Evaluation of models and other scientific information on protection of biota from radiation and chemical exposure

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Superfund Sites

In 1980, Congress established the Comprehensive Environmental Response Compensation and Liability Act (CERCLA), to address the growing threat that hazardous waste posed to both human and biota health. Informally called Superfund, any site outlined in the act grants the EPA the ability to clean up the contamination, while holding the appropriate parties responsible for the damages (US EPA 2017). Superfund cleanup is an intricate, multi-step process of planning, organizing, and implementing, beginning with an initial assessment and site inspection phase to effectively execute a cleanup. Contamination can occur from both chemical and radioactive sources. The scope of this summary focuses on the current modeling methods to determine radionuclide exposure to biota health, as there is a lack of consensus on how to detect, model, and assess radionuclide risk to biota at these Superfund sites (US EPA 2015). EPA has been developing an "Ecological Benchmarks for Radionuclides" calculator for Superfund site assessments.

While chemical and radionuclides differ, an EPA memo from 2014 (US EPA 2014) reveals that human health exposure assessment may be treated similarly within the Superfund remedial program. Ecological assessment for chemicals and radionuclides may also follow the same basic steps– characterizing the exposure setting, identifying pathways and receptors, estimating exposure point concentrations, and estimating exposures and intakes. By considering variations in the estimation methods of various organizations at an international and US states level, the Superfund remedial program can facilitate establishment of an ecological benchmark calculator most optimally applicable to addressing cleanups of radioactive contamination within their sites.

