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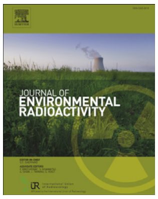

Making the most of what we have: application of extrapolation approaches in radioecological wildlife transfer models

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ABSTRACT

We will never have data to populate all of the potential radioecological modelling parameters required for wildlife assessments. Therefore, we need robust extrapolation approaches which allow us to make best use of our available knowledge. This paper reviews and, in some cases, develops, tests and validates some of the suggested extrapolation approaches.

The concentration ratio ($CR_{product\text{-}diet}$ or $CR_{wo\text{-}diet}$) is shown to be a generic (trans-species) parameter which should enable the more abundant data for farm animals to be applied to wild species.

An allometric model for predicting the biological half-life of radionuclides in vertebrates is further tested and generally shown to perform acceptably. However, to fully exploit allometry we need to understand why some elements do not scale to expected values.

For aquatic ecosystems, the relationship between $\log_{10}(a)$ (a parameter from the allometric relationship for the organism-water concentration ratio) and $\log(K_d)$ presents a potential opportunity to estimate concentration ratios using K_d values.

An alternative approach to the $CR_{wo\text{-}media}$ model proposed for estimating the transfer of radionuclides to freshwater fish is used to satisfactorily predict activity concentrations in fish of different species from three lakes. We recommend that this approach (REML modelling) be further investigated and developed for other radionuclides and across a wider range of organisms and ecosystems.

Ecological stoichiometry shows potential as an extrapolation method in radioecology, either from one element to another or from one species to another.

Although some of the approaches considered require further development and testing, we demonstrate the potential to significantly improve predictions of radionuclide transfer to wildlife by making better use of available data.

1. Introduction

The assessment of the exposure of wildlife to ionising radiation for planned, existing and emergency scenarios requires predictions to be made of the transfer of a wide range of radionuclides to a diversity of species. Most models assessing the exposure of wildlife for regulatory purposes use a simple concentration ratio ($CR_{wo\text{-}media}$) relating the whole organism activity concentration to that in an environmental medium (i.e. soil, air or water) (Beresford et al., 2008a). Other models use radionuclide biological half-lives and transfer from the diet (e.g. USDOE, 2002).

For many of the radionuclide-species combinations that require assessment, there are no empirical data. When empirical data are lacking, predictions are often made using transfer parameter values derived using extrapolation approaches, though clarity on the use of such approaches varies between publications/models. For instance, the $CR_{wo\text{-}media}$ value for an organism of 'similar taxonomy'

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may be assumed (e.g. a mammal value may be used to model birds if data for the latter are lacking) (e.g. Beresford et al., 2008b). Brown et al. (2013) recently evaluated how the most commonly used approaches performed against additional data now available (Copplestone et al., 2013). They concluded that the extrapolation approaches commonly used to date have under-predicted the empirical 95th percentile $\mathrm{CR}_{\text{wo-media}}$ value as often as they have over-predicted. This highlights the need to treat results from these previous extrapolations with caution, but there have been various recent advances that may bring greater confidence in the application of extrapolation methods. In this paper, we assess our ability to extrapolate radioecological data of relevance to wildlife radiological assessments considering these recent advances and future potential.

2. Transfer from the diet to terrestrial vertebrates is a constant across species

The transfer coefficient was first proposed by Ward et al. (1965) to describe the transfer of radiocaesium from the diet to the milk of dairy cattle. The authors defined the transfer coefficient as the ratio between the radiocaesium activity concentration in milk and the daily dietary radionuclide intake. Ward et al. (1965) reported that this parameter exhibited less variability between individual animals within their experimental herd than when transfer was expressed as the total amount of Cs excreted in milk (represented as a percentage of intake). Ward and Johnson (1965) subsequently defined the meat transfer coefficient as the ratio of the ^{137}Cs activity concentration in boneless meat to the dietary daily ^{137}Cs intake.

