Conference or Workshop Item

Johansen, M.P.; **Barnett, C.L.**; **Beresford, N.A.**; Brown, J.E.; Černe, M.; **Howard, B.J.**; Kamboj, S.; Keum, D-K.; Smodiš, B.; Twining, J.R.; Vandenhove, H.; Vives i Batlle, J.; Wood, M.D.; Yu, C.. 2011 Dose modelling comparison for terrestrial biota: IAEA EMRAS II Biota Working Group's Little Forest Burial Ground scenario. [Lecture] In: *Radioecology & Environmental Radioactivity - Environmental & Nuclear Renaissance, Hamilton, Ontario, Canada, 19-24 June 2011*. Hamilton, Ontario, McMaster University

Dose Modelling Comparison for Terrestrial Biota: IAEA EMRAS II Biota Working Group's Little Forest Burial Ground Scenario

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Radiological doses to terrestrial biota have been examined in a model inter-comparison study that emphasised the identification of factors causing variability in dose estimation. Radiological dose rates were modelled for ten species representing a diverse range of terrestrial plant and animals with varying behavioural and physical attributes. Dose to these organisms may occur from a range of gamma (Co-60, Cs-137), beta (Sr-90) and alpha (Th-232, U-234 and U-238, Pu-238, Pu-239/240 and Am-241) emitting radionuclides. Whilst the study was based on a specific site - the Little Forest Burial Ground, New South Wales, and Australia - it was intended to be representative of conditions at sites throughout the world where low levels of radionuclides exist in soil due to waste disposal or similar activities.

The design of the present study made use of the findings of previous modelling exercises [1-5] and examined how variation in dose estimates related to the following themes:

- soil-to-organism transfer and calculation methods;
- exposure pathway;
- progeny;
- dose calculation.

Participants included model-users with various levels of experience including the code developers/custodians for the ERICA Tool, FASTer-lite, K-Biota and RESRAD-BIOTA dose assessment codes described in Beresford et al. [1] and Vives i Batlle et al. [4]. All participants worked from the same set of site data including soil concentrations and species attributes, but were unconstrained with respect to transfer method, exposure and dose calculation assumptions. Model results included the prediction of internal, external and total weighted dose rates as well as whole-organism tissue concentrations. Variation among participant's approaches was quantified, for each species or radionuclide, by assessing the dissimilarity among modeling results expressed as normalized relative differences from the mean (Table 1). All codes provided for the use of probabilistic treatment of key parameters of soil concentrations and other input data to better encompass variability and uncertainty.

<u>Soil-to-organism transfer</u> has been identified in previous work as the foremost factor when considering sources of variation in typical biota dose estimation [2]. The present study encompassed a range of modelling approaches to derive soil-to-organism transfer including: allometric models; biokinetic compartment modelling; and use of whole-organism concentration ratios (CR_{wo}) from model defaults, and reference soil-to-organism concentration ratios ($CR_{wo\text{-}soil}$) from literature or other sources such as the draft IAEA handbook on radionuclide transfer parameters for wildlife. These multiple approaches resulted in a range of $CR_{wo\text{-}soil}$ values that varied from less than one order of magnitude for any nuclide for common organisms such as earthworm, up to four orders of magnitude for less studied species such as echidna and wallaby.

When considering variation in dose across all radionuclides, species having relatively high variation in transfer (e.g. yam) generally also had relatively high variation in internal and total dose rates (Table 1). In contrast, species with low variation in transfer (e.g. earthworm) had relatively low variation in dose rates.

Table 1 Overall measure of dissimilarity among modeling results expressed as arithmetic means, across all radionuclides, of normalized relative differences between approaches (see paper for specific statistical tests). Lower values indicate more agreement among the participant's results, higher values indicate more variation.

	Soil-to-organism transfer ($CR_{wo-soil}$)	Whole-organism Tissue Concentration	Internal dose rates	External dose rates	Total dose rates	Ratios of St. dev./mean on probabilistic distributions	
						CRs	Tot dose
Grass	0.44	0.44	0.65	0.38	0.61	0.51	0.34
Acacia	0.16	0.41	0.66	0.47	0.57	0.20	0.19
Yam	0.59	0.60	0.67	0.43	0.64	0.45	0.26
Earthworm	0.15	0.16	0.49	0.33	0.47	0.09	0.15
Insect	0.27	0.28	0.54	0.38	0.49	0.26	0.18
Goanna	0.65	0.64	0.64	0.40	0.60	0.19	0.10
Raven	0.34	0.57	0.64	0.47	0.61	0.22	0.71
Echidna	0.58	0.44	0.65	0.38	0.61	0.37	0.34
Fox	0.58	0.44	0.65	0.38	0.61	0.28	0.34
Wallaby	0.58	0.44	0.65	0.38	0.61	0.29	0.34

