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Predicting the radiation exposure of terrestrial wildlife in the Chernobyl exclusion zone: an international comparison of approaches

N A Beresford[1,10], C L Barnett[1], J E Brown[2], J-J Cheng[3], D Copplestone[4], S Gaschak[5], A Hosseini[2], B J Howard[1], S Kamboj[3], T Nedveckaite[6], G Olyslaegers[7], J T Smith[8], J Vives i Batlle[9], S Vives-Lynch[9] and C Yu[3]

[1] Centre for Ecology and Hydrology Lancaster, Lancaster Environment Centre, Library Avenue, Bailrigg, Lancaster LA1 4AP, UK
[2] Norwegian Radiation Protection Authority, Department of Emergency Preparedness and Environmental Radioactivity, Grini næringspark 13, Postbox 55, No-1332 Østeras, Norway
[3] Argonne National Laboratory, Building 900, 9700 South Cass Avenue, Argonne, IL 60439-4832, USA
[4] England and Wales Environment Agency, Richard Fairclough House, Knutsford Road, Warrington, Cheshire WA4 1HG, UK
[5] International Radioecology Laboratory, Ukraine
[6] Institute of Physics, Radiation Protection, Savanoriu Avenue 231, LT-02053 Vilnius, Lithuania
[7] Belgian Nuclear Research Centre, SCK.CEN, Radioecology Section, Radiation Protection Department, Boeretang 200, B-2400, Mol, Belgium
[8] School of Earth and Environmental Sciences, University of Portsmouth, Burnaby Building, Burnaby Road, Portsmouth PO1 3QL, UK
[9] Westlakes Research Institute, Westlakes Scientific Consulting Ltd., The Princess Royal Building, Westlakes Science and Technology Park, Moor Row, Cumbria, CA24 3LN, UK

E-mail: nab@ceh.ac.uk

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Abstract

There is now general acknowledgement that there is a requirement to demonstrate that species other than humans are protected from anthropogenic releases of radioactivity. A number of approaches have been developed for estimating the exposure of wildlife and some of these are being used to conduct regulatory assessments. There is a requirement to compare the outputs of such approaches against available data sets to ensure that they are robust and fit for purpose. In this paper we describe the application of seven approaches for predicting the whole-body (^{90}Sr, ^{137}Cs, ^{241}Am and Pu isotope) activity concentrations and absorbed dose rates for a range of terrestrial species within the Chernobyl exclusion zone. Predictions are compared against available measurement data, including estimates of external dose rate recorded by thermoluminescent dosimeters attached to rodent species. Potential reasons

[10] Author to whom any correspondence should be addressed.

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for differences between predictions between the various approaches and the available data are explored.

1. Introduction

In response to international recommendations (IAEA 2006, ICRP 2007, NEA 2007, IUR 2002), and to address the requirements of existing national legislation in some countries, a number of approaches have been developed specifically to estimate the exposure of non-human biota to ionising radiation. Some of the approaches are currently being used within the national regulatory frameworks of a number of countries (see Beresford *et al* 2008c for an overview).

The International Atomic Energy Agency (IAEA) initiated the Biota Working Group (BWG) within its Environmental Modelling for Radiation Safety (EMRAS) programme (IAEA 2010a) in response to the need for a forum to compare and improve the growing number of models/approaches, either already developed or under development, to estimate the exposure of wildlife to ionising radiation (Beresford *et al* 2008d, 2009). In total, 15 approaches were applied in the various modelling exercises of the BWG (IAEA 2010b). These ranged from freely available assessment tools (software) considering multiple ecosystems and enabling at least exposure (dose) and risk to be estimated, through moderately comprehensive in-house approaches (which may be encapsulated within a model), to more specific dosimetric or transfer tools, including adaptation of existing models developed for human exposure estimates. The methodologies evaluated by the BWG include most of those that we are aware of which are being applied by regulators and industry to conduct assessments in response to national requirements.

In previous papers, we have reported BWG exercises which compared the dosimetric (Vives i Batlle *et al* 2007) and transfer components (Beresford *et al* 2008e) of participating models. The exercise to compare predicted unweighted whole-body absorbed dose rates for a selection of the proposed ICRP Reference Animal and Plant geometries demonstrated that all the 11 participating approaches generally estimated comparable internal dose rates even though different assumptions were made (Vives i Batlle *et al* 2007). Variation was greater for the estimation of external dose rates, most notably for α- and low-energy β-emitters (e.g. from ^{3}H, plutonium and some naturally occurring radionuclides). However, external exposure of biota by α- and low-energy β-emitters is of little radiological significance due to the low range of α- and β-emitters in matter.

The comparison of predicted activity concentrations (Beresford *et al* 2008e) in a range of freshwater and terrestrial biota by eight of the participating models, assuming 1 Bq per unit media, demonstrated considerably more variability than the comparison of unweighted dose estimates. For many radionuclide-reference organism combinations, variability in predictions covered three or more orders of magnitude. Predictions were often most variable for poorly studied organisms, such as fish egg, bird egg, duck, amphibian and aquatic mammals. Some of the more extreme variability could be explained by the use of 'guidance' methodology to provide values by a number of approaches in the absence of data derived transfer parameters (see model descriptions below).

In this paper, we report the application of a number of the models participating in the BWG to a terrestrial scenario enabling a comparison of predictions with measured data. The data originate from studies conducted within the exclusion zone surrounding the Chernobyl nuclear power complex (Ukraine). In addition to enabling model-data comparisons, it was hoped that the exercise would enable the influence of user decisions to be evaluated. A companion paper compares application of the models to a freshwater site (Perch Lake, Canada) for which extensive data were available (Yankovich *et al* 2010). Further evaluations of the developing approaches will be conducted by the Biota Modelling Group as part of the IAEA EMRAS II programme (www-ns.iaea.org/projects/emras/emras2/default.htm#3).

2. Scenario description

A database of radionuclide activity concentrations in a range of biota was compiled from the open literature (Chesser *et al* 2000, Gaschak *et al* 2003, Jagoe *et al* 2002, Ryabokon *et al* 2005) and data holdings of the International Radioecology Laboratory (IRL) (including those described in Gaschak *et al* (2003)) and other BWG members (see Beresford *et al* 2005, 2008b). By preference, soil activity concentrations were collated from the same reference sources or were provided for the sampling sites by IRL. If this was not possible, soil concentrations were derived using deposition maps within a geographical information system and assuming appropriate home ranges for different animal species (Beresford *et al* 2005). Where reported soil results were given as $\mathrm{Bq\,m^{-2}}$, a soil bulk density of 1100 $\mathrm{kg\,m^{-3}}$ (UIAR 2001) and sampling depth of 10 cm were assumed to estimate a soil activity concentration. Results for plutonium isotopes in soil (and biota) were available for a number of isotope combinations (e.g. ^{238,239,240}Pu, ^{239,240}Pu etc). To determine isotope specific values, ratios in the release (Smith and Beresford 2005) were assumed to be applicable throughout the exclusion zone (^{238}Pu activities were corrected for decay). Soil concentrations of both ^{90}Sr and ^{137}Cs associated with the available biota data ranged over four orders of magnitude.

Available data covered a range of biota types including: graminaceous vegetation; invertebrates; birds; a wide range of mammal species (from small rodents to deer and carnivorous species) and amphibians (see table 1). The majority of collated data were for ^{137}Cs and ^{90}Sr, although some data were also available for actinide isotopes in small mammals and birds. The majority of activity concentration data selected for inclusion within the scenario were for multiple measurements (i.e. an observed mean and standard deviation were available or could be estimated). However, for a few data (predominantly for birds) only one measurement was available.

One of the requested outputs of the exercise was whole-organism activity concentrations. However, for larger animals, reported results are often tissue specific. To generate whole-body activity concentrations for comparison with the model outputs from the exercise it was assumed that: (i) ^{137}Cs activity concentrations in muscle were equal to those in whole-body; (ii) 90% of the whole-body ^{90}Sr burden was in bone, and that bone contributes 10% and 7% of the whole-bodyweight of mammals and birds, respectively by fresh weight. Some small mammal results were available as dry matter activity concentrations only; a conversion factor of 0.25 was applied to generate fresh weight activity concentration values from such data.

Dose rate estimates from studies in which thermoluminescent dosimeters (TLDs) were attached to species of small mammals were also available for five data entries (Chesser *et al* 2000, Beresford *et al* 2008b).

Participants were provided with a spreadsheet containing all available soil concentrations and requested to predict the whole-organism activity concentrations in biota. Internal, external and total unweighted absorbed dose rates were also requested for a subset of the data (typically one example of each species). Table 1 summarises the predictions which were requested by species; species are subsequently referred to by their Latin name. The full scenario description as provided to participants can be found in IAEA (2010b). The description provided some limited data for water activity concentrations for use in predictions of amphibian whole-body activity concentrations if required. The scenario did not specify assumptions that participants should make for potential model inputs such as occupancy factors or dietary intakes. Instead, useful world-wide websites from which information on animal behaviour could be acquired were provided within the scenario description.

Table 1. Number of predictions requested for the Chernobyl scenario summarised by species.

		Number of predictions					
Species	Common name (English)	^{90}Sr	^{137}Cs	Pu[a]	^{241}Am	Dose rate	TLD[b]
Aegithalos caudatus	Long-tailed tit	—	—	1	—	1	—
Apodemus flavicollis	Yellow necked mouse	5	5	1	—	2[c]	2
Apodemus sylvaticus	Wood mouse	1	1	—	—	1	—
Canis lupus	Wolf	2	2	—	—	1	—
Capreolus capreolus	Roe deer	7	7	—	—	1	—
Clethrionomys glareolus	Bank vole	7	6	2	1	2[c]	2
Erithacus rubecula	Robin	2	2	—	—	1	—
Hirundo rustica	Barn swallow	1	1	—	—	1	—
Lacerta agilis	Sand Lizard	1	1	—	—	1	—
Microtus arvalis	Common vole	2	2	—	—	1	—
Microtus oeconomus	Root vole	2	3	—	—	1	1
Microtus spp.	Vole species	1	1	1	—	1	1
Parus major	Great tit	2	2	1	—	1	—
Perdix perdix	Partridge	—	2	—	—	1	—
Rana esculenta	Edible frog	—	2	—	—	1	—
Rana terrestris	Brown frog	2	4	—	—	1	—
Sicista betulina	Northern birch mouse	1	1	—	—	1	—
Sorex araneus	Common shrew	5	5	—	—	1	—
Sturnus vulgaris	Starling	1	1	—	—	1	—
Sus scrofa	Wild boar	9	9	—	—	1	—
	Beetles	1	1	—	—	1	—
	Grassy vegetation	4	4	—	—	1	—

[a] Pu isotopes varied between data sources. [b] Participants were requested to predict the dose rate as would be recorded by a TLD attached to these animals. [c] More than one estimate requested for these species as TLD measurements available.

3. Application of participating models

The seven models which were applied to this exercise are all described in detail elsewhere and we will not repeat their description here. Below details of the application of each model to this exercise (including parameter values) are presented together with a brief overview of each model and references for their comprehensive descriptions.

To determine internal and external dose conversion coefficients (DCCs) relating unweighted absorbed dose to media or biota activity concentrations most approaches define organisms as simple size/mass dependent three-dimensional phantoms (i.e. ellipsoids and cylinders); Vives i Batlle *et al* (2007) presents a discussion and evaluation of the dosimetric components of most of the participating models. Organism dimensions and masses assumed by participants applying each model are presented in table 2. Note the considerable range in masses and dimensions used by the various participants is largely the consequence of default model parameters being used for given organism types by some participants compared to species specific values being derived by others. For instance, whilst the ERICA Tool default bird geometry, represented by a duck, has a mass of 1.3 kg some participants used a more realistic mass of $<$10 g for *A. caudatus* (see table 2).

Many of the models predict whole-organism activity concentrations using concentration ratios (CR) where:

$$\mathrm{CR} = \frac{\text{Activity concentration in biota whole-organism (Bq kg}^{-1}\text{ fresh weight (fw))}}{\text{Activity concentration in soil (Bq kg}^{-1}\text{ dry weight (d}w\text{))}}.$$

Table 2. Body masses and dimensions as assumed for each model application (note D-Max makes no assumptions with regard to these parameters see section 3.7).

