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Radionuclide biological half-life values for terrestrial and aquatic wildlife

Abstract

The equilibrium concentration ratio is typically the parameter used to estimate organism activity concentrations within wildlife dose assessment tools. Whilst this is assumed to be fit for purpose, there are scenarios such as accidental or irregular, fluctuating, releases from licensed facilities when this might not be the case. In such circumstances, the concentration ratio approach may under- or over-estimate radiation exposure depending upon the time since the release. To carrying out assessments for such releases, a dynamic approach is needed. The simplest and most practical option is representing the uptake and turnover processes by first-order kinetics, for which organism- and element-specific biological half-life data are required. In this paper we describe the development of a freely available international database of radionuclide biological half-life values. The database includes 1907 entries for terrestrial, freshwater, riparian and marine organisms. Biological half-life values are reported for 52 elements across a range of wildlife groups (marine=9, freshwater=10, terrestrial=7 and riparian=3 groups). Potential applications and limitations of the database are discussed.

1. Introduction

To estimate the uptake of radionuclides by wildlife, the whole organism[1] concentration ratio ($CR_{wo\text{-}media}$) is most commonly used (e.g. Beresford et al. 2008a; Hosseini et al. 2008; Strand et al. 2009; Yankovich et al. 2013; Howard et al. 2013; IAEA 2014). This is defined as the ratio of radionuclide activity concentration in the whole organism to that in the surrounding medium:

$$CR_{wo-media} = \frac{Activity\ concentration\ in\ whole\ organism\ (Bq\ kg^{-1}) fresh\ mass}{Activity\ concentration\ in\ media}$$

where, media maybe soil (Bq kg^{-1} dry mass), water (Bq L^{-1}) or air (Bq m^{-3}) dependent upon ecosystem and radionuclide.

[1]Organism less both gastrointestinal tract contents and fur/feathers

The concentration ratio is an aggregated transfer parameter, incorporating within it the physical, chemical and biological factors affecting the uptake of radioelements by biota in an empirical way. The turnover of elements differs depending on, for instance, ingestion or sorption processes, their chemical and biochemical behaviour and the requirements of the organism for the element or its analogue. Instantaneous equilibrium between the organism and the media activity concentrations is assumed in all models that use the $CR_{wo\text{-}media}$ concept (e.g. USDOE 2002; Brown et al. 2008; Beresford et al. 2008b).

Although some organisms may equilibrate relatively rapidly with radionuclides present in the surrounding media (timescales in the order of days to a few months), there are scenarios whereby equilibrium cannot be assumed. For example, after a short-term pulsed release of ^{99}Tc activity into the marine environment, the activity concentration in lobsters along the dispersion path begins to increase gradually with time. This is because lobsters have a biological half-life for technetium in the range of 60-300 days (Pentreath 1981). Technetium is soluble in seawater and the pulsed release will clear quickly from the area of sea where lobsters live. Therefore, its concentration in seawater will decrease sharply within a few days after a pulse discharge. Lobster specimens sampled from the area within days of the discharge, when water concentrations have declined, may appear to have an anomalously high $CR_{wo\text{-}media}$ value because they retain the technetium that they absorbed whilst seawater concentrations were high. Conversely, if sampled on the day of discharge $CR_{wo\text{-}media}$ would be low as little uptake would have occurred but seawater concentrations would be high.

If the timeframe of interest is long (e.g. years or decades of planned authorised discharges, involving continuous releases or gradual changes in discharge concentrations) then the $CR_{wo\text{-}media}$ approach is currently considered to be sufficient (Strand et al. 2009; IAEA 2014). However, if unplanned release scenarios involving abrupt changes in discharge concentrations are being modelled then the $CR_{wo\text{-}media}$ approach may be inadequate and dynamic models of radionuclide transfer to biota may be a better assessment tool. This is especially true for organisms that respond slowly to a change in ambient radioactivity concentration (Vives i Batlle 2012), and this has been highlighted in the post-accident assessment of the Fukushima accident (e.g. Kryshev & Sazykina 2011; Buesseler et al., 2011). Such dynamic models need to have rate constants, or biological half-life values ($T_{1/2b}$), describing the loss of radionuclides from organisms. Whilst the biological half-life is typically defined to described the rate of loss of radionuclide from an organism, it is also often used in the estimation of uptake (e.g. Whicker & Schultz 1982; Vives i Batlle et al. 2008).

At higher (more detailed) assessment tiers, the USDOE (2002) RESRAD BIOTA approach incorporates some simple foodchain modelling ability using allometric (or mass) expressions; these include allometric biological half-life relationships for a limited number of radionuclides (Higley et al. 2003). Further exploitation of the allometric $T_{1/2b}$ approach to other radionuclides was not possible because of a lack of $T_{1/2b}$ data from which to derive the relationships.

