Radiological Protection of the Environment

Nicholas A. Beresford (UK Centre for Ecology & Hydrology, Lancaster Environment Centre, LA1 4AP, United Kingdom)

David Copplestone (University of Stirling, FK9 4LA, United Kingdom)

The need for radiological environmental protection?

The system for ensuring the protection of humans from ionising radiation is internationally well established (ICRP, 2007), having begun development early in the twentieth century. However, there was an assumption that the control (or regulation) required to protect humans would ensure that other species were not put at risk. The 1990 Recommendations of the ICRP (International Commission on Radiological Protection) stated: '*The Commission believes that the standard of environmental control needed to protect man to the degree currently thought desirable will ensure that other species are not put at risk. Occasionally, individual members of non-human species might be harmed, but not to the extent of endangering whole species or creating imbalance between species. At the present time, the Commission concerns itself with mankind's environment only with regard to the transfer of radionuclides through the environment, since this directly affects the radiological protection of man.*' (ICRP, 1991). This assumption was generally accepted and adopted by those national authorities responsible for radiation protection and the impact of authorised releases of radioactivity on the environment (or wildlife) was not routinely assessed. Consequently, there were no commonly used models for conducting radiological environmental impact assessments.

From about 1990, the statement of the ICRP with regard to protection of the environment was increasingly questioned. Criticisms included: a lack of supporting data for the statement, potential scenarios where wildlife may be more exposed than humans and the need to demonstrate protection of the environment from any human activity. At about the same time some countries began to establish requirements and guidelines for the protection of wildlife (often termed 'non-human species'). To support these requirements, approaches and models were developed to assess the potential impact of authorised releases of radionuclides on the environment

Subsequently, the ICRP amended its recommendations to include the consideration of radiological protection of the environment with the objective '*to maintain biological diversity, conservation of species, protection of the health and status of natural habitats, communities and ecosystems, with targets related to populations or higher organisational levels rather than individual organisms*' (ICRP, 2007). The revised ICRP recommendations acknowledged the need for the development of a framework to assess non-human species, which the ICRP has subsequently begun. The International Atomic Energy Agency (IAEA) has a role in transforming the ICRP's recommendations into practical guidance for application in regulatory frameworks and the latest IAEA Safety Fundamentals acknowledges the need to consider the environment within radiological assessment: '*People and the environment, present and in the future, must be protected against radiation risks*' (IAEA, 2006). In response to changes in international recommendations, radiological environmental impact assessments are being conducted in many countries for a wide range of facility types (e.g., see Brown *et al.* (2016)).

Environmental radiological assessment approaches

A number of assessment approaches have been developed over the last 20 years. In common with approaches considering other non-radioactive environmental stressors, the more comprehensive methodologies use a tiered assessment approach beginning with a simplistic screening tier that requires comparatively little input and is highly conservative. An aim of this initial tier is to identify sites of negligible concern and remove them from the need for more refined higher tier assessments that require increasingly more data and resources. Software implementing two of these tiered assessment approaches has been made freely available: the ERICA Tool (http://www.erica-tool.com/ Brown *et al.* (2016)) and RESRAD-BIOTA (https://resrad.evs.anl.gov/codes/resrad-biota/, US DOE (2004)). The goal of radiological assessment, in common with other areas of environmental regulation, is usually to protect populations.

The developed approaches are primarily for the assessment of 'planned releases' (i.e., from operating or planned sites) and existing contamination scenarios (e.g., sites contaminated by historical activities). The approaches are not designed to assess the dynamic nature of accidental releases, although the Fukushima accident demonstrated the desire to predict the potential exposure of wildlife following large-scale accidents (Strand *et al.*, 2014). Below we give an overview of how the approaches estimate the exposure and risk of wildlife from ionising radiation.

Simplifying the ecosystem

It would be impossible to have screening tier assessment approaches that considered every potential species in any potential ecosystem. Therefore, the approaches make simplifications; ecosystems are usually simplified as generic marine, freshwater or terrestrial. Similarly, simplifications are made with regard to how organisms are represented within the approaches. The USDOE RESRAD-BIOTA approach simplifies 'organism' as a generic plant or generic animal (US DOE, 2004). The ICRP (2008) proposed a set of Reference Animals and Plants which they 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*'. The ERICA Tool (Brown *et al.*, 2016) uses an approach similar to that of the ICRP with 13 'Reference Organisms' for each of the three generic ecosystems. Reference Organisms are not specific species but are representative of an organism type (e.g., 'amphibian', 'reptile', 'macroalgae', 'mammal', 'tree', etc.). The ERICA Tool Reference Organisms encompass organism types that are: likely to be highly exposed; radiosensitive organisms; representative of different ecological niches; and representative of (European) protected species.

Dosimetry

In order to estimate the exposure (or dose rate) of organisms, dose coefficients (DCs), which relate dose rate (e.g., µGy/h), to the activity concentration (e.g., Bq/kg) in environmental media (water, soil, air, sediment) or within an organism, are used to calculate external or internal dose rate respectively (Vives i Batlle *et al.*, 2011). To calculate the DCs, organisms are typically assumed to have a homogenous geometry (usually an ellipsoid). The ERICA Tool and ICRP approaches select geometries (dimensions and masses) representative of a representative species for the reference organism type. RESRAD-BIOTA takes a more conservative approach in its initial screening tier by assuming a small geometry for the external DC and a large geometry for the internal DC; these assumptions maximise both external and internal dose rate estimates respectively. Weighted dose rates are estimated by applying a radiation-weighting factor to account for the relative biological effectiveness of different types of radiation. An overview of factors influencing DC values can be found in Vives i Batlle *et al.* (2011).

