates, reduced numbers of individuals (No reference is given). | **Acute**  Young earthworms (*E. foetida*), growth and development of clitellum (Suzuki and Egami, 1983), number of segments (Moment, 1972)  Earthworms, proliferation of epidermal cells (Suzuki and Egami, 1983)  **Chronic**  Earthworms (Chronic?: 204 mGy/day, no info on how many days), growth (Hingston et al., 2004)  Earthworms (*E. foetida*), 1-generations study, growth and exterior abnormalities (asymmetrical and segmented clitellum) (Hertel-Aas et al., 2007) |
| Reference Pine Tree (conifers) | **Acute**  Pine tree, mortality (Sparrow et al., 1965; Woodwell, 1967)  Pine-birch forest mortality (Tikhomirov and Fedotov,1982)  Seasonal effects pine trees LD50 (Karaban et al., 1980; Spirin et al., 1981)  Ash trees seeds (*Fraxinus Americana*), mortality (Heaslip,1973)  **Chronic**  Chornobyl: pine trees death (*Pinus sylvestris L.)* (Pautov and Il’chukov, 1993; UNSCEAR, 1996); coniferous forest: changes in species composition and diversity (mortality of more radiosensitive species) (UNSCEAR, 1996) | **Acute**  Pine trees, fertility and viability of pollen produced (Tikhomirov et al., 1978)  Pine-birch Forest, mass of pine pollen (Tikhomirov and Fedotov, 1982)  Ash seedlings, mortality and growth (Heaslip, 1973)  White spruce tree (*Picea glauca*), seed yield and quality of pollen (Rudolph, 1971)  **Chronic**  *P. rigida*, number of seeds in cones (Sparrow et al., 1965)  Pine trees, vegetative growth and production of male cones (Tikhomirov et al., 1978)  **Chornobyl** (Cs-137, Sr-90, and hot particles)  Coniferous trees, disturbances in reproduction (UNSCEAR, 1996)  Pine forest (50–60-year-old *P. sylvestris L.*), pollen viability (Kozubov and Taskaev, 1994b)  *P. sylvestris L.*, necrosis of the seed buds (No reference given)  Pine forest, reproductive ability (UNSCEAR,1996)  Scotch pines (*P. sylvestris L.*), branching pollen tube, pollen viability (Surso, 1993)  *P. sylvestris L.,* number of male flowers, number of seeds in cones, and seed germination (Kalchenko and Fedotov, 2001)  Pine forest (*P. sylvestris L.)*, number of seeds per cone, germination of seeds (Kozubov and Taskaev, 1994a) | **Acute**  Pine trees photosynthetic activity,  loss of needles and growth points (apical and lateral meristems) (Karaban et al., 1980; Spirin et al., 1981)  Pine trees, needle length (Sparrow et al., 1963); cell proliferation in the apical meristem, and needle formation (Karaban et al., 1980; Spirin et al., 1981).  *Pinus taeda* and *Pinus elliottii*, net rate of photosynthesis (Hadley and Woodwell, 1966)  **Chronic**  Mature *Pinus rigida*, needle growth, trunk growth (Woodwell and Miller, 1963; Sparrow et al., 1965).  1-year-old *P. sylvestris*, needle and stem growth (Sparrow et al., 1965)  2-year-old *Pinus banksiana* stem growth (Amiro, 1986)  Pines, photosynthetic capacity, growth and maturation (Bostrack and Sparrow, 1979)  **Chornobyl**  Pine trees *(P. sylvestris L.)*, susceptibility to xyloph agous insects attacks (Spirin et al., 1985a,b; Kozubov and Taskaev, 1994a)  Spruce trees, malformed needles, buds, and shoots (Kozubov et al., 1990)  *P. silvestris*, growth and morphological damage (Kozubov and Taskaev, 1994a)  Coniferous trees, growth and morphology (UNSCEAR, 1996)  *P. sylvestris,* multi-buds (Kozubov and Taskaev, 1994b)  Pine forest (35-year-old trees) death of shoots, generative organs, and dormant buds; anatomical and morphological changes in the needle structure; density of resin duct; growth of auxiblastes and needles (Abaturov et al., 1991)  *P. sylvestris L.,* growth, cactus-shaped and pineapple-shaped shoots, needles (Sidorov, 1994)  *P. sylvestris L*., growth of annual shoots and morphological changes in vegetative organs (Kalchenko and Fedotov, 2001)  Coniferous trees, death of growth points, partial dieback of and morphological changes (UNSCEAR, 1996).  Pine trees, shooting increment, growth, morphological alterations in needles (Sidorov, 1994)  *P. sylvestris L.*, mortality of central shoots and needles, number of chloroplasts, mass of needles per shoot, length of needles (Ladanova, 1994)  Scotch pines (*P. sylvestris L.*), length of shoots (Abaturov et al., 1996)  **Urals accident (90Sr contamination)**  Pines, growth and desiccation of needles in the lower part of the crown (UNSCEAR, 1996) |
| Reference Wild Grass (grasses) | **Acute**  LD50 Wheat, barley, oats (Sparrow and Sparrow, 1965) | **Acute**  Grasses (rice), YD50 (50% reduction in yield) (Filipas et al., 1992)  Pasture and forage crops, YD50 (Sparrow et al., 1971)  Grassland populations, changes in productivity and reproduction (UNSCEAR, 1996)  Barley seeds, structural aberrations in the root meristem (Geras’kin et al., 1996, 1999)  **Chronic?**  Threshold for diversity changes in old communities of grass in Colorado, USA (Woodwell and Oosting, 1965; Fraley and Whicker, 1973)  Winter rye-weed community, reproductive capacity and production of fertile rye seed (Holt and Bottino, 1972) | **Chornobyl**  Seeds of timothy-grass (*Plantago lanceolata L.*), growth (Frolova et al., 1991) |
| Reference Brown Seaweed (macro-algae) | NO DATA | **Acute**  Brown algae (*F. vesiculosus)*, germinations (Reynolds et al., 2007) | **Chronic**  *Fucus vesiculosus*, growth of germlings (Reynolds et al., 2007) |

