Radiat Environ Biophys (2007) 46:349–373
DOI 10.1007/s00411-007-0124-1

ORIGINAL PAPER

Inter-comparison of absorbed dose rates for non-human biota

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Received: 6 March 2007 / Accepted: 5 July 2007 / Published online: 31 July 2007

Abstract A number of approaches have been proposed to estimate the exposure of non-human biota to ionizing radiation. This paper reports an inter-comparison of the unweighted absorbed dose rates for the whole organism (compared as dose conversion coefficients, or DCCs) for both internal and external exposure, estimated by 11 of these approaches for selected organisms from the Reference Animals and Plants geometries as proposed by the International Commission on Radiological Protection. Inter-comparison results indicate that DCCs for internal exposure compare well between the different approaches, whereas variation is greater for external exposure DCCs. Where variation among internal DCCs is greatest, it is generally due to different daughter products being included in the DCC of the parent. In the case of external exposures, particularly to low-energy β-emitters, variations are most likely to be due to different media densities being assumed. On a radionuclide-by-radionuclide basis, the different approaches tend to compare least favourably for ^{3}H, ^{14}C and the α-emitters. This is consistent with models with different source/target geometry assumptions showing maximum

Dedication: This paper is dedicated to the memory of our co-author Dr. Masahiro Doi, who sadly passed away in July 2006. We will miss his friendship and input into the group.

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variability in output for the types of radiation having the lowest range across matter. The intercomparison demonstrated that all participating approaches to biota dose calculation are reasonably comparable, despite a range of different assumptions being made.

Introduction

Over the past decade, a number of approaches have been proposed to estimate the exposure of non-human biota to ionizing radiation. Some countries are now using these within their national regulatory frameworks for nuclear and other sites that may release radioactivity to the environment. To date, validation of these approaches has been limited, and there has been virtually no attempt to compare the outputs of the different approaches being applied. To address this gap, a new Biota Working Group (BWG; http://www.ns.iaea.org/projects/emras/emras-biota-wg.htm) was formed by the International Atomic Energy Agency (IAEA) as part of the Environmental Modelling for Radiation Safety (EMRAS) program in November 2004.

The primary objective of the EMRAS BWG, as set by its participants, is: 'to improve Member State's capabilities for protection of the environment by comparing and validating models being used, or developed, for biota dose assessment (that may be used) as part of regulatory process of licensing and compliance monitoring of authorized releases of radionuclides' [1].

The approaches considered by the BWG encompass those being developed and applied in Belgium, Canada, France, Lithuania, Russia, the UK and the USA, as well as the outputs of international programs. The purpose of this study was to perform an intercomparison of internal and external dose conversion coefficients estimated by these approaches for selected organisms (as listed in Table 1) from the Reference Animals and Plants geometries as proposed by the International Commission on Radiological Protection (ICRP) [2]. The comparison was intended to establish whether the results from different approaches are reasonably comparable, thus testing the scientific rigour of the calculation of doses to biota. The exercise was not intended to determine if the results of the different models were 'correct'.

The study covers a range of environmentally relevant media, allowing comparison of the underlying assumptions of the various approaches to dose calculation for different target organism-medium source configurations. A second exercise designed to compare the predicted whole-body specific activities for selected radionuclides in a range of non-human biota has been reported separately [3].

Key quantities relevant to biota dosimetry

Radionuclides in the environment lead to both external and internal exposure of plants and animals to ionizing radiation. Internal exposure arises following the uptake of radionuclides by organisms via pathways such as ingestion or root uptake. External radiation exposure depends on various factors, including contamination levels in the environment, the geometrical relationship between the radiation source and the organism, organism size, shielding properties of the medium, and the physical properties of the radionuclides present.

Dosimetry for biota, therefore, represents a wide range of exposure conditions, as well as the inevitable variability of species and habitats. Consequently, a number of extreme simplifications are made. One commonly used simplification is the reduction of the whole organism to simple shapes, such as ellipsoids and cylinders [4–6]. Although radionuclide concentrations in animals and plants display variations amongst tissues and organs as observed in humans, radionuclide kinetics in the organism and organ distribution are generally not taken into account. Hence, the endpoint considered is the average absorbed dose rate for the whole body per unit activity concentration in the organism or the surrounding media. This is estimated by the use of dose conversion coefficients (DCCs), which relate unweighted absorbed dose rate to the activity concentration in an organism or media.

Although current practice is to consider the absorbed dose rate averaged over the whole organism, there are instances where the non-uniform distribution of radionuclides in tissue can be important. One such instance is exposure of radiosensitive tissues to incorporated α-emitting radionuclides, resulting in significantly higher doses than obtained with a uniform distribution [7].

Absorbed dose, in all of the existing approaches to estimate non-human exposure, is defined in the conventional way as the amount of energy absorbed per unit mass of tissue of an organ or organism, given in units of Gray (Gy) [8]. Application of multiplicative radiation weighting factors based on experimental data for relative biological effectiveness to derive an equivalent dose is used for biota in some of the existing approaches. However, as there is currently no general agreement as to what appropriate radiation weighting factors should be applied for alpha and low-energy beta radiation, we have restricted our comparison to unweighted absorbed doses.

A fundamental quantity for estimating internal exposure is the absorbed fraction (AF), which is defined as the fraction of energy emitted by a decaying atom that is absorbed within the organism [5, 6, 9, 10]. In the simplest case, the organism is contained in an infinite homogeneous medium, activity is uniformly distributed throughout, and

Table 1 Proposed ICRP organism geometries [2] for which DCCs were to be determined, and habitats assumed for the exercise

Organism	Dimension[a]			Mass	Surface	Surface/volume	Ecosystem	Habitat
	a (cm)	b (cm)	c (cm)	(g)	(cm^2)	(cm^{-1})		
Duck	30	10	8	1.3E+03	6.3E+02	5.0E-01	Freshwater	S, OW
Frog	8	3	2.5	3.1E+01	5.2E+01	1.7E+00	Freshwater	S, IW
Salmonid egg	0.25	0.25	0.25	8.2E-03	2.0E-01	2.4E+01	Freshwater	BI, IW
Rat	20	6	5	3.1E+02	2.5E+02	7.9E-01	Terrestrial	U, S
Earthworm (elongated)	10	1	1	5.2E+00	2.5E+01	4.7E+00	Terrestrial	U, S

a, b, c: major, minor and second minor axis of ellipsoid

BI benthic interface, *S* shore/soil surface, *U* underground, *OW* on water, *IW* in water

the densities of both the medium and the organism are assumed to be equal. Under such conditions, both internal (D_{int}) and external (D_{ext}) radiation dose rates for mono-energetic α-, β-, and γ-radiation (in units of Gy s^{-1}) can be expressed as function of the absorbed fraction:

$$D_{\text{int}} = 1.6 \times 10^{-13} \cdot q \cdot E_i \cdot \text{AF}(E_i) \quad (1)$$

$$D_{\text{ext}} = 1.6 \times 10^{-13} \cdot q \cdot E_i \cdot (1 - \text{AF}(E_i)) \quad (2)$$

where 1.6×10^{-13} is a conversion factor (J MeV^{-1}), i denotes the radiation type (α-, β-, γ-radiation or spontaneous fission fragments), q is the radionuclide activity concentration in the organism or in the surrounding media (Bq kg^{-1}), and E_i is the energy (MeV)[1].

The absorbed dose rate can never exceed that in a uniform infinite media (D_∞), which for any given mono-energetic particle is:

$$D_\infty = 1.6 \times 10^{-13} \cdot q \cdot E_i \quad (3)$$

If the organism's dimensions are much smaller than the radiation range in the medium, especially for longer-range radiation (high-energy electrons and photons), then AF $\rightarrow$ (tends towards) 0, $D_{int} \rightarrow 0$ and $D_{ext} \rightarrow D_\infty$. Conversely, when the size of the organism is much larger than the radiation range in the medium (especially for α-particles and low-energy electrons with a range of less than 50–100 μm), then AF $\rightarrow$ 1, $D_{int} \rightarrow D_\infty$ and $D_{ext} \rightarrow 0$.

Materials and methods

Participants were asked to use their methodologies to determine unweighted absorbed dose rates to the whole organism assuming either a biota activity concentration of 1 Bq kg^{-1} given on a wet mass (WM) basis or a medium (water or soil) activity concentration of 1 Bq kg^{-1} (WM).

Hence, the outputs corresponded to the modelled DCC values as determined for the whole organism only, and shall be referred to as such hereafter. Results were requested to be reported in units of μGy h^{-1} per Bq kg^{-1} WM (internal dose), μGy h^{-1} per Bq L^{-1} (aquatic external dose rates from water) and μGy h^{-1} per Bq kg^{-1} WM (external dose from sediment or soil). Five types of DCC, or "dose categories" were specified: internal exposure, and external exposure in water, in soil, on soil and in sediment. Intercomparison of doses for organisms immersed in air was not possible due to a number of approaches not considering this and conflicting assumptions between those that did (e.g. some assume contaminated soil, others contaminated air). Unweighted dose rate estimates were requested to remove the uncertainty associated with the selection of multiplicative radiation weighting factors accounting for radiation quality from the comparison.

The following five Reference Animals, as proposed by the ICRP [2], were considered: duck, frog, salmonid egg, rat and elongated earthworm. The dimensions of these organisms are given in Table 1 together with the habitat to be assumed. The organisms were chosen to represent different geometry size classes ranging from very small (salmonid egg) to medium sized (duck). The shapes proposed are all ellipsoids with the exception of the elongated earthworm, which is considered (by the ICRP) as a cylinder. DCCs for each geometry were determined for seven radionuclides: ^{3}H, ^{14}C, ^{60}Co, ^{90}Sr, ^{137}Cs, ^{238}U and ^{241}Am selected so as to cover a range of energies and different types of radiation.

Where alternatives were not in-built into the method of calculation, the exercise recommended the following assumptions. Firstly, the radionuclide distribution in the media for organisms living in soil should be uniform to a depth of 50 cm. Secondly, organisms in soil should be set to a depth of 25 cm. Thirdly, the radionuclide distribution in the media for organisms living on soil should be uniformly contaminated to a depth of 10 cm.

[1] The equation for D_{ext} is an approximation that only holds if the organism and the surrounding medium are of the same density and elemental composition.

An effort was made to maximize independence among the approaches while the intercomparison was in progress. There was open discussion about the different approaches prior to the exercise. However, all model runs were performed independently, and submitted to an independent analyst/data custodian who was not involved in the running of any of the models. Statistical analysis results were disseminated after a final submission, whereupon discussion occurred without the possibility for resubmission of results after learning the outcome of this intercomparison.

Participating approaches

The group participants use, or are developing, biota dosimetry approaches to estimate both the transfer of radionuclides to biota and (by calculation of the absorbed fraction and DCC) the doses received in contaminated environments. The approaches participating in this exercise are briefly described in the following sections.

Participants provided details of which radionuclide progeny had been included in the calculation of DCCs and on what basis, together with all relevant geometry and radionuclide assumptions (Tables 2, 3). With the exception of EDEN 2, all approaches used ICRP publication 38 [11] for nuclide-specific energies and their emission probabilities.

Atomic Energy Canada Limited (AECL) approach

The AECL typically applies a multi-tiered approach in dose calculations, ranging from hyper-conservative Tier 1 to more realistic Tier 3. For screening purposes, hyper-conservative internal and external DCCs, which are not corrected for organism size and which assume 100% energy absorption by the organism, are applied [12]. For more realistic assessments, DCCs from Blaylock et al. [10], FASSET [13] or RESRAD-BIOTA [14] (as described below) are used, as appropriate. In most cases the latter, more realistic values, have been reported for this exercise.

ECOMOD (Russia)

ECOMOD [15] represents organisms as ellipsoids to estimate the absorbed fractions of radiation, using data from the literature [10, 16, 17]. These data are used to estimate unweighted absorbed doses for a limited number of radionuclides.

EDEN 2 (France)

The EDEN 2 approach is designed to calculate DCCs for user-defined geometries using Monte-Carlo computations based on the parameters defining the organism (density, elemental composition, activity concentration) being homogeneous over the whole volume [18]. The user can specify all required characteristics for the organisms of concern, which are represented by ellipsoids.

Two types of calculation are implemented, depending on the size of the target. For large organisms, the internal exposure DCCs for α- and β-irradiation may be calculated using a local deposition method, whilst external exposure is assumed to be negligible. For smaller organisms, all DCCs are calculated using a Monte-Carlo approach. Mono-energetic DCCs for given energies are calculated. Then, the DCC for any other energy is calculated by means of four-point Lagrange interpolation, and combined to generate the total DCC for a given energy spectrum. Radionuclide data from the NEA databank Joint Evaluated Fission and Fusion (JEFF) project [19] are used.

England and Wales Environment Agency 'R&D 128'

The R&D 128 approach was developed primarily to assess compliance with the EC Habitats Directive at sites receiving radioactive discharges [20, 21]. DCCs are estimated using simple functions for energy deposition in a medium of unit density from point isotropic sources to represent the absorption of photons and electrons. For photons, point-specific absorbed fractions from Berger [22] are applied to estimate the energy absorbed within a specified ellipsoidal or spherical volume. For electrons, tabulated data for point-β sources from Berger [23] are used to generate fractional absorption values that are relatively independent of energy. Energy absorbed fraction functions are fitted separately for photons and electrons to provide a reliable curve fitting interpolation between calculated values. These functions are then integrated numerically using a stochastic (Monte-Carlo) algorithm to calculate the absorbed fraction. The method, which has been validated against ICRP human dosimetry for argon and krypton, is fully described elsewhere [5]. The size of any organism (defined by the three axes of an ellipsoid) can be easily modified and DCCs recalculated using an ancillary spreadsheet tool. However, there is no provision for non-uniform distribution of internally incorporated radionuclides (e.g. internal organs), density variations between the organism and the medium (e.g. shielding layer of skin, fur) or for geometries different in shape from ellipsoids.

The approach treats ^{234}U as being in secular equilibrium with ^{238}U, i.e. the DCCs of ^{234}Th, ^{234m}Pa and ^{234}U are combined with the DCC of the parent ^{238}U. For the purposes of this intercomparison, R&D 128 DCCs excluding the last daughter product (^{234}U) were generated, given that the other approaches do not include this radionuclide.