To assess variation by specific radionuclide type, we used sequential regression analysis of tissue concentrations and doses with key input parameters (e.g. $CR_{wo-soil}$ values) after normalising soil concentrations and other parameters as appropriate. Using yam as an example, total dose rates were, in this instance, highly proportional to $CR_{wo-soil}$ values for beta emitters (e.g. Sr-90 R^2=0.96) and relatively proportional for alpha emitters (e.g. Th-232 R^2=0.76). In contrast, the total doses from gamma emitters were not proportional to $CR_{wo-soil}$ values for yam (e.g. Co-60 R^2=0.12) which is consistent with expected results in the instance where a subsurface organism is surrounded by soil contaminated with a strong gamma emitter. A non-proportional result was also seen when considering ground-surface dwelling insects and similar instances where the organism was located in or on soil contaminated with gamma emitting radionuclides in concentrations sufficient for external dose to dominate over the internal dose associated with transfer.

Residuals above and below regression lines indicate additional variation introduced by other factors, such as whether or not progeny are included as dose contributors, and are each considered below. Using this approach, the effective variation in whole-organism total dose rates attributed solely to soil-to-organism transfer across all ten species and nine radionuclides ranged from none for gamma emitters, to more than three orders of magnitude for alpha emitters.

The importance of soil-to-organism transfer was further tested by assessing results from the same model code, or model type. Three participants used the ERICA Tool as well as the same dose calculation parameters, but used different sources for $CR_{wo-soil}$ values. Whilst their results generally grouped together, they also indicated differences of up to two orders of magnitude. In addition, two participants used similar kinetic-allometric approaches to derive $CR_{wo-soil}$ values but with sometimes differing assumptions within the allometric equations. In many instances, the resulting tissue concentrations and doses were similar (e.g. U-234, U-238 for echidna, fox and wallaby). In other instances, however, they diverged up to two orders of magnitude (e.g. Pu-238, Pu-239, and Am-241 in echidna) due to the absence of consistent allometric methodology and parameters. These comparisons among similar models, and model types, highlight the importance of choosing the most representative transfer parameters for the conditions being modelled regardless of model type.

Overall, the results quantified in this study support the general understanding that soil-to-organism transfer is the dominant factor in determining variation in total dose outcomes to terrestrial biota, with potentially important exceptions where the external dose from gamma emitters dominates over internal dose from transferred radionuclides.

Exposure configuration assumptions were also examined as sources of variation, particularly with respect to how exposure to organisms can be conceptualized differently by the model users. The present study considered four zones with differing soil contaminant levels. In most instances, all participants used the same factors governing which zones of contamination were accessed by particular species. However, one tree species (Acacia) was described in the scenario as accessing the subsurface buried waste (higher contaminant levels) directly with a portion of its roots, whilst its remaining roots and above-ground portions accessed only the surface soils of the waste site cap which have orders of magnitude lower contaminant levels. This exposure configuration represents a realistic condition at shallow waste sites where organisms, both stationary and mobile, can access zones with differing contamination levels through rooting, burrowing, or regular movement across localized waste areas as part of their habitual routine. However, such a configuration is not generally available in models which have focused on transfer and dose assuming homogeneously contaminated soil.

To address the Acacia scenario, participants generally used similar $CR_{wo\text{-}soil}$ values (relatively low dissimilarity value of 0.16 in Table 1), but used a range of model exposure assumptions, and post-model manipulations, which yielded relatively high variation in total dose (dissimilarity value of 0.57 in Table 1). The corresponding range in total dose rates, attributed to exposure configuration, was approximately two orders of magnitude across all radionuclides. One participant considered dose to roots alone, which when compared dose to the trunk and upper portions, resulted in total dose differences of typically two orders of magnitude among radionuclides.

The Acacia was the organism with the most complex configuration in this scenario. However, results for other species (e.g., goanna and raven) also included variation associated with differing exposure configuration assumptions related to the proportion of time spent on the ground exposed to soil contaminants, versus time spent in trees away from contaminated soil. These results demonstrate how realistic exposure configurations may not easily fit into current models, and that differing interpretations of exposure by model users can lead to order-of-magnitude variation in dose estimates.

Differences in progeny assumptions contributed up to one order of magnitude variation in the present scenario. Of the radionuclides tested, the highest relative standard deviation (1.62) was associated with Th-232 (Table 2), indicating the largest dissimilarity among participant results. The variation was largely due to differing Th-232 model progeny assumptions among participants in contrast with other radionuclides where progeny assumptions were similar. The RESRAD-BIOTA code generally includes dose contribution from ingrown progeny when the half-life of the progeny is relatively short compared to that of the parent. In this instance, the RESRAD-BIOTA dose calculations for Th-232 included contributions from Ra-228, Ac-228 and Th-228 as the half-lives of these progeny are much less than that of the parent and many times less than the ~40 years that the contamination has been in place at the waste site. The resulting dose estimates were approximately one order of magnitude higher than that of other participants who did not include these progeny. The variation associated with Th-232 was much higher than that from the other radionuclides considered in this study. These results indicate the potential for order-of-magnitude variation associated with progeny assumptions for a typical waste site which may vary depending on the specific radionuclides and timeframes involved.