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1. LOGIC DIAGRAM TO RECONSTRUCT DOSE (RATE) – EFFECT RELATIONSHIPS FOR EXPERIMENTS DESCRIBED IN FREDERICA

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Description générée automatiquement

Fig.B.1. Example of criteria applied on each quality-assessed data set from FREDERICA to reconstruct dose rate–effect relationships when data exhibited a logistic pattern (one of the models used). The fitted model was used to estimate the EDR10 value; the y-axis represents a measure of response relative to the control treatment (where the control is shown as the data point marked on the y-axis). Figure adapted from Garnier-Laplace et al., 2010. A multi-criteria weight of evidence approach for deriving ecological benchmarks for radioactive substances. J. Radiol. Prot. 30, 215–233.

1. THE TWO STATISTICAL MODELS USED IN THE NEW METHODOLOGY TO DERIVE ADDITIONAL DCRLS
   1. Species and Endpoints Sensitivity Distributions
      * 1. The Species Sensitivity Distribution (SSD) is used to estimate the concentration of a chemical stressor that is hazardous to no more than a given proportion of the species comprising an ecosystem or a wildlife group. This method is widely used for chemicals, with the aim of deriving a Predicted No-Effect Concentration for ecosystems (EC, 2003) or Environmental Quality Standards (EC, 2011). A critical discussion of the SSD methodology is not repeated in this document, as it is well described elsewhere (e.g. Posthuma et al., 2002; Fox et al., 2021).
        2. The main caveat of the SSD lies in the major assumption adopted, namely that the effects data set is representative of the variation of sensitivity over the biodiversity within a given taxonomic group or ecosystem and over the many biological endpoints that would potentially give rise to ecological damage (e.g. Posthuma et al., 2019). This problem (of data representativeness) arises for all benchmarks derived from ecotoxicological studies because it is extremely unlikely to encounter a situation where data exists for all species. Other approaches, such as those based on (subjective) expert judgement may not always align explicitly with empirical data. Despite these caveats, derived benchmarks are valuable for environmental protection decisions, but decision-makers should nonetheless interpret them cautiously. The SSD method has previously been used within the ERICA and PROTECT EC-funded projects for cases of chronic external gamma exposure in order to estimate the dose rate corresponding to the 5th percentile of the SSD below which 95 % of species in an ecosystem and/or a wildlife group should be unharmed (Garnier-Laplace et al., 2010; IAEA, 2014).
        3. In this publication, the Endpoint Sensitivity Distribution (ESD), a method inspired from SSD, is applied to a set of critical radiotoxicity values, i.e. ED50 or EDR10 (respectively, for acute or chronic exposure) for ecologically relevant endpoints, such as reproduction, morbidity or mortality, for all species of the same taxonomic class or phylum, or broad group. Endpoint Sensitivity Distributions are used to derive DCRLs in a systematic manner for taxonomic groups such as family, class, phylum or broad non-human species groups (see Figure.3.1 and Table 3.1 in the main text for description of all non-human species groups). Although a DCRL can theoretically be derived for any taxonomic group using the ESD statistical extrapolation method, DRCLFamily was determined by a critical literature review and expert judgement as described in *Publication 108* (ICRP, 2008) as no family-level data set exists that meets the recommended minimum number of 10 data points required to implement a statistical extrapolation model (EC, 2003).
        4. Reproduction, morbidity, and mortality are considered to be ecologically relevant endpoints because variation in these characteristics can potentially lead to cascading impact on populations, communities, and ecosystems. Reproduction (e.g. fertility, fecundity) influences the size of a population, so if impacted by an environmental stressor, can clearly have ecological consequences. A significant mortality event would also influence population size, although in non-emergency situations the typical mortality endpoint of interest is the potential for lifespan shortening, which could reduce the reproductive capacity within a population. For morbidity (i.e., rate of disease or reduced fitness), effects potentially leading to population-level or higher impact would likely include slower development (and therefore reduced reproductive opportunities) or impacts on characteristics that may affect the ability to mate (e.g. asymmetry or reduced colouration/morphological features that are used to attract a mate).