Table 2 Geometry assumptions of the participating approaches

ICRP dimension or nearest available geometry used	As proposed by the ICRP—EA, EDEN, EPIC, ERICA, LIETDOS, RESRAD, SCK, SUJB; nearest default geometries—AECL, ECOMOD, FASSET			
Assumed tissue/org. density	1 g cm^{-3}—EA, ECOMOD, EDEN, EPIC, RESRAD, SCK, SUJB; 1.05 g cm^{-3} AECL, ERICA, FASSET, LIETDOS			
Scenario	Media density (g cm^{-3})	Uniform contamination assumed	Media depth	Assumed location of organism
Underground	1 - EA, 1.35 - SCK, 1.5 - EPIC, 1.6 - AECL, EDEN, ERICA, FASSET, LIETDOS, RESRAD, SUJB	AECL, EA, EDEN, EPIC, ERICA, FASSET, LIETDOS, RESRAD, SCK, SUJB	Infinite - EA, ECOMOD, EPIC, SUJB, 50 cm – AECL, EDEN, ERICA, FASSET, LIETDOS, RESRAD, SCK	Fully immersed - EA, ECOMOD, EPIC, SCK, SUJB, 25 cm depth – AECL, EDEN, ERICA FASSET, LIETDOS, RESRAD
On soil surface	1 - EA, 1.35 - SCK, 1.5 - EPIC, 1.6 - AECL, EDEN, ERICA, FASSET, LIETDOS, RESRAD, SUJB	AECL, EA, EDEN, EPIC, ERICA, FASSET, LIETDOS, RESRAD, SCK, SUJB	Infinite - EA, ECOMOD, SUJB, 5 cm - EPIC, 10 cm - AECL, EDEN, ERICA, FASSET, LIETDOS, RESRAD, SCK	On soil surface - AECL, EA, ECOMOD, EDEN, EPIC, ERICA, FASSET, LIETDOS, RESRAD, SCK, SUJB
Benthic interface	1 - EA, ERICA, FASSET, SUJB, 1.2 - RESRAD, 1.35 - SCK, 1.5 - EPIC, 1.6 - AECL, EDEN, LIETDOS	AECL, EA, EDEN, EPIC, ERICA, FASSET, LIETDOS, RESRAD, SCK, SUJB	Infinite - AECL, EA, ECOMOD, ERICA, FASSET, SUJB, 5 cm - EPIC, 10 cm – EDEN, LIETDOS, RESRAD, SCK.	At water/sed. interface – AECL, EA, ECOMOD, EDEN, EPIC, ERICA, FASSET, LIETDOS, SCK, SUJB, On sediment surface - RESRAD
In water	1 - AECL, EA, EDEN, EPIC, ERICA, FASSET, LIETDOS, RESRAD, SUJB	AECL, EA, EDEN, EPIC, ERICA, FASSET, LIETDOS, RESRAD, SCK, SUJB	Infinite - AECL, EA, ECOMOD, EPIC, ERICA, FASSET, SUJB, 100 cm - LIETDOS, 1,000 cm - EDEN	Fully immersed - AECL, EA, ECOMOD, EPIC, ERICA, FASSET, SUJB, 50 cm - LIETDOS, 500 cm – EDEN
On water	1 - AECL, EA, EDEN, EPIC, ERICA, FASSET, LIETDOS, SCK, SUJB	AECL, EA, EDEN, EPIC, ERICA, FASSET, LIETDOS, SCK, SUJB	Semi-infinite - EPIC, Infinite - AECL, EA, ECOMOD, ERICA, FASSET, SUJB, 10 cm - RESRAD, 100 cm - EDEN, 200 cm - SCK	At water/air interface - AECL, EA, ECOMOD, EDEN, EPIC, ERICA, FASSET, LIETDOS, RESRAD, SCK, SUJB

In this and subsequent tables, England and Wales Environment Agency 'R&D 128', EDEN 2, EPIC-DOSES3D, LIETDOS-BIO and RESRAD-BIOTA are abbreviated to EA, EDEN, EPIC, LIETDOS and RESRAD, respectively

Table 3 Radionuclide assumptions of the participating approaches

Nuclide	Daughters in equilibrium	Ext. α zero energy abs. assumed[f]	Ext. β zero energy absorption[a,g]	100 % int. α absorption[f]	100 % int. β absorption[g]	No. of α decays used[b,e]	No. of β decays used[b,e]	No. of γ decays used[b,d,e]
^{3}H			ECOMOD , EPIC, LIETDOS, SUJB		ECOMOD, EPIC, LIETDOS, SUJB	0 - AECL, EA, EDEN, EPIC, ERICA, FASSET, LIETDOS, RESRAD, SCK	1 - AECL, EA, ECOMOD, EDEN, EPIC, ERICA, FASSET, LIETDOS, RESRAD, SCK	0 - AECL, EA, EDEN, EPIC, ERICA, FASSET, SCK, 1 - LIETDOS
^{14}C			ECOMOD, LIETDOS		ECOMOD, EPIC, LIETDOS, SUJB	0 - AECL, EA, EDEN, EPIC, ERICA, FASSET, LIETDOS, SCK	1 - AECL, EA, ECOMOD, EDEN, EPIC, ERICA, FASSET, LIETDOS, RESRAD, SCK	0 - AECL, EA, EDEN, EPIC, ERICA, FASSET, SCK, 3 - LIETDOS
^{90}Sr	^{90}Y: AECL, EA, ECOMOD, EDEN, EPIC, ERICA, FASSET, LIETDOS, RESRAD, SUJB; ^{90,90m}Y: SCK		LIETDOS		LIETDOS, SUJB	0 - AECL, EA, EDEN, EPIC, ERICA, FASSET, LIETDOS, SCK	2 - AECL, EA, ECOMOD, EPIC, ERICA, FASSET, LIETDOS, RESRAD, SCK 3 - EDEN	1 - EDEN, 3 -SCK, 5 - EPIC, 7 – AECL, EA, ERICA, FASSET, 12 - LIETDOS
^{137}Cs	^{137m}Ba: AECL, EA, EDEN, EPIC, ERICA, FASSET, RESRAD, SCK, SUJB				LIETDOS, SUJB	0 - AECL, EA, EDEN, EPIC, ERICA, FASSET, LIETDOS, SCK	1 - ECOMOD, 2 - LIETDOS, SCK, 4 - RESRAD, 8 - EDEN, 13 – AECL, EA, EPIC, ERICA, FASSET	1 - SCK, 2 - ECOMOD, 3 - AECL, EA, EPIC, ERICA, FASSET, RESRAD, 7 - EDEN, 8- LIETDOS
$^{6^{\circ}}$Co					LIETDOS, SUJB	0 - AECL, EA, EDEN, EPIC, ERICA, FASSET, LIETDOS, SCK	1 - RESRAD, 2 - SCK, 3 – EDEN, LIETDOS, 4 - AECL, EA, EPIC, ERICA, FASSET	2 - AECL, EA, ECOMOD, EPIC, ERICA, FASSET, LIETDOS, RESRAD, SCK, 6 - EDEN
^{241}Am		AECL, EA, ECOMOD, EPIC, ERICA, FASSET, RESRAD, SCK, SUJB	EPIC, LIETDOS	AECL, EA, ECOMOD, EDEN[c], EPIC, ERICA, FASSET, LIETDOS, RESRAD, SUJB	EPIC, LIETDOS	5 – AECL, EA, ERICA, FASSET, LIETDOS, SCK, 10 - EPIC, 42 - EDEN	0 - SCK, 1 - ECOMOD, 5 - RESRAD, 13 - LIETDOS, 37 - AECL, EA, EPIC, ERICA, FASSET, 233 - EDEN	3 – ECOMOD, SCK, 5 - RESRAD, 8 - AECL, EA, EPIC, ERICA, FASSET, 12 - LIETDOS, 136 - EDEN

Table 3 continued

Nuclide	Daughters in equilibrium	Ext. α zero energy abs. assumed[f]	Ext. β zero energy absorption[a,g]	100 % int. α absorption[f]	100 % int. β absorption[g]	No. of α decays used[b,e]	No. of β decays used[b,e]	No. of γ decays used[b,d,e]
^{238}U	0: EPIC, SUJB, ^{234}Th, ^{234}Pa: ECOMOD, ^{234}Th, ^{234,234m}Pa: EA, EDEN, ERICA, RESRAD, SCK ^{234}Th, ^{234,234m}Pa, ^{234}U: AECL, FASSET	AECL, EA, ECOMOD, EPIC, ERICA, FASSET, RESRAD, SCK, SUJB	EPIC, LIETDOS	AECL, EA, ECOMOD, EDEN[c], EPIC, ERICA, FASSET, LIETDOS, RESRAD, SUJB	LIETDOS	3 - EA, EDEN, LIETDOS, SCK, 6 - EPIC	2 – ECOMOD, 4 - LIETDOS, RESRAD, 10 – AECL, EPIC, 26 – SCK, 109 - EA, 880 - EDEN	2 - ECOMOD, 4 - LIETDOS, RESRAD, 6 - EPIC, 147 - SCK, 170 - EA, 372 - EDEN

[a] For SCK ^{3}H & ^{14}C: Yes; for SCK ^{60}Co, ^{90}Sr and ^{137}Cs: No (except animals on water)

[b] SUJB average energies used

[c] Except for salmon egg and earthworm

[d] EDEN includes X-rays

[e] SUJB average energies given

[f] Not assumed for salmon egg or bacteria

[g] Not assumed for salmon egg

EPIC-DOSES3D

EPIC-DOSES3D was developed for the EC Inco-Copernicus Programme's EPIC project [24] and allows for user-defined biological objects of arbitrary size and shape. 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 simulations. The energy deposition along these tracks is quantified by dose attenuation functions; empirical formulae defining dose distribution functions for α and β radiation around point isotropic sources are used [25–27]. The absorbed fraction is obtained by integration of energy deposited over all tracks within the organisms.

For the case of an organism exposed on the ground surface or at the sediment/water interface, the kinetic energy released in the material (kerma) at a specified location in a given environment is derived. The ratio of the mean absorbed dose in an organism and the kerma in that environment is then calculated for the different energies characteristic of different radionuclides. This ratio allows the absorbed dose to the target geometry to be derived. Further details are provided elsewhere [28].

FASSET (Framework for the Assessment of Environmental Impact)

FASSET was developed under an EC 5th Framework project [13, 29]. Transfer from contaminated media is estimated using concentration ratios (CRs), predominantly derived from the literature, which are presented as look-up tables. DCCs are presented for a range of terrestrial and aquatic reference organisms (defined as ellipsoid geometries representative of species corresponding to the reference organisms). For terrestrial systems, DCCs are estimated using a Monte-Carlo approach. For aquatic systems, the approach, as used in the Environment Agency R&D 128 methodology, is applied. In this exercise the most appropriate of the default DCC values for the geometries, as presented for the FASSET framework [4, 13], are used (i.e. DCC specifically for the ICRP defined geometries are not calculated).

ERICA (Environmental Risk from Ionising Contaminants—assessment and management)

ERICA, an EC 6th Framework project [7], is an evolution of the FASSET project aiming to provide an integrated approach to scientific, managerial and societal issues concerned with the environmental effects of ionizing radiation. Whilst the ERICA outputs contain a tool to derive DCCs for user-defined geometries, DCCs for all of the proposed ICRP geometries are provided as defaults and have been used in this exercise.

Within the ERICA approach, reference organisms are defined as simple three-dimensional phantoms, i.e. ellipsoids and cylinders, as model geometric equivalents of reference organisms according to average characteristics of mass and size. The approach considers a layer of non-active tissue, i.e. the outer layers of the skin and/or fur causing a shielding effect for the living organism. This is especially important for β-radiation.

Monte-Carlo techniques are applied that include all relevant radiation transport processes, such as coherent and incoherent scattering, photoelectric absorption, pair production and production of fluorescent photons after photoeffect. For electrons, a thick-target Bremsstrahlung approach is used instead of an electron transport simulation [6]. For the calculation of DCCs for organisms in soil, a uniformly contaminated volume source is assumed. For estimation of external exposure, calculations are made for species on the ground, and a volume source with a depth of 10 cm is assumed. A key quantity for estimating internal doses is the absorbed fraction which, in this method, is calculated as a function of energy and organism size. Due to the short range of α-radiation, α-absorbed fractions are assumed to be 1.

LIETDOS-BIO (Lithuania)

LIETDOS-BIO is a tool for calculating radiation doses to aquatic and terrestrial animals and plants. This approach was developed to address contamination issues associated with nuclear power production in Lithuania [30]. The code is designed to be consistent with MCNPX[2], a commonly used general purpose Monte-Carlo radiation transport code [31]. An in-built method for describing phantoms allows DCC values to be calculated for organisms of any size or form.

RESRAD-BIOTA (United States of America)

The RESRAD-BIOTA code [14] was designed to be consistent with, and to provide a tool for implementing, the USDOE Graded Approach for Evaluating Radiation Doses to Aquatic and Terrestrial Biota [32]. Three levels of evaluation are available, ranging from Level 1 in which conservative assumptions are made but few inputs are required to Level 3 in which fewer assumptions are made, but more site- or receptor-specific input data are required.

[2] MCNPX (Monte Carlo N-Particle Transport Code Version X) is an extension of the Monte Carlo N-Particle Transport Code (MCNP) capable of simulating particle interactions of 34 different types of particles at all energies, including those simulated by MCNP.

RESRAD-BIOTA has the capability of evaluating radiation exposures for specific organisms, provided the users input their exposure parameters. The code contains a set of geometries that span the expected range of organism sizes that are of use in evaluating radiation doses to a user-selected organism. Internal and external exposure DCCs are estimated using the Monte-Carlo n-particle transport code (MCNP), through derivation of the photon and electron absorbed fractions in the energy range 1 keV to 3 MeV. Linear interpolation between these energies is used to calculate the absorbed fraction for a required energy. Absorbed fractions are then used to calculate the internal and external exposure DCCs for a given radionuclide.

SCK·CEN approach (Belgium)

The SCK·CEN approach consists of a software package, written in MathCad 2001i professional [33], which is divided into three sub-programs. The first sub-program calculates the energy absorption in a reference organism due to gamma irradiation 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. Appropriate mass attenuation data are taken from the literature [34].

The DCCs are calculated using a point kernel technique (corrected with a build-up factor) [35]. For β-DCCs, an approach using the Bethe-Bloch formula [8] is implemented. For α radiation the same equations are used, except that in this case, no relativistic or Bremsstrahlung effects need to be taken into account. Radionuclide-specific DCCs are determined by linear interpolation, taking into account the nuclide-specific energies emitted and their emission probabilities.

SÚJB approach (Czech Republic)

The SÚJB approach for estimating absorbed DCCs uses derived dose rate formulas as published by the IAEA [27, 36]. Selected categories of organisms are represented by ellipsoid geometries of stated dimensions. These geometries are used to estimate the absorbed fractions by numeric integration of point sources, and absorbed doses are determined from the absorbed fractions using radionuclide data (of relevance here, no daughter products are included in the estimation of ^{238}U).

Statistical analysis methodology

The data submitted by the participants were processed using the R software for Statistical Computing, version 2.3.0 [37]. Of the 25 packages supplied with R, the "Moments" package [38] was used here.

For any dose category, determinations were supplied by each of the participants for every radionuclide and organism (where included in their approach). To identify a central value for a given parameter to enable comparison of the different approaches, the following analysis strategy was adopted:

- Conduct initial exploratory data analysis to identify outliers.
- Perform statistical distribution tests on the remaining data.
- Calculate a robust mean and standard deviation for the parameter.
- Score each approach for performance.