More complex and more realistic models (i.e., including individual organs) have been generated for a number of wildlife types (e.g., see Ruedig *et al.* (2015)). These are not proposed for regulatory assessments, but they have been useful in demonstrating whether simple homogenous geometry assumptions are generally fit for purpose in the available regulatory assessment models. **Voxel** models could also have a useful role in interpreting wildlife dose-effect studies.

Estimating organism activity concentrations

If organism activity concentrations need to be predicted, equilibrium concentration ratios ($CR_{wo\text{-}media}$) relating whole organism radionuclide activity concentration to those in media (typically soil, water or air) are commonly used (Beresford *et al.*, 2008). This approach is pragmatic being simple to apply and some data are available (IAEA, 2014). However, $CR_{wo\text{-}media}$ values can be highly variable, ranging over four orders of magnitude for a given radionuclide-organism combination, leading to considerable uncertainty in predictions.

Benchmarks

For assessments, estimated dose rates need to be put into context with some form of risk criteria (i.e., we need to be able to judge if the estimated dose rate will potentially cause harm or not). Prior to the development of radiological environmental protection approaches, a number of publications had compiled data on the effects of radiation on wildlife from the available literature considering population relevant endpoints such as mortality, fertility and fecundity (NCRP, 1991; IAEA, 1992; UNSCEAR, 1996). Through 'expert judgement', these reviews reached broadly similar conclusions (Text Box 10.x; see original references for exact wording). Although these values were not originally proposed as benchmarks for environmental assessment, they are now sometimes being used as such.

Text Box 10.x: Early estimates of dose rates below which population level effects would not be expected in wildlife.

IAEA (1992)
Terrestrial plants: 10 mGy/d
Terrestrial animals: 1 mGy/d
Aquatic organisms: 10 mGy/d

NCRP (1991)
Aquatic organisms: 10 mGy/d

UNSCEAR (1996)
Terrestrial plants: < 10 mGy/d
Terrestrial animals: 400 µGy/h (mortality)
Terrestrial animals: 40-100 µGy/h (reproduction)
Aquatic organisms: 400 µGy/h

The ICRP have proposed 'derived consideration reference levels' (DCRLs) for their suite of Reference Animals and Plants (ICRP, 2008). These are defined as '*one order of magnitude broad bands of dose rates covering the level where the dose rates warrant a more considered level of evaluation of the situation*'. The DCRLs range from 0.1 - 1 mGy/d (for Reference Deer, Rat, Duck and Pine tree) to 10 – 100 mGy/d (for Reference Seaweed, Bee, Crab and Earthworm). As for the UNSCEAR, IAEA and ICRP reviews the DCRLs were based on expert judgement, though the decision process was better documented.

To be consistent with approaches used for chemical regulation, Garnier-Laplace *et al.* (2010) applied the species sensitivity distribution approach as described in Chapters 3 (Section 3.) and 12 (Section 12.) to derive a screening dose rate (equating to a predicted no-effect concentration as used for risk assessment of chemical stressors). This approach provided a framework for a more transparent and objective derivation of the screening dose rate than the previous derivation of benchmarks using expert judgement. The resultant estimated screening dose rate was 10 µGy/h and this value is used as the default in the ERICA Tool. The screening dose rate derived was generic across all ecosystem and organism types. It would be beneficial to be able to derive organism-specific (e.g., at the level of terrestrial vertebrates, plants, fish, etc.) screening dose rates as the application of a single screening dose rate identifies the most exposed and not necessarily the most at-risk organism. However, data availability precluded Garnier-Laplace *et al.* (2010) from being able to derive organism-specific values. The screening dose rate is for use in screening assessments to help screen sites out from the requirement for further assessment and to identify those that need more detailed consideration; it is not a regulatory 'limit'. The screening dose rate is applicable to the additional dose rate arising from the source(s) under assessment and not the total dose rate including natural background exposure; this is consistent with the radiological protection of humans. For comparison, weighted dose rates to terrestrial and aquatic wildlife due to naturally occurring radionuclides of the ^{238}U and ^{232}Th series, and ^{40}K are typically in the region of 1 µGy/h or less; this does not include the exposure of burrowing animals to ^{222}Rn and daughter products which may be of the order of 10's µGy/h (Beresford *et al.*, 2012).

The scientific controversy

Three accidents, Chernobyl (Ukraine, 1986), Fukushima (Japan, 2011) and Kyshtym (Russian Urals, 1957) have resulted in releases of radioactivity sufficient to result in radiation induced effects in local wildlife. Such sites provide an ideal opportunity to obtain data under realistic conditions of exposure with the potential to investigate population to ecosystem level impacts, and to improve and test our environmental assessment approaches. However, whilst it is accepted that radiation-induced effects have occurred in these areas, there are a number of reports of significant impacts on wildlife at extremely low dose rates, for example below the proposed screening dose rate or DCRLs discussed above, and in the range of typical background exposure rates (Beresford *et al.*, 2020a). There are many factors that might contribute to the reported observations at low dose rates including: poor estimates of exposure; lack of consideration of confounding factors; residual influence of acute/high exposures soon after the accident; or interpretation of statistical results. Furthermore, some studies directly conflict in the findings, e.g., for mammals and leaf litter decomposition rates (Beresford *et al.*, 2020b). These scientific disagreements on the impacts of radiation at contaminated field sites have a relatively high media profile and the potential to impact on public opinion. This controversy needs to be resolved to maintain confidence in the environmental radiation protection approaches that have been developed over the last 20 years and are now being used for the regulation of radioactive releases into the environment from sources ranging from hospitals to nuclear power facilities. Recent studies have attempted to start to address these uncertainties with priorities for future research being identified (Beresford *et al.*, 2020a).

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