Commonly used assessment tools exploit the $CR_{wo\text{-}media}$ model with the tacit assumption that this is generally likely to be conservative. However, it has been noted that wildlife assessment models do not include direct deposition of radionuclides to vegetation surfaces and that under conditions of continuous aerial discharge this may contribute a significant proportion of radioactivity entering food chains (Copplestone et al. 2010). At the time of writing this paper we are aware that the IAEA is working on an assessment approach for wildlife which does include this deposition pathway (see Beresford et al. 2015a), but, which as a consequence, requires some knowledge of the biological half-life of radionuclides in wildlife. Similarly, reported $CR_{wo\text{-}media}$ values are, in theory at least, equilibrium values and an increasing number of radioecological studies utilise inductively coupled plasma mass spectrometry (ICP-MS) analyses to derive $CR_{wo\text{-}media}$ values from stable element data which should be at equilibrium (e.g. Barnett et al. 2011,2014; Higley 2010; Tagami and Uchida 2010; Takata et al. 2010; Sheppard 2013). Application of an equilibrium $CR_{wo\text{-}media}$ value to a short-lived radionuclide will over-estimate the resultant whole organism activity concentrations and dose rate. IAEA (2010) propose an approach whereby equilibrium activity concentrations could be corrected (to $CR_{wo\text{-}corrected}$) for application to short-lived radionuclides, but this again requires some knowledge of biological half-life:

$$CR_{wo-corrected} = CR_{wo-media} \times K \qquad (2)$$

where:

$$K = \frac{T_{1/2p}}{T_{1/2b} + T_{1/2p}} \qquad (3)$$

where, $T_{1/2p}$ is the physical half-life of the radionuclide under assessment.

There are, as demonstrated here, a number of requirements for a comprehensive database of wildlife radionuclide $T_{1/2b}$ values. However, such a database has to date not been available. In this paper we describe the development of a $T_{1/2b}$ database for wildlife.

2. Methods

The work described here was conducted by an international working group under the auspices of the International Atomic Energy Agency's MODARIA programme (see: http://www-ns.iaea.org/projects/modaria/). The review and compilation of $T_{1/2b}$ values was divided amongst the group members depending upon their prior expertise (i.e. by ecosystem and/or organism).

Prior to beginning the review a recording sheet, in MS Excel™, was designed to allow easy collation of the various components into the final database. The recording sheet entry fields are listed in Table 1. The wildlife group categorisations were broadly compatible with those used in the Wildlife Transfer Database (as described by Copplestone et al. 2013) and subsequently by the IAEA (Howard et al. 2013; IAEA 2014). The 'Changeover time' is defined as the time of intersection of two successive depuration curves which are governed by their respective biological half-lives when the two are plotted as regression lines on a logarithmic scale (this parameter is useful if fractions of loss in each component are not directly reported). No attempt was made to standardise the English common names used; similarly we have not updated Latin species names, but we acknowledge that these may have changed since the original publications.

The review was undertaken to identify studies reporting either $T_{1/2b}$ values (i.e. the time taken for the initial activity concentration in an organism, or tissue, to half) or elimination rate constants from which $T_{1/2b}$ (d) values could subsequently be estimated as:

$$T_{1/2b} = \frac{\ln 2}{k} \quad (4)$$

Some $T_{1/2b}$ values were estimated from reported percentages of initial activity remaining (A_t) at time t, where:

$$k = \frac{\ln(\frac{100}{A_t})}{t} \quad (5)$$

and $T_{1/2b}$ is subsequently estimated from k as in Equation (4).

The review used Web of Knowledge (http://wok.mimas.ac.uk/), SCOPUS (http://www.scopus.com/), IAEA INIS (http://www.iaea.org/inis/) and Pubmed (http://www.ncbi.nlm.nih.gov/pubmed). Targeted searches of grey literature catalogues (e.g. the U.S. Department of Energy portal: http://www.osti.gov/scitech/) were also conducted. The on-line versions of key journals in the area (e.g. *Journal of Environmental Radioactivity*, *The Science of the Total Environment*, *Radiation Protection Dosimetry*, *Health Physics*, *International Journal of Radiation Biology*, *Journal of Radiological Protection* and *Journal of Radiation Research*) were also searched to identify appropriate studies. Search terms included: “biological half-life”, “biological period”, “kinetic transfer modelling”, “accumulation rate”, “depuration rate” and organism names.

Reviews of the Japanese and Russian language literature to identify data appropriate for inclusion in the database were also conducted. It was necessary to estimate k and hence $T_{1/2b}$ values from some of the Russian language literature by fitting appropriate exponential relationships to reported data using MATCAD software. Some additional Russian language values, for birds, were also obtained from the review of Fesenko et al. (2015).

In some instances, previously published reviews were used to identify source references. Where possible the source references were consulted rather than relying on data from the earlier compilation; these reviews are identified below. The reviews were also used as a starting point for additional searches to identify any papers citing them which may have appropriate data. We also benefited from the knowledge of working group members who identified appropriate sources they were aware of, including in-house studies (e.g. PhD. studies funded by the Institute for Radiological Protection and Nuclear Safety and published in French).

For the terrestrial ecosystem the earlier key reviews used were those of Kitchings et al. (1976), Whicker & Schultz (1982), Stara et al. (1971) and DiGregorio et al. (1978). The freshwater ecosystem review of Alonzo (2009) was used as the primary source of freshwater information with additional work focussing on identifying appropriate publications subsequent to the year 2000. For the marine ecosystem, the important reviews were those of Vives i Batlle et al. (2007; 2008; 2009) (covering principally ^{99}Tc, ^{129}I, ^{137}Cs, ^{239,240}Pu and ^{241}Am), CIESM (2002) EPA (2013) Gomez et al. (1987) and Phillips & Russo (1978).