Outliers in this exercise are identified from a purely statistical perspective, as there are no experimentally measured or previously agreed reference DCC values available. Likewise, no assumption is made that the mean from all predictions is the most accurate prediction. In the absence of reference data, the statistical methodology used in this study is simply a means to compare the outputs for all models.

Exploratory data analysis

Assuming the absence of any systematic bias for each individual approach, all results should follow a simple statistical distribution. If the distribution is normal, then the reported values should lie, with 95% probability, within 2-σ uncertainty range of the calculated reference value. In practice, outliers straying well outside this range are found. Initial exploratory data analysis to assess this was conducted using a "box plot" diagram. The box plot displays a measure of central tendency (the median), two measures of dispersion (the range and inter-quartile range), the skewness (from the orientation of the median relative to the quartiles) and potential outliers (marked individually). Given the large number of data to be processed, the key advantage of the box plot over numerical methods (such as Grubb's, extreme studentized deviate, Dixon's or Rosner's tests) is ready outlier visualisation.

Normality tests

A preliminary test (Shapiro-Wilk) was performed to determine whether the results were normally distributed. Having found that to be the case, data were subjected to D'Agostino's test for skewness and the Anscombe-Glynn's test for kurtosis[3]. These tests are powerful at detecting

[3] Skewness and kurtosis are measures of the lack of symmetry and the heaviness of the tails in a distribution, relative to the normal distribution.

deviations from normality caused by asymmetry or non-normal tail heaviness, respectively, by computing a *P*-value from the sum of the squares of these discrepancies.

The previous tests differ in how they quantify the deviation from normality, but they test the null hypothesis—that the data are sampled from a normal distribution. The null hypothesis is rejected, and the alternative hypothesis accepted, when the *P*-value is small. If the distribution is normal, the *P*-value will tend to be large:

- P-values > 0.10 indicate no evidence against the null hypothesis;
- $0.05 < P < 0.10$ indicates weak evidence against the null hypothesis in favour of the alternative hypothesis;
- $0.01 < P < 0.05$ indicates moderate evidence against the null hypothesis in favour of the alternative hypothesis;
- $0.001 < P < 0.01$ is indicative of strong evidence against the null hypothesis in favour of the alternative hypothesis; and
- $P < 0.001$ indicates very strong evidence against the null hypothesis in favour of the alternative hypothesis.

For this work, $P > 0.05$ was chosen as the criterion for passing the normality test.

D'Agostino's and Anscombe-Glynn's tests were chosen as tests in preference to the Kolmogorov–Smirnov or the Shapiro–Wilk test alone because the latter is generally less powerful than tests specifically designed to assess the shape of a distribution [39].

Any data point failing one or more tests was identified as an outlier, and the remaining data were re-tested without it until no further outliers were detected and the eventual residual data were found to conform to a normal distribution. From this the robust mean and associated standard deviation were estimated.

Calculation of reference data and scoring of each approach for performance

The performance of the participating approaches 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 [40]. This approach represents a simple method to give each approach a normalized performance score for bias. The performance is 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 ≥ 3 indicates that the measurements are highly biased [41]. This scoring system is now included in the International Organisation for Standardisation guidelines as a standard method for laboratory assessment [42] and has been used successfully by the IAEA in previous intercomparisons [43].

In order to assess the overall performance of the approaches on a dose category basis, an "efficacy measure" was computed, as suggested by [41]. This efficacy measure is defined as the "percentage of approaches producing results of acceptable quality" (i.e. with absolute value of Z between 0 and 2) and was calculated for each of the five dose categories (internal exposure, and external exposure in soil, water, sediment and on soil/shore).

Issues in results interpretation

The assumptions and calculation differences embedded within each approach are too numerous to enable a concise and systematic presentation of the data. Mean values and their confidence intervals were, therefore, statistically derived from data satisfying certain criteria with no regard to their inherent quality. This approach is not a substitute for expert opinion in cases where the data are more skewed with a greater spread.

No value judgement is, therefore, passed on outlying values. Statistical tests have limited power for screening such values out. When 'inaccurate' results outweigh 'accurate' results numerically, the few good data may be rejected.

In the case of ^{3}H and ^{14}C external doses, a significant number of participants reported values as 'zero', whilst some reported a numerically small non-zero value (Tables 5, 6, 7, 8). Consequently, the ^{3}H and ^{14}C external doses were excluded from consideration in the statistical analysis.

A limited number of cases, similarly requiring deviation from the basic analysis procedure, were treated individually. These were outputs when a number of models made different methodological assumptions (e.g. number of daughter radionuclides or source/target geometry), resulting in greater statistical spread than that allowed by a simple normal distribution, as described in the "Results—Identification of outliers" section.

In terms of evaluating Z-scores for every approach, it is important to exercise caution. The approaches are not absolutely independent from each other in terms of how the DCC is calculated. For example, a minority of the approaches adopt common DCC values in some instances (see sections "Results" and "Discussion—Analysis of robust means and *Z*-scoring"). However, generally, there are variations in respect of radionuclide assumptions and even wider variations in the definitions of source–target geometries for external doses (e.g. media density, tissue/organism density, media depth, location of organism in media). All these varying assumptions (summarized in Tables 2, 3) contribute to the variability in DCCs observed in this study, particularly for external exposure, with no individual set of

assumptions being absolutely right or wrong. Therefore, in the present study, it was decided to refrain from passing value judgements on each specific approach based on ranking their performance by means of *Z*-scores.

As some of the approaches (e.g. ERICA, EPIC-DOSES3D) were undergoing development, the results presented below, although they represent the current state of the art at the time of the exercise, may not be definitive.

Results

Calculated DCCs for internal irradiation and external irradiation in water, in soil, on soil and in sediment are given in Tables 4, 5, 6, 7, 8, respectively. It must be noted that the approaches used here have been applied by specific participants who were either involved in the development of the approach or its use in assessments. Some aspects of some approaches may be open to interpretation.

On initial inspection, internal exposure DCCs for the different approaches are relatively homogeneous; typically coefficients of variation (CVs)[4] are about 23% of the mean (range between 4 and 59%). Coefficients of variation between different approaches are greater for external exposure DCCs. Here, typical CVs are around 120% of the mean (range between 29 and 280%). Whilst external DCCs from ^{238}U are low, this radionuclide, along with ^{3}H and ^{14}C, was found to contribute the most to the variability; as noted above external DCCs for ^{3}H and ^{14}C were excluded from subsequent analyses. Without ^{3}H, ^{14}C and ^{238}U, typical CVs for external irradiation would be significantly reduced to around 71% of the mean (range between 29 and 230%).

Some groupings of apparently 'anomalous' DCCs stand out. Internal exposure DCCs for ^{238}U and ^{241}Am are consistently low for SCK·CEN. For external exposure DCCs in water, values from SCK·CEN for ^{90}Sr (reported as zero), as well as ^{238}U (significantly higher), are in contrast with the rest.

External DCCs for ^{90}Sr reported by the ERICA and related FASSET approaches are lower for terrestrial organisms than those of other approaches. This is likely to be a consequence of the consideration of a shielding skin/fur layer within these approaches (for terrestrial but not aquatic organisms).

For external exposure DCCs in soil, EPIC-DOSES3D reports comparatively high ^{137}Cs and ^{60}Co values. This may be due to the combined effect of infinite absorbing medium and, to a lesser extent, differing density assumptions (1.5 g cm^{-3}) compared with most other approaches, as shown in Table 2. To illustrate this, note that the density assumed in EPIC-DOSES3D is 50% higher than that assumed by the England and Wales Environment Agency R&D 128 methodology, and the DCCs differ in a similar proportion.

Internal exposure DCC values for aquatic organisms for ^{238}U from FASSET are higher than those of all other approaches (with the exception of AECL, which adopts the FASSET values in these instances). FASSET assumes ^{234}U is in secular equilibrium with ^{238}U.

Identification of outliers

Identification of outliers using the box plot method is depicted in Figs. 1 and 2, illustrating examples for internal irradiation and external irradiation in water, respectively. As the number of data contained in the box plot increases, there is an increasing likelihood that data points may appear just slightly outside the box plot's upper and lower limit (quartile ± 1.5 × interquartile range). Grubb's outlier testing was applied, where necessary, to confirm that any such data points were, in fact, genuine outliers.

It is a general conclusion from the data set as examined that most outlier-stripped data follow normal distributions with a varying degree of skewness. This was confirmed by further statistical analysis, as described in the "Materials and methods—Statistical analysis methodology" section. Occasional exceptions to this were cases where the outlier-stripped data subset contained identical values, adversely affecting the Shapiro-Wilk test.

Although 11 approaches result in a relatively small sample size of 11 DCCs to be statistically analyzed for each dose category/organism/radionuclide combination, normal distributions were consistently observed over some 90 separate samples, justifying a statistical analysis based on normality tests. A tendency to register normal rather than flat distributions implies that results tend to converge around some central value. This suggests that most of the approaches calculate a similar value of the DCC, with some random variation.

Deviations from normality observed during outlier identification and removal were as follows:

- All ^{3}H internal dose data were found to fail normality tests, but not Grubb's test for outliers. This is because for ^{3}H, all approaches except ECOMOD, EDEN and SCK·CEN generate a DCC of 3.3×10^{-6} μGy h^{-1} per Bq kg^{-1}, as seen in Table 4. The data are therefore not normally distributed, as there is significant repetition of a single value. Moreover, the ECOMOD, EDEN and SCK·CEN determinations are close to the values reported by the other participants.

[4] The CVs in Tables 4, 5, 6, 7 and 8 are calculated using the raw rather than the robust mean and standard deviation of data, differing in this respect from efficiency measures. For this reason, CVs and *Z*-scores as given in this paper are not directly comparable.

Table 4 Calculated DCCs (μGy h^{-1} per Bq kg^{-1}) for internal irradiation

Nuclide	Organism	AECL	EA	ECOMOD	EDEN	EPIC	ERICA	FASSET	LIETDOS-BIO	RESRAD-BIOTA	SCK·CEN	SÚJB	Min	Max	Range[a]	CV (%)[b]
^{3}H	Duck	3.3E–06	3.3E-06	4.2E-06	5.9E-06	3.3E-06	3.3E-06	3.3E-06	3.3E-06	3.3E-06	2.4E-06	3.3E-06	2.4E-06	5.9E-06	2.4E+00	2.5E+01
	Frog	3.3E-06	3.3E-06	4.2E-06	5.9E-06	3.3E-06	3.3E-06	3.3E-06	3.3E-06	3.3E-06	2.4E-06	3.3E-06	2.4E-06	5.9E-06	2.5E+00	2.5E+01
	Salmonid egg	3.3E-06	3.3E-06	4.2E-06	5.9E-06	3.3E-06	n/a	n/a	3.3E-06	3.3E-06	2.5E-06	3.3E-06	2.5E-06	5.9E-06	2.3E+00	2.7E+01
	Rat	3.3E-06	3.3E-06	4.2E-06	5.9E-06	3.3E-06	3.3E-06	3.3E-06	3.3E-06	3.3E-06	2.4E-06	3.3E-06	2.4E-06	5.9E-06	2.5E+00	2.5E+01
	Earthworm	3.3E-06	3.3E-06	4.2E-06	5.9E-06	3.3E-06	3.3E-06	3.3E-06	3.3E-06	3.3E-06	2.9E-06	3.3E-06	2.9E-06	5.9E-06	2.1E+00	2.3E+01
^{14}C	Duck	2.8E-05	2.9E-05	2.8E-05	2.7E-05	2.8E-05	2.9E-05	2.9E-05	2.9E-05	2.9E-05	2.1E-05	2.9E-05	2.1E-05	2.9E-05	1.4E+00	8.1E+00
	Frog	2.8E-05	2.8E-05	2.8E-05	2.7E-05	2.8E-05	2.8E-05	2.8E-05	2.9E-05	2.9E-05	2.1E-05	2.9E-05	2.1E-05	2.9E-05	1.4E+00	8.1E+00
	Salmonid egg	2.8E-05	2.8E-05	4.2E-06	2.6E-05	2.8E-05	n/a	n/a	2.9E-05	2.8E-05	2.2E-05	2.9E-05	4.2E-06	2.9E-05	6.9E+00	3.2E+01
	Rat	2.8E-05	2.9E-05	2.8E-05	2.7E-05	2.8E-05	2.9E-05	2.9E-05	2.9E-05	2.9E-05	2.1E-05	2.9E-05	2.1E-05	2.9E-05	1.4E+00	8.4E+00
	Earthworm	2.8E-05	2.8E-05	2.8E-05	2.7E-05	2.8E-05	2.8E-05	2.8E-05	2.9E-05	2.8E-05	2.5E-05	2.9E-05	2.5E-05	2.9E-05	1.1E+00	3.7E+00
^{90}Sr	Duck	6.3E-04	6.3E-04	6.5E-04	6.0E-04	6.3E-04	6.3E-04	6.3E-04	6.5E-04	6.3E-04	4.7E-04	6.5E-04	4.7E-04	6.5E-04	1.4E+00	8.4E+00
	Frog	5.7E-04	5.8E-04	6.5E-04	5.6E-04	5.6E-04	5.9E-04	5.7E-04	6.5E-04	6.0E-04	4.6E-04	6.5E-04	4.6E-04	6.5E-04	1.4E+00	9.2E+00
	Salmonid egg	1.4E-04	2.0E-04	2.2E-04	2.1E-04	1.7E-04	n/a	n/a	2.6E-04	2.0E-04	3.0E-04	6.5E-04	1.4E-04	6.5E-04	4.6E+00	5.9E+01
	Rat	6.1E-04	6.2E-04	6.5E-04	5.9E-04	6.1E-04	6.2E-04	6.4E-04	6.5E-04	6.2E-04	4.6E-04	6.5E-04	4.6E-04	6.5E-04	1.4E+00	8.8E+00
	Earthworm	5.1E-04	4.7E-04	5.3E-04	4.7E-04	4.4E-04	5.2E-04	5.1E-04	5.3E-04	5.1E-04	5.5E-04	6.5E-04	4.4E-04	6.5E-04	1.5E+00	1.0E+01
^{137}Cs	Duck	1.8E-04	1.8E-04	1.9E-04	1.8E-04	1.9E-04	1.9E-04	1.8E-04	2.1E-04	1.9E-04	2.5E-04	1.6E-04	1.6E-04	2.5E-04	1.5E+00	1.1E+01
	Frog	1.5E-04	1.5E-04	1.5E-05	1.5E-04	1.6E-04	1.5E-04	1.5E-04	1.6E-04	1.6E-04	1.3E-04	1.2E-04	1.5E-05	1.6E-04	1.1E+01	3.1E+01
	Salmonid egg	7.9E-05	9.5E-05	1.0E-04	1.0E-04	1.1E-04	n/a	n/a	1.3E-04	1.0E-04	8.5E-05	1.1E-04	7.9E-05	1.3E-04	1.6E+00	1.4E+01
	Rat	1.6E-04	1.7E-04	1.7E-04	1.6E-04	1.7E-04	1.7E-04	2.0E-04	1.8E-04	1.7E-04	1.9E-04	1.4E-04	1.4E-04	2.0E-04	1.4E+00	8.8E+00
	Earthworm	1.4E-04	1.4E-04	1.5E-04	1.3E-04	1.5E-04	1.4E-04	1.4E-04	1.4E-04	1.4E-04	1.1E-04	1.2E-04	1.1E-04	1.5E-04	1.3E+00	8.2E+00
^{60}Co	Duck	2.0E-04	2.2E-04	1.4E-04	2.2E-04	2.4E-04	2.4E-04	2.0E-04	3.0E-04	2.3E-04	5.2E-04	2.9E-04	1.4E-04	5.2E-04	3.7E+00	3.9E+01
	Frog	9.9E-05	1.0E-04	3.6E-05	1.1E-04	1.1E-04	1.1E-04	9.9E-05	1.3E-04	1.1E-04	2.0E-04	1.3E-04	3.6E-05	2.0E-04	5.5E+00	3.4E+01
	Salmonid egg	5.0E-05	5.4E-05	1.4E-06	5.4E-05	5.9E-05	n/a	n/a	6.1E-05	5.7E-05	5.3E-05	6.0E-05	1.4E-06	6.1E-05	4.3E+01	3.7E+01
	Rat	n/a	1.6E-04	1.0E-04	1.6E-04	1.7E-04	1.7E-04	n/a	2.1E-04	1.7E-04	3.6E-04	2.1E-04	1.0E-04	3.6E-04	3.6E+00	3.8E+01
	Earthworm	n/a	7.6E-05	1.8E-05	7.4E-05	7.9E-05	7.7E-05	n/a	7.7E-05	7.8E-05	1.1E-04	9.4E-05	1.8E-05	1.1E-04	6.3E+00	3.3E+01
^{241}Am	Duck	3.2E-03	3.2E-03	3.2E-03	3.0E-03	3.2E-03	3.2E-03	3.2E-03	3.2E-03	3.2E-03	1.2E-03	3.2E-03	1.2E-03	3.2E-03	2.7E+00	2.0E+01
	Frog	3.2E-03	3.2E-03	3.2E-03	3.0E-03	3.2E-03	3.2E-03	3.2E-03	3.2E-03	3.2E-03	1.2E-03	3.2E-03	1.2E-03	3.2E-03	2.8E+00	2.0E+01
	Salmonid egg	3.2E-03	3.2E-03	3.2E-03	3.0E-03	3.2E-03	n/a	n/a	3.2E-03	3.2E-03	1.2E-03	3.2E-03	1.2E-03	3.2E-03	2.7E+00	2.2E+01
	Rat	3.2E-03	3.2E-03	3.2E-03	3.0E-03	3.2E-03	3.2E-03	3.2E-03	3.2E-03	3.2E-03	1.2E-03	3.2E-03	1.2E-03	3.2E-03	2.8E+00	2.0E+01
	Earthworm	3.2E-03	3.2E-03	3.2E-03	3.0E-03	3.2E-03	3.2E-03	3.2E-03	3.2E-03	3.2E-03	1.4E-03	3.2E-03	1.4E-03	3.2E-03	2.3E+00	1.8E+01
^{238}U	Duck	5.7E-03	2.9E-03	3.0E-03	2.8E-03	2.5E-03	2.4E-03	5.7E-03	2.4E-03	2.5E-03	1.8E-03	2.5E-03	1.8E-03	5.7E-03	3.2E+00	4.3E+01
	Frog	5.7E-03	2.9E-03	3.0E-03	2.7E-03	2.5E-03	2.4E-03	5.7E-03	2.4E-03	2.5E-03	1.5E-03	2.5E-03	1.5E-03	5.7E-03	3.9E+00	4.5E+01
	Salmonid egg	5.3E-03	2.6E-03	2.9E-03	2.4E-03	2.4E-03	n/a	n/a	2.4E-03	2.5E-03	1.3E-03	2.5E-03	1.3E-03	5.3E-03	4.2E+00	4.0E+01
	Rat	2.4E-03	2.9E-03	3.0E-03	2.8E-03	2.5E-03	2.4E-03	2.4E-03	2.4E-03	2.5E-03	1.6E-03	2.5E-03	1.6E-03	3.0E-03	1.8E+00	1.4E+01
	Earthworm	2.4E-03	2.8E-03	3.0E-03	2.7E-03	2.5E-03	2.4E-03	2.4E-03	2.4E-03	2.5E-03	1.6E-03	2.5E-03	1.6E-03	3.0E-03	1.8E+00	1.4E+01