Framework of Ecological Risk Assessment at EPA

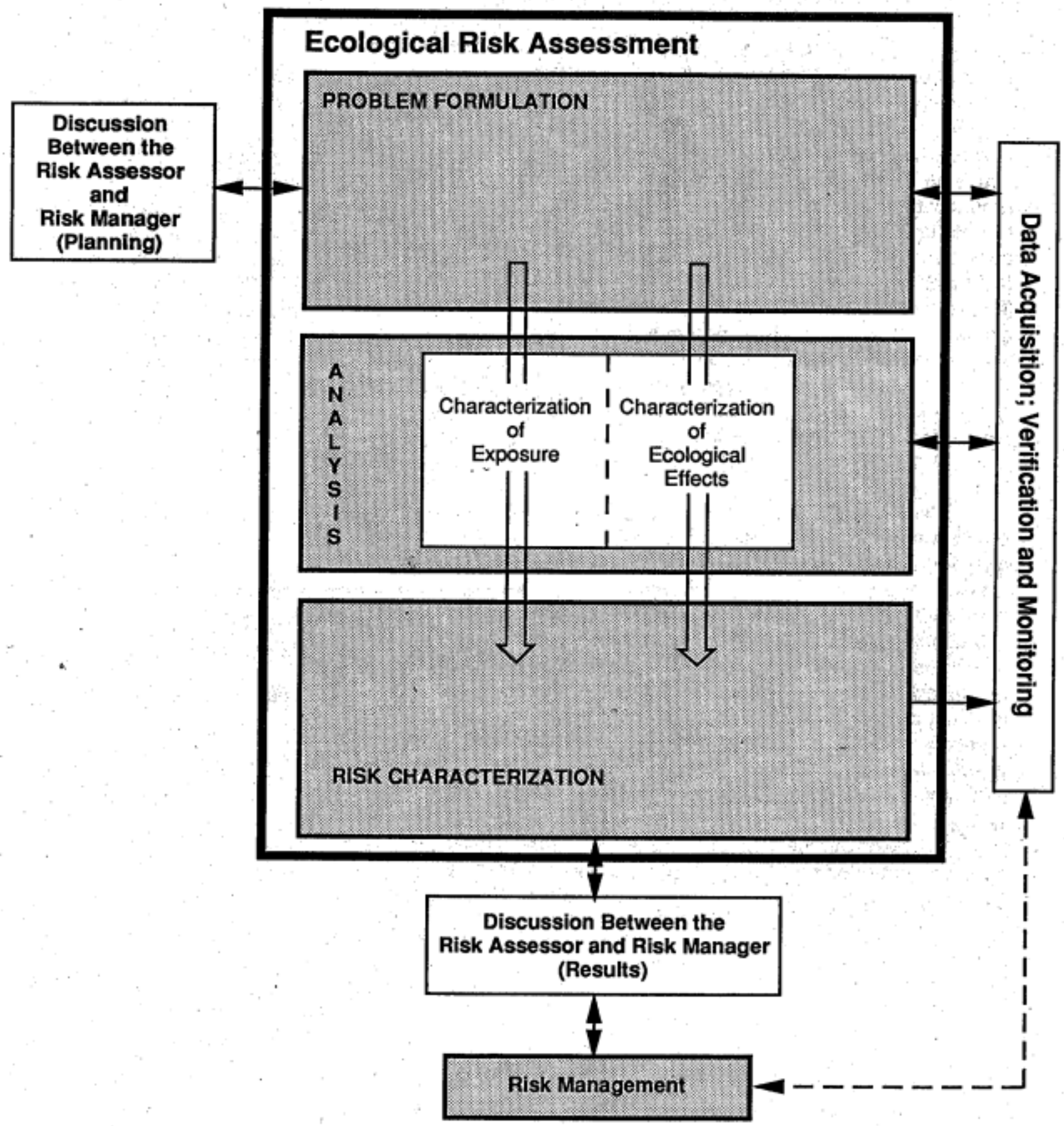

Figure 1. Framework for Ecological Risk Assessment

Figure 1 outlines the framework of the EPA's approach to ecological risk assessment. The process contains two key elements– the characterization of exposure and the characterization of ecological effects. The cumulative effects of these components can characterize the overall risk to an ecosystem. Three phases are enacted to achieve this, beginning with problem formulation. This includes the initial identification of exposure and effects, and aligning these to data, policy, and regulatory needs to proceed. Factors specific to a site define the restrictions and feasibility of the analysis. The second phase is analysis, which involves the characterization of exposure and ecological effects. Characterization of exposure measures the spatial and temporal distribution of the stressor and its contact with the environment, while the characterization of ecological effects identifies and quantifies the effect the stressor has on the environmental component. Finally, EPA's environmental analysis involves risk characterization, which synthesizes the results of the previous steps with a summary of assumptions, uncertainties, strengths and weaknesses of the analysis (US EPA 1992).

Biota Dosimetry Overview and Assumptions

Contaminants in the environment can result in both internal and external exposure of biota to ionizing radiation. Internal exposure occurs through pathways that uptake radionuclides into an organism. External exposures are more context-dependent, relying on factors such as the intensity of an environment, the relationship between the source and organism, organism size, and radionuclide properties (IAEA). The IAEA has a compiled database to provide parameters which estimate the transfer of radioactivity to non-human biota (Beresford et al. 2009), which can be accessed here.

To deal with the diversity of biota exposed to radiation, the International Commission on Radiological Protection (ICRP) has set up a system of reference points with known DCCs through a series of reference animals and plants. These can be found in the ICRP Publication 108 (pages 29-35). This model assumes simple body shapes of uniform composition density, homogenous internal contamination, limited external radiation sources, and the truncation of decay chains (Ulanovsky 2016). Simplifications are often made when dosing radiation in an environment. Commonly, organisms are reduced to simple shapes (ellipsoids, cylinders), and organism dose rates are considered as a whole, not detailing possible variations between different tissues. Dose conversion coefficients (DCCs) are used to estimate the dose rate in an organism or surrounding media, by relating the unweighted absorbed dose rate to the effective concentration in the organism or media. The absorbed fraction (AF) is another key estimator of internal radiation exposure, which measures the fraction of energy emitted by a decaying atom that has been absorbed by an organism (IAEA). The DOE also uses an organism wizard tool, which allows users to make their own organism to define within a model. Individual geometry is selected, which determines DCFs, and specific weight and internal ingestion parameters are set. This allows for radionuclide models to track site-specific biota (US DOE, 2004).

