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PREDICTING EXPOSURE OF WILDLIFE IN RADIONUCLIDE CONTAMINATED WETLAND ECOSYSTEMS

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Highlights:

1) Terrestrial parameters provided acceptable predictions for wetland species.
2) Choice of reference organism and occupancy factor resulted in largest differences.
3) Soil density and saturation should be considered when assessing doses in wetlands.

ABSTRACT

Many wetlands support high biodiversity and are protected sites, but some are contaminated with radionuclides from routine or accidental releases from nuclear facilities. This radiation exposure needs to be assessed to demonstrate radiological protection of the environment. Existing biota dose models cover generic terrestrial, freshwater, and marine ecosystems, not wetlands specifically. This paper, which was produced under IAEA's Environmental Modelling for Radiation Safety (EMRAS) II programme, describes an evaluation of how models can be applied to radionuclide-contaminated wetlands. Participants used combinations of aquatic and terrestrial model parameters to assess exposure. Results show the importance of occupancy factor and food source (aquatic or terrestrial) included. The influence of soil saturation conditions on external dose rates is also apparent. In general, terrestrial parameters provided acceptable predictions for wetland organisms. However, occasionally predictions varied by three orders of magnitude between assessors. Possible further developments for biota dose models and research needs are identified.

Keywords: biota dose model, radiation dose, swamp, ^{137}Cesium, ^{14}Carbon

Capsule: Terrestrial parameters provide acceptable predictions for wetland organisms

1. Introduction

With a renewed interest in nuclear power in many countries (Marcus, 2008; Joskow and Parsons, 2012) and with the recognition by the International Commission on Radiological Protection (ICRP) for an explicit consideration of radiological protection of the environment (ICRP, 2007; 2009), robust methods for assessing radiation doses and effects to wildlife are becoming increasingly important. This challenging task has been addressed by radioecologists by the development of a number of biota dose estimation models (see Vives i Batlle et al., 2011; Beresford et al., 2009) that can be used in environmental risk assessments such as the ERICA Tool (Brown et al., 2008) and RESRAD-Biota (USDoE, 2004) which are freely available software. However, these models are in need of validation.

The International Atomic Energy Agency (IAEA) launched the Environmental Modelling for Radiation Safety (EMRAS) programme in 2005-2008 (IAEA, 2012) and EMRAS II in 2009-2012 (IAEA in-press) to facilitate international collaboration for improving environmental dose assessments. Within these programmes biota dose model inter-comparisons were performed for terrestrial (Beresford et al., 2010; Johansen et al., 2012), and freshwater lake ecosystems (Yankovich et al., 2010; IAEA, in-press). These studies showed that model results can vary by up to three orders of magnitude in dose predictions (Beresford et al., 2010; Johansen et al., 2012), with most variation attributed to modelled uptake of radionuclides by organisms. To help refine the models, further inter-comparison exercises were recommended (Beresford et al., 2009), especially for those exposure scenarios not specifically considered in available models and radionuclide-organism combinations not yet assessed.

In general, current biota dose models consider three generic ecosystem types: terrestrial, freshwater, and marine. Available models do not consider wetlands explicitly, although, RESRAD-Biota does include an option to assess riparian animals. However, such ecosystems require assessment, as numerous wetlands are protected under the RAMSAR convention (Mitsch and Gosselink, 2000), support high biodiversity, and data show that some are contaminated with radionuclides (see below).

There are a variety of wetland types, with a range of typical features. Wetlands include the structural groups: marshes, swamps, bogs, and fens (Tiner, 1999). *Marshes* are defined as regularly or constantly flooded wetlands with emergent, herbaceous vegetation adapted to saturated soil conditions and mineral soil substrates (Mitsch and Gosselink, 2000). *Swamps* are dominated by trees or shrubs and often have a high biodiversity and productivity. Wetlands dominated by reed grasses and forested fens can be included in the *swamps* category. *Bogs* are peat-accumulating wetlands that have no significant inflows or outflows and support acidophilic mosses. *Fens* are also peat-accumulating but receive some drainage inflow from surrounding mineral soils and usually support marsh-like vegetation.

This study focused on swamps in temperate/sub-tropical regions, which often are wetlands that can be nutrient sinks, filtering particles from temporarily inflowing water. Many radionuclides have an affinity to sediment particles and these types of wetlands may, therefore, accumulate and function as sinks for such radionuclides (e.g., Walling and Bradley, 1988; Burrough et al., 1999; Kaplan et al., 2014).

The objective of this study was to investigate how current models for wildlife radiation dose assessments can be applied to radionuclide contaminants (particularly ^{137}Cs and ^{14}C) in wetlands. Here we report results of a model-to-model inter-comparison exercise considering three wetlands. We focused on differences between how exercise participants, representing ‘informed users’ and model developers (Wood et al., 2009), approached a wetland scenario, to evaluate differences in predictions between different model applications used to run the scenario.