Species	EA R&D128		ERICA		LIETDOS-BIOTA		RESRAD-BIOTA		FASTer-EPIC Doses 3D		DosDimEco	
	Mass (g)	Dimensions (cm)	Mass (g)	Dimensions (cm)	Mass (g)	Dimensions (cm)	Mass (g)	Dimensions (cm)	Mass (g)	Dimensions (cm)	Mass (g)	Dimensions (cm)
A. caudatus	1500	35 × 15 × 15	1260	30 × 10 × 8	1320	30 × 10 × 8	8.5	10 × 2 × 2	9.3	4.8 × 2.2 × 2.1	25	5 × 1.6 × 1.6
A. flavicollis	20	10 × 2 × 2	314	20 × 6 × 5	330	20 × 6 × 5	30	10 × 2 × 2	34	7.2 × 3 × 3	25	5 × 1.6 × 1.6
A. sylvaticus	20	10 × 2 × 2	314	20 × 6 × 5	330	20 × 6 × 5	30	10 × 2 × 2	20	6.8 × 2.4 × .4	25	5 × 1.6 × 1.6
C. lupus	5500	67 × 35 × 18	6.6[eis] 2.5×10^5[ieo]	n/s 130 × 60 × 60[ieo]	—	—	4.1×10^4	50 × 26 × 13[e] 100 × 42 × 33[i]	4.5×10^4	86 × 24 × 24	8.0×10^4	80 × 20 × 0
C. capreolus	800	30 × 15 × 10	2.5×10^5	130 × 60 × 60	2.45×10^5	130 × 60 × 60	n/s	50 × 26 × 13[e] 100 × 42 × 33[i]	1.8×10^4	70 × 32 × 15	3.5×10^4	70 × 22.5 × 22.5
C. glareolus	20	10 × 2 × 2	314	20 × 6 × 5	330	20 × 6 × 5	23	10 × 2 × 2	23.5	7.4 × 2.8 × 2.2	25	5 × 1.6 × 1.6
E. rubecula	1500	35 × 15 × 15	1260	30 × 10 × 8	1320	30 × 10 × 20	19	10 × 2 × 2	18.1	6 × 3 × 2.4	25	5 × 1.6 × 1.6
H. rustica	1500	35 × 15 × 15	1260	30 × 10 × 8	1320	30 × 10 × 20	19	10 × 2 × 2	—	—	25	5 × 1.6 × 1.6
L. agilis	2260	120 × 0.6 × 0.6	744	116 × 3.5 × 3.5	—	—	12	10 × 2 × 2	—	—	—	
M. arvalis	20	10 × 2 × 2	314	20 × 6 × 5	330	20 × 6 × 5	50	10 × 2 × 2	—	—	25	5 × 1.6 × 1.6
M. oeconomus	20	10 × 2 × 2	314	20 × 6 × 5	330	20 × 6 × 5	50	10 × 2 × 2	50	10.6 × 3 × 3	25	5 × 1.6 × 1.6
Microtus spp.	20	10 × 2 × 2	314	20 × 6 × 5	330	20 × 6 × 5	23	10 × 2 × 2	—	—	25	5 × 1.6 × 1.6
P. major	1500	35 × 15 × 15	1260	30 × 10 × 8	1320	30 × 10 × 20	18	10 × 2 × 2	18.1	6 × 3 × 2.4	25	5 × 1.6 × 1.6
P. perdix	1500	35 × 15 × 15	1260	30 × 10 × 8	1320	30 × 10 × 20	395	10 × 2 × 2[e] 45 × 8.7 × 4.9[i]	—	—	310	20 × 6 × 5
R. esculenta	2260	120 × 0.6 × 0.6	31.4	8 × 3 × 2.5	33	8 × 3 × 2.5	47	10 × 2 × 2[e] 45 × 8.7 × 4.9[i]	56	7.6 × 4.4 × 3.2	—	—
R. terrestris	2260	120 × 0.6 × 0.6	31.4	8 × 3 × 2.5	33	8 × 3 × 2.5	23	10 × 2 × 2[e] 45 × 8.7 × 4.9[i]	22.6	6 × 3 × 2.4	—	—
S. betulina	20	10 × 2 × 2	314	20 × 6 × 5	33	8 × 3 × 2.5	30	10 × 2 × 2	—	—	25	5 × 1.6 × 1.6
S. araneus	20	10 × 2 × 2	314	20 × 6 × 5	33	8 × 3 × 2.5	10	10 × 2 × 2	9.5	5.6 × 1.8 × 1.8	25	5 × 1.6 × 1.6
S. vulgaris	1500	35 × 15 × 15	1260	30 × 10 × 8	1320	30 × 10 × 20	75	10 × 2 × 2[e] 45 × 8.7 × 4.9[i]	—	—	25	5 × 1.6 × 1.6
S. scrofa	5500	67 × 35 × 18	2.5×10^5	130 × 60 × 60	—	—	2.5×10^5	100 × 42 × 33[e] 270 × 66 × 48[i]	—	—	8.0×10^4	80 × 20 × 20
Beetle	1	1.5 × 0.6 × 0.3	0.17	1.7 × 0.6 × 0.3	—	—	0.1	0.2 × 0.2 × 0.2[e] 2.5 × 1.2 × 0.6[i]	—	—	—	—
Grassy veg.	0.2	10 × 0.2 × 0.2	2.62	5 × 1 × 1	4	5 × 1 × 1	n/s	2.5 × 1.2 × 0.6	—	—	—	—

[eis] Mass assumed for external in soil dose estimate. [ieo] Mass and dimensions assumed for internal and external on soil dose estimates. [e] Dimensions assumed for external dose estimate. [i] Dimensions assumed for internal dose estimate. n/s not specified.

Table 3. Strontium-90 CR (biota:soil) values applied by the participating models (dimensionless). (Note: n/r—not reported by this model; n/a—predictions made by approaches other than CR values (see text for details); shaded cells denote CR values which are derived from guidance approaches for use when data are lacking for EA R&D 128 (see section 3.1 for details).)

Species	EA R&D128	ERICA	LIETDOS-BIOTA	RESRAD-BIOTA	DosDiMEco	D-Max
Apodemus flavicollis	5	1.74	1.25	n/a	n/a	10
Apodemus sylvaticus	5	1.74	1.25	n/a	n/a	20
Canis lupus	5	1.74	1.3	n/a	n/a	20
Capreolus capreolus	5	1.74	1.96	1.74	n/a	10
Clethrionomys glareolus	5	1.74	1.25	n/a	n/a	10
Erithacus rubecula	5	0.55	0.49	n/a	n/a	20
Hirundo rustica	5	0.55	0.49	n/a	n/a	20
Lacerta agilis	5	11.8	47	n/a	n/a	10
Microtus arvalis	5	1.74	1.25	n/a	n/a	10
Microtus oeconomus	5	1.74	1.25	n/a	n/a	10
Microtus spp.	5	1.74	1.25	n/a	n/a	10
Parus major	5	0.55	0.49	n/a	n/a	20
Perdix perdix	5	0.55	0.49	n/a	n/a	20
Rana terrestris	5	0.83	n/r	n/a	n/a	n/r
Sicista betulina	5	1.74	1.25	n/a	n/a	20
Sorex araneus	5	1.74	1.25	n/a	n/a	20
Sturnus vulgaris	5	0.55	0.49	n/a	n/a	20
Sus scrofa	5	1.74	4.8	n/a	n/a	20
Beetles	5	0.41	n/r	0.06	n/a	10
Grass vegetation	5	0.21	0.21	0.21	0.03	10

The CR values as applied in this exercise by the various models using this approach are compared in tables 3 and 5.

In all instances the models were applied by individuals/organisations who had been, to differing degrees, involved in the development of the approach they were using.

3.1. EA R&D 128

The EA (Environment Agency) R&D 128 approach was developed primarily to assess compliance with the European Commission (EC) Birds and Habitats Directives at sites receiving radioactive discharges in England and Wales (Copplestone *et al* 2001, 2003, Allott and Copplestone 2008). The model uses CR values from literature reviews (with a bias toward data collected in the UK) to estimate activity concentrations in biota (Copplestone *et al* 2001) and the dosimetric methodology is described in Vives i Batlle *et al* (2004).

The DCCs and CR values applied to the Chernobyl scenario were those contained within the freshwater (v1.15) and terrestrial (v1.20) spreadsheets released in 2003 (Copplestone *et al* 2003).

In cases where no data were identified to derive a CR value for a particular organism–radionuclide combination a guidance-derived approach to fill in gaps (see tables 3–5) as described in Copplestone *et al* (2003). For ^{90}Sr, a CR value of 5 was used for all biota which was based on one set of measurements of mice collected from a woodland near to the Sellafield reprocessing plant. For ^{137}Cs a CR value of 9 as presented by Copplestone *et al* (2001) for carnivorous mammals was assumed for the *L. agilis* and both frog species. The carnivorous mammal ^{137}Cs CR value was derived from Lowe and Horrill (1991) from measurements of samples collected soon after the fallout of the Chernobyl accident in the UK (this source also provided the ^{137}Cs CR value for birds).

Table 4. Caesium-137 CR (biota:soil) values applied by the participating models (dimensionless). (Note: n/r—not reported by this model; n/a—predictions made by approaches other than CR values (see text for details); shaded cells denote CR values which are derived from guidance approaches for use when data are lacking for EA R&D 128 (see section 3.1 for details).)

Species	EA R&D128	ERICA	LIETDOS-BIOTA	RESRAD-BIOTA	DosDiMEco	D-Max
Apodemus flavicollis	0.01	2.87	11.4	n/a	n/a	10
Apodemus sylvaticus	0.01	2.87	11.4	n/a	n/a	20
Canis lupus	9	2.87	4.96	n/a	n/a	20
Capreolus capreolus	2.2	2.87	1.84	2.87	n/a	10
Clethrionomys glareolus	0.01	2.87	11.4	n/a	n/a	10
Erithacus rubecula	1.6	0.75	0.76	n/a	n/a	20
Hirundo rustica	1.6	0.75	0.76	n/a	n/a	20
Lacerta agilis	9	3.59	23.2	n/a	n/a	10
Microtus arvalis	0.01	2.87	11.4	n/a	n/a	10
Microtus oeconomus	0.01	2.87	11.4	n/a	n/a	10
Microtus spp.	0.01	2.87	11.4	n/a	n/a	10
Parus major	1.6	0.75	0.76	n/a	n/a	10
Perdix perdix	1.6	0.75	0.76	n/a	n/a	20
Rana esculenta	9	0.54	0.43	n/a	n/a	10 700[a]
Rana terrestris	9	0.54	0.43	n/a	n/a	10 700[a]
Sicista betulina	0.01	2.87	11.4	n/a	n/a	20
Sorex araneus	0.01	2.87	11.4	n/a	n/a	20
Sturnus vulgaris	1.6	0.75	0.76	n/a	n/a	20
Sus scrofa	9	2.87	2.41	n/a	n/a	20
Beetles	0.04	0.13	n/r	0.06	n/a	10
Grass vegetation	0.14	0.69	0.69	0.69	0.04	10

[a] CR biota:water ($l\ kg^{-1}$).

Table 5. Plutonium and ^{241}Am CR (biota:soil) values applied by the participating models (dimensionless). (Note: n/a—predictions made by approaches other than CR values (see text for details); shaded cells denote CR values which are derived from guidance approaches for use when data are lacking for either EA R&D 128 or ERICA (see sections 3.1 and 3.2 for details).)

	EA R&D128	ERICA	LIETDOS-BIOTA	RESRAD-BIOTA	DosDiMEco	D-Max
Pu isotopes						
Aegithalos caudatus	7×10^{-1}	2.34×10^{-2}	1×10^{-5}	n/a	n/a	1×10^{-2}
Apodemus flavicollis	5×10^{-4}	2.34×10^{-2}	5.67×10^{-3}	n/a	n/a	1×10^{-2}
Clethrionomys glareolus	5×10^{-4}	2.34×10^{-2}	5.67×10^{-3}	n/a	n/a	1×10^{-2}
Microtus spp.	5×10^{-4}	2.34×10^{-2}	5.67×10^{-3}	n/a	n/a	1×10^{-2}
Parus major	7×10^{-1}	2.34×10^{-2}	1×10^{-5}	n/a	n/a	1×10^{-2}
^{241}Am						
Clethrionomys glareolus	2.7×10^{-4}	4.08×10^{-2}	7.49×10^{-3}	n/a	n/a	1×10^{-2}

Dose conversion coefficients provided within the R&D128 spreadsheets for default reference organisms were used (i.e. species specific DCCs were not generated). The reference organism geometry and assumptions made concerning occupancy factors are presented in tables 2 and 6 respectively.

3.2. ERICA

ERICA was an EC 6th Framework project to provide an integrated approach to scientific, managerial and societal issues concerned with the environmental effects of ionising radiation

Table 6. Occupancy factors applied in each of the approaches to the Chernobyl scenario (note D-Max makes no assumptions with regard to these parameters see section 3.7).