Two basic assumptions are made to integrate radiological and ecological models. First, it is assumed organisms consume radioactive substances as ordinary chemical compounds, without the ability to discern their radioactivity. A substance with an identical chemical form, regardless if stable or radioactive, is indistinguishable to an organism. Second, the elemental composition of biomass for each species is distinctive, and on average constant. For said organism to produce more biomass, it must consume a set quantity of elements from its environment. Often, parameters are estimated utilizing a tiered approach, which facilitates decision-making throughout estimation. Lower tiers are typically highly conservative, requiring minimal data input. As the tiers progress to higher levels, they are more realistic and require more detailed assessment and parameters. The purpose of the lower tiers is to rapidly screen situations where there is little to no risk with a high degree of confidence.

State Chemical Models

The Risk Assessment Information System (RAIS) is a project sponsored by the U.S. Department of Energy (DOE), Office of Environmental Management, and the Oak Ridge Operations (ORO) Office. It offers an ecological benchmark tool for both chemical and radionuclide concentrations in the environment, to help gauge the threat they pose to ecological components. This encompasses screening benchmarks in surface water, sediment, surface soil, and biota applicable to a range of aquatic organisms, soil invertebrates, mammals, and terrestrial plants (RAIS). This compiles benchmarks from both state, national, and international agencies. The RAIS Ecological Benchmark User guide can be found here. Prior to RAIS, The DOE released chemical specific toxicology benchmarks in 1996 for aquatic biota which can be found here, on pages 22-27.

Models for Radionuclide Assessment of Non-Human Biota

RESRAD-BIOTA

RESRAD-BIOTA is a computer code that executes the U.S. Department of Energy's Graded Approach methodology as laid out in the DOE Technical Standard DOE-STD-1153-2019, "A Graded Approach for Evaluating Radiation Doses to Aquatic and Terrestrial Biota". The graded approach follows three primary steps: data assembly, general screening, and analysis. Data assembly exists to prepare information to define the evaluation area. Sources of radioactivity are considered, as well as the key receptors and routes of exposure to these receptors. Next, the geographic boundaries of the evaluation area are set. Data on radionuclide concentrations in water, sediments, and soil to be used on the later screening phase may be organized, and tissue data may be collected using field measurements to supplement the general screening phase (US DOE 2020).

In the general screening phase, media concentrations in a selected area are compared to generic Biota Concentration Guides (BCGs). The DOE BCGs for specific radionuclides represent limiting concentrations in an environmental media. The comparison to a medias concentration with the generic guide is done using the sum of fractions rule. The sum of fractions is determined by dividing each nuclide in the mixture's concentration by its limit, then adding the resulting values. If the sum of fractions from a contaminated area is less than the background area, the contamination passed the general screening (US NRC 2017). This is a RESRAD-BIOTA Level 1 evaluation. The analysis phase of the DOE Graded Approach is more complicated, requiring more detailed components for dose evaluation of biota. These estimates are less conservative and more realistic to the specific site. Site-specific screenings are a RESRAD-BIOTA Level 2 Evaluation, which applies knowledge of site-specific conditions and receptors, using the mean radionuclide concentrations instead of the default or maximum values used in Level 1. The temporal and spatial distribution of contamination is also considered. Following the RESRAD-BIOTA Level 2 screening evaluation, a sum of fractions is performed. If the sum of fractions is less than one, then the site passed the screening evaluation, and no further analysis is needed. If greater than one, then a site-specific analysis is required. Site-specific analysis is a RESRAD-BIOTA Level 3 Evaluation. It employs a kinetic/allometric model with a more thorough analysis of riparian and terrestrial animals. Known characteristics of these animals are required for the analysis. A correction factor can be applied to the contaminated media to account for intermittent source exposure in areas that lack uniform radionuclide distribution. Parameters that influence the internal dosage of an organism such as mass, consumption rates, food sources, lifespan, etc.) can be modified to specifically cater to the model (US NRC 2017).