For the terrestrial environment, whilst they are not wild animals, data from the domesticated dog (*Canis lupus familiaris*) and cat (*Felis silvestris catus*) have been included in the database as these are unlikely to be collated anywhere else and are of relevance to some species of wildlife; farm animal data were excluded from the database with the exception that it is possible that some goose and duck data originate from domesticated species.

2.1 Quality control

An independent quality check was conducted by co-authors not involved in the actual data compilation. As a minimum, 10% of the entered data were confirmed by going back to the source reference. Additionally, for some key data sources all entries were checked. Any issues raised were investigated and corrected as required in consultation with the originators of those entries in the database.

Some of the compiled data have already been used in the development of allometric approaches for terrestrial (Beresford & Wood 2014; Beresford et al. 2015b) and marine (Vives i Batlle et al., 2007) wildlife and as such have been subjected to additional quality checking. In the case of the reptile data this involved confirmation of most entries into the database (Beresford & Wood 2014).

A column was added to the database to record which entries had been quality controlled (approximately 40% of entries were quality controlled as described above). The database was also reviewed for duplicate entries and the few identified were removed.

Some (n=165), predominantly freshwater, ecological half-life (i.e. parameter describing the overall rate of reduction in radionuclide levels of animals in contaminated environments) data for Cs and Sr were identified during the review and these have been retained within the database (as a separate datasheet). It is important to note that these have not been quality controlled and they are not discussed further below.

3. Results

The database resulting from the review is freely available (Beresford et al. 2015c; http://doi.org/10.5285/b95c2ea7-47d2-4816-b942-68779c59bc4d); this contains all reference details and hence these are not repeated in this paper.

The database contains 1907 entry lines split between organisms from three generic ecosystems as follows: marine (n=547); freshwater (n=530); and terrestrial (n=743). Additionally there are 87 entries for riparian organisms which live in both freshwater and terrestrial ecosystems (i.e. amphibians and some species of reptiles and birds). Sixty-five entries from the Japanese literature were for 'brackish water' species, in the database these are classified as marine ('Brackish species' appears within the notes column to identify the entries). Table 2 summarises the available $T_{1/2b}$ values by wildlife group (as defined in Copplestone et al. (2013)) and by generic ecosystem. In some instance entries may be for different tissues from the same study. We should also note that it is likely that the database entries are a mix of mean values and single data.

The compiled database contained $T_{1/2b}$ values for a total of 52 elements (27 for freshwater, 48 for terrestrial, 24 for marine and 10 for riparian) (Table 2). For all three ecosystems data for Cs were the most numerous entries (Figure 1), with some commonality in the other dominant elements (i.e. Co, Sr, Ru and Mn). Iodine data were relatively numerous within the terrestrial and marine organism data, but not within the freshwater data. Relatively more Co values were available for freshwater and marine organisms than for terrestrial organisms; in the marine ecosystem these data originate primarily for Japanese literature. The large number of data classified as 'other' within Figure 1 for terrestrial organisms reflects the greater number of elements for which data are available for this ecosystem (see Table 2) and that few data are available for many of these. For marine organisms, entries for Tc were relatively numerous; no data for the element were available for freshwater or terrestrial organism. Differences between data availability are in-part driven by different radioecological issues between the ecosystems and potentially by the focus of some of the key review sources used to begin to establish the database (e.g. Tc was a focus of the review of marine data by Vives i Batlle et al. (2007)).

Data on biological half-lives ranged from single components of loss to up to four components (i.e. four $T_{1/2b}$ values) of loss recorded for some entries. In part, the number of reported loss components is determined by the experimental approach with respect to the total study duration and also the interval between measurements (Fesenko et al. 2015). For instance, short-term studies will not provide estimates of longer components of loss, whilst if sampling is at too large an interval early in the study the shortest components of loss may be missed.

Most entries were for the whole organism (n=1417). However, some entries (n=126) do not have a record for the tissue sampled. In most instances, these records are for organisms where it is highly likely that the values are for the whole organism or at least for soft tissues (e.g. terrestrial arthropods, marine mussels, macroalgae). Other entries are for elements where the value can be assumed to be representative of whole organism loss rates (e.g. Cs).

Supplementary information entered was, in some instances, sparse (e.g. few data on sex) though many entries recorded study length (n=885), temperature (n=845), live-weight (n=844) and age (n=904). With respect to age, entries were available for different live-stages such as tadpole, fry and larvae.

The database is too diverse in terms of organisms, elements, administration routes and how $T_{1/2b}$ values are presented (i.e. number of loss components) to attempt any analyses in this paper.

4. Discussion

There are a number of reasons why $T_{1/2b}$ values are required to improve radiological assessments (as discussed above). The database we describe here represents a significant resource by which we may begin to improve, or test, available assessment approaches. For some elements the database may also be useful to those assessing the exposure of wildlife to metals (e.g. the database contains $T_{1/2b}$ values for Ag, Cr, Hg, Pb, Zn etc.).