N/A radionuclide/reference organism combination not included in the approach in question

[a] Range = ratio of maximum to minimum

[b] CV (coefficient of variation) = ratio of the standard deviation to the mean, expressed as a percentage. When the mean value is near zero, the CV is sensitive to change in the standard deviation, limiting its usefulness

Table 5 Calculated DCCs (μGy h^{-1} per Bq l^{-1}) for external irradiation in water

Nuclide	Organism	AECL	EA	ECOMOD	EDEN	EPIC	ERICA	FASSET	LIETDOS-BIO	RESRAD-BIOTA	SCK·CEN	SÚJB	Min	Max	Range	CV (%)
^{3}H	Duck	6.6E-11	9.2E-11	n/a	4.9E-06	zero	3.6E-13	6.6E-11	6.4E-12	4.6E-11	zero	zero	3.6E-13	4.9E-06	n/c	2.6E+02
	Frog	1.8E-10	1.6E-10	n/a	4.9E-06	zero	2.5E-12	1.8E-11	2.2E-11	5.5E-11	zero	zero	2.5E-12	4.9E-06	n/c	2.6E+02
	Salmonid egg	4.8E-09	3.4E-09	n/a	4.9E-06	1.1E-14	n/a	n/a	2.7E-10	1.3E-09	zero	zero	1.1E-14	4.9E-06	n/c	2.4E+02
^{14}C	Duck	1.5E-08	1.8E-08	n/a	5.9E-07	1.2E-16	1.8E-08	1.5E-08	2.6E-09	9.9E-09	zero	2.0E-08	1.2E-16	5.9E-07	n/c	2.5E+02
	Frog	4.8E-08	4.2E-08	n/a	6.6E-07	4.0E-10	5.9E-08	4.8E-11	8.9E-09	1.6E-08	zero	6.7E-08	4.8E-11	6.6E-07	n/c	2.1E+02
	Salmonid egg	1.4E-06	9.1E-07	n/a	1.4E-06	5.4E-07	n/a	n/a	1.0E-07	4.8E-07	zero	1.0E-06	1.0E-07	1.4E-06	n/c	5.9E+01
^{90}Sr	Duck	2.3E-05	2.2E-05	n/a	2.8E-07	1.3E-05	2.0E-05	2.3E-05	n/a	1.7E-05	zero	2.7E-05	2.8E-07	2.7E-05	n/c	4.6E+01
	Frog	8.0E-05	7.3E-05	6.4E-05	6.7E-05	9.0E-05	6.3E-05	8.0E-05	n/a	2.2E-05	zero	9.0E-05	2.2E-05	9.0E-05	n/c	2.9E+01
	Salmonid egg	5.1E-04	4.5E-04	5.1E-04	3.2E-04	4.8E-04	n/a	n/a	n/a	4.1E-04	zero	1.0E-03	3.2E-04	1.0E-03	n/c	4.2E+01
^{137}Cs	Duck	2.9E-04	2.9E-04	2.8E-04	8.9E-05	1.5E-04	2.8E-04	2.9E-04	n/a	1.3E-04	8.4E-05	1.4E-04	8.4E-05	2.9E-04	3.4E+00	4.4E+01
	Frog	3.2E-04	3.2E-04	3.1E-04	2.1E-04	3.3E-04	3.2E-04	3.2E-04	2.8E-04	1.2E-04	8.4E-05	1.7E-04	8.4E-05	3.3E-04	3.9E+00	3.6E+01
	Salmonid egg	3.9E-04	3.7E-04	3.6E-04	1.4E-04	3.8E-04	n/a	n/a	n/a	1.9E-04	6.7E-05	2.0E-04	6.7E-05	3.9E-04	5.8E+00	4.9E+01
^{60}Co	Duck	1.3E-03	1.3E-03	1.3E-03	4.2E-04	6.3E-04	1.3E-03	1.3E-03	n/a	5.7E-04	3.3E-04	6.0E-04	3.3E-04	1.3E-03	3.9E+00	4.7E+01
	Frog	1.4E-03	1.4E-03	1.4E-03	1.0E-03	1.4E-03	1.4E-03	1.4E-03	1.2E-03	5.3E-04	3.6E-04	6.9E-04	3.6E-04	1.4E-03	3.9E+00	3.6E+01
	Salmonid egg	1.5E-03	1.4E-03	1.4E-03	4.8E-04	1.4E-03	n/a	n/a	n/a	7.0E-04	3.4E-04	8.5E-04	3.4E-04	1.5E-03	4.4E+00	4.7E+01
^{241}Am	Duck	1.2E-05	1.2E-05	1.0E-05	1.2E-05	5.6E-06	1.1E-05	1.2E-05	n/a	6.6E-06	1.8E-06	7.9E-06	1.8E-06	1.2E-05	6.6E+00	3.8E+01
	Frog	1.5E-05	1.5E-05	1.2E-05	2.3E-05	1.4E-05	1.4E-05	1.5E-05	8.0E-06	7.2E-06	2.8E-06	9.0E-06	2.8E-06	2.3E-05	8.1E+00	4.3E+01
	Salmonid egg	1.9E-05	1.9E-05	1.2E-05	6.0E-05	4.0E-05	n/a	n/a	n/a	6.1E-06	1.3E-06	9.5E-06	1.3E-06	6.0E-05	4.5E+01	9.4E+01
^{238}U	Duck	2.9E-05	2.9E-05	5.6E-06	8.4E-06	4.7E-08	9.5E-08	2.9E-05	n/a	1.9E-05	2.4E-04	2.4E-07	4.7E-08	2.4E-04	5.2E+03	2.0E+02
	Frog	7.3E-05	6.7E-05	6.0E-06	6.7E-05	2.5E-07	2.7E-07	7.3E-05	1.6E-06	2.2E-05	2.5E-04	2.7E-07	2.5E-07	2.5E-04	1.0E+03	1.4E+02
	Salmonid egg	4.2E-04	3.7E-04	9.6E-05	2.9E-04	1.1E-05	n/a	n/a	n/a	3.2E-04	2.2E-04	2.9E-07	2.9E-07	4.2E-04	1.5E+03	7.6E+01

N/A radionuclide/reference organism combination not included in the approach in question; *N/C* not calculated

Table 6 Calculated DCCs (μGy h^{-1} per Bq kg^{-1}) for external irradiation in soil

Nuclide	Organism	AECL	EA	ECOMOD	EDEN	EPIC	ERICA	FASSET	LIETDOS-BIO	RESRAD-BIOTA	SCK·CEN	SÚJB	Min	Max	Range	CV (%)
^{3}H	Rat	zero	9.5E-11	n/a	4.9E-06	Zero	zero	zero	4.3E-11	9.5E-11	zero	zero	4.3E-11	4.9E-06	n/c	2.0E+02
	Earthworm	zero	5.5E-10	n/a	4.9E-06	Zero	zero	zero	3.0E-10	3.5E-10	zero	zero	3.0E-10	4.9E-06	n/c	2.0E+02
^{14}C	Rat	zero	2.3E-08	n/a	6.1E-07	1.0E-14	zero	zero	1.6E-08	2.3E-08	zero	6.2E-08	1.0E-14	6.1E-07	n/c	2.0E+02
	Earthworm	zero	1.4E-07	n/a	6.8E-07	5.5E-10	zero	zero	8.1E-08	8.4E-08	zero	2.4E-07	5.5E-10	6.8E-07	n/c	1.2E+02
^{90}Sr	Rat	4.3E-04	3.6E-05	n/a	1.9E-05	6.5E-05	1.2E-10	zero	3.2E-05	3.8E-05	5.2E-06	4.3E-05	1.2E-10	4.3E-04	n/c	1.8E+02
	Earthworm	4.3E-04	1.8E-04	1.3E-04	9.5E-05	3.1E-04	1.5E-10	1.0E-11	3.4E-04	1.5E-04	5.9E-05	2.6E-04	1.0E-11	4.3E-04	4.3E+07	8.0E+01
^{137}Cs	Rat	2.4E-04	3.0E-04	1.5E-04	1.5E-04	4.7E-04	2.8E-04	7.9E-05	2.7E-04	2.7E-04	1.9E-04	3.1E-04	7.9E-05	4.7E-04	5.9E+00	4.3E+01
	Earthworm	3.0E-04	3.3E-04	3.0E-04	1.3E-04	5.2E-04	3.0E-04	1.5E-04	2.6E-04	3.0E-04	1.6E-04	3.4E-04	1.3E-04	5.2E-04	4.1E+00	3.9E+01
^{60}Co	Rat	1.5E-03	1.3E-03	1.3E-03	4.9E-04	2.0E-03	1.2E-03	n/a	1.2E-03	1.2E-03	7.2E-04	1.3E-03	4.9E-04	2.0E-03	4.0E+00	3.3E+01
	Earthworm	1.5E-03	1.4E-03	1.4E-03	5.6E-04	2.1E-03	1.3E-03	n/a	1.1E-03	1.4E-03	7.2E-04	1.4E-03	5.6E-04	2.1E-03	3.8E+00	3.4E+01
^{241}Am	Rat	1.7E-06	1.3E-05	1.1E-05	1.1E-05	1.9E-05	5.5E-06	9.6E-07	5.6E-06	3.5E-06	4.0E-06	1.7E-05	9.6E-07	1.9E-05	2.0E+01	7.3E+01
	Earthworm	2.6E-06	1.6E-05	1.2E-05	1.8E-05	2.4E-05	6.1E-06	2.6E-06	5.5E-06	3.8E-06	3.3E-06	1.8E-05	2.6E-06	2.4E-05	9.1E+00	7.6E+01
^{238}U	Rat	1.1E-06	3.9E-05	5.6E-06	2.4E-05	2.1E-07	1.0E-07	1.2E-09	1.4E-06	3.9E-05	5.5E-04	5.2E-07	1.2E-09	5.5E-04	4.6E+05	2.7E+02
	Earthworm	1.1E-06	1.5E-04	5.8E-06	8.3E-05	6.4E-07	1.2E-07	1.5E-08	2.1E-06	1.2E-04	5.3E-04	5.6E-07	1.5E-08	5.3E-04	3.6E+04	2.0E+02

N/A radionuclide/reference organism combination not included in the approach in question; *N/C* not calculated

- For internal doses, there is a case, namely ^{238}U for frog, for which there is some evidence against the null hypothesis of normality. The internal ^{90}Sr DCC for frog and ^{238}U DCC for rat and earthworm, with *P*-values of 7.4×10^{-3}, 1.5×10^{-3} and 2.8×10^{-3}, respectively, shows stronger evidence against the null hypothesis in the Shapiro-Wilk test. However, in all these cases, skewness and kurtosis tests are passed. To investigate this anomaly, which seems to occur when data are very closely grouped together, Grubb's outlier testing was performed. This showed that these data are not outliers.
- For external doses (water: ^{238}U for duck and frog; in soil: ^{238}U for rat and earthworm, on soil: ^{241}Am for rat and ^{238}U for earthworm), a similar anomaly (as above) was encountered. Variability in ^{238}U DCC determination is likely to have occurred due to the inclusion of different daughter decay products by different approaches, resulting in a greater statistical spread which may not conform to a simple normal distribution but a multi-modal one (as discussed in the "Statistical analysis methodology—Issues in results interpretation" subsection).