This approach allows for flexibility. It provides the user with a tiered approach with a start and endpoint in the analysis, increasing in complexity. A generally cost-effective and easy-to-implement assessment measure, the DOE's graded approach incorporates guidance for biota dose assessment, building off the general BCGs and facilitating analysis with more nuance and site-specific detail.

ERICA

The ERICA tool was developed under the European Atomic Energy Community (EURATOM) a treaty involving all members of the EU to form a common market for peaceful atomic energy. It is now the most widely used model to estimate radiological risk to terrestrial, freshwater, and marine wildlife. The tool is comprehensive and follows a tiered approach to calculate and inform ecological assessment decisions.

Tier 1 assessments are concentration based using pre-calculated environmental media concentration limits (EMCLs). These EMCLs are then used to estimate risk quotients. Tier 2 calculates dose rates, allowing the user to input most of the parameters. These include: concentration ratios, distribution coefficients, percentage dry weight soil or sediment, dose conversion coefficients, radiation weighting factors and occupancy factors. If available, the user may also include whole-body activity concentrations rather than use the preset concentration ratios. Tier 3 furthers this analysis by allowing the user to define underlying probability distribution functions if they are known or defined. Using the FREDERICA database, these results can contextualize the data on dose-effect relationships and background dose rates. There are preset models embedded to allow for a more conservative estimate of media concentrations if measurements are not available.

For the sake of dosimetry, reference organisms are defined as three dimensional phantoms (i.e. ellipsoids and cylinders), creating geometric equivalents of organisms based on average mass and size. This approach assumes that a layer of non-active tissue, (outer skin layers/fur) provide a degree of radioactive shielding for the organism. The user can also define their own geometries for considering additional organisms ("The ERICA Tool", 2016).

FASSET

The FASSET project launched in 2000 under the EC 5th Framework Programme to develop an assessment of ionizing radiation in European ecosystems. 15 organizations from seven European nations collaborated to deliver its final report in 2004. The approach utilizes a two-phase strategy of problem formulation and assessment.

The framework also includes a variety of agreed upon presets to perform this analysis. Radionuclides from 20 elements were selected for the framework, which encompass a range of environmental mobilities, uptake rates, and include emitters of α, β and γ radiation. In performing this source characterization, areas of priority were highlighted for further assessment. FASSET then compiled ecosystem information to narrow down the seven maximally exposed components. The ecosystems of focus were forests, semi-natural pastures and heathlands, agricultural ecosystems, wetlands, freshwater, marine, and brackish waters. Organisms were also characterized with a base of 31 reference organisms. These were not actual and defined species, rather a representation of vital ecosystem components that make up suitable targets for assessment. FASSET analysis focuses no four categories of effect on radionuclide risk. First, morbidity, which includes growth rate, immune system effects, and central nervous system damage due to embryonic exposure. Second is mortality due to somatic mutation, cancer induction, and deterministic effects in tissues that would change age-dependent death rates. The final two analysis considerations are organismal reproductive success (fertility and fecundity) and mutation of germ and somatic cells (Larsson, 2004).

England and Wales Environment Agency

A tool was developed by the England and Wales Environment Agency to assess Natura 2000 sites to comply with the EC Habitats Directive in England and Wales, with a similar style to ERICA. It uses a smaller range of organisms and radionuclides. Dose conversion coefficients are estimated with simple functions for energy deposition of unit density from point isotropic sources, which represent absorption of photons and electrons. Energy absorbed fractions are fitted separately for photons and electrons, which allows for an interpolation between calculated

values. The functions are integrated using a stochastic (Monte-Carlo) algorithm to calculate absorbed fraction. Concentration ratios are pulled from literature reviews to estimate concentrations in biota. The aim of this model is to provide conservative values where data-derived or site-specific concentration ratios were lacking. This was later adapted for use within the FASSET and ERICA approaches.
The guidance aims to provide conservative values where data-derived (or site-specific) CR values are lacking as the overall approach to the assessment is to be conservative. This guidance was later adapted for use within the FASSET and subsequent ERICA approaches (IAEA).