The application of dynamic models to environmental assessment of radioactivity could be criticised as being overly complex (IAEA, in-press). For many planned release situations it is likely that the $CR_{wo\text{-}media}$ model will lead to appropriate assessments (Strand et al. 2009; IAEA 2014). Though, as noted above, for routine aerial releases the $CR_{wo\text{-}media}$ model may under predict activity concentrations in organisms and the current approaches may not be optimised for all planned release scenarios. Application of equilibrium $CR_{wo\text{-}media}$ models to accidental situations or irregular pulsed discharges from licensed facilities is outside of the intended scope of their application. In aquatic ecosystems, immediately after pulsed releases, when media activity concentrations are high, $CR_{wo\text{-}media}$ models are likely to over-predict exposure by not taking into account biological half-life (or uptake rate) and the consequent lack of equilibrium. Subsequently they may under-predict as water concentrations decrease more rapidly than those in exposed organisms; in the longer-term the $CR_{wo\text{-}media}$ model should adequately predict exposure in the post-accident situation. In the terrestrial ecosystem, immediately after a release the $CR_{wo\text{-}media}$ model may again over-predict exposure. However, there is the possibility of under prediction when there is significant direct deposition on vegetation surfaces (i.e. contamination is not dominated by the soil-plant route assumed in the $CR_{wo\text{-}media}$ model). Whilst inappropriate, equilibrium $CR_{wo\text{-}media}$ models were applied to assess risk to biota following the Fukushima accident (Garnier Laplace et al. 2011; Strand et al. 2014). Although such assessments may have aimed to be conservative, as we demonstrate above, the resultant predictions may not always have been conservative. Some attempts to conduct more relevant assessments in the marine ecosystem using dynamic models have been made (Kryshev et al. 2012; Vives i Batlle et al. 2014). However, more recent analyses suggests that these models over predicted the rates of decline in fish (Johansen et al. 2015). This was potentially because the models assumed single loss component (Vives i Batlle 2015); a more robust $T_{1/2b}$ database is expected to improve the parameterisation of such dynamic models.

4.1 Use of the database

We envisage that the database will be useful in both parameterising and testing models. Indeed some parts of the compiled database have already been used to test allometric models for homoeothermic vertebrates (Beresford & Vives i Battle 2013; Beresford et al. 2015b) and reptiles (Beresford & Wood 2014).

Users of the database will need to consider their needs and the suitability of the data that it contains. For instance, we have included $T_{1/2b}$ values derived from studies using a number of exposure routes. However, it is probable that for some elements intravenously administered radionuclides will behave differently to those orally ingested (e.g. Mayes et al. 1996). The study length and experimental protocol (e.g. time of first measurement, frequency of measurements, time taken to reach limits of detection etc.) can influence the resultant $T_{1/2b}$ values and the number of components of loss observed. Experimental protocols of insufficient length to enable multiple components of loss to be observed are likely to result in $T_{1/2b}$ values which under-estimate the rate of loss (and consequently over estimate organism activity concentrations) in the short-term, but, over-estimate the rate of loss in the longer-term. Beresford & Wood (2014) present an evaluation of the database with respect to reptiles. They highlighted that some of the entries were based upon only two time points and chose not to use these data in their analyses. Future, users will need to similarly critically evaluate the data. The present database provides them with a valuable resource from which to begin this evaluation.

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References

Alonzo, F., (2009). Transferts au sein de l'écosystème aquatique d'eau douce : proposition de valeurs de paramètres pour Symbiose. IRSN, rapport DEI/SECRE/2007-056_ 2009-051.

Barnett, C.L., Howard B.J, Oughton, D.H., Coutris, C., Potter, E.D., Franklin, T., Walker L.A., Wells, C., (2011). Transfer of elements to owls (*Tyto alba, Strix aluco*) determined using neutron activation and gamma analysis. Radioprotection 46, S79-S84. http://dx.doi.org/10.1051/radiopro/20116703s

Barnett, C.L., Beresford, N.A., Walker, L.A., Baxter, M., Wells, C., Copplestone, D., (2014). Transfer parameters for ICRP reference animals and plants collected from a forest ecosystem Radiat. Environ. Biophys. 53, 125-149. http://dx.doi.org/10.1007/s00411-013-0493-6

Beresford, N.A., Barnett, C.L., Howard, B.J., Scott, W.A., Brown, J.E., Copplestone D., (2008a). Derivation of transfer parameters for use within the ERICA Tool and the default concentration ratios for terrestrial biota. J. Environ. Radioact. 99, 1393-1407. http://dx.doi.org/10.1016/j.jenvrad.2008.01.020

Beresford, N.A., Barnett, C.L., Brown, J., Cheng, J-J. Copplestone, D., Filistovic, V., Hosseini, A., Howard, B.J., Jones, S.R., Kamboj, S., Kryshev, A., Nedveckaite, T., Olyslaegers, G., Saxén, R., Sazykina, T., Vives i Batlle, J., Vives-Lynch, S., Yankovich, T., Yu, C., (2008b). Inter-comparison of models to estimate radionuclide activity concentrations in non-human biota. Radiat. Environ. Biophys., 47, 491–514. http://dx.doi.org/10.1007/s00411-008-0186-8