Following the publications of Ward and co-workers in the 1960s, the transfer coefficient was adopted as the basis for quantifying transfer to milk (F_m, d l^{-1} or d kg^{-1}), and meat and eggs (F_f, d kg^{-1}) for all radionuclides. By the late 1970s to early 1980s, transfer coefficient values were being recommended for most radionuclide-animal product combinations (e.g. Ng, 1982; Ng et al., 1977, 1979, 1982) and the International Atomic Energy Agency (IAEA) recommended their use (IAEA, 1994). These recommended values have been incorporated into many predictive food chain models (e.g. Brown and Simmonds, 1995; Müller and Pröhl, 1993; USNRC, 1977; Yu et al., 2001).

On the basis of the many studies conducted over the approximately 50 years since the transfer coefficient concept was introduced, it has generally been accepted that transfer coefficients for smaller animals are higher than those for larger animals, and that those for adults are lower than those for young (and hence smaller) livestock. For instance, F_f values for sheep meat recommended by IAEA (2010) for many radionuclides are *circa* one order of magnitude higher than those recommended for beef. Similarly, F_m values for goat milk tend to be one order of magnitude higher than those recommended for cow milk. The use of transfer coefficients has also been suggested for wildlife (e.g. Thomas et al., 1994; MacDonald, 1996; Moss and Horrill, 1996) and some models use simple food chains to estimate radionuclide concentrations in wildlife (e.g. USDOE, 2002).

However, it has been suggested that much of the observed difference in $F_{f,m}$ values is a consequence of differences in dry matter intake, between animals of differing age or species, rather than any difference in radionuclide transfer (e.g. Smith and Beresford, 2005; Galeriu et al., 2007; Beresford et al., 2007). The rational for this is that the transfer coefficient is defined as:

$$F_f = \frac{\text{Radionuclide activity concentration in meat } (\text{Bq kg}^{-1})}{\text{Daily dry matter intake } (\text{kg d}^{-1}) \times \text{Radionuclide activity concentration of the diet} (\text{Bq kg}^{-1}\text{ DM})}$$

Consequently, the concentration ratio ($\mathrm{CR}_{\text{meat-diet}}$) is equal to:

$$\mathrm{CR}_{\text{meat-diet}} = F_f\left(\text{d kg}^{-1}\right) \times \text{Daily dry matter intake } \left(\text{kg d}^{-1}\right)$$

The above equations are for meat but a similar derivation can be performed for milk or eggs.

A between species similarity in *CR* values for animal derived food products should not be surprising, given that the concentrations of many elements in meat, or milk, are similar across species (Mertz, 1986, 1987). A particular advantage of being able to assume that the milk or meat *CR* for many radionuclides varies little between species is that generic values can be derived for animals for which no data are currently available. Recognising this, the IAEA (2010) summarised milk and meat *CR* values, as well as transfer coefficients.

We would also expect that *CR* values for wildlife would vary little between species (Beresford et al., 2004) and would be similar to those of farm animals. To test this hypothesis, Table 1 presents Cs $\mathrm{CR}_{\text{meat-diet}}$ values for seven herbivorous species of wild mammals and birds. The $\mathrm{CR}_{\text{meat-diet}}$ values for these species are similar to those for the meat of farm animals in IAEA (2010), which presents a generic value of 0.39 based on data for four farm animal species. Since Cs is relatively homogenously distributed throughout the body tissues (Yankovich et al., 2010a), it can then be assumed that, for Cs $\mathrm{CR}_{\text{meat-diet}} \approx \mathrm{CR}_{\text{org-diet}}$ (where $\mathrm{CR}_{\text{org-diet}}$ is the ratio of the radionuclide activity concentration in the whole organism to that in its diet). Currently there are few data with which to test our hypothesis for the transfer of other radionuclides to wild animals. For many elements other than Cs, distribution is not homogenous throughout the body tissues. However, for such elements an assumption that the distribution within the body was similar across animal species would be reasonable (e.g. Sr accumulates in the bone of all vertebrates).

3. Allometry

Size affects rates of biological processes from cellular metabolism to population dynamics (Peters, 1983; Hoppeler and Weibel, 2005). The dependence of a biological variable (Y) on body mass (M) is typically characterised by an allometric scaling law. There are several allometric equations that can be proposed, the simplest being to assume that:

$$Y = aM^b$$

where a and b (the allometric exponent) are constants, b is dimensionless and a has the units of the variable, Y, per mass to the power of $-b$.

Kleiber (1932) found that basal metabolic rate (measured as heat production) across 13 groups of mature animals, ranging from

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