   2. Inferring chronic effects from data for acute exposures
      * 1. Acute-to-Chronic Transformation of Radiation Effects model (ACTR) is a statistical extrapolation model that aims at empirically transforming observed data of acute radiotoxicity (ED50) into predicted data of chronic radiotoxicity (EDR10) for any given combination of species and endpoint. The ACTR model described herein is based on a method published by Duboudin et al. (2004) in which the authors conceived and applied Acute-to-Chronic Transformation of effects data (ACT) for chemical substances. .
        2. The ACTR model consists of a four-step process described in detail in Beaugelin-Seiller et al. (2020), and summarised as follows:
2. EDR10 and ED50 data are first log-transformed, and the mean and standard deviation of the distributions of the two sets of transformed data are determined by taxonomic class or phylum.
3. Different linear models are tested to predict average chronic distribution parameters from the acute distribution parameters, for all of the taxa. The best linear models, one model for the mean and one for the standard deviation, are selected, using a process combining a bootstrap with a cross-validation method.
4. The best models are fitted to the corresponding observed chronic data (EDR10) for each class or phylum.
5. The fitted models are applied for final generation of the predicted EDR10 from the ED50 observed for a given class or phylum.
   * + 1. For each class or phylum where the number of data points are sufficient to allow its application, the ACTR method significantly expands the available data for chronic radiation effects by predicting chronic radiotoxicity values (EDR10) for species where only acute exposure data (ED50) exist. Specifically, when 220 chronic exposure data are observed for 30 species, the ACTR model can add 320 predicted EDR10 values (from acute ED50 values) for 44 additional species. This thereby enhances the breadth of species and effect information that can be used for radiological impact assessments. As such, combining both observed and predicted EDR10 values has generated sufficiently large data sets to allow the building of ESD for the class or phylum level under consideration.
       2. The implementation of the ACTR model using data from the FREDERICA database was possible for several classes or phyla of organisms, with good overall predictive power (Beaugelin-Seiller et al., 2020). The 5th percentile of the predicted distribution is within the 95 % confidence interval of the observed 5th percentile for all taxa except two. For those two,‘Birds’ and ‘Grasses and Monocots’, the predicted 5th percentile is lower but of the same order of magnitude, suggesting that the ACTR model may be conservative in these cases. For Fish, the prediction is close to (but about 4 times higher than) the upper boundary of the confidence interval of the observed 5th percentile one. More details, including the evaluation of the ACTR model’s performance and uncertainty analysis, are available in Beaugelin-Seiller et al. (2020).
       3. Finally, a systematic review of the full effects data extracted from FREDERICA and quality-assessed (see Annex B) was implemented as follows:
6. Building of dose (rate)-response relationships for acute and chronic external gamma irradiation regimes and estimation of the critical effect values (ED50 and EDR10) by species and endpoint, along with estimation of the standard error.
7. Allocation of the tested species into a given class or phylum, highlighting the correspondence of the class with one or several of the 12 existing RAPs at the family level.
8. Application of the ESD model to two consistent sets of data (i.e. acute observed ED50 and chronic EDR10 observed and predicted using the ACTR model) by class, by phylum and by broad non-human species groups (i.e. invertebrates, vertebrates, and plants.
   * + 1. In summary, acute and chronic ESDs have been fitted to radiation effects data categorised by class (or higher taxonomical levels): observed ED50 data sets are used for acute exposure and a combination of observed and “ATCR-predicted” EDR10 for chronic exposure. For both, the ESD was species-weighted so that any species was equally represented regardless of its number of endpoint data.
   1. References