Beresford, N.A., Vives I Batlle, J., (2013). Estimating the biological half-life for radionuclides in homoeothermic vertebrates: A simplified allometric approach. Rad. Environ. Biophys. 52, 505-511. http://dx.doi.org/10.1007/s00411-013-0481-x

Beresford, N.A., Wood, M.W., (2014). A new simplified allometric approach for predicting the biological half-life of radionuclides in reptiles. J. Environ. Radioact. 138, 116-121 http://dx.doi.org/10.1016/j.jenvrad.2014.08.012

Beresford, N.A., Barnett, C.L., Chaplow, J., (2015a) Workshop report: STAR-MODARIA workshop on 'Making data available', IAEA Vienna, 20-21 April 2015. STAR (Contract Number: Fission-2010-3.5.1-269672). https://wiki.ceh.ac.uk/download/attachments/215451067/STAR%20Workshop%20Report%20Vienna%20April%202015.pdf?api=v2

Beresford, N.A., Wood, M.D., Vives i Batlle, J., Yankovich, T.L., Bradshaw, C., Willey, N.,(2015b). Making the most of what we have: application of extrapolation approaches in radioecological wildlife transfer models. J. Environ. Radioact. http://dx.doi.org/10.1016/j.jenvrad.2015.03.022

Beresford, N.A., Beaugelin-Seiller, K., Wells, C., Vives-Lynch, S., Vives i Batlle, J., Wood, M.D., K. Tagami, Real, A., Burgos, J., Fesenko, S., Cujic, M., Kryshev, A., Pachal, N., Su, B.S., Barnett, C.L., S. Uchida, Hinton, T., Mihalík, J., Stark, K., Willrodt, C., Chaplow J., (2015c). A database of radionuclide biological half-life values for wildlife. NERC-Environmental Information Data Centre. http://doi.org/10.5285/b95c2ea7-47d2-4816-b942-68779c59bc4d

Brown, J.E., Alfonso, B., Avila, R., Beresford, N.A., Copplestone, D., Pröhl, G., Ulanovsky A., (2008). The ERICA Tool. J. Environ. Radioact. 99, 1371-1383. http://dx.doi.org/10.1016/j.jenvrad.2008.01.008

Buesseler, K., Aoyama, M., Fukasawa, M., (2011). Impacts of the Fukushima nuclear power plants on marine radioactivity. Environ. Sci. Technol. 45, 9931-9935.

CIESM (2002). Metal and radionuclides bioaccumulation in marine organisms. Mediterranean Science Commission (CIESM) Workshop Monographs n°19, 128 pages, Monaco. Available from: www.ciesm.org/publications/Ancona02.pdf [Accessed 3 June 2014].

Copplestone, D., Brown, J.E., Beresford, N. A., (2010). Considerations for the integration of human and wildlife radiological assessments. J. Radiol. Prot. 30, 283-297.http://dx.doi.org/10.1088/0952-4746/30/2/S05

Copplestone, D., Beresford, N.A., Brown, J., Yankovich, T., (2013). An international database of radionuclide Concentration Ratios for wildlife: development and uses. J. Environ. Radioact. 126, 288-298.

DiGregorio, D., Kitchings, T., Van Voris, P., (1978). Radionuclide transfer in terrestrial animals. Health Phys. 34, 3-31.

EPA (2013). Laboratory-Determined Concentration Factors and Elimination Rates of Some Anthropogenic Radionuclides in Marine Vertebrates and Invertebrates. United States Environment Protection Agency Report 520/1-85-015, 108 pp.

Fesenko, S., Isamov, N., Barnett, C.L., Beresford, N.A., Howard, B.J., Sanzharova, N., Fesenko, E., (2015). Review of Russian language studies on radionuclide behaviour in agricultural animals: biological half-lives. J. Environ. Radioact. 142, 136-151.

Garnier-Laplace, J., Beaugelin-Seiller, K., Hinton, T.G. (2011). Fukushima wildlife dose reconstruction signals ecological consequences. Environ. Sci. Technol. 45, 5077−5078.

Gomez, L.S., Marietta, M.G., Jackson, D.W., (1987). Compilation of Selected Marine Radioecological Data for the U.S. Subseabed Program: Summaries of Available Radioecological Concentration Factors and Biological Half-Lives. Sandia National Laboratories Reprot SAND86-2674 UC-70.

Higley, K.A., Domotor, S.L., Antonio, E.J., (2003). A kinetic-allometric approach to predicting tissue radionuclide concentrations for biota. J. Environ. Radioact. 66, 61-74.

Higley, K.A., (2010). Estimating transfer parameters in the absence of data. Radiat. Environ. Biophys. 49, 645-656. doi:10.1007/s00411-010-0326-9

Hosseini, A., Thorring, H., Brown, J.E., Saxen, R, Ilus, E. (2008). Transfer of radionuclides in aquatic ecosystems - Default concentration ratios for aquatic biota in the Erica Tool. J. Environ. Radioact. 99, 1408-1429.