Table 2 Relative standard deviation of normalised model results for a given species, treating all of the study species data for each radionuclide as a set. Higher values indicate more variation among participant results.

	CR	Tissue conc.	Internal dose rates	External dose rates	Total dose rates
Co-60	0.47	0.66	0.77	0.43	0.40
Sr-90	1.15	1.46	1.49	1.59	1.39
Cs-137	0.82	0.75	0.83	0.42	0.57
Th-232	0.97	1.40	1.62	0.50	1.62
U-234	1.26	1.31	1.35	0.48	1.35
U-238	1.17	1.31	1.36	1.53	1.35
Pu-238	0.70	0.80	0.87	1.08	0.88
Pu-239	0.75	0.79	0.87	0.54	0.87
Am-241	1.03	1.14	1.12	0.53	1.10

Dose calculation parameters, including radiation weighting factors and dose conversion coefficients (DCCs), had a combined contribution to variation in total dose rates of up to one order of magnitude as attributed in this study. This is consistent with a recent study of ten currently available biota dose modelling codes indicating variation of ±30% for internal dose rates, and within one order of magnitude for external dose rates, associated with the DCCs for 74 radionuclides [4]. The present study did not separate the relative contributions to dose variation attributed to DCCs versus that from radiation weighting factors. Most study participants used radiation weighting factors values of 10, 3, and 1 for alpha, low-energy beta, and high-energy beta plus gamma emissions respectively (defaults in the ERICA Tool), with two participants using 20, 1, 1 (defaults in RESRAD-BIOTA). These weighting factors generally relate linearly to internal dose rates and therefore the expected effect of the above differences is consistent with the observed variation of less than one order of magnitude.

Probabilistic assessment capability has been included in some biota dose assessment codes. Soil concentrations and $CR_{wo\text{-}soil}$ values may be entered as distributions, instead of single values, for use in Monte Carlo, Latin Hypercube, and other statistically-based methods. In the present study, most participants made use of probabilistic functions, particularly with respect to soil concentration input and $CR_{wo\text{-}soil}$ input. The relative spread of distributions was measured as a range (5^{th} to 95^{th}) for each model outcome, and compared across all outcomes as standard deviation divided by mean (Table 1). The resulting ranges (5^{th} to 95^{th}) of total doses were smaller for gamma emitters, typically 1-2 orders of magnitude on average, with some exceptions to three orders of magnitude. The beta emitter (Sr-90) had relatively large ranges, approximately three orders of magnitude, but including spreads of up to five orders of magnitude. Alpha emitter spreads were typically approximately 2-3 orders of magnitude with some reaching 3-4 orders of magnitude. The spread in total dose distributions partly reflected that of the variability in soil data used in the scenario. For example, the highest spread in total dose distributions in Table 1 was that of raven, which had dose exposure exclusively from a soil zone with relatively high uncertainty. However, this study did not control for the number of different parameters treated as probability distributions, or how participant codes combined uncertainty, which can have a multiplicative effect on overall spread.

Results of the present study provide estimates of the variation in model outcomes attributed to typical parameters used in biota dose modelling. Whilst the variation estimates here result from a particular scenario, they are intended to provide insight into the general case of estimating biota doses at terrestrial sites. A range of approaches and models were used for dose estimation for a wide range of terrestrial biota organism types considering alpha, beta, and gamma emitting radionuclides. Results are summarized as follows (in decreasing order of influence):

- The dominant factor in determining variation in total dose outcomes was soil-to-organism transfer with up to three orders of magnitude of total dose rate variation attributed to solely to transfer. However transfer had minimal influence on total dose rates in a few instances where the external dose from gamma emitters dominated over internal dose from transferred radionuclides.
- Exposure configuration assumptions varied among participants in some instances causing up to two orders of magnitude variation in total dose rates.
- Differences in progeny assumptions contributed up to one order of magnitude variation in the present scenario, primarily from differing treatment of progeny ingrowth for Th-232.
- Dose calculation parameters, including radiation weighting factors and dose conversion coefficients (DCCs), had a combined contributed variation in total dose rates of up to, but typically less than one order of magnitude.

These results highlight the need for effective dissemination of representative $CR_{wo\text{-}soil}$ information, particularly in emerging/evolving biota transfer databases. The exercise suggests the need for continued evaluation of the underlying mechanisms governing soil-to-organism transfer leading to more confident uses of $CR_{wo\text{-}soil}$ values and kinetic-allometric parameters appropriate for site conditions. Additional empirical research is needed to improve data for less well studied species, and to improve the methods for estimating transfer rates when data are lacking for species of interest. The exposure pathways and configurations available in current codes are limited when considering instances where organisms, both stationary and mobile, can access different contamination zones through rooting, burrowing, or routine periodic use of localized waste areas as part of their habitual routine.

References

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