Discussion

The results as presented immediately suggest a number of factors that might have caused variation in the DCC data for the different approaches:

- For both internal and external exposure, variability as a consequence of different number of decays or daughter products being included (most notably for ^{238}U) within the estimation of DCC (Table 3).
- For external exposure, differing media geometries being assumed, e.g. the effect of medium thickness and immersion depth of the target receptor for γ-emitters, or shielding effects such as varying soil density.

Effect of number of daughter products

The comparative effect of including different numbers of uranium daughters, from 0 up to 4 (^{234}Th, ^{234m}Pa, ^{234}Pa and ^{234}U) on internal and external dose was assessed by performing repeated runs of the Environment Agency R&D 128 biota dose calculation program for ^{238}U. Results are given in Table 9, where it can be seen that ^{234}Th increases the ^{238}U low β-internal dose by a factor of 2.4, and further addition of daughters has no effect except for ^{234}U, which would increase the dose by a further factor of 1.5. ^{234}Th increases the ^{238}U $\beta + \gamma$ internal dose by a factor of 7, ^{234m}Pa by a further factor of 4 to 12 (depending on

Table 7 Calculated DCCs (μGy h^{-1} per Bq kg^{-1}) for external irradiation on soil

Nuclide	Organism	AECL	EA	ECOMOD	EDEN	EPIC	ERICA	FASSET	LIETDOS-BIO	RESRAD-BIOTA	SCK·CEN	SÚJB	Min	Max	Range	CV (%)
^{3}H	Duck	Zero	4.6E-11	n/a	n/a	n/a	zero	n/a	zero	9.4E-14	n/a	n/a	9.4E-14	4.6E-11	n/c	1.4E+02
	Frog	Zero	7.8E-11	n/a	4.9E-06	n/a	zero	n/a	zero	9.6E-13	n/a	n/a	9.6E-13	4.9E-06	n/c	1.7E+02
	Rat	Zero	4.8E-11	n/a	4.9E-06	n/a	zero	n/a	zero	2.7E-13	n/a	n/a	2.7E-13	4.9E-06	n/c	1.7E+02
	Earthworm	Zero	2.8E-10	n/a	4.9E-06	n/a	n/a	n/a	zero	6.9E-12	n/a	n/a	6.9E-12	4.9E-06	n/c	1.7E+02
^{14}C	Duck	Zero	8.9E-09	n/a	n/a	n/a	zero	n/a	zero	3.1E-09	n/a	2.0E-08	3.1E-09	2.0E-08	n/c	8.0E+01
	Frog	Zero	2.1E-08	n/a	5.9E-07	n/a	zero	n/a	zero	1.0E-08	n/a	6.7E-08	1.0E-08	5.9E-07	n/c	1.6E+02
	Rat	Zero	1.1E-08	n/a	5.9E-07	n/a	zero	n/a	zero	3.5E-09	n/a	3.1E-08	3.5E-09	5.9E-07	n/c	1.8E+02
	Earthworm	Zero	7.0E-08	n/a	5.9E-07	n/a	n/a	n/a	zero	4.2E-08	n/a	1.2E-07	4.2E-08	5.9E-07	n/c	1.3E+02
^{90}Sr	Duck	2.6E-04	1.1E-05	n/a	1.6E-08	n/a	1.5E-11	n/a	8.8E-06	8.5E-06	1.8E-06	2.7E-05	1.5E-11	2.6E-04	1.7E+07	2.2E+02
	Frog	2.6E-04	3.6E-05	3.2E-05	2.4E-06	n/a	1.6E-11	n/a	n/a	2.6E-05	6.4E-06	9.0E-05	1.6E-11	2.6E-04	1.6E+07	1.5E+02
	Rat	2.6E-04	1.8E-05	n/a	3.2E-07	n/a	1.6E-11	9.0E-11	n/a	1.3E-05	3.0E-06	2.2E-05	1.6E-11	2.6E-04	1.6E+07	2.3E+02
	Earthworm	2.6E-04	9.0E-05	n/a	2.0E-05	n/a	n/a	1.1E-10	9.6E-07	6.8E-05	1.8E-05	1.3E-04	1.1E-10	2.6E-04	2.3E+06	1.2E+02
^{137}Cs	Duck	1.1E-04	1.4E-04	1.4E-04	3.3E-05	7.1E-05	1.1E-04	n/a	7.7E-05	8.4E-05	7.8E-05	1.4E-04	3.3E-05	1.4E-04	4.3E+00	3.7E+01
	Frog	1.2E-04	1.6E-04	1.6E-04	4.7E-05	7.6E-05	1.1E-04	n/a	1.1E-04	8.9E-05	7.9E-05	1.7E-04	4.7E-05	1.7E-04	3.5E+00	3.6E+01
	Rat	1.1E-04	1.5E-04	7.3E-05	3.7E-05	7.3E-05	1.1E-04	1.0E-04	8.6E-05	8.5E-05	8.3E-05	1.5E-04	3.7E-05	1.5E-04	4.2E+00	3.6E+01
	Earthworm	1.2E-04	1.7E-04	n/a	4.2E-05	7.7E-05	n/a	1.2E-04	1.5E-04	9.3E-05	7.1E-05	1.7E-04	4.2E-05	1.7E-04	4.1E+00	4.0E+01
^{60}Co	Duck	n/a	6.4E-04	6.4E-04	1.7E-04	2.8E-04	4.6E-04	n/a	3.6E-04	4.0E-04	2.8E-04	6.0E-04	1.7E-04	6.4E-04	3.9E+00	4.1E+01
	Frog	n/a	7.0E-04	6.9E-04	1.7E-04	3.0E-04	4.9E-04	n/a	4.4E-04	4.1E-04	3.1E-04	6.9E-04	1.7E-04	7.0E-04	4.1E+00	4.2E+01
	Rat	n/a	6.7E-04	6.7E-04	1.9E-04	2.9E-04	4.8E-04	n/a	4.0E-04	4.0E-04	3.0E-04	6.5E-04	1.9E-04	6.7E-04	3.6E+00	4.0E+01
	Earthworm	n/a	7.1E-04	n/a	1.8E-04	3.0E-04	n/a	n/a	4.2E-04	3.8E-04	3.0E-04	7.2E-04	1.8E-04	7.2E-04	4.0E+00	4.9E+01
^{241}Am	Duck	2.3E-06	5.8E-06	5.0E-06	1.3E-06	1.5E-06	2.4E-06	n/a	2.0E-06	1.4E-06	1.4E-06	7.9E-06	1.3E-06	7.9E-06	6.1E+00	7.4E+01
	Frog	2.9E-06	7.3E-06	6.0E-06	8.8E-06	1.7E-06	2.6E-06	n/a	1.9E-06	1.5E-06	2.1E-06	9.0E-06	1.5E-06	9.0E-06	6.0E+00	7.0E+01
	Rat	2.9E-06	6.5E-06	5.5E-05	8.8E-06	1.6E-06	2.5E-06	2.5E-06	2.1E-06	1.4E-06	2.0E-06	8.5E-06	1.4E-06	5.5E-05	3.9E+01	1.8E+02
	Earthworm	2.9E-06	8.2E-06	n/a	8.8E-06	1.8E-06	n/a	2.9E-06	2.2E-06	1.6E-06	1.6E-06	9.2E-06	1.6E-06	9.2E-06	5.8E+00	7.7E+01
^{238}U	Duck	3.2E-08	1.4E-05	2.6E-06	1.5E-06	1.1E-08	4.3E-08	n/a	6.1E-07	9.3E-06	2.2E-04	2.4E-07	1.1E-08	2.2E-04	2.0E+04	2.8E+02
	Frog	8.5E-08	3.3E-05	2.8E-06	7.7E-06	2.5E-08	4.8E-08	n/a	6.6E-07	2.1E-05	2.3E-04	2.7E-07	2.5E-08	2.3E-04	9.5E+03	2.4E+02
	Rat	8.3E-08	2.0E-05	2.6E-06	6.3E-06	1.6E-08	4.7E-08	7.3E-08	6.4E-07	1.3E-05	2.4E-04	2.6E-07	1.6E-08	2.4E-04	1.5E+04	2.8E+02
	Earthworm	8.6E-08	7.5E-05	n/a	2.1E-05	3.6E-08	n/a	8.6E-08	7.4E-07	5.5E-05	2.2E-04	2.8E-07	3.6E-08	2.2E-04	6.3E+03	1.8E+02

N/A radionuclide/reference organism combination not included in the approach in question; *N/C* not calculated

Table 8 Calculated DCCs (μGy h^{-1} per Bq kg^{-1}) for external irradiation on sediment

Nuclide	Organism	AECL	EA	ECOMOD	EDEN	EPIC	ERICA	FASSET	LIETDOS-BIO	RESRAD-BIOTA	SCK·CEN	SÚJB	Min	Max	Range	CV (%)
^{3}H	Frog	n/a	1.6E-10	n/a	4.9E-06	n/a	1.3E-12	9.0E-11	n/a	n/a	n/a	n/a	1.3E-12	4.9E-06	3.9E+06	2.0E+02
	Salmonid egg	zero	3.4E-09	n/a	4.9E-06	n/a	n/a	n/a	1.4E-08	8.8E-11	n/a	0.0E+00	0.0E+00	4.9E-06	n/c	2.2E+02
^{14}C	Frog	n/a	4.2E-08	n/a	5.9E-07	n/a	3.0E-08	2.4E-08	n/a	n/a	n/a	n/a	2.4E-08	5.9E-07	2.5E+01	1.6E+02
	Salmonid egg	1.4E-06	9.1E-07	n/a	6.0E-07	n/a	n/a	n/a	1.4E-06	2.5E-07	n/a	1.0E-06	2.5E-07	1.4E-06	5.6E+00	4.8E+01
^{90}Sr	Frog	n/a	7.3E-05	n/a	7.8E-07	n/a	3.2E-05	4.0E-05	n/a	n/a	n/a	9.0E-05	7.8E-07	9.0E-05	1.1E+02	7.5E+01
	Salmonid egg	5.1E-04	4.5E-04	n/a	6.6E-05	n/a	n/a	n/a	1.1E-06	1.8E-04	2.1E-05	1.0E-03	1.1E-06	1.0E-03	9.6E+02	1.1E+02
^{137}Cs	Frog	n/a	3.2E-04	n/a	5.3E-05	n/a	1.6E-04	1.6E-04	n/a	n/a	n/a	n/a	5.3E-05	3.2E-04	6.0E+00	6.3E+01
	Salmonid egg	3.9E-04	3.7E-04	n/a	5.4E-05	7.8E-05	n/a	n/a	1.5E-04	9.6E-05	5.8E-05	2.0E-04	5.4E-05	3.9E-04	7.2E+00	7.8E+01
^{60}Co	Frog	n/a	1.4E-03	n/a	2.0E-04	n/a	7.0E-04	7.0E-04	n/a	n/a	n/a	n/a	2.0E-04	1.4E-03	7.1E+00	6.6E+01
	Salmonid egg	1.5E-03	1.4E-03	n/a	2.2E-04	3.0E-04	n/a	n/a	7.4E-04	5.0E-04	2.7E-04	8.5E-04	2.2E-04	1.5E-03	6.8E+00	7.0E+01
^{241}Am	Frog	n/a	1.5E-05	n/a	9.1E-06	n/a	7.0E-06	7.5E-06	n/a	n/a	n/a	n/a	7.0E-06	1.5E-05	2.1E+00	3.7E+01
	Salmonid egg	1.9E-05	1.9E-05	n/a	1.0E-05	1.8E-06	n/a	n/a	5.6E-06	3.4E-06	8.5E-07	9.5E-06	8.5E-07	1.9E-05	2.2E+01	8.2E+01
^{238}U	Frog	n/a	6.7E-05	n/a	7.0E-06	n/a	1.4E-07	3.7E-05	n/a	n/a	n/a	n/a	1.4E-07	6.7E-05	4.9E+02	1.1E+02
	Salmonid egg	4.2E-04	3.7E-04	n/a	5.8E-05	5.4E-08	n/a	n/a	2.6E-06	1.6E-04	1.9E-04	2.9E-07	5.4E-08	4.2E-04	7.8E+03	1.1E+02

N/A radionuclide/reference organism combination not included in the approach in question; *N/C* not calculated

geometry), and the remaining daughters result in no change. However, in terms of total dose, which is dominated by the α-dose, the only important effect is the doubling of α-dose when including ^{234}U in addition to the other daughters. This is clearly the reason for the high ^{238}U internal DCCs estimated for aquatic organisms by the FASSET methodology; previously published values from the Environment Agency R&D 128 methodology [21] are comparatively high (values presented for this exercise were re-estimated with ^{234}U excluded).

With respect to external exposure, ^{234}Th increases the ^{238}U low β-dose by a factor of approximately 3, and further addition of daughters has no effect except for ^{234}U which increases the dose by a further factor of 1.4. ^{234}Th increases the ^{238}U $\beta + \gamma$ external dose by a factor of 9 to 20 (depending on geometry), ^{234m}Pa by a further 6- to 50-fold, and the remaining daughters result in little change. In terms of total dose (dominated by $\beta + \gamma$), the addition of the first two daughters has the biggest effect, with factors in the order of 9 to 20 (^{234}Th) and 6 to 50 (^{234m}Pa).

Effect of soil/sediment depth and target position

Some methodologies employed in this paper differ in the consideration of infinite versus finite source depth (approximately 50 cm) for external doses. The effect of different depth assumptions on the DCC can be calculated, but this requires complex self-absorption calculations. Fortunately, most of this effort can be averted by using the dose-rate conversion factors in air for photon sources in soil derived by Kocher and Sjoreen [44]. These authors have performed calculations considering photon-emitting sources uniformly distributed within soil slabs of different thickness. These calculations are for above-ground receptors; however, the result is insensitive to the height of the receptor for less than 10 m, so the results are applicable to organisms living on the soil. Moreover, photon transport in air is negligible when calculating the effect of sources below ground surface.