Howard, B.J., Beresford, N.A., Copplestone, D., Telleria, D., Proehl, G., Fesenko, S., Jeffree, R., Yankovich, T., Brown, J., Higley, K., Johansen, M., Mulye, H., Vandenhove, H., Gashchak, S., Wood, M.D., Takata, H., Andersson, P., Dale, P., Ryan, J., Bollhöfer, A., Doering, C., Barnett, C.L., Wells, C., (2013). The IAEA Handbook on Radionuclide Transfer to Wildlife. J. Environ. Radioact. 121, 55–74.http://dx.doi.org/10.1016/j.jenvrad.2012.01.027

IAEA. 2010. Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Terrestrial and Freshwater Environment: Technical Reports Series No. 472. IAEA, Vienna. http://www-pub.iaea.org/MTCD/publications/PDF/trs472_web.pdf

IAEA. 2014. Handbook of parameter values for the prediction of radionuclide transfer to wildlife. Technical Reports Series No. 479. IAEA, Vienna. http://www-pub.iaea.org/MTCD/Publications/PDF/Trs479_web.pdf

IAEA. *In-press*. Modelling the exposure of wildlife to radiation: evaluation of current approaches and identification of future requirements. Report of Working Group 4 Biota Modelling Group of EMRAS II. Reference Approaches for Biota Dose Assessment. Environmental modelling for radiation safety (EMRAS II) programme.

Johansen, M.P., Ruedig, E., Tagami, K., Uchida, S., Higley, K., Beresford, N.A., (2015). Radiological dose rates to marine fish from the Fukushima Daiichi accident: the first three years across the north Pacific Environ. Sci. Technol. 49, 1277-1285

Kitchings, T., DiGregorio, D., van Voris, P., (1976). A review of the ecological parameters of radionuclide turnover in vertebrate food chains In: Cushing, C.E., Cutshall, N.H., Fraley, L.F., French, N.R., Murphy, P.G., Sharitz, R.R., Trabalka, J.R., Turner, F.R., Whicker, F.W., Wolfe, D.A. (eds) Radioecology and Energy Resources. Dowden, Hutchinson & Ross, Inc, Stroudsburg, Pennsylvania, p304-31.

Kryshev, A.I., Sazykina, T., (2011). Evaluation of the irradiation dose rate for marine biota in the region of the destroyed Fukushima reactor (Japan) in March-May 2011, Atomnaya Énergiya 111, 41-45.

Kryshev, I. I., Kryshev, A. I., Sazykina, T. G., (2012). Dynamics of radiation exposure to marine biota in the area of the Fukushima NPP in March-May 2011. J. Environ. Radioact. 114, 157−161.

Mayes, R.W., Beresford, N.A., Howard, B.J., Vandecasteele, C.M. & Stakelum, G., (1996). Use of the true absorption coefficient as a measure of the bioavailability of radiocaesium in ruminants. Radiation and Environmental Biophysics, 35, 101-109. http://dx.doi.org/10.1007/BF02434032

Pentreath, R.J., (1981). The biological availability to marine organisms of transuranium and other long-lived nuclides. Impacts of Radionuclide Releases into the Marine Environment, IAEA, Vienna 241-272.

Phillips, G.R., Russo, R.C., (1978). Metal bioaccumulation in fishes and aquatic invertebrates: A literature review. U.S. Environmental Protection Agency Report EPA-600-3-78-103, Office of Research and Development, Environmental Research Laboratory, Duluth, Minnesota, 116 pp.

Sheppard, S.C., (2013). Transfer factors to Whitetail deer: comparison of stomach-content, plant-sample and soil-sample concentrations as the denominator. J. Environ. Radioact., 126, 434-437.

Stara, J.F., Nelson, N.S., Della Rosa, R.J., Bustad, L.K., (1971). Comparative metabolism of radionuclides in mammals: a review. Health Phys. 20, 113-137.

Strand, P., Beresford, N.A., Copplestone, D., Godoy, J., Jianguo, L., Saxen, R., Yankovich, T.L., Brown, J.E., (2009). Environmental Protection: Transfer Parameters for Reference Animals and Plants. ICRP Publication 114. Ann. ICRP Vol 39 (6). Elsevier. http://www.icrp.org/publication.asp?id=ICRP%20Publication%20114

Strand, P., Aono, T., Brown, J. E., Garnier-Laplace, J., Hosseini, A., Sazykina, T., Steenhuisen, F., Vives i Batlle, J., (2014). Assessment of Fukushima-derived radiation doses and effects on wildlife in Japan. Environ. Sci. Technol. Lett. 1, 198−203.

Tagami, K., Uchida, S., (2010). Can elemental composition of crop leaves be used to estimate radionuclide transfer to tree leaves? Radiat. Environ. Biophys. 49, 583-590.doi:10.1007/s00411-010-0316-y

Takata, H., Aono, T., Tagami, K., Uchida, S., (2010). Concentration ratios of stable elements for selected biota in Japanese estuarine areas. Radiat. Environ. Biophys. 59, 591-601.doi:10.1007/s00411-010-0317-x

USDoE, (2002). A Graded Approach for Evaluating Radiation Doses to Aquatic and Terrestrial Biota. U.S. Department of Energy, Washington D.C., U.S.A. Technical Standard DOE-STD-1153-2002.

Vives i Batlle, J., Wilson, R.C., McDonald, P., (2007). Allometric methodology for the calculation of biokinetic parameters for marine biota. Sci. Total Environ. 388, 256-269.