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1. POTENTIAL APPLICATION OF THE BROADENED RAP APPROACH
   * + 1. The alternative approach and set of additional DCRLs proposed are benchmarks that may be used in various types of impact or risk assessment. *Publication 124* (ICRP, 2014) recommends adopting the lower boundary of the relevant DCRL as the reference level for planned exposed situations. In other situations where chronic exposure is relevant, i.e. existing exposure situations and medium to long-term exposure (months, years) after an emergency, the DCRLs correspond to the exposure range to target when applying optimisation of environmental radiological protection as a guide to scale the level of protective effort required. Figure D.1 gives an indication of the level of confidence related to the selection of one or another DCRL boundaries as benchmark in radiological environmental impact assessments. Further advice and guidance on the use of the DCRLs for environmental radiological protection are under preparation.
       2. In the acute stages of an emergency, the safety of humans and socio-economic considerations linked to for example widespread contamination are likely to be the initial priority. However, focus will turn to wide environmental considerations including potential risks of exposure to populations of non-human species (wildlife) and conservation objectives for example as well as the risks and impacts from any protective or remedial actions. Here the acute ESD per class, phylum or broad group could be useful retrospectively to support dialogue with stakeholders about ecological impacts that may have occurred.
       3. Figures D.2 and D.3 are examples with simple guidance on how to read and use a chronic or an acute ESD.
       4. The integration of the proposed methodology along with the existing RAP family and related DCRLs will be examined further in Part 2 in this series of publications on ‘Considering the environment when applying the system of radiological protection’ subtitled ‘Practical use of benchmarks and integration within the system’.

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Fig.D.1. Lower boundary of the DCRLs (and Extrapolation Factor - EF) per taxonomic group and related level of confidence associated to their selection as benchmark in environmental impact assessments as explained in the legend. The color refers to the taxonomic level: orange for family, blue for higher levels (class, phylum, broad group). Taxonomic groups represented in the figure are far from exhaustive.