ECOMOD

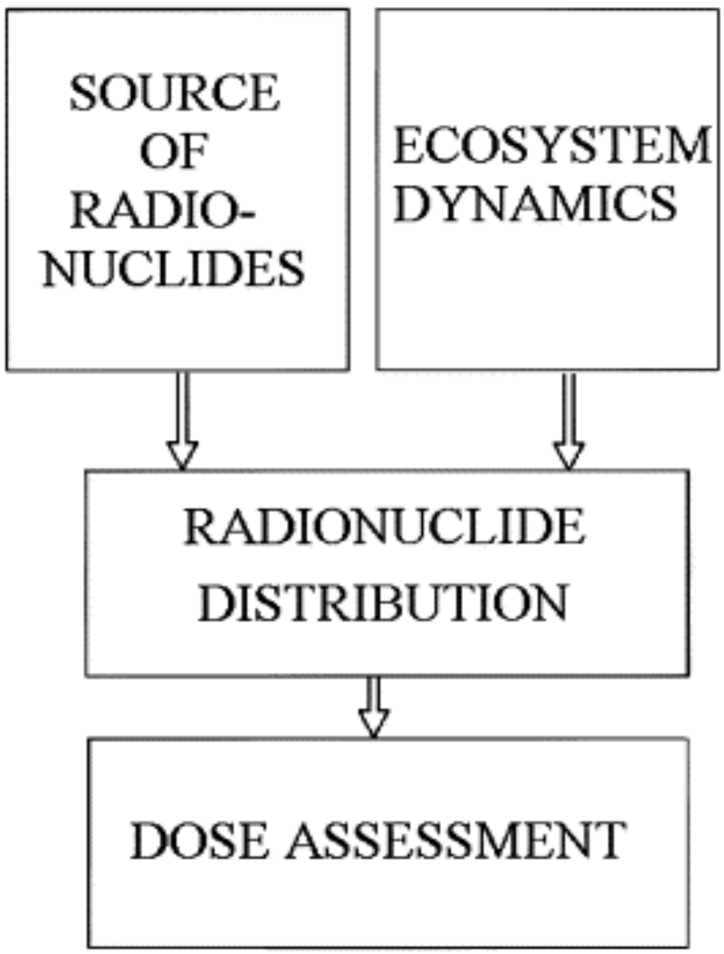

Figure 1: ECOMOD model adapted from IAEA

ECOMOD is a radioecological model developed by Russian scientists to simulate dynamic/migratory radioecological processes in aquatic ecosystems. The three basic modules involved are illustrated above in Figure 1. The “ECOSYSTEM” program calculates the dynamics of biomass of the essential components of the ecosystem. These typically include phytoplankton, macroalgae, zooplankton, and fish of different feeding and living habits. These calculations are based on a set of non-linear ecological equations. Output from this module (biomass density, growth rate and mortality during the growing period) is the input information for the "RADIONUCLIDE DISTRIBUTION" program. The "RADIONUCLIDE DISTRIBUTION" program calculates the radionuclide transfer between an aquatic medium and the food chains within its organisms. Two subprograms exist within this module, one for abiotic and the other for biotic transfer within aquatic systems. This program can run for several radionuclides at once. The output from this module is the radionuclide concentrations within aquatic organisms, which serves as the input for the "DOSE ASSESSMENT" program. This block completes the complex and calculates doses to aquatic organisms. This program can be run independently of the other two, using experimental data rather than inputted information. This model prediction has been used to dose components of the Chernobyl NPP cooling pond shortly after the accident (Sazykina, 2000).