Vives Batlle, J., Wilson, R.C., Watts, S.J., Jones, S.R., McDonald, P., Vives-Lynch, S., (2008). Dynamic model for the assessment of radiological exposure to marine biota. J. Environ. Radioact. 99, 1711-1730.

Vives i Batlle, J., Wilson, R.C., Watts, S.J., McDonald, P., Craze, A., (2009). Derivation of allometric relationships for radionuclides in marine phyla. Radioprotection 44, 47-52.

Vives i Batlle, J., (2012). Radioactivity in the Marine Environment. In: Meyers, R.A. (Ed.), Encyclopaedia of Sustainability Science and Technology, Springer Science & Business Media, LLC, pp. 8387 – 8425.

Vives i Batlle, J., Aono, T., Brown, J.E., Hosseini, A., Garnier-Laplace, J., Sazykina, T., Steenhuisen, F., Strand, P., (2014). The impact of the Fukushima nuclear accident on marine biota: retrospective assessment of the first year and perspectives. Sci. Total Environ. 487, 143–153.

Vives i Batlle, J. (2015). Dynamic modelling of radionuclide uptake by marine biota: application to the Fukushima nuclear power plant accident. J. Environ. Radioact. http://dx.doi.org/10.1016/j.jenvrad.2015.02.023

Whicker, F.W., Schultz, V., (1982). Radioecology: nuclear energy and the environment, Vol II. CRC Press, Boca Raton, FL.

Yankovich, T., Beresford, N.A., Fesenko S., Fesenko, J., Phaneuf, M., Dagher, E., Outola, I., Andersson, P., Thiessen, K., Ryan, J., Wood, M.D., Bollhöfer, A., Barnett, C.L., Copplestone, D., (2013). Establishing a database of radionuclide transfer parameters for freshwater wildlife. J. Environ. Radioact. 126, 299-313. http://dx.doi.org/10.1016/j.jenvrad.2012.07.014

Table 1. Parameters included in the database template.

Parameter
Entry ID
Common name (English)
Latin name
Wildlife group
Ecosystem (Marine, Freshwater, Terrestrial or Riparian)
Radionuclide
Live weight (kg)
Developmental stage (e.g. adult, tadpole etc.)
Compartment (whole organism or specific tissue)
Experiment type
Length of study (d)
Temperature (ºC)
Biological half-life (d) (four columns were included to enable recordings of multiple loss components)
Fraction released (four columns, one for each component of loss)
Number of measurements (made in study) to determine $T_{1/2b}$
Measurement interval (d)
Changeover time (d) (repeated for multiple loss components)
Percentage left at time (t)
Time (t) (d) (referring to the above percentage left)
Organism dimensions (length, width, depth) (m)
Sex
Elimination rate (i.e. k; d^{-1})
Reference
Notes
Comment on if the value has been independently quality controlled

Table 2. A summary by generic ecosystem and wildlife group of the $T_{1/2b}$ values presented in the compiled database.

Wildlife group	Number of entries	Number of species*	Element
Marine			
Annelid	9	≥5	Cd, Cr, Tc
Crustacean	39	≥11	Cd, Co, Cs, I, Pu, Se, Sr, Tc, Zn
Echinoderm#	21	>4	Ca, Co, Cs, Mn, Tc, Zn
Fish	192	≥19	Ce, Co, Cr, Cs, Fe, I, In, Mn, Nb, Ru, Sr, Tc, Zn, Zr
Macroalgae	52	25	Am, Ce, Cs, I, Po, Pu, Sr, Tc, U, Zn
Mollusc	227	≥24	Ag, Am, Cd, Ce, Cm, Co, Cs, I, Mn, Pu, Ru, Sb, Se, Sr, Tc, Zn
Phytoplankton	5	n/a	Am, Pu
Sea anemones/true coral	1	1	Cs
Zooplankton	1	n/a	Am
Freshwater			
Algae	22	≥9	Ce, Co, Cs, Fe, P, Sr, Y
Bryophytes#	12	2	Ag, Am, Co, Cs, I, Mn, Ru
Crustacean	23	4	Am, Co, Hg, Ra, Ru, W
Fish	246	>23	Ag, Am, Ce, Co, Cs, Fe, H, Hg, I, Mn, P, Ra, Rb, Ru, Sr, Zn
Insect larvae	20	4	Am, Co, Cu, Ni, Pb, Ra, Ru, U, Zn
Mollusc	83	≥9	Ag, Am, Ca, Cd, Ce, Co, Cr, Cs, H, Mn, Na, Ra, Ru, S, Zn
Phytoplankton	22	≥3	Ag, Am, Co, Cs, Mn, Ra, Ru, Zn
Reptile	42	1	Sr, Ra
Vascular plant	24	≥8	Am, Ce, Co, Cs, Na, Sr
Zooplankton	36	1	Ag, Am, Co, Cs, Hg, Mn, Ra, Ru
Terrestrial			
Annelid	56	≥9	Cd, Co, Cs, Cu, Hf, Hg, I, Mn, Pb, Sc, Sr, Tb, U, Zn
Arachnid	11	≥6	Ca, Cs, K, Na, P, Zn
Arthropod	119	>53	As, Ca, Co, Cr, Cs, Cu, Fe, I, Ir, K, Na, P, Pb, Rb, Ru, Sr, W, Y, Zn
Bird	4	2	Cs, I
Mammal	522	≥40	Ag, Am, Au, Be, C, Cd, Ce, Cf, Co, Cr, Cs, Eu, Fe, H, Hg, I, In, Ir, K, Mn, Na, Nb, Np, P, Pa, Pb, Po, Pu, Ra, Rb, Ru, Sb, Sc, Se, Sn, Sr, Tb, Te, Th, U, W, Y, Zn, Zr
Mollusc	2	1	Cs, Na
Reptile	29	6	Co, Cr, Cs, Fe, I, Mn, Na, Rb, Zn
Riparian			
Amphibian	15	6	Co, Cs, I, Mn, Rb, Sr, Zn
Bird	32	≥2	Ba, Co, Cr, Cs, I, Se, Zn
Reptile	40	3	Cs, Sr