	EA R&D 128			ERICA			LIETDOS-BIOTA			RESRAD-BIOTA			FASTer–EPIC Doses 3D			DosDiMEco		
Species	In air	On soil	In soil	In air	On soil	In soil	In air	On soil	In soil	In air	On soil	In soil	In air	On soil	In soil	In air	On soil	In soil
A. caudatus	0.5	0.5		0.2	0.8					0.5	0.5		0.8	0.2		0.25[a]	0.25[a]	
A. flavicollis		0.4	0.6		0.5	0.5		0.5	0.5		0.5	0.5		0.5	0.5		0.25[b]	0.5[b]
A. sylvaticus		0.4	0.6		0.5	0.5		0.5	0.5		0.5	0.5		0.5	0.5		0.5	0.5
C. lupus		0.6	0.4		0.1	0.9					1			1			1	
C. capreolus		0.5	0.5		1			1			1			1			1	
C. glareolus		0.6	0.4		0.3	0.7		0.5	0.5		0.25	0.75		0.5	0.5		0.5	0.5
E. rubecula	0.5	0.5		0.5	0.5		0.5	0.5		0.5	0.5		0.8		0.2	0.25[a]	0.25[a]	
H. rustica	0.5	0.5		0.65	0.35		0.5	0.5		0.5	0.5					50[a]		
L. agilis	0.1	0.4	0.5		0.6	0.4					0.25	0.75						
M. arvalis		0.4	0.6		0.3	0.7		0.5	0.5		0.25	0.75					0.5	0.5
M. oeconomus		0.4	0.6		0.3	0.7		0.5	0.5		0.25	0.75		0.5	0.5		0.5	0.5
Microtus spp.		0.4	0.6		0.3	0.7		0.5	0.5		0.25	0.75					0.5	0.5
P. major	0.5	0.5		0.2	0.8		0.3	0.7		0.5	0.5		0.8	0.2		0.25[a]	0.25[a]	
P. perdix	0.5	0.5		0.1	0.9			1		0.5	0.5					0.5	0.5	
R. esculenta	0.04[c]	0.16[c]	0.2[c]		0.35[d]						0.19[e]			0.75[f]				
R. terrestris	0.1	0.4	0.5		0.54	0.46		0.5	0.5		0.58[g]			0.75[f]				
S. betulina		0.4	0.6		1			1			0.5	0.5					0.25[b]	0.5[b]
S. araneus		0.4	0.6		0.9	0.1		1			0.25	0.75		0.5	0.5		0.35	0.65
S. vulgaris	0.5	0.5		0.7	0.3		0.5	0.5		0.5	0.5					0.25[a]	0.25[a]	
S. scrofa		0.6	0.4		1						1						1	
Beetle		1.0			0.5	0.5					1							
Grassy veg.	0.5		1.0		1							1						

[a] In air/trees—0.5. [b] In air/trees—0.25. [c] Water—0.18, sediment–water interface—0.18 sediment—0.24. [d] Water—0.23, sediment—0.42. [e] Water—0.39, sediment–water interface—0.42. [f] Water—0.25. [g] Sediment–water interface—0.42.

(Howard and Larsson 2008). The ERICA Tool is the software package which implements the ERICA approach (Brown *et al* 2008). In this package, transfer from contaminated media to a range of terrestrial and aquatic reference organisms is estimated using CR values, predominantly derived from original literature (Beresford *et al* 2008a, Hosseini *et al* 2008). The dosimetric component of the approach, for terrestrial organisms, assumes that a layer of non-active tissue (i.e. the outer layers of the skin and/or fur) provide a shielding effect for the organism. Monte Carlo techniques are applied that include all relevant radiation transport processes (Ulanovsky *et al* 2008). The ERICA software and associated documentation are available from: http://www.ceh.ac.uk/PROTECT/ERICAdeliverables.html. The DCC and CR values applied in this exercise were those contained within the first full release version of the ERICA Tool (April 2007) and as documented by Ulanovsky *et al* (2008) and Beresford *et al* (2008a) respectively.

Dose conversion coefficient values for the most appropriate default reference organism from the ERICA Tool were used (i.e. species specific DCCs were not generated). The only exception was in the case of wolf for which a different geometry was assumed for internal and external exposure on soil from that assumed for external exposure in soil. The latter was generated using the Tool's 'add organism' function. However, this function has a maximum allowed within soil organism mass of 6.6 kg which is considerably smaller than a wolf. The reference organism geometry and assumptions made for occupancy factors are presented in tables 2 and 6, respectively.

Whole-body bird ^{241}Am and Pu activity concentrations were estimated assuming the same CR values as those for mammals (this assumption was made to derive the default bird CR values for the two radionuclides in the ERICA Tool (Beresford *et al* 2008a)).

For four of the required frog predictions, ^{137}Cs water activity concentrations were presented in the scenario description in addition to those for soil. Whole-body ^{137}Cs activity concentrations of 4150 Bq kg^{-1} (fw) and 35 600 Bq kg^{-1} (fw) were estimated for frogs at the two sites for which data were available using a terrestrial ecosystem CR value and soil activity concentrations. If the aquatic CR and water activity concentrations were used, whole-body activity concentrations of 3440 Bq kg^{-1} (fw) and 130 000 Bq kg^{-1} (fw) respectively were predicted; for consistency the values estimated from soil activity concentrations were reported.

3.3. LIETDOS-BIOTA

This is an approach being developed to address contamination issues associated with nuclear power production in Lithuania (Nedveckaite *et al* 2007).

Estimates of whole-body activity concentrations were made using CR values taken from Larsson *et al* (2004), the ERICA Tool (grassy vegetation only), Mcgee *et al* (1996) or derived from data obtained in Lithuania after the Chernobyl accident (Nedveckaite 2004).

A Monte Carlo transport code is used for DCC derivation; a specially derived method for describing phantoms allows DCC values to be calculated for organisms of any size or shape (see IAEA 2010b for more details). Appropriate geometries (see table 2) were selected from Brown *et al* (2003a); occupancy assumptions used are shown in table 6.

3.4. RESRAD-BIOTA

The RESRAD-BIOTA code (available from http://www.ead.anl.gov/resrad) was designed to be consistent with, and provide a tool for, implementing the US Department of Energy's graded approach for biota dose assessment (US DOE 2002, Higley *et al* 2003c, 2003a). The code includes a kinetic-allometric approach (Higley *et al* 2003b) to estimate the transfer of radionuclides to birds and mammals although CR values can also be applied. The internal and external dose conversion coefficients are estimated using a Monte Carlo transport code.

The parameters used to apply RESRAD-BIOTA to the scenario are presented in tables 2, 6 and 7. Whenever kinetic-allometric approaches were applied, predictions were made to obtain the maximum tissue activity concentration for a given species (corresponding to the assumed maximum life span of each animal). To estimate the radionuclide activity concentration in animal food sources, default CR values from the ERICA Tool were used for a variety of terrestrial invertebrate and plant reference organisms. For green frog (for which water concentrations were presented in the scenario), freshwater mollusc and crustacean activity concentrations were estimated using CR values from the ERICA Tool (see Hosseini *et al* 2008). Results reported for grassy vegetation, beetles (assuming flying insect CR) and roe deer were also estimated using CR values from the ERICA Tool (tables 3 and 4).

The CR values used from the ERICA Tool were those contained within the first full release version of the ERICA Tool (April 2007). The activity concentration of the diet of wolf was estimated from the calculated activity concentrations in roe deer and rodent species. Ingestion of contaminated water was assumed for edible and brown frogs at rates of 6.32 and 3.28 g d^{-1} respectively. Soil inhalation and ingestion rates assumed for vertebrate organisms (with the exception of roe deer) can be found in IAEA (2010b). Gastrointestinal absorption coefficients were assumed to be the same for all ingested sources with values of 1, 0.3 and 1×10^{-3} being used for ^{137}Cs, ^{90}Sr and both actinide elements respectively.

There are eight different sets of DCCs in the RESRAD-BIOTA database, each corresponding to a specific body mass with predetermined ellipsoidal dimensions. Based on the assumed body mass for each organism, the DCCs for a body mass closest to the assumed value were selected for dose calculation. In some cases, when the assumed body mass fell between two specific values, to obtain more conservative (i.e. higher) dose estimates, the DCC corresponding to the larger predetermined dimensions was used in internal dose calculations and the smaller predetermined dimensions in external dose calculations.

3.5. FASTer-EPIC doses 3D

The FASTer model is multi-compartmental model that can be used to simulate transfer through a simple terrestrial food-chain. It was originally configured to consider a simple food-chain consisting of vegetation-herbivore-carnivore in part to provide transfer parameters for organism–radionuclide combinations for which data were lacking within the EC funded FASSET project (Brown *et al* 2003a, Avila *et al* 2004). It has also been used to provide a few default CR values within the ERICA Tool database although none of the ERICA Tool CR values used in this exercise were derived using the FASTer model.

The configuration of the model has been simplified due to fundamental concerns involving the conceptualisation of the system which required population-related parameters (see IAEA 2010b). The simplified model uses equilibrium activity concentration of prey species as inputs to the model for carnivorous animals. The model uses allometric relationships to describe dietary intake rates and radionuclide biological half-lives; the latter were mostly derived from US DOE (2002) and Higley *et al* (2003b) (i.e. those used in the RESRAD-BIOTA code).

For this exercise, the FASTer model was used in conjunction with the EPIC DOSES3D computer code for the calculation of doses to biota (Golikov and Brown 2003, Brown *et al* 2003b). The software enables the user to define organisms of any size and shape and can be used to derive DCCs for any radionuclide for which transformation data are available. The absorbed fractions for specific geometries are calculated from the chord distribution function that describes numerous possible path lengths within the organism by means of Monte Carlo

Table 7. Dietary parameters and assumed life span as applied to the Chernobyl scenario in the RESRAD-BIOTA, FASTer-EPIC doses 3D and DosDiMEco models.

	RESRAD-BIOTA			FASTer–EPIC doses 3D			DosDiMEco		
Species	Fresh matter intake rate (g d^{-1})	Diet composition[a]	Life span (y)	Dry matter intake rate (g d^{-1})	Diet composition[a]	Life span (y)	Dry matter intake rate (g d^{-1})	Diet composition	Life span (y)
A. caudatus	2.6	100% fi	2	2.7	40% fi, 20% si, 20% di, 20% g&h	2	2.7	Grain	19
A. flavicollis	6.3	38% fi, 52% g&h 10% s	1	5.2	40% g&h, 40% si, 20% l&b	1	4.0	Herbs	8
A. sylvaticus	6.3	38% fi, 52% g&h 10% s	1	3.4	40% g&h, 40% si, 20% l&b	1.7	4.0	Herbs	8
C. lupus	1030	90% roe deer; 10% rodent species	7	1160	100% roe deer	7	2520	Herbivorous mammals	10
C. capreolus	n/a[b]	n/a[b]	n/a[b]	397	33% g&h, 33% s, 33% t	11.5	1160	Herbs	8
C. glareolus	7.4	97% g&h, 3% si	1	3.8	60% g&h, 20% l&b, 20% si	2	4.0	Herbs	8
E. rubecula	4.4	10% di, 10% si, 30% fi, 25% g&h, 25% t	2	4.1	40% si, 40% di, 20% g&h	2	4.9	Grain	19
H. rustica	4.4	100% fi	3	—	—	—	3.6	Grain	19
L. agilis	2.3	10% di, 30% si, 20% fi, 20% gas, 20% t	3	—	—	—	—	—	—
M. arvalis	6.6	100% g&h	0.42	—	—	—	4.2	Herbs	8
M. oeconomus	6.6	100% g&h	0.42	6.7	100% g&h	3	5.3	Herbs	8
Microtus spp.	7.4	97% g&h, 3% si	1	—	—	—	4.8	Herbs	8
P. major	4.3	10% di, 10% si, 30% fi, 25% g&h, 25% t	3	4.1	40% fi, 20% si, 20% di, 20% g&h	3	4.9	Grain	19
P. perdix	31.8	86% g&h, 14% fi	3	—	—	—	32.6	Grain	19
R. esculenta	6.4	10% si, 10% gas, 50% fi, 15% c, 15% m	5	0.4	25% si, 25% gas, 25% di, 25% fi	8	—	—	—
R. terrestris	3.7	20% si, 30% gas, 50% fi	5	0.2	25% si, 25% gas, 25% di, 25% fi	8	—	—	—
S. betulina	6.3	38% fi, 52% g&h 10% s	1	—	—	—	2.0	Herbs	8
S. araneus	4.9	30% di, 20% gas, 25% si, 20% g&h, 5% fi	1	1.9	25% si, 25% di, 25% fi, 25% gas	1.5	2.1	Herbs	8
S. vulgaris	10.8	5% di, 5% si, 20% fi, 35% g&h, 35% t	5	—	—	—	16.9	Grain	19
S. scrofa	4000	86 % s, 12% si, 2% di	10	—	—	—	2320	Herbs	8

[a] c—freshwater crustacean, di—detritivorous invertebrates, fi—flying insects, gas—gastropod, g&h—grass and herbs, l&b—lichen & bryophytes, m—freshwater mollusc, s—shrub, si—soil invertebrates, t—tree. [b] Not applicable—CR value used for this species.

simulations. Geometry and occupancy assumptions are presented in tables 2 and 6, respectively. For both species of frogs, occupancy factors for freshwater and terrestrial ecosystems of 0.25 and 0.75, respectively, were assumed.

In the original FASTer model (see Brown *et al* 2003a), a correction factor was applied in situations where biological half-lives were equal to, or longer than, the life expectancy of the animal. However, the original equations, describing these correction factors, did not include terms that characterised transfer from one mammal generation to the next (e.g. through transfer *in utero*) and were not grounded in any cited (physiological) theory. Therefore, an alternative pragmatic approach was taken whereby the model predictions were selected at 50% of the life expectancy of the animal (see table 7) with the underlying assumption that the organism is introduced to the contaminated environment with no residual activity (i.e. as a 'clean' specimen). This was considered to represent an average individual in the population. Whilst the FASTer model was derived for mammals, for this exercise the models parameters were also assumed to be applicable to birds and poikilothermic amphibians and reptiles. Assumed masses and dietary compositions are presented in table 7. To derive the activity concentrations in the dietary components assumed for the different animals (see table 7), biota-soil CR values were used from a development version (28/03/2006) of the ERICA Tool database. For the biota–radionuclide combinations considered, the only difference in CR values to the final version of the ERICA Tool database (Beresford *et al* 2008a) was the CR value for Pu to tree (a value of 2.07×10^{-5} was used whereas the final database version was 3.15×10^{-2}). Allometric parameters used in the derivation of fresh and dry matter ingestion rates were taken from Nagy (1987). No soil ingestion was assumed for rodents, whilst for roe deer soil ingestion was assumed to represent 10% of the dry matter intake. A different gastrointestinal absorption coefficient was assumed for ^{137}Cs ingested as soil (0.1) than that ingested as dietary components (1.0). Gastrointestinal absorption coefficient of 0.2 for ^{90}Sr and 5×10^{-4} for both actinide elements were assumed for all sources of intake.