Other Assessments*

EDEN

EDEN is a proposed computer tool to evaluate dose rate of non-human biota exposure to ionizing radiation, developed by researchers at the Institute of Radioprotection and Nuclear Safety in Paul-les-Durance, France. Parameters of the model include the geometry and position of the ionizing source and target, properties of the source such as radiation type and energy emissions. Target organisms are described by their geometry, chemical composition, and lifestyle. EDEN provides a user-friendly interface to build the exposure scenario of interest (Beaugelin-Seiller et al. 2005).

CASTEAUR

CASTEAUR is another calculation code developed by the Institute of Radioprotection and Nuclear Safety designed to estimate spatial and temporal variation in river radionuclide concentrations, specifically from liquid released from nuclear installations. In this model, the ecosystem parameters are described by dissolved fraction, suspended matter, and sediments. Biota within the ecosystem are divided by trophic level, leaving primary producers, first order consumers, and fish to be considered by the model. One run of CASTEAUR yields several parameter values used to characterize a "reach" (homogenous zone of the river). These values are length, width, flow rate, diffusion coefficient, and nature (mineral or phytoplankton), load, and critical deposition tension of suspended materials. Predefined constants within the model include feeding, and growth rates, diet for fish, and distribution coefficients, accumulation, and depuration kinetics for each radionuclide (IAEA).

DosDiMEco

DosDiMEco (page 8) is a software package of three subprograms which calculates energy absorption of a reference organism, developed by SCK·CEN. The first estimates gamma irradiation, and the remaining two estimate alpha and beta radiation. Mass attenuation data are taken from the literature (IAEA).

FASTer

The FASTer model (pages 13-15) was designed (also under the EC 5th Framework project) to consider food chain transfer parameters between vegetation, herbivores, and carnivores, something that was lacking in the FASSET project. It also provides select default concentration ratio values which are found within the ERICA Tool database. A linear differential equation is used to describe the rate of change of the radionuclide inventory (IAEA).

LAKECO-B

LAKECO-B (pages 18-20) is a box-type model developed by the Dutch lab KEMA. It is used to estimate radionuclide concentrations in lakes and reservoirs. It uses a dynamic calculation to assess activity in a water column, in sediment, and in biota. The model describes the change of the concentrations by means of linear differential equations. The following processes are considered by the model: particle scavenging/sedimentation, molecular diffusion, enhanced migration of radionuclides due to physical and biological mixing, particle reworking, and downward transfer of radionuclides in the seabed due to sedimentation. LAKECO-B has been modified to have more environmental parameters (such as potassium concentration) and less model specific parameters, to decrease the sensitivity of the model. Environmental parameters control this aquatic model (IAEA).

*Other model descriptions (EPIC DOSES3D, LEITDOS-BIOTA, D-MAX, and SUJB) are included in the IAEA report, but little to no information outside of this report is available online. Models described in this section are less widely used and more tailored to a specific analysis.

Radionuclide Assessment in the Field

An overview of the literature on radionuclide assessment reveals a strong preference for the Erica Tool for radionuclide dose assessment in the field setting. The following are some instances of this tool in action:

Paired with MicroShield® Pro, a photon and gamma ray shielding program used to design radiation shields, the ERICA Tool (v2.0) was used to estimate the likely radiological doses and risks of naturally occurring radioactive materials (NORM) from a decommissioned offshore oil and gas pipeline in Australia. Using the activity concentrations of NORM, exposure scenarios were modelled comparing exposures from both an intact and decommissioned pipeline with corrosive breakthrough to predict dose rates on marine organisms. The study was particularly useful in highlighting the importance of using scale-specific solubility data values for ERICA assessments (MacIntosh 2022).

ERICA was also used to evaluate the marine environment of Fukushima after the nuclear accident in the northwest Pacific, where 2 tiers of assessment were done. Isotopes of 137Cs, 134Cs and 90Sr were used at their highest activity concentrations, while ERICA default parameters for distribution coefficient, concentration ratio, dose conversion coefficients, occupancy factors, and uncertainty factor were maintained. After one tier of analysis, it was found that at least one value was above the recommended screening dose rate and that a Tier 2 assessment was needed (Yu 2015). The assessment yielded that radioactive contaminants from the Fukushima Nuclear Accident would not have a significant effect on marine biota at the population level, which corroborated other findings in the literature.