Analysis of the published data [44] reveals that, for each energy, data fit to the equation:

$$\mathrm{DCC} = \mathrm{DCC}_{\infty} \cdot (1 - e^{-\mu \times \mathrm{depth}}) \quad (4)$$

where DCC_{∞} and μ are fitting constants representing the DCC under the assumption of infinite soil thickness and the dependency with depth, respectively (Table 10).

At 0.6 MeV, for example, the DCCs at 10- and 50-cm depths are 79% and virtually 100% of those of infinitely deep soil, respectively. The higher the energy, the more accentuated is the deviation of a DCC for a 10-cm soil slab from a DCC for infinitely deep soil. Hence, at 10 MeV and a 50-cm depth, the difference related to assuming infinite

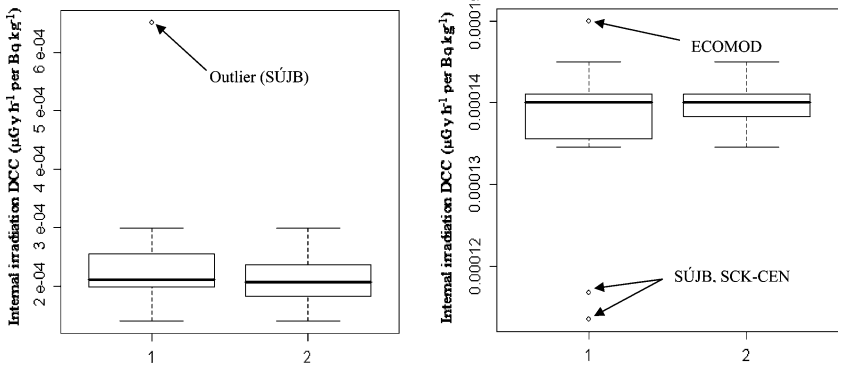

Fig. 1 Examples of internal irradiation DCC box plots for ^{90}Sr in salmonid egg (*left*) and ^{137}Cs in earthworm (*right*). Box plots prior and after outlier removal are labelled *1* and *2*, respectively

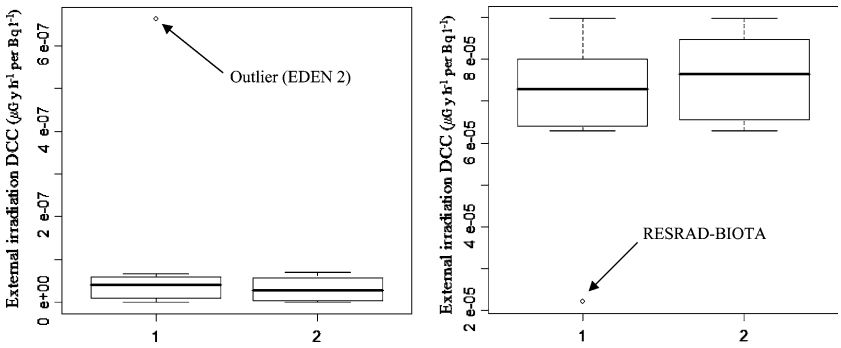

Fig. 2 Examples of external irradiation in water DCC box plots for ^{14}C and in frog (*left*) and ^{90}Sr in frog (*right*). Box plots prior and after outlier removal are labelled *1* and *2*, respectively

depth is less than 4%, but a difference of 52% is observed if 10 cm is taken as the soil depth. This analysis demonstrates that there is no appreciable difference in results between assuming either: (a) that the radioactivity is distributed within the first 50 cm of soil; or (b) it is distributed to an infinite depth. Under an assumption of a depth of less than or equal to 10 cm (as assumed by many of the approaches, see Table 2), there would, however, be some differences, especially for high-energy photons.

This interpretation is confirmed by published effective dose equivalent data [45, 46] for sources distributed to different depths of soil having a density of 1.6 g cm^{-3}. Such data reveal that, for depths of greater than or equal to 15 cm, the dose is more than 90% of that calculated under the assumption of infinite depth for energies below 1 MeV. This implies that for a selection of typical radionuclides (^{14}C, ^{60}Co, ^{90}Sr, ^{137}Cs, ^{238}U and ^{241}Am), 15 cm depth doses would be approximately 90% or more than the dose at an infinite depth. An exception is ^{60}Co where, on account of its greater than 1 MeV transitions, the proportion is somewhat lower at 84%[5]

Kamboj et al. [46] arrived at a mathematical fit of dose coefficients at different depths, covering the above selection of radionuclides, as described by:

$$D_T = D_\infty \cdot (1 - A \cdot e^{-K_a \rho T} - B \cdot e^{-K_b \rho T}) \quad (5)$$

where A, B, K_a, and K_b are four fitting functions, ρ is the soil density (1.6 g cm^{-3}) and T is the thickness of soil (cm).

Using this fit, it is calculated that, for a depth of 50 cm, DCCs for ^{14}C, ^{60}Co, ^{90}Sr, ^{137}Cs, ^{238}U and ^{241}Am are virtually indistinguishable (less than 0.2% difference) from infinite depth DCCs, confirming the analysis in Table 10.

Similar calculations were performed to illustrate the effect of a receptor organism that is at a 25-cm depth inside a soil slab of 50 cm. This case can be treated as two 25 cm slabs, one above and one below the target, i.e. as twice the dose for a homogeneous, isotropic source on top of a soil slab of 25-cm thickness. From the data presented in Table 10, it is evident that there is little difference between the two assumptions used, of infinite soil thickness and 50 cm contaminated soil layer (with a less than 5% difference at energy less than 1.25 MeV).

The above analyses are made on the assumption of uniform distribution of the source term within the depth profiles examined. In reality, sources are not distributed uniformly in aquatic sediments, but generally peak at a specific level that will change with time.

It is concluded that, for external exposure from soil/sediment, observed discrepancies in external dose are unlikely to be completely explained by variations in soil depth, source position in or above soil, or height above it. The factor that is more likely to have an influence on

[5] In this calculation ^{90}Sr includes ^{90}Y, ^{137}Cs includes ^{137m}Ba, and ^{238}U includes ^{234}Th, ^{234m}Pa and ^{234}Pa in secular equilibrium with the parent radionuclide.

Table 9 Comparative effect of including different numbers of uranium daughters on the internal and external exposure DCCs (calculated using the England and Wales Environment Agency R&D 128 methodology)

Nuclide combination	Internal exposure DCC (μGy h^{-1}/Bq kg^{-1})					External exposure DCC (μGy h^{-1}/Bq kg^{-1})				
	Duck	Frog	Salmonid egg	Rat	Earthworm	Duck	Frog	Salmonid egg	Rat	Earthworm
Low energy β (<10 keV)										
^{238}U + ^{234}Th, ^{234m}Pa, ^{234}Pa and ^{234}U	1.8E-06	1.8E-06	1.8E-06	1.8E-06	1.8E-06	3.2E-11	5.3E-11	1.1E-09	3.3E-11	1.9E-10
^{238}U + ^{234}Th, ^{234m}Pa and ^{234}Pa	1.2E-06	1.2E-06	1.2E-06	1.2E-06	1.2E-06	2.3E-11	3.9E-11	8.3E-10	2.4E-11	1.4E-10
^{238}U + ^{234}Th and ^{234m}Pa	1.2E-06	1.2E-06	1.2E-06	1.2E-06	1.2E-06	2.3E-11	3.8E-11	8.2E-10	2.3E-11	1.3E-10
^{238}U + ^{234}Th	1.2E-06	1.2E-06	1.2E-06	1.2E-06	1.2E-06	2.3E-11	3.8E-11	8.2E-10	2.3E-11	1.3E-10
^{238}U	4.9E-07	4.9E-07	4.9E-07	4.9E-07	4.9E-07	7.4E-12	1.2E-11	2.5E-10	7.4E-12	4.2E-11
High energy β (>10 keV) + γ										
^{238}U + ^{234}Th, ^{234m}Pa, ^{234}Pa and ^{234}U	5.1E-04	4.7E-04	1.6E-04	5.0E-04	3.9E-04	2.9E-05	6.7E-05	3.7E-04	4.0E-05	1.5E-04
^{238}U + ^{234}Th, ^{234m}Pa and ^{234}Pa	5.0E-04	4.6E-04	1.6E-04	4.9E-04	3.8E-04	2.9E-05	6.7E-05	3.7E-04	3.9E-05	1.5E-04
^{238}U + ^{234}Th and ^{234m}Pa	5.0E-04	4.6E-04	1.6E-04	4.9E-04	3.8E-04	2.6E-05	6.4E-05	3.7E-04	3.6E-05	1.5E-04
^{238}U + ^{234}Th	4.1E-05	4.0E-05	3.8E-05	4.0E-05	3.9E-05	4.1E-06	5.0E-06	7.3E-06	4.6E-06	5.7E-06
^{238}U	5.8E-06	5.7E-06	5.2E-06	5.8E-06	5.5E-06	2.1E-07	3.4E-07	8.0E-07	2.5E-07	5.2E-07
Alpha										
^{238}U + ^{234}Th, ^{234m}Pa, ^{234}Pa and ^{234}U	5.2E-03	5.2E-03	5.2E-03	5.2E-03	5.2E-03	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
^{238}U + ^{234}Th, ^{234m}Pa and ^{234}Pa	2.4E-03	2.4E-03	2.4E-03	2.4E-03	2.4E-03	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
^{238}U + ^{234}Th and ^{234m}Pa	2.4E-03	2.4E-03	2.4E-03	2.4E-03	2.4E-03	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
^{238}U + ^{234}Th	2.4E-03	2.4E-03	2.4E-03	2.4E-03	2.4E-03	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
^{238}U	2.4E-03	2.4E-03	2.4E-03	2.4E-03	2.4E-03	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Total										
^{238}U + ^{234}Th, ^{234m}Pa, ^{234}Pa and ^{234}U	5.7E-03	5.6E-03	5.3E-03	5.7E-03	5.5E-03	2.9E-05	6.7E-05	3.7E-04	4.0E-05	1.5E-04
^{238}U + ^{234}Th, ^{234m}Pa and ^{234}Pa	2.9E-03	2.9E-03	2.6E-03	2.9E-03	2.8E-03	2.9E-05	6.7E-05	3.7E-04	3.9E-05	1.5E-04
^{238}U + ^{234}Th and ^{234m}Pa	2.9E-03	2.9E-03	2.6E-03	2.9E-03	2.8E-03	2.6E-05	6.4E-05	3.7E-04	3.6E-05	1.5E-04
^{238}U + ^{234}Th	2.5E-03	2.5E-03	2.5E-03	2.5E-03	2.5E-03	4.1E-06	5.0E-06	7.3E-06	4.6E-06	5.7E-06
^{238}U	2.4E-03	2.4E-03	2.4E-03	2.4E-03	2.4E-03	2.1E-07	3.4E-07	8.0E-07	2.5E-07	5.2E-07

Table 10 Variation of external DCCs for different source depths for a target above the soil—data from Kocher and Sjoreen [44]

Parameter	0.2	0.3	0.4	0.5	0.6	γ-energy (MeV)			2	3	4	5	6	8	10
						0.8	1.0	1.5							
Fitting constants															
DCC_{∞}	1.9E-04	4.6E-04	6.6E-04	7.3E-04	7.9E-04	1.4E-03	1.7E-03	2.6E-03	3.3E-03	4.9E-03	6.4E-03	7.8E-03	9.1E-03	1.2E-02	1.4E-02
μ	5.0E-01	1.8E-01	1.5E-01	1.4E-01	1.6E-01	1.3E-01	1.2E-01	1.1E-01	1.0E-01	8.5E-02	7.7E-02	7.3E-02	7.0E-02	6.7E-02	6.6E-02
r^2	8.7E-01	1.0E+00	1.0E+00	1.0E+00	1.0E+00	1.0E+00	1.0E+00	1.0E+00	1.0E+00	1.0E+00	1.0E+00	1.0E+00	1.0E+00	1.0E+00	9.9E-01
DCC ratio															
DCC_{50}/DCC_{∞}	1.0E+00	1.0E+00	1.0E+00	1.0E+00	1.0E+00	1.0E+00	1.0E+00	1.0E+00	1.0E+00	9.9E-01	9.8E-01	9.7E-01	9.7E-01	9.7E-01	9.6E-01
DCC_{25}/DCC_{∞}	1.0E+00	9.9E-01	9.7E-01	9.7E-01	9.8E-01	9.7E-01	9.5E-01	9.3E-01	9.3E-01	8.8E-01	8.6E-01	8.4E-01	8.3E-01	8.1E-01	8.1E-01
DCC_{10}/DCC_{∞}	9.9E-01	8.3E-01	7.7E-01	7.4E-01	7.9E-01	7.4E-01	7.0E-01	6.6E-01	6.5E-01	5.7E-01	5.4E-01	5.2E-01	5.0E-01	4.9E-01	4.8E-01

DCC_{∞} and μ: fitting constants in $DCC = DCC_{\infty}(1 - e^{-\mu \times depth})$; r^2: coefficient of determination; DCC_x: for assumed depth x

external dose variability for different calculation methodologies is difference in the number of decay modes and energies considered for the radionuclide (see Table 3), as well as shielding factors such as soil density. For example, the published data considered in this analysis [44] are for a soil density of 1.4 g cm^{-3}. However, this publication states that, in practice, the shielding provided by a given thickness of material is proportional to density. Hence, treating the soil at unit density (the lowest density assumed within any of the approaches) should give an approximately 40% higher estimation of the external dose.

Analysis of robust means and *Z*-scoring

Arithmetic means and associated standard deviations relating to the robust (i.e. outlier-removed) subset, along with the means and associated standard deviations of the raw data, are given in Tables 11, 12, 13, 14 and 15. The robust statistics were used in calculating *Z*-scoring values, as summarized in Table 16. It must be noted that the actual means and standard deviations used to calculate the *Z*-scores contain many more significant digits compared to the reported values in Tables 11, 12, 13, 14, 15. Therefore, calculation of *Z*-scores using values from the truncated data presented in these tables may result in somewhat different *Z*-scores from those reported in Table 16.

As explained in the "Statistical analysis methodology—Issues in results interpretation" subsection, the data from Table 16 should not be used to pass value judgements on the validity of any approach, considering that most discrepancies are attributable to varying degrees of conservatism and/or radionuclide/source–target geometry assumptions. In addition, there are limitations inherent in ranking approaches when there are some in which the DCCs are calculated using a stand-alone code outside the approach itself (e.g. RESRAD-BIOTA used MCNP to calculate DCCs and LIETDOS-BIO used a Monte Carlo approach consistent with MCNPX). Similar limitations exist when the DCCs are simply taken from other approaches or published data (e.g. AECL, which adopts FASSET and RESRAD-BIOTA DCCs in several instances).

On a radionuclide-by-radionuclide basis, the highest *Z*-scores tend to relate to ^{3}H, ^{14}C and the α-emitters (^{238}U and ^{241}Am); the radionuclides whose emissions tend to have shorter ranges in matter. A shorter range implies a higher variability of the DCC in response to variations in density, target layering (i.e. the presence of skin or fur), or other assumptions by the dose calculation method influencing the degree of radiation self-absorption within the target organism.