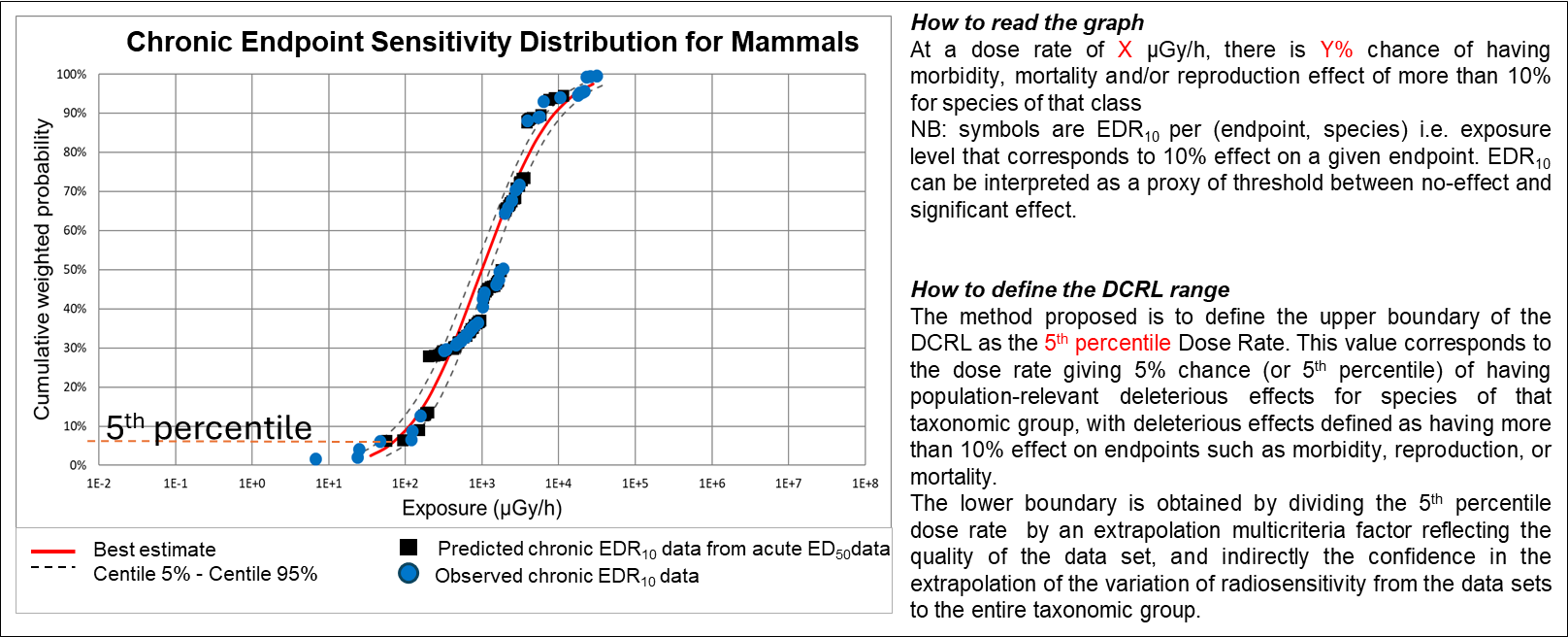


Fig.D.2. Simple guidance on how to read and use a chronic ESD illustrated for mammals.

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Fig. D. 3. Example of how to use an acute ESD to support the interpretation of dose estimates or measurements in the early phase of an emergency. Fish was selected for illustration.

ABBREVIATIONS

ACTR Acute-To-Chronic Transformation of Radiation Effects model

AOP Adverse Outcome Pathway

DC Dose Coefficients

DCRL Derived Consideration Reference Level

DCRLFamily Derived Consideration Reference Level at the level of family

DCRLClass or Phylum Derived Consideration Reference Level at the level of class or phylum

EDR10 The dose rate giving a 10 % change in observed effect in comparison with a control

ED50 The dose giving 50 % change in observed effect in comparison with a control

EF Extrapolation Factor

EMRAS IAEA environmental modelling for radiation safety programme

ERICA Environmental Risk from Ionising Contaminants: Assessment and management

ERP Environmental Radiological Protection

ESD Endpoint Sensitivity Distribution

FREDERICA The FREDERICA Wildlife Radiation Effects Database

Gy Gray

IAEA International Atomic Energy Agency

ICRP International Commission on Radiological Protection

PROTECT PROTECTion of the environment from ionising radiation in a regulatory context

RAP Reference Animal and Plant

RAPFamily Reference Animal and Plant at the level of family

RAPClass or Phylum Reference Animal and Plant at the level of class or phylum

RBE Relative Biological Effectiveness

RNAseq RiboNucleic Acid sequencing

SDGs Sustainable Development Goals

SSD Species Sensitivity Distribution

GLOSSARY

Only terms not yet included in the ICRP Glossary are included here. The ICRP Glossary can be viewed at: http://icrpaedia.org/ICRP\_Glossary.

Benchmark

A point of reference against which things may be compared.

DCRLFamily

Derived consideration reference level determined by use of expert judgement and relating to RAPFamily. The expert judgement was based on careful analysis of a critical literature review, available data and uncertainties. The set of DCRLFamily is published in Publication 108 (ICRP, 2008).