Instances of ERICA in application have also occurred at Chernobyl, to evaluate the fundamental assumption of EPA and DOE's screening levels that mean contaminant concentrations can conservatively estimate individual exposure. This hypothesis was explored using ERICA, and found that even in the most conservatively chosen measures results underpredicted contamination concentrations of modeled external exposure of GPS tracked wolves in Chernobyl. The study deemed the ERICA tool as a high-performance tool in the model comparison. Researchers offered three suggestions to reduce the probability of under-estimating exposure in screening-level assessments: (1) acknowledge larger uncertainty in results based on measures of central tendency (2) Apply larger uncertainty factors to data derived from central tendency measures (3) Use a probabilistic approach that captures variance in measures of central tendency (Hinton 2017).

Another study done on biota at Chernobyl utilized the ERICA Tool to calculate the dose rates for 90Sr and 137Cs using ERICA's default parameters, which were found to be consistent with field data. The study further found that ERICA's calculations for plutonium isotopes were much higher (2-5 times for small mammals and 10-14 times for birds) than what was calculated using experimental data (Oskolkov 2011). This is a recurring issue in radionuclide estimation measures, as a discrepancy exists between laboratory and field data surrounding. It was found in the comparison of radiosensitivity from species in the Chernobyl-Exclusion Zone that field conditions estimates were approximately 8 times lower than the ones from a controlled experiment. This difference in estimates indicates a lack of full mechanistic understanding from sampling field strategies, which likely fails to account for confounding factors (Garnier-Laplace 2013).

Grand Summary Table

Rad Model	User Information	Biota Covered
RESRAD-BIOTA	RESRAD-BIOTA: A Tool for Implementing a Graded Approach to Biota Dose Evaluation. User's Guide, Version 1. (DOE Report No. DOE/EH-0676; ISCORS Technical Report 2004-02, January 2004)	Organisms classified by: terrestrial animal, terrestrial plant, aquatic animal, riparian animal. Organism parameters can then be inputed, new organisms can be added using the Organism Wizard.
ERICA	ERICA Assessment Tool Help Function Document	Default Reference Organisms (page 14): **Freshwater**: amphibian, benthic fish, bird, crustacean, insect larvae, mammal, mollusc- bivalve, mollusc – gastropod, pelagic fish, phytoplankton, reptile, vascular plant, zooplankton **Marine**: benthic fish, bird, crustacean, macroalgae, mammal, mollusc- bivalve, pelagic fish, phytoplankton, polychaete worm, reptile, sea anemones & true coral, vascular plant, zooplankton **Terrestrial**: amphibian, annelid, arthropod – detritivorous, bird, flying insect, grasses & herbs, lichen & bryophytes, mammal – large, mammal-small-burrowing, mollusc – gastropod, reptile, shrub, tree Screen dose-rates found on page 15.
FASSET	Handbook for Assessment of the Exposure of Biota to Ionising Radiation from Radionuclides in the Environment	Reference organisms defined by their habitat: forest, semi-natural pasture and healthland, agriculture,

		freshwater, marine, brackish waters, and rivers Transfer Factors and DCCs for organisms in these ecosystems can be found on **pages 57- 80**
ECOMOD	ECOMOD — An ecological approach to radioecological modelling	Used in aquatic ecosystems: main organisms include phytoplankton, macroalgae, zooplankton, and fish of different feeding and living habits
EDEN	E.D.E.N.: A tool for the estimation of dose coefficients for non-human biota	Study system is defined within the tool. Shape of organisms (ellipses) and media, their composition, and radioactive sources (page S923).
CASTEAUR	CASTEAUR: A tool for operational assessments of radioactive nuclides transfers in river ecosystems	Considers main biotic components of river ecosystems: phytoplankton, zooplankton, macrobenthos and fish (planktivorous and omnivorous)

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