As stated in the " EDEN 2 (France)" subsection of the "Participating approaches" section, two types of calcula-

Table 11 Performance statistics for internal exposure DCCs

Nuclide	Organism	Original dataset *P*-values			Robust dataset *P*-values			Grubbs	Original dataset mean		Robust dataset mean	
		Shapiro-Wilk	D'Agostino	Anscombe	Shapiro-Wilk	D'Agostino	Anscombe	Test	Mean	±SD	Mean	Robust SD
^{3}H	Duck	1.3E-04	4.2E-02	4.0E-03	1.5E-02	7.3E-01	5.7E-02	9.6E-01	3.5E-06	8.8E-07	3.3E-06	1.4E-08
	Frog	1.4E-04	4.4E-02	4.2E-03	1.5E-02	7.3E-01	5.7E-02	9.6E-01	3.5E-06	8.9E-07	3.3E-06	1.4E-08
	Salmonid egg	1.7E-03	7.5E-02	1.5E-02	7.0E-03	n/a[a]	8.4E-01	1.2E-01	3.6E-06	9.6E-07	3.3E-06	4.1E-09
	Rat	1.5E-04	4.5E-02	4.3E-03	1.5E-02	7.3E-01	5.7E-02	9.6E-01	3.5E-06	8.9E-07	3.3E-06	1.4E-08
	Earthworm	1.3E-05	2.0E-02	1.6E-03	1.5E-02	7.2E-01	5.6E-02	9.6E-01	3.6E-06	8.4E-07	3.3E-06	1.4E-08
^{14}C	Duck	4.5E-06	9.9E-03	3.6E-04	3.0E-01	3.8E-01	4.1E-01	n/r[b]	2.8E-05	2.2E-06	2.8E-05	5.1E-07
	Frog	1.8E-06	8.7E-03	2.9E-04	1.3E-01	3.4E-01	2.6E-01	n/r	2.8E-05	2.2E-06	2.8E-05	4.3E-07
	Salmonid egg	5.0E-05	2.5E-02	2.3E-03	2.4E-01	n/a	1.1E-01	n/r	2.5E-05	7.9E-06	2.8E-05	8.0E-07
	Rat	3.7E-06	9.6E-03	3.4E-04	3.0E-01	3.8E-01	4.1E-01	n/r	2.8E-05	2.3E-06	2.8E-05	5.1E-07
	Earthworm	3.7E-04	2.9E-02	3.0E-03	1.1E-01	2.7E-01	1.2E-01	n/r	2.8E-05	1.0E-06	2.8E-05	4.4E-07
^{90}Sr	Duck	1.0E-05	1.2E-02	5.0E-04	8.7E-02	4.7E-01	2.3E-01	n/r	6.2E-04	5.2E-05	6.3E-04	1.4E-05
	Frog	9.1E-02	3.8E-01	1.7E-01	7.4E-03	4.3E-01	2.2E-01	6.8E-01	5.9E-04	5.4E-05	6.0E-04	3.8E-05
	Salmonid egg	6.7E-04	3.1E-02	3.1E-03	8.6E-01	6.5E-01	5.9E-01	n/r	2.6E-04	1.5E-04	2.1E-04	4.9E-05
	Rat	2.9E-04	2.4E-02	1.6E-03	4.4E-01	8.5E-01	4.9E-01	n/r	6.1E-04	5.4E-05	6.3E-04	2.1E-05
	Earthworm	9.6E-02	1.9E-01	4.2E-02	4.5E-01	5.4E-01	9.5E-01	n/r	5.2E-04	5.4E-05	5.0E-04	3.3E-05
^{137}Cs	Duck	2.1E-01	8.2E-03	6.0E-02	8.9E-01	9.3E-01	2.5E-01	n/r	1.9E-04	2.1E-05	1.8E-04	1.1E-05
	Frog	1.5E-05	1.3E-02	5.9E-04	1.0E-01	2.9E-01	4.4E-01	n/r	1.4E-04	4.1E-05	1.5E-04	1.2E-05
	Salmonid egg	8.2E-01	8.7E-01	5.3E-01	n/r	n/r	n/r	n/r	1.0E-04	1.4E-05	1.0E-04	1.4E-05
	Rat	9.3E-01	9.5E-01	4.6E-01	n/r	n/r	n/r	n/r	1.7E-04	1.5E-05	1.7E-04	1.5E-05
	Earthworm	1.4E-02	1.9E-01	3.2E-01	5.2E-01	9.0E-01	5.4E-01	n/r	1.4E-04	1.1E-05	1.4E-04	3.1E-06
^{60}Co	Duck	2.5E-03	4.3E-02	4.3E-03	4.7E-01	9.6E-01	4.6E-01	n/r	2.5E-04	1.0E-04	2.3E-04	4.6E-05
	Frog	2.6E-02	6.0E-01	2.6E-02	1.3E-01	n/a	2.9E-01	n/r	1.1E-04	3.8E-05	1.1E-04	5.1E-06
	Salmonid egg	5.1E-05	1.9E-02	1.2E-03	6.2E-01	9.6E-01	3.3E-01	n/r	5.0E-05	1.9E-05	5.6E-05	3.9E-06
	Rat	1.4E-02	9.3E-02	1.4E-02	2.0E-01	4.8E-01	2.1E-01	3.1E-01	1.9E-04	7.3E-05	1.7E-04	3.4E-05
	Earthworm	1.4E-02	1.9E-01	2.2E-02	9.4E-01	n/a	7.3E-01	n/r	7.6E-05	2.5E-05	7.7E-05	1.7E-06
^{241}Am	Duck	1.0E-07	6.7E-03	1.8E-04	2.5E-01	5.3E-01	1.5E-01	n/r	3.0E-03	6.1E-04	3.2E-03	6.7E-06
	Frog	1.1E-07	6.7E-03	1.9E-04	2.5E-01	4.0E-01	2.0E-01	n/r	3.0E-03	6.1E-04	3.2E-03	7.9E-06
	Salmonid egg	2.5E-06	1.4E-02	7.8E-04	6.0E-01	n/a	2.8E-01	n/r	3.0E-03	6.6E-04	3.2E-03	1.9E-05
	Rat	1.0E-07	6.6E-03	1.8E-04	2.6E-01	4.4E-01	1.6E-01	n/r	3.0E-03	6.1E-04	3.2E-03	7.3E-06
	Earthworm	1.3E-07	6.8E-03	1.9E-04	2.9E-01	7.4E-01	1.2E-01	n/r	3.0E-03	5.4E-04	3.2E-03	1.4E-05
^{238}U	Duck	4.2E-04	1.1E-01	2.2E-01	1.1E-01	4.3E-01	2.2E-01	n/r	3.1E-03	1.3E-03	2.5E-03	3.6E-04
	Frog	1.0E-03	1.4E-01	2.5E-01	2.0E-02	4.4E-01	3.8E-01	3.2E-01	3.1E-03	1.4E-03	2.6E-03	2.3E-04
	Salmonid egg	1.7E-03	8.8E-02	7.6E-03	8.7E-01	n/a	7.8E-01	n/r	2.7E-03	1.1E-03	2.4E-03	1.4E-05
	Rat	1.2E-02	2.4E-01	4.2E-02	1.5E-03	2.6E-01	8.4E-01	2.5E-01	2.5E-03	3.6E-04	2.6E-03	2.2E-04
	Earthworm	1.1E-02	1.9E-01	2.1E-02	2.8E-03	1.7E-01	3.8E-01	6.4E-02	2.5E-03	3.3E-04	2.5E-03	2.0E-04

N/A not available (insufficient number of data to perform statistical test); *N/C* not calculated (data fail normality tests, but not Grubb's test for outliers); *N/R* additional test not required to assess robustness (applies also to Tables 12, 13, 14, 15)

Table 12 Performance statistics for external exposure DCCs in water

Nuclide	Organism	Original dataset *P*-values			Robust dataset *P*-values			Grubbs	Original dataset mean		Robust dataset mean	
		Shapiro-Wilk	D'Agostino	Anscombe	Shapiro-Wilk	D'Agostino	Anscombe	Test	Mean	± S.D.	Mean	Robust SD
^{90}Sr	Duck	1.2E-01	1.8E-01	1.1E-01	n/r	n/r	n/r	n/r	1.8E-05	8.5E-06	1.8E-05	8.5E-06
	Frog	4.4E-02	1.3E-01	3.6E-02	2.9E-01	8.7E-01	2.1E-01	n/r	7.0E-05	2.1E-05	7.6E-05	1.1E-05
	Salmonid egg	9.1E-03	n/a	1.4E-02	2.5E-01	n/a	4.5E-01	n/r	5.3E-04	2.2E-04	4.5E-04	7.2E-05
^{137}Cs	Duck	1.6E-02	8.7E-01	1.4E-02	n/c	n/c	n/c	9.0E-01	2.0E-04	9.0E-05	2.0E-04	9.0E-05
	Frog	1.1E-02	8.6E-01	1.2E-02	n/c	n/c	n/c	9.0E-01	2.5E-04	9.1E-05	2.5E-04	9.1E-05
	Salmonid egg	1.0E-02	3.3E-01	6.4E-01	n/c	n/c	n/c	2.5E-01	2.6E-04	1.3E-04	2.6E-04	1.3E-04
^{60}Co	Duck	7.3E-03	8.8E-01	9.0E-03	n/c	n/c	n/c	8.2E-01	9.0E-04	4.2E-04	9.0E-04	4.2E-04
	Frog	3.0E-03	2.8E-01	8.1E-01	n/c	n/c	n/c	2.1E-01	1.1E-03	4.0E-04	1.1E-03	4.0E-04
	Salmonid egg	8.0E-02	7.7E-01	7.9E-02	n/r	n/r	n/r	n/r	1.0E-03	4.8E-04	1.0E-03	4.8E-04
^{241}Am	Duck	5.8E-02	2.8E-01	5.6E-01	n/r	n/r	n/r	n/r	9.0E-06	3.4E-06	9.0E-06	3.4E-06
	Frog	5.7E-01	8.8E-01	4.2E-01	n/r	n/r	n/r	n/r	1.2E-05	5.3E-06	1.2E-05	5.3E-06
	Salmonid egg	1.2E-01	2.4E-01	3.6E-01	n/r	n/r	n/r	n/r	2.1E-05	2.0E-05	2.1E-05	2.0E-05
^{238}U	Duck	5.1E-06	1.2E-02	5.0E-04	2.8E-02	7.9E-01	4.0E-02	1.0E+00	3.6E-05	7.4E-05	1.3E-05	1.3E-05
	Frog	3.9E-04	4.0E-02	4.8E-03	3.3E-03	7.0E-01	1.1E-02	1.0E+00	5.1E-05	7.4E-05	3.1E-05	3.4E-05
	Salmonid egg	4.0E-01	8.1E-01	1.9E-01	n/r	n/r	n/r	n/r	2.1E-04	1.6E-04	2.1E-04	1.6E-04

Table 13 Performance statistics for external exposure DCCs in soil

Nuclide	Organism	Original dataset *P*-values			Robust dataset *P*-values			Grubbs	Original dataset mean		Robust dataset mean	
		Shapiro-Wilk	D'Agostino	Anscombe	Shapiro-Wilk	D'Agostino	Anscombe	Test	Mean	±SD	Mean	Robust SD
^{90}Sr	Rat	1.5E-05	1.6E-02	9.2E-04	8.1E-01	9.5E-01	9.9E-01	n/r	7.4E-05	1.3E-04	3.0E-05	2.1E-05
	Earthworm	6.2E-01	6.8E-01	4.9E-01	n/r	n/r	n/r	n/r	1.8E-04	1.4E-04	1.8E-04	1.4E-04
^{137}Cs	Rat	6.0E-01	5.8E-01	3.1E-01	n/r	n/r	n/r	n/r	2.4E-04	1.1E-04	2.4E-04	1.1E-04
	Earthworm	1.6E-01	5.7E-01	3.0E-01	n/r	n/r	n/r	n/r	2.8E-04	1.1E-04	2.8E-04	1.1E-04
^{60}Co	Rat	7.4E-01	9.8E-01	3.8E-01	8.9E-01	n/a	5.1E-01	n/r	1.2E-03	4.1E-04	1.3E-03	1.5E-04
	Earthworm	3.3E-01	9.9E-01	3.6E-01	n/r	n/r	n/r	n/r	1.3E-03	4.3E-04	1.3E-03	4.3E-04
^{241}Am	Rat	3.1E-01	6.1E-01	3.6E-01	n/r	n/r	n/r	n/r	8.4E-06	6.1E-06	8.4E-06	6.1E-06
	Earthworm	6.0E-02	5.7E-01	2.0E-01	n/r	n/r	n/r	n/r	1.0E-05	7.7E-06	1.0E-05	7.7E-06
^{238}U	Rat	1.6E-07	6.8E-03	1.9E-04	6.8E-04	2.4E-01	9.6E-01	3.3E-01	6.0E-05	1.6E-04	1.1E-05	1.7E-05
	Earthworm	1.9E-05	1.9E-02	1.4E-03	4.3E-04	2.2E-01	8.7E-01	1.6E-01	8.2E-05	1.6E-04	3.7E-05	5.9E-05

tion are implemented in EDEN 2: Monte Carlo and local deposition. The Monte-Carlo approach was used to provide DCC values for this exercise (Tables 4, 5, 6, 7, 8). As an additional test (conducted using the duck, frog and rat geometries), it was decided to investigate whether the alternative local deposition approach provided results closer to the robust mean than the Monte Carlo simulation.

The use of the local deposition approach tends to bring some EDEN 2 results somewhat closer to the robust mean of all the approaches. For internal exposure, the local deposition approach essentially modifies the β DCCs. For example, the ^{3}H DCC becomes 3.1×10^{-6} μGy h^{-1} per Bq kg^{-1} for all organisms, instead of 5.9×10^{-6} μGy h^{-1} per Bq kg^{-1}. For ^{90}Sr, the internal DCC calculated with the local deposition approach is evaluated at 6.2×10^{-4} μGy h^{-1} per Bq kg^{-1} versus 5.6 to 6.0×10^{-4} μGy h^{-1} per Bq kg^{-1} calculated using the Monte-Carlo code. For external exposure, the local deposition hypothesis leads to a zero DCC for pure α- and β-emitters and a decrease in the DCC for radionuclides comprising various types of radioactive decay. As an illustration, the ^{241}Am DCC for a duck in water falls from 1.2×10^{-5} μGy h^{-1} per Bq kg^{-1} (Monte-Carlo calculation) to 4.3×10^{-6} μGy h^{-1} per Bq kg^{-1} (local deposition).