DCRLClass or Phylum, DCRL for broad non-human species groups

Derived consideration reference level determined by fitting the Endpoint Sensitivity Distribution (ESD) model to radiation effects data relating to RAPClass or Phylum. DCRL for broad non-human species groups relates to ESD established for vertebrates, invertebrates and plants.

Environmental impact of ionising radiation

Effects of exposure to ionising radiation resulting from human activities on living organisms.

Meta-analysis

Technique that statistically combines the results of quantitative studies.

Morbidity

Reduction of fitness of individuals making it more difficult for them to survive.

Mortality

Reduction of survival of individuals.

Non-human species

All species excluding humans.

Reduced reproductive success

Reduction of fertility or fecundity of individuals.

ACKNOWLEDGEMENTS

The Task Group 99, titled ‘Reference Animals and Plants Monographs,’ was established by the ICRP Main Commission on 17 April 2015 under the former Committee 5. In 2017, it expanded into a joint effort with Committees 1 and 4 to advance radiological protection for the environment. Task Group 99’s original terms of reference were to update the ICRP Reference Animals and Plants (RAPs) data and methodologies to improve their practical application in radiological protection across planned, emergency, and existing exposure scenarios. This included the update on dosimetry, radionuclide transfers, and effects data, aiming to organise these elements coherently for effective Radiological Environmental Impact Assessments. Since TG99’s inception, ICRP has released two publications on RAPs dose assessments (*Publications 136* and *148*), and the IAEA has initiated a revision of the Safety Report Series No. 19 (SRS-19) to provide comprehensive data for wildlife dose assessments in planned exposure situations. The latter includes detailed radionuclide transfer and dosimetry methods, backed by extensive modelling approaches and databases.

Recognising the need to avoid overlap and integrate outcomes from these and other initiatives, Task Group 99 proposed revised terms of reference, which the Main Commission approved in January 2022. The updated focus was on enhancing the representativeness of the RAPs and refining the data and methods for defining Derived Consideration Reference Levels for animals and plants across the three exposure situations. Task Group 99 worked closely with Task Group 105, which is testing the practicality and benefits/impacts of the broadened RAP approach through case studies, as well as with other Task Groups dealing with environmental radiological protection, such as Task Group 125, to ensure coordinated and harmonised further development of radiological protection recommendations for the protection of the environment

ICRP thanks all those involved in the development of this publication for their hard work and dedication over many years. This publication is dedicated to the memory of N.A. Beresford, who passed away in May 2023. N.A Beresford's invaluable contributions to Task Group 99 were instrumental in advancing our work until his last days. His dedication, expertise, and tireless efforts have left a lasting impact on the field, and his legacy continues to inspire our work.

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\*Although formally not a Main Commission member since 1988, the Scientific Secretary is an integral part of the Main Commission.

Finally, thank you very much to all organisations and individuals who took the time to provide comments on the draft of this publication during the consultation process.

1. Note that the acronym ‘ERP’ may take different meanings in different contexts, but is used throughout this publication to mean environmental radiological protection [↑](#footnote-ref-2)
2. In the literature, ‘non-human species’ are referred to using different terminology including: ‘biota’, ‘non-human biota’, ‘organisms’, ‘non-human organisms’, ‘flora and fauna’ and ‘wildlife’. Here, the term ‘non-human species’ is used to differentiate humans from other species and because the term ‘biota’ typically refers to ‘collective animal and plant life of a particular geographical region’ (OED). [↑](#footnote-ref-3)
3. Three exposure situations are defined in the ICRP Glossary (ICRP Glossary - ICRPaedia): ‘planned exposure situations’, ‘emergency exposure situations’ and ‘existing exposure situations’. [↑](#footnote-ref-4)
4. This adjective refers to taxonomy which is the science of classifying living organisms based on their similarities and evolutionary relationships. Originally published by Carl Linnaeus in 1758 as *Systema Naturӕ*, it arranges organisms into a hierarchical structure, from broad categories like kingdoms down to specific species names, with phylum, class, order, family, genus as intermediate groups. While scientific consensus of taxonomy specifics may not always be reached, the organisational approach facilitates communication and common understanding across scientific disciplines. [↑](#footnote-ref-5)