3.6. DosDiMEco

This model is under development by SCK·CEN (Belgium) and an extended description can be found in Olyslaegers (2010). The approach consists of a software package, written in MathCad® 2001i professional, which is divided into three sub-programs. The first sub-program calculates the energy absorption in a reference organism due to gamma radiation originating from a certain contaminated volume. The two remaining sub-programs follow a similar approach, but calculations are performed for a volumetric contamination by an α- or a β-emitter. DCCs are calculated using a point kernel technique corrected with a build-up factor (see Vives i Batlle *et al* (2007)) and Olyslaegers (2010) for details).

Concentration ratio values for plants and invertebrates are predominantly derived from review publications (see Olyslaegers (2010) for details). Terrestrial mammal and bird concentrations are calculated from the intake rate (using allometric relationships between body mass and dietary intake rate described by Nagy (1987)) and the fractional absorption of the radionuclide from the gastrointestinal tract (see Olyslaegers (2010) for details). This is combined with a retention function to calculate whole-body activity concentrations as described by Coughtrey and co-workers (Coughtrey and Thorne 1983, Coughtrey *et al* 1983, 1984) and the ICRP (1979, 1981, 1995); retention functions were integrated over the whole life span. If no retention functions were available, the biological half-lives given in Argonne National Laboratory (2005a, 2005b, 2005c) were used. Gastrointestinal absorption coefficients of 2×10^{-4} and 0.4 were assumed for all vertebrates for ^{241}Am and ^{90}Sr respectively. For ^{137}Cs a value of 0.99 was assumed for birds and monogastric mammals, and a value of 0.6 assumed for ruminants.

The parameters used to apply DosDiMEco to the Chernobyl scenario are presented in tables 2, 6 and 7.

3.7. D-Max

The D-Max model does not explicitly calculate internal and external dose rates to an organism, but instead determines maximum internal or external dose for any given organism/medium combination by assuming an organism or medium which is effectively infinite in extent with respect to the radiation path length (Smith 2005). For an equal activity concentration in the organism and the medium in which it resides, radiations escaping the organism (or tissue) are approximately balanced by the incoming radiations from the outside medium. So, the maximum total dose to any organism size is given by the higher of the two maximum internal or external dose values. It is expected that this approach is likely to overestimate dose rates to small organisms from gamma-emitters. This approach is similar to that taken in the initial screening tiers of some other models (e.g. RESRAD-BIOTA see US DOE (2002), although the RESRAD-BIOTA model was not applied in this manner in this exercise).

Model approaches used to estimate activity concentrations were selected by the developer to yield conservative estimates. Soil–plant radionuclide concentrations were selected from literature values (Coughtrey and Thorne 1983, IAEA 1994, Sokolik *et al* 2004, Smith and Beresford 2005) and values were chosen to reflect conditions high radionuclide uptake. Activity concentrations in mammals and birds were estimated using dietary concentration ratios (i.e. ratio of the activity concentration in the animal (fw) to that in the diet (dw)). For Cs and Sr in herbivorous animals, CR values were derived as the product of the ‘best estimate’ equilibrium transfer coefficient (defined as the ratio of the activity concentration in a tissue to the rate of radionuclide ingestion) and feed intake rates as presented by IAEA (1994) for farm animals. On the basis of these estimates, 2–3 times higher conservative whole-body CR values were chosen for use in the model. For Sr, this value accounted for the higher accumulation in bone Multiplying the resultant dietary CR values by the plant–soil CR values results in the model’s biota to media CR values.

For carnivorous/omnivorous birds and mammals a prey–predator concentration ratio of 2 is assumed for Cs and Sr. This was justified on the basis of the considerable evidence of bioaccumulation of Cs at higher trophic levels (e.g. Lowe and Horrill (1991)). For Pu and Am, the same concentration ratio is applied to carnivorous/omnivorous birds and mammals as for herbivorous species.

For terrestrial reptiles, insects and amphibians, concentration ratios are assumed to be the same as those for herbivorous or omnivorous/predatory mammals; justified by consideration of feeding habits.

Tables 3–5 present biota to media CR values as used for this approach in this exercise. Where water activity concentrations were available for frog species, whole-body activity concentrations were estimated assuming a CR value for predatory and omnivorous fish. Further details of the D-Max approach can be found in IAEA (2010b).

4. Statistical analyses

To analyse the estimated dose rates, performance of the participating models was assessed by comparing reported results with the estimated reference values, using a ‘Z-score’, which is a measure of how many standard deviation units away from the mean a particular data value lies. The approach is the same as that previously used by Vives i Batlle *et al* (2007) to analyse estimated dose rates in an earlier inter-comparison exercise. It is used here for consistency with our previous publication and because it represents a simple method to quantify how far a model prediction is from the centre of the results distribution. The performance was considered satisfactory if a relative bias is equal to or better than 25% (absolute value of Z is between 0 and 2). Z-values between 2 and 3 indicate that the results are more biased, and Z-values $\geqslant 3$ indicates that the measurements are highly biased. An 'adjusted' mean and associated standard deviation was generated for each comparison by the removal of any outlying predictions. Z-scores were then estimated using the adjusted mean and standard deviation as the reference value where:

$$Z = \frac{\text{predicted dose rate} - \text{`adjusted' dose rate}}{\text{`adjusted' SD}}.$$

Note that no judgement is made as to if any prediction, including those identified as outliers, is right or wrong, the adjusted mean was generated simply to enable some statistical comparison of the different models dose rate predictions as no measured data were available for this comparison. As the D-Max model aims to predict the maximum total dose rate outputs from this model were not included in the statistical evaluation.

Z-scoring was not used to compare predicted with observed biota activity concentrations because when the standard deviation of the observed data is relatively large compared to the mean, the scoring method tends to more clearly identify those models which overestimate rather than those which underestimate. This is because if the standard deviation is sufficiently large (33% of the mean or more), an extreme under prediction will record a Z-score of less than 3; hence over predictions are better identified than under predictions (see IAEA 2010b for further discussion).

5. Results

Of the models applied, complete sets of predictions were only obtained from application of RESRAD-BIOTA, ERICA and EA R&D 128.

5.1. Activity concentrations

Tables 8–13 compare the predictions of the various participants with the measured data; predictions varying by more than an order of magnitude from the observed data are highlighted. Note where the observed data mean does not have an associated standard deviation, the sample size was one. In the following discussion section, discrepancies between models and predictions varying by more than an order of magnitude from the measured data are identified.

5.2. Unweighted absorbed dose rates

The combined (i.e. totalled for all radionuclides) unweighted internal dose rates and total dose rates predicted by each model are compared in table 14 (the combined external dose rate can be estimated as the difference between the total and internal dose rates). In virtually all cases the internal dose was predicted to be the dominant contributor to the total dose rate.

For more than 50% of the comparisons, the variability in internal dose rate between the participating models was less than an order of magnitude. The most variable predictions were for *A. caudatus* (long-tailed tit), *R. esculenta* (edible frog) and *P. perdix* (partridge).

With two exceptions, all models predicted external dose rates to within an order of magnitude of each other. The exceptions were for *H. rustica* (barn swallow) (input soil

Table 8. A comparison of measured to predicted ^{137}Cs and ^{90}Sr whole-body activity concentrations (Bq kg^{-1} fw) in mouse species and shrews. (Note: shaded cells denote predictions which deviate from the observed data by more than one order of magnitude.)

			Measured data			Model predictions						
Data ID[a]	Nuclide	Species	Mean	SD	n	EA R&D128	ERICA	Lietdos Biota	RESRAD-BIOTA	FASTer-EPIC Doses 3D	DosDiMEco	D-Max
CT1c	Cs-137	*A. flavicollis*	3.7×10^4	5.7×10^4	4	5.1×10^2	1.1×10^5	4.5×10^5	7.9×10^4	1.8×10^5	6.2×10^3	3.9×10^5
CT1c	Sr-90	*A. flavicollis*	1.0×10^4	3.9×10^3	4	4.8×10^4	1.7×10^4	1.2×10^4	2.7×10^4	1.9×10^5	4.4×10^3	9.6×10^4
CT2c	Cs-137	*A. flavicollis*	7.3×10^4	7.3×10^4	11	1.2×10^3	2.6×10^5	1.0×10^6	1.8×10^5	4.0×10^5	1.4×10^4	8.9×10^5
CT2c	Sr-90	*A. flavicollis*	1.6×10^4	1.4×10^4	11	2.0×10^5	6.6×10^4	4.7×10^4	1.1×10^5	7.5×10^5	1.7×10^4	3.8×10^5
CT4c	Cs-137	*A. flavicollis*	7.2×10^3	1.1×10^4	13	2.3×10^1	5.0×10^3	2.0×10^4	3.5×10^3	7.8×10^3	2.8×10^2	1.7×10^4
CT4c	Sr-90	*A. flavicollis*	5.0×10^2	2.3×10^2	11	3.9×10^3	1.4×10^3	9.8×10^2	2.2×10^3	1.6×10^4	3.6×10^2	7.9×10^3
CT33b	Cs-137	*A. flavicollis*	6.0×10^4	3.7×10^4	10	5.6×10^2	1.2×10^5	4.9×10^5	8.7×10^4	1.9×10^5	6.9×10^3	4.3×10^5
CT33b	Sr-90	*A. flavicollis*	2.5×10^4	6.1×10^3	10	9.3×10^4	3.2×10^4	2.3×10^4	5.3×10^4	3.7×10^5	8.6×10^3	1.9×10^5
CT34b	Cs-137	*A. flavicollis*	3.1×10^3	2.0×10^3	18	9.6×10^1	2.1×10^4	8.4×10^4	1.5×10^4	3.3×10^4	1.2×10^3	7.4×10^4
CT34b	Sr-90	*A. flavicollis*	7.4×10^3	5.2×10^3	18	1.1×10^4	3.8×10^3	2.7×10^3	6.3×10^3	4.4×10^4	1.0×10^3	2.2×10^4
CT31a	Cs-137	*A. sylvaticus*	4.6×10^5	6.1×10^5	12	2.6×10^3	5.7×10^5	2.2×10^6	4.0×10^5	8.3×10^5	3.2×10^4	3.9×10^6
CT31a	Sr-90	*A. sylvaticus*	3.3×10^4	2.6×10^4	4	4.9×10^5	1.7×10^5	1.2×10^5	2.8×10^5	2.8×10^6	4.6×10^4	2.0×10^6
CT3b	Cs-137	*S. betulina*	4.0×10^5	2.3×10^5	10	2.8×10^4	6.3×10^6	2.5×10^7	4.4×10^6	—	6.0×10^5	4.4×10^7
CT3b	Sr-90	*S. betulina*	4.1×10^5	1.9×10^5	10	7.0×10^6	2.4×10^6	1.8×10^6	4.0×10^6	—	1.1×10^6	2.8×10^7
CT3c	Cs-137	*S. araneus*	1.2×10^6	1.7×10^6	14	2.8×10^4	6.3×10^6	2.5×10^7	2.2×10^6	4.8×10^5	2.9×10^5	4.4×10^7
CT3c	Sr-90	*S. araneus*	4.2×10^5	2.7×10^5	14	7.0×10^6	2.4×10^6	1.8×10^6	8.7×10^6	3.0×10^6	5.4×10^5	2.8×10^7
CT29c	Cs-137	*S. araneus*	6.8×10^4	1.8×10^4	10	1.6×10^3	3.6×10^5	1.4×10^6	1.2×10^5	2.7×10^4	1.7×10^4	2.5×10^6
CT29c	Sr-90	*S. araneus*	5.6×10^4	6.5×10^4	9	2.7×10^5	9.5×10^4	6.8×10^4	3.4×10^5	1.1×10^5	2.1×10^4	1.1×10^6
CT32b	Cs-137	*S. araneus*	3.4×10^5	2.3×10^5	65	1.3×10^3	2.8×10^5	1.1×10^6	9.8×10^4	2.2×10^4	1.3×10^4	2.0×10^6
CT32b	Sr-90	*S. araneus*	1.3×10^5	7.6×10^4	65	2.8×10^5	9.8×10^4	7.1×10^4	3.5×10^5	1.2×10^5	2.2×10^4	1.1×10^6
CT33c	Cs-137	*S. araneus*	2.5×10^4	1.2×10^4	32	5.6×10^2	1.2×10^5	4.9×10^5	4.3×10^4	9.5×10^3	5.8×10^3	8.7×10^5
CT33c	Sr-90	*S. araneus*	3.2×10^4	2.1×10^4	32	9.3×10^4	3.2×10^4	2.3×10^4	1.1×10^5	3.9×10^4	7.1×10^3	3.7×10^5
CT34c	Cs-137	*S. araneus*	3.4×10^3	1.8×10^3	5	9.6×10^1	2.1×10^4	8.4×10^4	7.4×10^3	1.6×10^3	9.8×10^2	1.5×10^5
CT34c	Sr-90	*S. araneus*	1.7×10^4	9.2×10^3	5	1.1×10^4	3.8×10^3	2.7×10^3	1.4×10^4	4.6×10^3	8.4×10^2	4.4×10^4

[a] The data ID in this and subsequent tables relates the predictions back to the scenario input data which can be found in IAEA (2010b); each number represents a site where a letter appears in the ID after the number this denotes that more than one biota type has been predicted for this location.