#The wildlife groups are not included in Copplestone et al. (2013); *where ≥ used some data have been entered with no Latin species name, or as spp. etc..

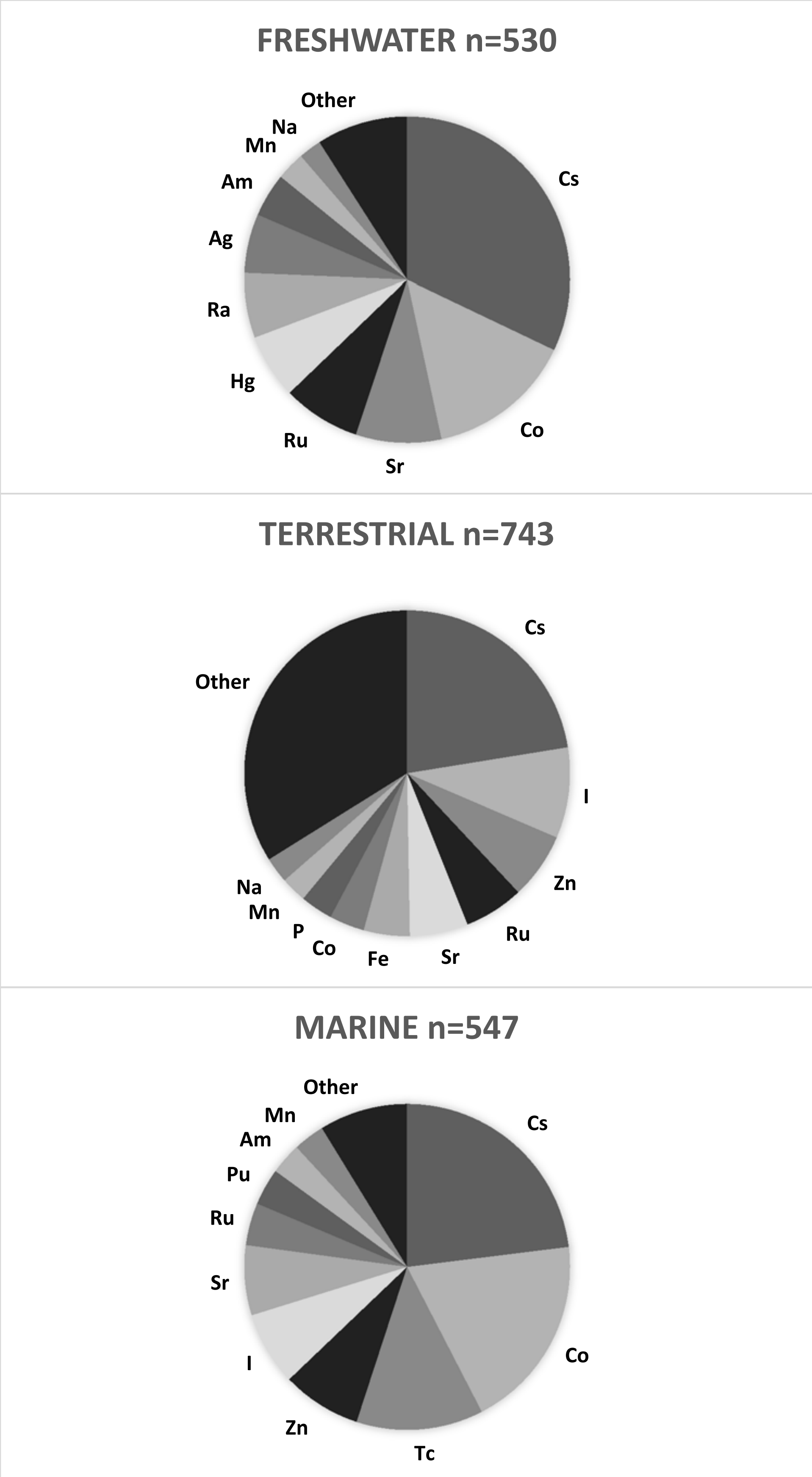

Figure 1. Summary of entries by radionuclide for the three generic ecosystems considered; the 10 elements contributing most entrees for each ecosystem are presented separately.