Efficacy measures rank as follows: External sediment (90%) > External water (82%) > External soil (73%) > Internal (55%) > External on soil/shore (45%), with only the latter scoring less than 50%. The relatively low efficacy measure for internal exposure reflects the fact that, for certain radionuclides, a few approaches (e.g. ECOMOD, EDEN 2 and SCK·CEN for ^{3}H, and SCK·CEN for ^{241}Am) give DCCs significantly off-range whilst the rest report almost identical values. This results in an isolated group of elevated *Z*-scores, reducing the overall efficacy measure. However, overall, the inter-compared DCCs for internal irradiation have relatively low dispersion, as illustrated by the low coefficients of variation in Table 4.

The lower efficacy measure for external on soil/shore DCCs, is likely to be due to additional assumptions concerning the position of the target above-ground and differences in source–target geometry/shielding factors, as explained above in subsection "Effect of soil/sediment depth and target position".

Conclusions

An exercise directed at the comparison of screening-level approaches for the calculation of unweighted absorbed dose rates (reported as DCCs) in biota has been successfully performed. Unweighted internal and external DCCs for a selection of the proposed ICRP Reference Animal geometries were calculated. The data submitted by the participants were subject to exploratory statistical analysis to identify and remove outliers. Statistics were then calculated for the robust data (which were found to follow normal distributions) as the basis for scoring each approach for performance.

The purpose of this study was to compare screening and simple site-specific approaches designed for biota dose assessment for regulatory purposes. These approaches are not intended to generate a scientifically realistic representation of reality. Rather, they purport to represent a highly variable quantity (the biota DCC) that cannot be measured, but rather must be modelled. Therefore, at the outset of this work, it was expected that the different approaches would give rise to differences, based on the different physical and ecological assumptions made. Hence, no value judgement was passed on the validity of any approach.

On initial inspection of the data, inter-comparison results indicated that, whilst DCCs for internal exposure compare well between the different approaches, variation is greater for external exposure DCCs. Whilst external doses from β-emitters are low, there is considerable variation for such doses between the different approaches. It is generally accepted that external exposure of living organisms by short-range α- or β-radiation (e.g. from ^{3}H, plutonium and some naturally occurring radionuclides) is of little radiological significance, due to their low range in matter. This prevents such radiation from reaching the radiosensitive targets, including vitally important organs, such as germ cells and hemopoetic cells. For example, the range of ^{3}H β-radiation in soft biological tissue is less than 10 μm, and for α-particles of 5 MeV, the range is on the order of 50 μm, which is too short to cross surface tissue and reach radiosensitive cells. Therefore, whole-body averaging of the external low energy β doses received by non-radiosensitive integument tissue (i.e. the external covering of the body, such as skin, feathers, scales, etc.) makes little sense from a radiobiological point of view.

It is not practically feasible to investigate method-by-method to try to attribute all degrees of variability to a specific set of assumptions. However, it is possible to conclude here that where variation among internal DCCs is greatest, it is generally as a consequence of different daughter products being included (e.g. ^{238}U) in the DCC of the parent. In the case of external exposures, particularly to low-energy β-emitters, variations are most likely to be due to different media densities being assumed.

On a radionuclide-by-radionuclide basis, the approach *Z*-scores higher than 2 tend to relate to ^{3}H, ^{14}C and the α-emitters. This is consistent with radiation with the lowest range across matter being most adversely affected by source–target geometry effects.

The efficacy measure of this intercomparison is about 70% on average, and on that basis it can be concluded that the intercomparison was successful in demonstrating that all approaches to biota dose calculation considered in this exercise give reasonably comparable results. This is the case even though different assumptions (including the use of default geometry DCCs, rather than estimation of bespoke values for this exercise) are made by the various approaches (Tables 2, 3).

Now that the differences between the approaches are known and some of them have been explained; the information can be utilized by users wishing to assess and interpret the consistency of their biota dosimetry methodology with the approaches participating in this intercomparison. This study will also allow differences associated with dosimetry calculations to be put into context with those associated with transfer and other aspects of an assessment of non-human biota.

As a follow-up to this work, a similar exercise to compare the transfer components of the participating approaches has been performed, in which a nominal level of 1 Bq per unit media was used to estimate the activity concentration for a range of radionuclides in 19 terrestrial and freshwater organisms [3]. This is to be followed by scenario testing against environmental monitoring data. On-going scenarios include Perch Lake (freshwater) and

Table 14 Performance statistics for external exposure DCCs on soil/on shore

Nuclide	Organism	Original dataset *P*-values			Robust dataset *P*-values			Grubbs	Original dataset mean		Robust dataset mean	
		Shapiro-Wilk	D'Agostino	Anscombe	Shapiro-Wilk	D'Agostino	Anscombe	Test	Mean	±SD	Mean	Robust SD
^{90}Sr	Duck	1.1E-05	2.1E-02	1.6E-03	1.3E-01	n/a	6.3E-02	6.3E-01	3.9E-05	8.8E-05	5.1E-06	5.0E-06
	Frog	1.6E-03	5.3E-02	1.0E-02	2.0E-01	n/a	6.3E-02	6.7E-01	5.6E-05	8.6E-05	1.7E-05	1.6E-05
	Rat	1.1E-05	2.1E-02	1.6E-03	6.6E-02	n/a	1.8E-01	4.1E-01	3.9E-05	8.8E-05	8.0E-06	9.3E-06
	Earthworm	6.3E-02	1.9E-01	1.5E-01	n/r	n/r	n/r	n/r	7.3E-05	8.8E-05	7.3E-05	8.8E-05
^{137}Cs	Duck	3.8E-01	7.9E-01	7.1E-01	n/r	n/r	n/r	n/r	9.8E-05	3.6E-05	9.8E-05	3.6E-05
	Frog	4.9E-01	9.9E-01	4.1E-01	n/r	n/r	n/r	n/r	1.1E-04	4.0E-05	1.1E-04	4.0E-05
	Rat	4.7E-01	7.2E-01	6.9E-01	n/r	n/r	n/r	n/r	9.7E-05	3.4E-05	9.7E-05	3.4E-05
	Earthworm	6.7E-01	9.2E-01	3.7E-01	n/r	n/r	n/r	n/r	1.1E-04	4.5E-05	1.1E-04	4.5E-05
^{60}Co	Duck	4.3E-01	9.7E-01	2.8E-01	n/r	n/r	n/r	n/r	4.3E-04	1.7E-04	4.3E-04	1.7E-04
	Frog	2.7E-01	9.8E-01	2.9E-01	n/r	n/r	n/r	n/r	4.7E-04	1.9E-04	4.7E-04	1.9E-04
	Rat	3.0E-01	9.3E-01	2.3E-01	n/r	n/r	n/r	n/r	4.5E-04	1.8E-04	4.5E-04	1.8E-04
	Earthworm	1.8E-01	n/a	5.4E-01	n/r	n/r	n/r	n/r	4.3E-04	2.1E-04	4.3E-04	2.1E-04
^{241}Am	Duck	9.8E-03	2.1E-01	5.4E-01	1.2E-01	n/a	1.5E-01	5.1E-01	3.1E-06	2.3E-06	1.8E-06	4.7E-07
	Frog	2.3E-02	5.2E-01	1.5E-01	n/c	n/c	n/c	5.7E-01	4.4E-06	3.1E-06	4.4E-06	3.1E-06
	Rat	1.0E-06	8.4E-03	2.7E-04	5.1E-03	2.9E-01	7.1E-01	3.5E-01	8.5E-06	1.6E-05	3.9E-06	2.9E-06
	Earthworm	5.0E-03	4.5E-01	1.6E-01	n/c	n/c	n/c	5.8E-01	4.4E-06	3.3E-06	4.4E-06	3.3E-06
^{238}U	Duck	5.0E-03	4.5E-01	1.6E-01	5.6E-02	n/a	2.7E-01	5.4E-02	2.5E-05	6.9E-05	1.9E-07	2.5E-07
	Frog	2.1E-06	1.1E-02	4.7E-04	8.7E-02	n/a	2.7E-01	5.5E-02	3.0E-05	7.3E-05	2.2E-07	2.7E-07
	Rat	1.4E-07	6.7E-03	1.9E-04	9.0E-02	n/a	8.5E-02	2.3E-02	2.5E-05	7.1E-05	9.5E-08	9.4E-08
	Earthworm	4.2E-04	4.6E-02	8.1E-03	3.0E-03	2.3E-01	6.4E-01	1.1E-01	4.2E-05	7.4E-05	1.9E-05	3.0E-05

Table 15 Performance statistics for external exposure DCCs on sediment

Nuclide	Organism	Original dataset *P*-values			Robust dataset *P*-values			Grubbs	Original dataset mean		Robust dataset mean	
		Shapiro-Wilk	D'Agostino	Anscombe	Shapiro-Wilk	D'Agostino	Anscombe	Test	Mean	±SD	Mean	Robust SD
^{90}Sr	Frog	8.8E-01	n/a	6.3E-01	n/r	n/r	n/r	n/r	4.7E-05	3.5E-05	4.7E-05	3.5E-05
	Salmonid egg	1.5E-01	n/a	4.3E-01	n/r	n/r	n/r	n/r	3.2E-04	3.6E-04	3.2E-04	3.6E-04
^{137}Cs	Frog	5.8E-01	n/a	n/a	n/r	n/r	n/r	n/r	1.7E-04	1.1E-04	1.7E-04	1.1E-04
	Salmonid egg	4.9E-02	4.0E-01	6.7E-01	n/c	n/c	n/c	3.6E-01	1.8E-04	1.4E-04	1.8E-04	1.4E-04
$^{6^{\circ}}$Co	Frog	6.1E-01	n/a	n/a	n/r	n/r	n/r	n/r	7.5E-04	4.9E-04	7.5E-04	4.9E-04
	Salmonid egg	1.3E-01	5.2E-01	5.0E-01	n/r	n/r	n/r	n/r	7.3E-04	5.1E-04	7.3E-04	5.1E-04
^{241}Am	Frog	1.6E-01	n/a	n/a	n/r	n/r	n/r	n/r	9.6E-06	3.5E-06	9.6E-06	3.5E-06
	Salmonid egg	2.2E-01	5.9E-01	4.5E-01	n/r	n/r	n/r	n/r	8.6E-06	7.1E-06	8.6E-06	7.1E-06
^{238}U	Frog	5.4E-01	n/a	n/a	n/r	n/r	n/r	n/r	2.8E-05	3.1E-05	2.8E-05	3.1E-05
	Salmonid egg	8.8E-02	4.9E-01	5.4E-01	n/r	n/r	n/r	n/r	1.5E-04	1.7E-04	1.5E-04	1.7E-04

the Chernobyl exclusion zone (terrestrial) (see http://www.ns.iaea.org/projects/emras/emras-biota-wg.htm).

It should be noted that, as protection of the environment from ionizing radiation is a relatively new field, some of the approaches described in this paper are 'works in progress', and as such their DCC values may change in the future. In fact, one of the objectives of the EMRAS Biota Working Group is to provide a forum for discussion

Table 16 Summary of all Z-scoring tables for the EMRAS DCC comparison exercise

DCC	AECL	EA	ECOMOD	EDEN	EPIC	ERICA	FASSET	LIETDOS	RESRAD	SCK·CEN	SÚJB	Efficacy measure
Internal	7.7E+00	8.0E-01	1.8E+01	4.3E+01	1.1E+00	5.0E-01	1.5E+00	1.5E+01	5.0E-01	4.9E+01	1.7E+00	5.5E+01
±1 SD	3.6E+01	1.6E+00	4.1E+01	1.2E+02	1.5E+00	4.0E-01	3.0E+00	3.2E+01	4.0E-01	8.3E+01	2.4E+00	
Internal excl. ^{3}H and ^{14}C	1.1E+01	1.0E+00	5.0E+00	4.3E+00	1.3E+00	3.0E-01	1.7E+00	2.0E+01	4.0E-01	5.1E+01	2.1E+00	4.5E+01
±1 SD	4.3E+01	1.8E+00	9.4E+00	7.7E+00	1.7E+00	3.0E-01	3.6E+00	3.6E+01	4.0E-01	9.3E+01	2.7E+00	
External water	8.0E-01	7.0E-01	7.0E-01	9.9E+03	9.0E-01	8.0E-01	8.0E-01	1.0E+00	8.0E-01	2.9E+00	1.2E+00	8.2E+01
±1 SD	4.0E-01	4.0E-01	3.0E-01	3.3E+04	3.0E-01	3.0E-01	3.0E-01	5.0E-01	1.0E+00	3.9E+00	1.5E+00	
External soil	2.1E+00	6.0E-01	4.0E-01	3.4E+00	1.5E+00	7.0E-01	1.0E+00	5.0E-01	6.0E-01	3.9E+00	8.0E-01	7.3E+01
±1 SD	4.8E+00	6.0E-01	2.0E-01	6.5E+00	1.1E+00	4.0E-01	4.0E-01	3.0E-01	5.0E-01	8.5E+00	4.0E-01	
External on soil/shore	4.4E+00	1.5E+01	6.0E+00	4.9E+00	8.0E-01	6.0E-01	5.0E-01	2.0E+00	9.3E+00	2.1E+02	1.8E+00	4.5E+01
±1 SD	1.1E+01	4.5E+01	8.0E+00	1.3E+01	1.0E-01	4.0E-01	3.0E-01	4.3E+00	2.9E+01	6.0E+02	2.7E+00	
External sediment	1.2E+00	1.0E+00	n/c	5.5E+03	8.0E-01	6.0E-01	3.0E-01	6.0E-01	6.0E-01	8.0E-01	7.0E-01	9.0E+01
±1 SD	5.0E-01	5.0E-01	n/c	2.0E+04	1.0E-01	5.0E-01	4.0E-01	4.0E-01	5.0E-01	3.0E-01	6.0E-01	
Overall score (including ^{3}H and ^{14}C)	3.2E+00	3.6E+00	6.2E+00	3.1E+03	1.0E+00	6.0E-01	8.0E-01	3.7E+00	2.4E+00	5.4E+01	1.2E+00	6.9E+01
±1 SD	2.8E+00	6.3E+00	8.2E+00	4.5E+03	3.0E-01	1.0E-01	5.0E-01	6.1E+00	3.9E+00	9.2E+01	5.0E-01	1.9E+01
Overall score (excluding ^{3}H and ^{14}C)	3.8E+00	3.7E+00	3.0E+00	3.1E+03	1.1E+00	6.0E-01	9.0E-01	4.8E+00	2.3E+00	5.4E+01	1.3E+00	6.7E+01
±1 SD	4.1E+00	6.3E+00	2.9E+00	4.5E+03	3.0E-01	2.0E-01	6.0E-01	8.5E+00	3.9E+00	9.2E+01	6.0E-01	2.1E+01

between modellers, which will hopefully lead to the improvement of current tools and approaches that are being applied in biota dose assessment.

Acknowledgments The authors would like to thank all other participants of the Biota Working Group who have commented on this work. The authors would also like to thank Professor J. Pentreath, the Chairperson of ICRP Committee 5, for permission to use the proposed RAP geometries.

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