Table 9. A comparison of measured to predicted ^{137}Cs and ^{90}Sr whole-body activity concentrations in vole species. (Note: shaded cells denote predictions which deviate from the observed data by more than one order of magnitude.)

			Measured data			Model predictions						
Data ID	Nuclide	Species	Mean	SD	n	EA R&D128	ERICA	Lietdos Biota	RESRAD-BIOTA	FASTer-EPIC Doses 3D	DosDiMEco	D-Max
CT1c	Cs-137	*C. glareolus*	4.4×10^4	2.9×10^4	15	5.1×10^2	1.1×10^5	4.5×10^5	9.9×10^4	1.8×10^5	6.3×10^3	3.9×10^5
CT1c	Sr-90	*C. glareolus*	1.5×10^4	5.4×10^3	15	4.8×10^4	1.7×10^4	1.2×10^4	5.4×10^4	3.1×10^5	4.5×10^3	9.6×10^4
CT2b	Cs-137	*C. glareolus*	5.8×10^4	5.2×10^4	35	1.2×10^3	2.6×10^5	1.0×10^6	2.3×10^5	4.1×10^5	1.4×10^4	8.9×10^5
CT2b	Sr-90	*C. glareolus*	1.7×10^4	9.8×10^3	35	2.0×10^5	6.6×10^4	4.7×10^4	2.1×10^5	1.2×10^6	1.8×10^4	3.8×10^5
CT4b	Cs-137	*C. glareolus*	5.1×10^3	1.2×10^4	45	2.3×10^1	5.0×10^3	2.0×10^4	4.4×10^3	8.0×10^3	2.8×10^2	1.7×10^4
CT4b	Sr-90	*C. glareolus*	8.1×10^2	1.1×10^3	25	3.9×10^3	1.4×10^3	9.8×10^2	4.5×10^3	2.5×10^4	3.7×10^2	7.9×10^3
CT29a	Cs-137	*C. glareolus*	6.0×10^5	1.6×10^6	32	1.6×10^3	3.6×10^5	1.4×10^6	3.2×10^5	5.7×10^5	2.0×10^4	1.2×10^6
CT29a	Sr-90	*C. glareolus*	2.4×10^4	1.1×10^4	13	2.7×10^5	9.5×10^4	6.8×10^4	3.1×10^5	1.8×10^6	2.5×10^4	5.5×10^5
CT33a	Cs-137	*C. glareolus*	7.1×10^4	4.6×10^4	39	5.6×10^2	1.2×10^5	4.9×10^5	1.1×10^5	2.0×10^5	7.0×10^3	4.3×10^5
CT33a	Sr-90	*C. glareolus*	1.9×10^4	7.4×10^3	39	9.3×10^4	3.2×10^4	2.3×10^4	1.0×10^5	5.9×10^5	8.6×10^3	1.9×10^5
CT34a	Cs-137	*C. glareolus*	3.8×10^3	7.7×10^2	3	9.6×10^1	2.1×10^4	8.4×10^4	1.9×10^4	3.4×10^4	1.2×10^3	7.4×10^4
CT34a	Sr-90	*C. glareolus*	7.7×10^3	4.1×10^3	3	1.1×10^4	3.8×10^3	2.7×10^3	1.2×10^4	7.0×10^4	1.0×10^3	2.2×10^4
CT30a	Cs-137	*M. arvalis*	7.0×10^3	8.1×10^3	28	1.1×10^3	2.5×10^5	9.9×10^5	1.1×10^5	—	6.7×10^3	8.7×10^5
CT30a	Sr-90	*M. arvalis*	7.9×10^3	1.5×10^4	25	2.3×10^5	8.1×10^4	5.9×10^4	6.2×10^4	—	1.0×10^4	4.7×10^5
CT31b	Cs-137	*M. arvalis*	1.1×10^6	—	1	2.6×10^3	5.7×10^5	2.2×10^6	2.5×10^5	—	1.5×10^4	2.0×10^6
CT31b	Sr-90	*M. arvalis*	1.4×10^4	—	1	4.9×10^5	1.7×10^5	1.2×10^5	1.3×10^5	—	2.2×10^4	9.9×10^5
CT29b	Cs-137	*M. oeconomus*	3.8×10^5	3.1×10^5	19	1.6×10^3	3.6×10^5	1.4×10^6	1.6×10^5	2.7×10^4	1.6×10^4	1.2×10^6
CT29b	Sr-90	*M. oeconomus*	9.5×10^4	6.5×10^4	3	2.7×10^5	9.5×10^4	6.8×10^4	7.2×10^4	2.4×10^5	2.0×10^4	5.5×10^5
CT30b	Cs-137	*M. oeconomus*	1.5×10^4	3.0×10^3	60	1.1×10^3	2.5×10^5	9.9×10^5	1.1×10^5	1.9×10^4	1.1×10^4	8.7×10^5
CT30b	Sr-90	*M. oeconomus*	6.8×10^3	6.2×10^3	9	2.3×10^5	8.1×10^4	5.9×10^4	6.2×10^4	2.0×10^5	1.7×10^4	4.7×10^5
CT42	Cs-137	*M. oeconomus*	5.3×10^3	5.5×10^3	41	2.8×10^2	6.2×10^4	2.5×10^5	2.7×10^4	4.8×10^3	2.8×10^3	2.2×10^5
CT32a	Cs-137	*Microtus spp.*	6.1×10^5	2.8×10^5	11	1.3×10^3	2.81×10^5	1.1×10^6	2.5×10^5	—	6.8×10^3	9.8×10^5
CT32a	Sr-90	*Microtus spp.*	1.1×10^5	3.5×10^4	11	2.8×10^5	9.8×10^4	7.1×10^4	3.2×10^5	—	1.1×10^4	5.7×10^5

Table 10. A comparison of measured to predicted ^{137}Cs and ^{90}Sr whole-body activity concentrations (Bq kg^{-1} fw) in bird, lizard and frog species. (Note: shaded cells denote predictions which deviate from the observed data by more than one order of magnitude.)

			Measured data			Model predictions						
Data ID	Nuclide	Species	Mean	SD	n	EA R&D128	ERICA	Lietdos Biota	RESRAD-BIOTA	FASTer-EPIC Doses 3D	DosDiMEco	D-Max
Bird species												
CT37	Cs-137	*E. rubecula*	1.5×10^3	1.0×10^3	8	5.1×10^4	2.4×10^4	2.4×10^4	2.4×10^4	3.8×10^4	9.0×10^2	6.3×10^5
CT37	Sr-90	*E. rubecula*	3.6×10^4	2.8×10^4	8	1.6×10^5	1.7×10^4	1.5×10^4	1.9×10^5	2.2×10^5	1.4×10^4	6.3×10^5
CT38	Cs-137	*E. rubecula*	7.1×10^2	5.2×10^2	6	2.3×10^4	1.1×10^4	1.1×10^4	1.0×10^4	1.7×10^4	4.0×10^2	2.8×10^5
CT38	Sr-90	*E. rubecula*	5.0×10^3	2.5×10^3	6	5.5×10^4	6.0×10^3	5.4×10^3	6.6×10^4	7.6×10^4	4.8×10^3	2.2×10^5
CT7	Cs-137	*H. rustica*	1.4×10^3	—	1	2.0×10^4	9.6×10^3	9.7×10^3	3.5×10^3	—	2.3×10^2	2.6×10^5
CT7	Sr-90	*H. rustica*	1.7×10^3	—	1	2.1×10^4	2.4×10^3	2.1×10^3	1.2×10^4	—	1.2×10^3	8.6×10^4
CT35	Cs-137	*P. major*	1.1×10^5	1.1×10^5	15	3.3×10^5	1.6×10^5	1.6×10^5	1.5×10^5	2.2×10^5	5.9×10^3	4.1×10^6
CT35	Sr-90	*P. major*	4.9×10^4	3.1×10^4	15	7.5×10^5	8.3×10^4	7.4×10^4	9.8×10^5	9.4×10^5	6.5×10^4	3.0×10^6
CT36a	Cs-137	*P. major*	1.8×10^4	1.6×10^4	26	6.5×10^4	3.0×10^4	3.1×10^4	3.0×10^4	4.4×10^4	1.2×10^3	8.1×10^5
CT36a	Sr-90	*P. major*	5.7×10^3	4.8×10^3	26	1.2×10^5	1.4×10^4	1.2×10^4	1.6×10^5	1.5×10^5	1.1×10^4	4.9×10^5
CT8	Cs-137	*P. perdix*	2.8×10^2	—	1	3.6×10^3	1.7×10^3	1.7×10^3	2.5×10^3	—	6.6	4.5×10^4
CT9	Cs-137	*P. perdix*	2.4×10^5	—	1	1.7×10^4	8.0×10^3	8.1×10^3	1.2×10^4	—	3.1×10^1	2.1×10^5
CT10	Cs-137	*S. vulgaris*	2.9×10^3	—	1	2.8×10^4	1.3×10^4	1.3×10^4	1.4×10^4	—	4.0×10^2	3.5×10^5
CT10	Sr-90	*S. vulgaris*	9.7×10^3	—	1	3.0×10^4	3.2×10^3	2.9×10^3	3.9×10^4	—	2.0×10^3	1.2×10^5
Lizard												
CT1b	Cs-137	*L. agilis*[a]	1.1×10^6	4.1×10^5	4	2.0×10^7	7.9×10^6	5.1×10^7	5.9×10^5	—	—	2.2×10^7
CT1b	Sr-90	*L. agilis*[a]	4.5×10^5	1.8×10^5	3	7.0×10^6	1.7×10^7	6.6×10^7	5.3×10^6	—	—	1.4×10^7
Frog species				—								
CT5a	Cs-137	*R. esculenta*	2.6×10^3	1.1×10^3	33	7.0×10^4	4.2×10^3	3.4×10^3	2.4×10^3	1.5×10^2	—	4.0×10^3
CT6a	Cs-137	*R. esculenta*	2.2×10^4	2.8×10^4	15	6.0×10^5	3.6×10^4	2.9×10^4	5.2×10^4	1.3×10^3	—	1.5×10^5
CT5b	Cs-137	*R. terrestris*	5.6×10^3	5.4×10^3	20	7.0×10^4	4.2×10^3	3.4×10^3	1.6×10^3	1.3×10^2	—	4.0×10^3

Table 10. (Continued.)

Data ID	Nuclide	Species	Measured data: Mean	SD	n	Model predictions: EA R&D128	ERICA	Lietdos Biota	RESRAD-BIOTA	FASTer-EPIC Doses 3D	DosDiMEco	D-Max
CT6b	Cs-137	*R. terrestris*	5.3×10^4	5.0×10^4	14	6.0×10^5	3.6×10^4	2.9×10^4	1.5×10^4	1.1×10^3	—	1.5×10^5
CT40	Cs-137	*R. terrestris*	1.1×10^5	8.2×10^4	4	8.0×10^5	4.8×10^4	3.8×10^4	1.8×10^4	1.5×10^3	—	—
CT40	Sr-90	*R. terrestris*	1.8×10^5	1.4×10^5	4	4.1×10^5	6.8×10^4	—	1.7×10^5	1.0×10^5	—	—
CT41	Cs-137	*R. terrestris*	1.2×10^5	7.0×10^4	4	5.3×10^5	3.2×10^4	2.6×10^4	1.2×10^4	1.0×10^3	—	—
CT41	Sr-90	*R. terrestris*	6.9×10^4	4.2×10^4	4	2.0×10^5	3.4×10^4	—	8.2×10^4	5.2×10^4	—	—

[a] The wrong soil concentrations were supplied for this prediction in the scenario description the results presented here are calculated from the correct soil concentrations and hence differ to those in IAEA (2010b).

Table 11. A comparison of measured to predicted ^{137}Cs and ^{90}Sr whole-body activity concentrations (Bq kg^{-1} fw) in large mammal species. (Note: shaded cells denote predictions which deviate from the observed data by more than one order of magnitude.)

			Measured data			Model predictions						
Data ID	Nuclide	Species	Mean	SD	*n*	EA R&D128	ERICA	Lietdos Biota	RESRAD-BIOTA	FASTer-EPIC Doses 3D	DosDiMEco	D-Max
CT13	Cs-137	*C. capreolus*	2.7×10^3	1.9×10^3	6	5.2×10^3	3.3×10^3	5.2×10^3	7.5×10^3	2.2×10^2	1.8×10^4	5.2×10^3
CT13	Sr-90	*C. capreolus*	2.1×10^3	1.2×10^3	5	2.4×10^3	8.3×10^2	9.3×10^2	8.3×10^2	2.2×10^3	8.9×10^1	4.8×10^3
CT14	Cs-137	*C. capreolus*	8.6×10^1	6.9×10^1	2	1.2×10^3	8.0×10^2	1.2×10^3	1.8×10^3	5.2×10^1	4.3×10^3	1.2×10^3
CT14	Sr-90	*C. capreolus*	6.9×10^2	2.0×10^2	2	6.0×10^2	2.1×10^2	2.3×10^2	2.1×10^2	5.6×10^2	2.2×10^1	1.2×10^3
CT15	Cs-137	*C. capreolus*	7.5×10^3	6.7×10^3	2	1.9×10^4	1.2×10^4	1.9×10^4	2.7×10^4	7.8×10^2	6.5×10^4	1.9×10^4
CT15	Sr-90	*C. capreolus*	9.6×10^3	7.7×10^3	2	1.0×10^4	3.6×10^3	4.1×10^3	3.6×10^3	9.7×10^3	3.9×10^2	2.1×10^4
CT16	Cs-137	*C. capreolus*	7.7×10^3	3.1×10^3	3	1.3×10^4	8.2×10^3	1.3×10^4	1.8×10^4	5.4×10^2	4.5×10^4	1.3×10^4
CT16	Sr-90	*C. capreolus*	2.8×10^3	4.0×10^3	3	6.0×10^3	2.1×10^3	2.4×10^3	2.1×10^3	5.6×10^3	2.2×10^2	1.2×10^4
CT17	Cs-137	*C. capreolus*	2.0×10^5	9.1×10^4	2	1.8×10^4	1.2×10^4	1.8×10^4	2.6×10^4	7.7×10^2	6.4×10^4	1.8×10^4
CT17	Sr-90	*C. capreolus*	1.0×10^4	8.8×10^2	2	1.0×10^4	3.6×10^3	4.1×10^3	3.6×10^3	9.7×10^3	3.9×10^2	2.1×10^4
CT18	Cs-137	*C. capreolus*	1.9×10^3	3.1×10^2	2	4.5×10^4	2.9×10^4	4.5×10^4	6.4×10^4	1.9×10^3	1.6×10^5	4.5×10^4
CT18	Sr-90	*C. capreolus*	1.5×10^4	6.4×10^3	2	2.7×10^4	9.2×10^3	1.0×10^4	9.2×10^3	2.5×10^4	9.9×10^2	5.3×10^4
CT19	Cs-137	*C. capreolus*	4.4×10^3	3.4×10^3	2	4.0×10^3	2.5×10^3	4.0×10^3	5.6×10^3	1.6×10^2	1.4×10^4	4.0×10^3
CT19	Sr-90	*C. capreolus*	1.9×10^3	6.9×10^1	2	1.6×10^3	5.5×10^2	6.2×10^2	5.5×10^2	1.5×10^3	5.9×10^1	3.1×10^3
CT11	Cs-137	*C. lupus*	5.0×10^3	3.2×10^3	2	1.3×10^4	4.2×10^3	7.2×10^3	6.7×10^3	2.6×10^4	5.5×10^2	2.9×10^4
CT12	Cs-137	*C. lupus*	4.5×10^3	4.9×10^2	2	9.7×10^3	3.1×10^3	5.3×10^3	5.0×10^3	1.9×10^4	4.0×10^2	2.1×10^4
CT12	Sr-90	*C. lupus*	6.2×10^2	6.8×10^2	2	1.2×10^3	4.2×10^2	3.1×10^2	4.7×10^3	2.1×10^3	6.2×10^1	4.8×10^3
CT20	Cs-137	*S. scrofa*	8.2×10^3	3.2×10^3	2	1.6×10^5	5.0×10^4	4.1×10^4	1.8×10^4	—	1.6×10^3	3.5×10^5
CT20	Sr-90	*S. scrofa*	1.5×10^4	8.3×10^3	2	2.8×10^4	9.6×10^3	1.4×10^4	1.5×10^4	—	8.0×10^2	1.1×10^5
CT21	Cs-137	*S. scrofa*	7.5×10^2	3.5×10^2	3	6.4×10^4	2.0×10^4	1.7×10^4	7.5×10^3	—	6.6×10^2	1.4×10^5
CT21	Sr-90	*S. scrofa*	1.4×10^3	6.2×10^2	3	8.6×10^3	3.0×10^3	4.3×10^3	4.5×10^3	—	2.5×10^2	3.4×10^4
CT22	Cs-137	*S. scrofa*	3.0×10^2	1.4×10^2	5	4.8×10^4	1.5×10^4	1.3×10^4	5.6×10^3	—	4.9×10^2	1.1×10^5
CT22	Sr-90	*S. scrofa*	2.2×10^3	—	1	8.3×10^3	2.9×10^3	4.2×10^3	4.4×10^3	—	2.4×10^2	3.3×10^4

Table 11. (Continued.)

			Measured data			Model predictions						
Data ID	Nuclide	Species	Mean	SD	n	EA R&D128	ERICA	Lietdos Biota	RESRAD-BIOTA	FASTer-EPIC Doses 3D	DosDiMEco	D-Max
CT23	Cs-137	*S. scrofa*	2.8×10^{3}	7.9×10^{2}	2	1.3×10^{4}	4.1×10^{3}	3.4×10^{3}	1.5×10^{3}	—	1.3×10^{2}	2.8×10^{4}
CT23	Sr-90	*S. scrofa*	8.7×10^{2}	2.7×10^{1}	2	1.7×10^{3}	6.1×10^{2}	8.7×10^{2}	9.2×10^{2}	—	5.0×10^{1}	7.0×10^{3}
CT24	Cs-137	*S. scrofa*	1.5×10^{5}	1.8×10^{4}	2	3.3×10^{5}	1.0×10^{5}	8.6×10^{4}	3.9×10^{4}	—	3.4×10^{3}	7.3×10^{5}
CT24	Sr-90	*S. scrofa*	7.1×10^{3}	7.4×10^{1}	2	5.5×10^{4}	1.9×10^{4}	2.7×10^{4}	2.9×10^{4}	—	1.6×10^{3}	2.2×10^{5}
CT25	Cs-137	*S. scrofa*	6.0×10^{4}	8.2×10^{4}	2	1.0×10^{5}	3.2×10^{4}	2.6×10^{4}	1.2×10^{4}	—	1.0×10^{3}	2.2×10^{5}
CT25	Sr-90	*S. scrofa*	3.8×10^{4}	9.2×10^{3}	2	1.8×10^{4}	6.3×10^{3}	9.1×10^{3}	9.6×10^{3}	—	5.2×10^{2}	7.3×10^{4}
CT26	Cs-137	*S. scrofa*	6.3×10^{3}	9.0×10^{3}	3	1.4×10^{4}	4.4×10^{3}	3.6×10^{3}	1.6×10^{3}	—	1.4×10^{2}	3.1×10^{4}
CT26	Sr-90	*S. scrofa*	1.4×10^{3}	9.3×10^{2}	3	1.9×10^{3}	6.8×10^{2}	9.7×10^{2}	1.0×10^{3}	—	5.6×10^{1}	7.8×10^{3}
CT27	Cs-137	*S. scrofa*	5.3×10^{3}	2.8×10^{3}	3	1.2×10^{5}	3.8×10^{4}	3.1×10^{4}	1.4×10^{4}	—	1.2×10^{3}	2.7×10^{5}
CT27	Sr-90	*S. scrofa*	1.7×10^{3}	8.2×10^{2}	3	1.7×10^{4}	6.0×10^{3}	8.6×10^{3}	9.1×10^{3}	—	5.0×10^{2}	6.9×10^{4}
CT28	Cs-137	*S. scrofa*	4.4×10^{3}	4.3×10^{3}	5	1.3×10^{4}	4.1×10^{3}	3.4×10^{3}	1.5×10^{3}	—	1.3×10^{2}	2.9×10^{4}
CT28	Sr-90	*S. scrofa*	1.4×10^{3}	1.2×10^{3}	5	1.9×10^{3}	6.5×10^{2}	9.4×10^{2}	9.9×10^{2}	—	5.4×10^{1}	7.5×10^{3}

Table 12. A comparison of measured to predicted ^{137}Cs and ^{90}Sr whole-body activity concentrations (Bq kg^{-1} fw) in beetles and grassy vegetation. (Note: shaded cells denote predictions which deviate from the observed data by more than one order of magnitude.)

			Measured data			Model predictions						
Data ID	Nuclide	Species	Mean	SD	n	EA R&D128	ERICA	Lietdos Biota	RESRAD-BIOTA	FASTer-EPIC Doses 3D	DosDiMEco	D-Max
CT1d	Cs-137	Beetles	6.1×10^4	9.0×10^4	5	1.4×10^3	5.2×10^3		2.2×10^3	—		3.9×10^5
CT1d	Sr-90	Beetles	1.8×10^4	3.5×10^4	4	4.8×10^4	3.9×10^3		6.1×10^2	—		9.6×10^4
CT1a	Cs-137	Grassy vegetation	2.8×10^4	7.3×10^3	4	5.6×10^3	2.7×10^4	2.7×10^4	2.7×10^4	—	1.7×10^3	5.6×10^4
CT1a	Sr-90	Grassy vegetation	7.8×10^2	2.4×10^2	4	4.8×10^4	2.0×10^3	2.0×10^3	2.0×10^3	—	2.7×10^2	1.4×10^4
CT2a	Cs-137	Grassy vegetation	3.6×10^4	—	1	1.3×10^4	6.2×10^4	6.2×10^4	6.2×10^4	—	3.9×10^3	1.3×10^5
CT2a	Sr-90	Grassy vegetation	5.6×10^2	—	1	1.9×10^5	7.8×10^3	7.8×10^3	7.8×10^3	—	1.1×10^3	5.4×10^4
CT3a	Cs-137	Grassy vegetation	5.2×10^7	4.3×10^7	4	3.1×10^5	1.5×10^6	1.5×10^6	1.5×10^6	—	9.5×10^4	3.1×10^6
CT3a	Sr-90	Grassy vegetation	4.2×10^4	4.8×10^4	4	7.0×10^6	2.9×10^5	2.9×10^5	2.9×10^5	—	4.0×10^4	2.0×10^6
CT4a	Cs-137	Grassy vegetation	6.6×10^3	4.0×10^3	4	2.5×10^2	1.2×10^3	1.2×10^3	1.2×10^3	—	7.5×10^1	2.5×10^3
CT4a	Sr-90	Grassy vegetation	4.4×10^1	2.1×10^1	4	3.9×10^3	1.6×10^2	1.6×10^2	1.6×10^2	—	2.2×10^1	1.1×10^3

Table 13. A comparison of measured to predicted Pu and ^{241}Am whole-body activity concentrations (Bq kg^{-1} fw). (Note: shaded cells denote predictions which deviate from the observed data by more than one order of magnitude.)

		Measured data			Model predictions						
Data ID	Nuclide/species	Mean	SD	N	EA R&D128	ERICA	LIETDOS-BIOTA	FASTer–EPIC Doses 3D	RESRAD-BIOTA	DosDiMEco	D-Max
	$^{239/240}$Pu										
CT36b	*A. caudatus*	4.3×10^{0}	6.3×10^{0}	4	1.2×10^{3}	4.0×10^{1}	1.7×10^{-2}	1.1×10^{0}	2.6×10^{-1}	1.1×10^{1}	1.7×10^{1}
CT33b	*A. flavicollis*	6.9×10^{-1}	4.8×10^{-1}	2	2.9×10^{-1}	1.4×10^{1}	3.3×10^{0}	3.7×10^{-1}	1.8×10^{-1}	1.7×10^{0}	5.8×10^{0}
CT33a	*C. glareolus*	9.6×10^{-1}	1.1×10^{0}	2	2.9×10^{-1}	1.4×10^{1}	3.3×10^{0}	4.0×10^{-1}	2.1×10^{-1}	1.7×10^{0}	5.8×10^{0}
CT39	*C. glareolus*	5.0×10^{-1}	4.0×10^{-2}	28	3.8×10^{-2}	1.8×10^{0}		5.2×10^{-2}	2.8×10^{-2}	2.2×10^{-1}	7.6×10^{-1}
CT32a	*Microtus spp.*	3.5×10^{-1}	2.4×10^{-1}	2	5.2×10^{-1}	2.4×10^{1}	5.9×10^{0}		3.8×10^{-1}	1.3×10^{0}	1.0×10^{1}
	$^{238/239/240}$Pu										
CT36a	*P. major*	9.3×10^{0}	1.4×10^{1}	4	1.2×10^{3}	4.0×10^{1}	1.7×10^{-2}	1.4×10^{0}	4.2×10^{-1}	9.8×10^{0}	1.7×10^{1}
	^{241}Am										
CT39	*C. glareolus*	4.8×10^{0}	4.4×10^{0}	28	2.9×10^{-2}	4.4×10^{0}	8.0×10^{-1}	9.2×10^{-2}	3.4×10^{-2}	1.2×10^{-1}	1.1×10^{0}

Table 14. Predicted internal and total (internal + external) unweighted absorbed dose rates combined for all radionuclides considered. (Note: n/r—not reported; n/a—not applicable for this model (see text); shaded cells denote a z-score $\geqslant 3$ (note D-Max was not included in statistical analyses).)

		Absorbed dose rate (μGy h^{-1})													
		EA R&D128		ERICA		Lietdos Biota		RESRAD-BIOTA		FASTer-EPIC Doses 3D		DosDiMEco		D-Max[a]	
Data ID	Species	Internal dose	Total dose	Internal dose	Total dose	Internal dose	Total dose	Internal dose	Total dose	Internal dose	Total dose	Internal dose	Total dose	Internal dose	Total dose
CT1a	Grassy vegetation	10	24	4.8	15	n/r	n/r	5.2	19	n/r	n/r	n/r	n/r	n/a	35
CT1d	Beetles	16	22	2.0	10	n/r	n/r	0.6	10	n/r	n/r	n/r	n/r	n/a	250
	Reptile														
CT1b	*L. agilis*	90	96	92	93	n/r	n/r	23	34	n/r	n/r	n/r	n/r	n/a	250
	Frogs														
CT6a	*R. esculenta*	100	110	260	280	n/r	n/r	1.9	3.9	0.2	9.4	n/r	n/r	n/a	70
CT6b	*R. terrestris*	390	410	47	65	n/r	n/r	110	120	61	75	n/r	n/r	n/a	n/r
	Birds														
CT36b	*A. caudatus*	3.4	3.4	0.1	0.1	n/r	n/r	4.4×10^{-4}	4.9×10^{-4}	2.2×10^{-3}	2.2×10^{-3}	4.1×10^{-4}	4.1×10^{-4}	n/a	0.1
CT37	*E. rubecula*	87	95	15	19	n/r	n/r	110	120	86	87	37	38	n/a	700
CT7	*H. rustica*	17	19	3.3	4.6	n/r	n/r	7.2	8.3	n/r	n/r	3.3	3.4	n/a	180
CT36a	*P. major*	93	96	14	19	n/r	n/r	97	100	62	63	29	31	n/a	700
CT9	*P. perdix*	19	20	2.8	3.9	n/r	n/r	9.5	10	n/r	n/r	0.1	0.6	n/a	150
CT10	*S. vulgaris*	24	25	4.5	6.3	n/r	n/r	25	26	n/r	n/r	5.7	6.3	n/a	240
	Rodents														
CT33b	*A. flavicollis*	51	60	41	50	99.6	115	44	55	240	260	27	34	n/a	320
CT34b	*A. flavicollis*	6.1	7.5	6.0	7.4	16.2	18.8	5.9	7.7	30	32	3.3	4.4	n/a	49
CT31a	*A. sylvaticus*	270	310	200	240	464	535	220	280	1650	1720	140	180	n/a	3130
CT33b	*C. glareolus*	51	60	41	51	99.6	115	77	91	360	370	27	35	n/a	320
CT34b	*C. glareolus*	6.1	7.5	6.0	7.7	16.2	18.8	10	12	44	46	3.3	4.6	n/a	49
CT31b	*M. arvalis*	270	310	200	249	464	535	110	170	n/r	n/r	67	110	n/a	1560
CT42	*M. oeconomus*	31	36	23	28	51.4	59.2	13	20	29	35	13	17	n/a	180

Table 14. (Continued.)

		Absorbed dose rate (μGy h^{-1})													
		EA R&D128		ERICA		Lietdos Biota		RESRAD-BIOTA		FASTer-EPIC Doses 3D		DosDiMEco		D-Max[a]	
Data ID	Species	Internal dose	Total dose	Internal dose	Total dose	Internal dose	Total dose	Internal dose	Total dose	Internal dose	Total dose	Internal dose	Total dose	Internal dose	Total dose
CT32a	*Microtus spp.*	160	180	110	130	236	271	220	250	n/r	n/r	34	55	n/a	820
CT34c	*S. araneus*	6.1	7.5	6.0	7.9	16.2	18.8	9.0	11	3.2	5.3	2.8	4.2	n/a	97
CT3b	*S. betulina*	3900	4370	2590	2830	5390	6187	2990	3590	n/r	n/r	3300	3710	n/a	38 700
	Large mammals														
CT13	*C. capreolus*	2.3	2.5	2.3	2.4	1.4	1.6	2.0	2.3	3.3	3.4	0.1	0.2	n/a	12
CT11	*C. lupus*	3.9	4.1	1.8	1.9	n/r	n/r	6.5	6.7	9.3	9.3	0.6	0.7	n/a	18
CT28	*S. scrofa*	3.9	4.1	1.8	1.9	1.5	n/r	1.2	1.3	n/r	n/r	0.2	0.3	n/a	18

[a] D-Max results are not directly comparable to other model predictions as it predicts a 'maximum' total dose rate without any assumptions of geometry.

concentrations ^{137}Cs and ^{90}Sr) and long-tailed tit (input soil concentrations Pu isotopes) for which DosDiMEco predicted lower dose rates than the other participating models by approximately one and three orders of magnitude respectively. Total dose rate predictions were again most variable for *A. caudatus*, *P. perdix* and *R. esculenta*.

Comparing the radionuclide specific contributions to the total dose rates, there were a few notable differences between models:

- *M. oeconomus* (root vole)—greater contribution of ^{137}Cs predicted by LIETDOS-BIOTA;
- grassy vegetation—greater contribution of ^{90}Sr predicted by EA R&D128;
- beetle—dominance of external dose rate contribution to total dose rate predicted by RESRAD-BIOTA;
- lack of contribution of ^{90}Sr to external dose rate predicted by the ERICA Tool;
- relative contributions of ^{90}Sr and ^{137}Cs to internal dose rate for rodent species between different models;
- greater contributions to internal dose rate of Pu isotopes and ^{241}Am predicted by the ERICA Tool.

The D-Max model, which estimates a maximum total dose rate as opposed to the ‘best estimate’ predicted by the other models, predicted the highest total dose rate of any model for all but 3 of the 22 predictions. Nevertheless, the majority of D-Max predictions were within an order of magnitude of the mean of the total dose estimates of the other models and there was only one instance (*L. agilis*) for which this model estimated a dose rate more than an order of magnitude higher than any other model.

5.3. Thermoluminescent dosimeter predictions

With the exception of the *M. oeconomus* sample (from Chesser *et al* 2000), the data for dose rates estimated by TLDs attached to rodent species came from the study described by Beresford *et al* (2008b) which was conducted at three forest sites during the summer of 2005. In this study, TLDs were placed at various heights above and below the soil surface at the three study sites in addition to being attached to animals. These TLDs were paired, one was prepared in the same manner as those attached to the animals and the other was encased in 2 cm of Perspex. The dose rates recorded by TLDs prepared in the same manner as those attached to the study animals and placed at various heights above and below the soil surface were on average 1.95 times higher than the dose rates recorded by TLDs situated in the same location but shielded by 2 cm of Perspex. It was assumed by Beresford *et al* (2008b) that the ‘additional’ dose was due to exposure to beta radiation (excluded by the Perspex) and that it would be representative of exposure to beta-emitting radionuclides as recorded by the TLDs on the animal collars. However, this would not be representative of the whole-body external beta dose rates, therefore the results of the TLDs attached to the animals were corrected (i.e. divided by 1.95) to derive the external gamma dose rate. The results for the *M. oeconomus* TLDs (from Chesser *et al* 2000) were similarly corrected. These corrected results are compared to the model predictions here.

Beresford *et al* (2008b) reported that ^{137}Cs contributed $\geqslant$99% of the total external dose rate at all three of their study sites. Consequently, table 15 compares the ^{137}Cs external dose rates predicted by the participating models to the available TLD measurements.

Predictions were all within an order of magnitude of the observed data mean, with the majority being within the standard deviation of the data. Results for *M. oeconomus* as reported by Chesser *et al* (2000) were the least well predicted.

Table 15. TLD dose rate predictions (μGy h^{-1}) given by the participating models. (Note: all predictions are within one order of magnitude of the observed data.)

		Measured data			Model predictions					
Data ID	Species	Mean	SD	*n*	EA R&D128	ERICA	LIETDOS-BIOTA	FASTer–EPIC Doses 3D	RESRAD-BIOTA	DosDiMEco
CT32a	*Microtus spp.*	44	15	11	18	22	34	—	27	12
CT33a	*C. glareolus*	13	6.2	39	7.8	9.9	15	12	12	5.3
CT33b	*A. flavicollis*	17	12.6	10	7.8	8.4	15	12	10	4.5
CT34a	*C. glareolus*	2.1	0.62	3	1.3	1.7	2.5	2.1	2.1	0.90
CT34b	*A. flavicollis*	1.5	0.60	18	1.3	1.4	2.5	2.1	1.8	0.77
CT42	*M. oeconomus*	16	4.0	13	3.9	5.0	7.5	6.2	6.1	2.7

6. Discussion

6.1. Whole-body activity concentrations

The Chernobyl scenario has allowed predictions of the seven participating models to be compared to available ^{90}Sr and ^{137}Cs whole-body activity concentrations in a wide range of vertebrate species. It has enabled a more limited comparison for lower organisms and also actinide elements. In many instances, the majority of predictions were within an order of magnitude of the measured data. However, there were predictions more than an order of magnitude either side of the data mean for most comparisons. Furthermore, there was considerable variation in predicted whole-body activity concentrations between the participating models with 3–4 orders of magnitude difference in predictions for a number of comparisons. In this section we attempt to understand some of the reasons for poor predictions by some models and the variation between predictions. To aid this discussion, figures 1–3 present summaries of predictions by organism type for each model. To allow easy comparison within these figures, predicted activity concentrations were normalised to the observed data mean for each prediction; the figures present the mean of the normalised predictions.

6.1.1. D-Max. The D-Max model generally over predicted whole-body activity concentrations, often by more than an order of magnitude, most especially for ^{137}Cs. This model is stated to be conservative and hence this outcome was to be anticipated (if it was to meet its conservative aim). There were a few instances when it predicted values below the data mean, although the degree of under prediction was usually less than for most other models.

6.1.2. DosDiMEco. The DosDiMEco model tended to under predict whole-body activity concentrations usually having the lowest prediction of any of the models. The model used CR values for grass and (agricultural) grain from those recommended for human food-chain modelling in IAEA (1994) to estimate the radionuclide intake rates of herbivorous/omnivorous species. It is unlikely that these values will accurately model the transfer of radionuclides to the diet of wild animals in the Chernobyl exclusion zone.

The model was subsequently re-run using CR values for 'grass&herb' from the ERICA Tool instead of the IAEA CR values for both grain and grass. Predicted ^{90}Sr activity concentrations for all mammals and birds increased by approximately six times over the initial estimates. Those for ^{137}Cs increased by approximately: 15 times for herbivorous and carnivorous mammals; 60 times for rodent species and; 120 times for bird species.

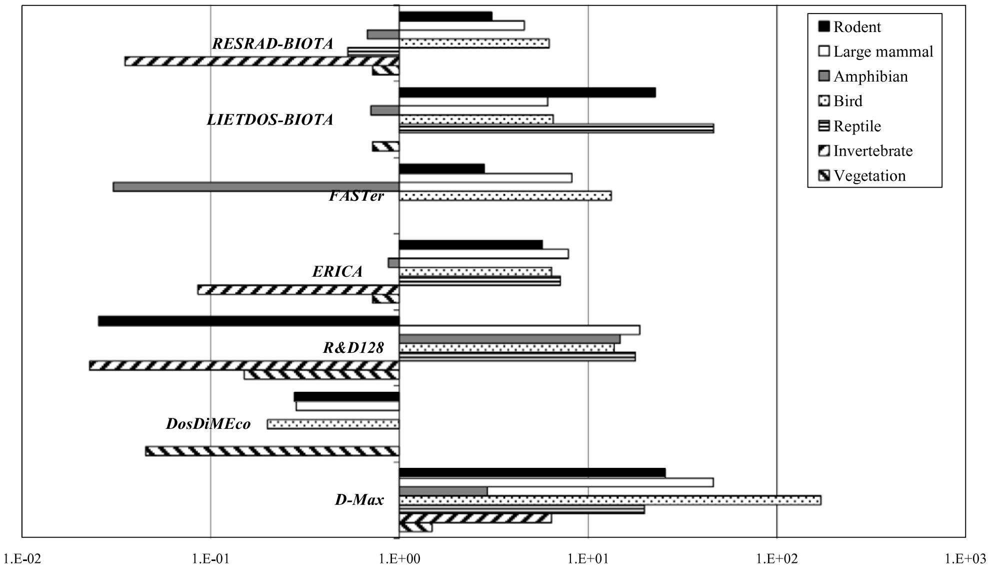

Figure 1. A comparison of the mean normalised predicted ^{137}Cs activity concentrations (fresh weight) for each model by organism type.

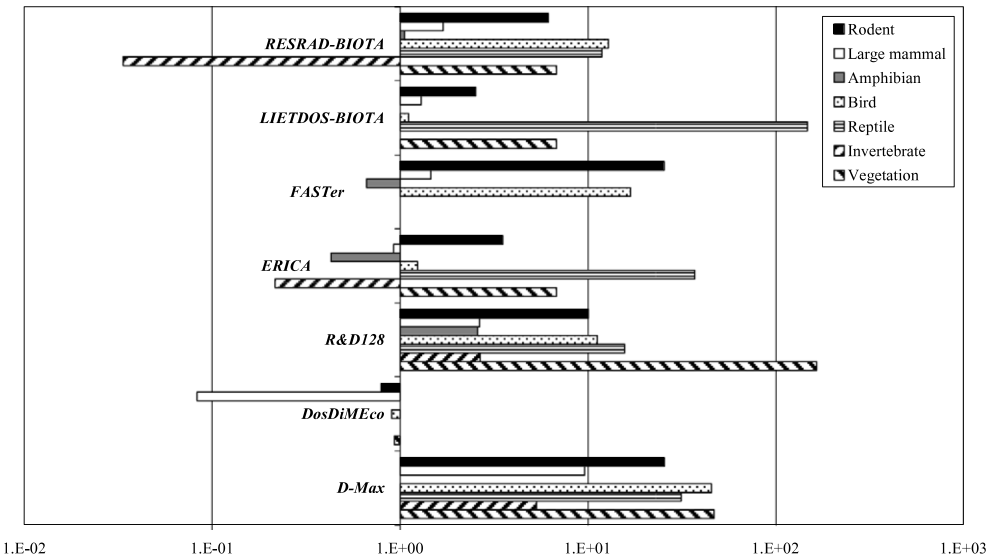

Figure 2. A comparison of the mean normalised predicted ^{90}Sr activity concentrations (fresh weight) for each model by organism type.

Consequently, with the revised parameters the model would not consistently underestimate ^{90}Sr and ^{137}Cs activity concentrations for any animal type included within the scenario for which it was used to provide predictions.

6.1.3. EA R&D128. The EA R&D128 model consistently under predicted ^{137}Cs activity concentrations in rodent species by typically 1–2 orders of magnitude (tables 8 and 9). This is

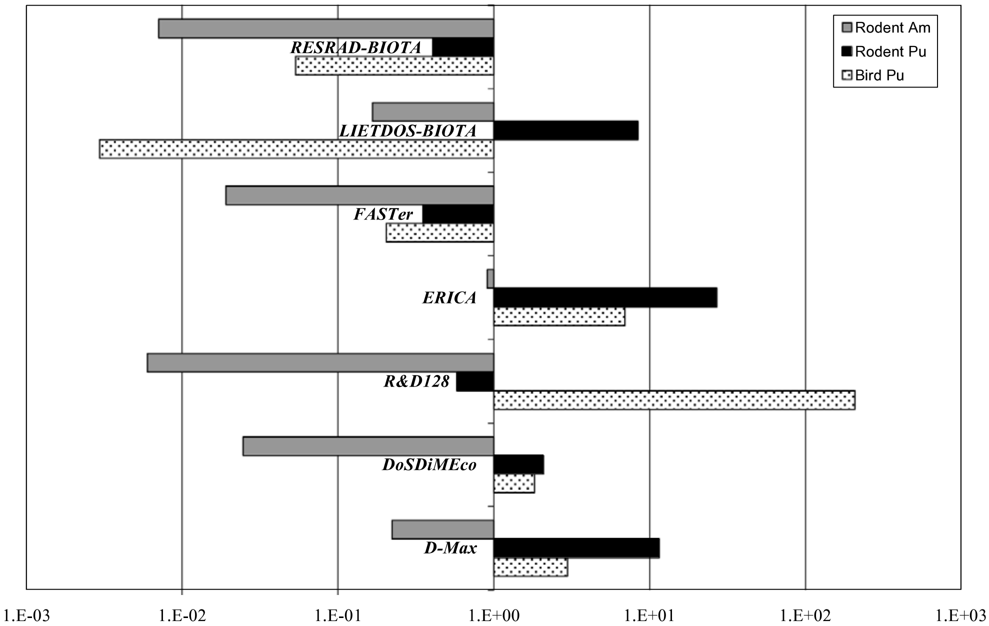

Figure 3. A comparison of the mean normalised predicted ^{241}Am and Pu isotope activity concentrations (fresh weight) for each model by organism type (Note: only one prediction was made of both ^{241}Am activity concentrations in rodent species and Pu isotopes in bird species).

consistent with observations in Beresford *et al* (2008e) where it was noted that the CR value used in EA R&D128 was based upon a single study of a coastal sand dune ecosystem close to the Sellafield reprocessing plant (UK) and that this value was unlikely to be applicable to many other ecosystems.

The EA R&D128 approach consistently over predicted ^{137}Cs activity concentrations in frog species by approximately an order of magnitude (table 10). The CR value of 9 used in this model was derived from values for red fox (*Vulpes vulpes*) determined in the UK during 1986 following the Chernobyl accident (Lowe and Horrill 1991). The same CR was also applied to estimate ^{137}Cs activity concentrations in *C. lupus* and *S. scrofa* which were not consistently over predicted and the one sample of *L. agilis* which was over predicted to the same degree as the frog species.

Strontium-90 activity concentrations in bird species, grassy vegetation and rodent species all tended to be over predicted using the EA R&D128 approach. A CR value of 5 (derived for mice in a woodland close to the Sellafield reprocessing plant) is used for all organisms within this approach to estimate ^{90}Sr activity concentrations.

6.1.4. ERICA Tool & RESRAD-BIOTA—Invertebrate predictions. RESRAD-BIOTA used CR values from the ERICA Tool to predict activity concentrations in the one sample of invertebrates (‘beetle’) included in the scenario. However, the ERICA Tool contains default CR values for a number of different terrestrial invertebrates and the values used by RESRAD-BIOTA were not the same as those used for the application of the ERICA Tool itself to this scenario (tables 3 and 4). Both models under predicted ^{137}Cs and ^{90}Sr activity concentrations for the beetle sample. Although only one invertebrate sample was included in the scenario, and hence we should not give undue weight to this observation, RESRAD-BIOTA and the FASTer model used invertebrate CR values from the ERICA Tool to estimate radionuclide intake rates by some bird and mammal species. Therefore, if the ERICA Tool does under predict activity concentrations in invertebrate reference organisms this will impact on the predictions for higher organism by these two models.

6.1.5. LIETDOS-BIOTA—^{137}Cs activity concentrations in rodent species. The LIETDOS-BIOTA model tended to over predict ^{137}Cs concentrations in rodent species. The CR value used by this model was 11.4 (table 4) which was derived from studies conducted in Lithuania following deposition from the Chernobyl accident (Nedveckaite 2004).

6.1.6. Predicted Pu activity concentrations. Plutonium isotope concentrations in the two bird species were relatively poorly predicted by a number of models (table 13). Over predictions of more than two orders of magnitude were made by the EA R&D128 approach, whilst RESRAD-BIOTA and LIETDOS-BIOTA under predicted by more than one and two orders of magnitude respectively. Due to the lack of specific data, the EA R&D128 approach assumes that Pu activity concentrations in birds are the same as the fresh weight activity concentration of soil (corrected from the models input of dry weight soil concentrations). Consequently, it is not surprising that the EA R&D128 model overestimates. Predictions by RESRAD-BIOTA are discussed in section 6.1.7 below.

Although the ERICA Tool predicted the ^{241}Am and Pu activity concentrations in *C. glareolus* relatively well (table 13) it over predicted Pu activity concentrations in the other three rodent samples by more than an order of magnitude. The Pu CR value used (2.34×10^{-2}) was derived from 18 data entries (representing 123 measurements from 6 reference sources (Beresford *et al* 2008a)) for a range of rodent species and larger mammals.

6.1.7. RESRAD-BIOTA and FASTer predictions. The RESRAD-BIOTA and FASTer models differ from the 'equilibrium CR' approaches taken by all the other models with the exception of DosDiMEco.

The two models are comparable in concept and utilise similar allometric relationships to describe the biological half-life of radionuclides and also dietary intake rates. However, the FASTer and RESRAD-BIOTA models predicted very different activity concentrations to each other in some instances. To explain these differences, sensitivity analyses were conducted. The results showed the differences were caused by the use of different parameter values, notably, the food sources and the ingestion rate of each food source, and to lesser extent, the CR of each food source, the biological loss rate, and the consideration of soil/sediment ingestion and inhalation pathways in RESRAD-BIOTA. By using the same input parameter values, RESRAD-BIOTA and FASTer generated comparable results, within 13%.

Overall, RESRAD-BIOTA and FASTer performed similarly to those using simple CR approaches. However, both models had a tendency to over predict the transfer of ^{90}Sr to some bird and rodent species. The high CR values used for the food sources of birds and rodents might be the cause of the overestimation. The FASTer model also underestimated ^{137}Cs activity concentrations in amphibians by more than an order of magnitude. In this case, an allometric relationship derived to predict food ingestion rates for (poikilothermic) reptiles (Nagy 2001) was applied to amphibians (frogs) and probably resulted in the underestimation of the food ingestion rates which, consequently, led to underestimation of tissue concentrations.

6.1.8. Scenario. The ability of the participating models to accurately predict whole-body activity concentrations in the species considered is dependent upon how appropriate the input soil data were (i.e. was it sufficiently replicated to encompass the likely heterogeneity, was it representative of the home range of the animals in question?). A similar caveat with respect to replication can be expressed about the available biota data, especially for birds (measured data were based upon samples sizes ranging from one to 65 replicates).

All approaches assumed that the transfer of radionuclides to biota was consistent throughout the exclusion zone. In reality this will not be the case, some of the differing agreement between predictions and observations will be a consequence of site specific factors such as soil characteristics (see Sobotovich *et al* 2003) and the contribution of 'hot particles' to the radionuclide deposit (potentially significant and variable within the exclusion zone (Kashparov *et al* 1999)).

These factors may contribute to some of the data and model prediction comparisons above, especially where most or all of the participants predicted the available data relatively poorly (see examples in all of tables 8–13).

6.2. Absorbed dose rates

Some of the variation between internal, and consequently, total absorbed dose rates predicted by the different participating models can obviously be readily explained by differences in the predicted whole-body activity concentrations. For instance, the comparatively high internal ^{90}Sr dose rate predicted for grassy vegetation by EA R&D128, the high internal Pu dose rate predicted for long-tailed tit by the ERICA Tool, the low internal dose rate predicted for the sand lizard by RESRAD-BIOTA, high internal dose rates predicted for rodent species by FASTer and the low ^{137}Cs internal dose rate predicted by EA R&D128.

Other aspects of the results can be related back to the findings of the comparison of DCC values (see Vives i Batlle *et al* 2007); for example, the comparative lack of external dose from ^{90}Sr predicted by the ERICA Tool. This previous assessment, which included most the majority of the models participating in this exercise, demonstrated the models all generally estimated comparable unweighted (especially internal) dose rates (Vives i Batlle *et al* 2007). The assessment of Vives i Batlle *et al* demonstrated that the effect of using model default geometries versus bespoke geometries derived to better represent organism under consideration was minimal. Consequently, the large variation in assumed masses by different participants in this exercise for some species (see table 2 above) contributes little to the observed variation in predictions.

Given the relatively low contribution of external exposure to the total dose rate in this scenario, assumptions with regard to occupancy do not greatly influence comparisons between the predictions of the participating models. The most extreme variation in assumptions, for both occupancy and methods of determining transfer, made by different modellers were for the frog predictions. However, variations in estimated dose rates (table 14) (and whole-body activity concentrations see table 10) were no more variable for frogs than any other organisms considered.

The dose rates predicted by the D-Max model are not comparable to those of the other models assessed here since it aims to predict an overall maximum dose rate with no assumptions of geometry or occupancy.

There was reasonably good agreement between the TLD measurements of gamma dose rate and predicted external ^{137}Cs dose rates for five of the six possible comparisons. All of these data were from the study of Beresford *et al* (2008b) conducted in 2005. This paper also provided the justification for (i) the value used to correct the TLD readings (to remove the beta dose contribution) and (ii) assuming that the external gamma dose rate could be equated the external ^{137}Cs dose rates predicted by the models. However, the other available data set, which was not predicted as well, originated from a study conducted in the mid-1990's (Chesser *et al* 2000). It is therefore likely that the correction factor used and the assumed dominance of ^{137}Cs may not have been applicable to this data set.

Perhaps the most notable aspect of the predicted dose rates is that overall they are less variable between models than may have been expected from the high variability observed in predictions of activity concentration. A good example of this is the total absorbed dose rate predictions of EA R&D128 for rodent species. These are comparable to those for the other models. However, this model consistently under predicts ^{137}Cs whole-body activity concentrations by more than one order of magnitude and predicts activity concentrations to be lower than all the other participating models by up to three orders of magnitude (tables 8 and 9). Conversely, this model tended to overestimate ^{90}Sr whole-body activity concentrations (tables 8 and 9). Therefore, the overestimation of ^{90}Sr whole-body activity concentrations and underestimation of ^{137}Cs appear to 'balance out' to produce a total dose rate estimate comparable with that of the other models. Future inter-model evaluations should not rely upon total dose rate as the output to be compared.

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