2. Methods

2.1 Biota dose models and participants

Six groups participated in this inter-comparison exercise (Table 1) using different models, namely K-Biota (Keum, 2012; Keum et al., 2011), RESRAD-Biota (USDoE, 2004) and ERICA Tool (Brown et al., 2008). Four groups used the ERICA Tool, of which two used included default transfer parameters (concentration ratios, CRs) (Beresford et al., 2008; Hosseini et al., 2008) and two used CRs from the IAEA technical report series (TRS) handbook on wildlife transfer (IAEA, 2014; Howard et al., 2013; Yankovich et al. 2013b). The handbook on wildlife transfer, referred to as the TRS in the subsequent text, was also used with RESRAD-Biota and K-Biota applications. It should be noted that the database underlying the TRS was initially based upon the ERICA Tool, with additional data being added where available (Copplestone et al., 2012).

2.2 Description of the wetland areas

Data from three wetlands were combined to provide a range of organisms, soil types, and radionuclides: Steel Creek Swamp (South Carolina, USA), Utnora Swamp (Sweden), and Duke Swamp (Canada) (Table 2). Routine releases were the cause of contamination in Steel Creek Swamp while accidental releases contaminated Utnora and Duke Swamp.

2.2.1 Steel Creek Swamp

Steel Creek, a 20 km long creek, drains a 290 km^2 watershed (Figure 1) situated on the US Department of Energy Savannah River Site in South Carolina, USA (N33°06’50’’, W81°37’50’’). The creek received cooling water from nuclear reactors between 1954 and 1974 (Paller et al., 2008). A floodplain borders the main channel and the creek is shallow (< 1m) and 3 - 5 m wide. Soil was sampled down to a depth of 1 meter along three transects perpendicular to the creek (Figure 1) and ^{137}Cs activity concentrations are available (Brisbin et al, 1974a). Most of the activity was in the top 10-cm of profiles. In addition, water, vegetation, amphibians, reptiles, and invertebrates activity concentrations were available (RAC, 2001; Brisbin et al., 1974b; Anderson et al., 1973; Dapson and Kaplan, 1975; Table 3).

2.2.2 Utnora Swamp

Utnora Swamp (Figure 2) is a 0.024 km^2 riparian swamp next to Verkmyra Stream, which flows out of Hille Lake, in the central-eastern part of Sweden (N60°46’20’’, E17°16’30’’). The swamp received fallout following the Chernobyl accident in 1986. Verkmyra Stream floods the swamp every spring, resulting in deposition of radioactive material, mainly ^{137}Cs (Stark et al., 2006). Available samples from this area were soil/sediment profiles down to a depth of 50 cm, water, vegetation, and amphibians (Stark et al., 2004; Stark unpublished data; Table 3). Most of the activity (60 – 90%) in soil was found in the top 10-cm layer.

2.2.3 Duke Swamp

The Duke Swamp (Figure 3) is a 0.102 km^2 wetland in the Atomic Energy of Canada Limited’s Chalk River facility in Ontario, Canada (N46°02’40’’, W77°24’40’’) that receives radionuclides, including ^{14}C, through groundwater transport from a waste management area situated approximately 400 m east of the swamp (Kim et al., 2011; Yankovich et al., 2008a). Past assessments indicated that the primary contributor to dose to biota is likely to be ^{14}C (Zach et al. 1998) from ^{14}C volatilised into the atmosphere rather than via direct transfer from groundwater (Yankovich et al. 2013a). A detailed survey of ^{14}C in soil to a depth of 5 cm and surface vegetation had been conducted. A subset of locations was selected for detailed biota sampling to obtain a range of activity concentrations across Duke Swamp. Samples included in this study were of soil, air, vegetation, invertebrates, amphibians, reptiles, and rodents (Yankovich et al., 2013a; Table 3).

2.3 Input data and exercise instructions

Participants were given measured activity concentrations in soil, water, and air, as available for the three wetland areas (Table 2). No other parameters were specified in the scenario description, although basic information for sites and a list of species to consider were provided (Table 3; IAEA in press). Soil concentrations were presented on a dry mass basis; hence, fresh mass concentrations had to be estimated if required. Water concentrations (only available for Steel Creek and Utnora Swamps), were given for filtered water. To provide soil ^{14}C concentration in Duke Swamp for those models requiring this input, available ^{14}C specific activity concentrations in soil were calculated by assuming the mean soil organic matter content determined for the site (95%; Yankovich et al., 2014) and an assumed carbon content of soil organic matter of 58% (Brady, 1990).

Participants were asked to estimate whole organism radionuclide activity concentrations, unweighted internal, external, and total absorbed dose rates to all species listed in Table 3. Deterministically predicted best estimates of mean, minimum, and maximum activity concentrations and average dose rates over a year were requested. Evaluation included model-model comparisons of organism concentrations and dose rates, model-measurement comparisons of organism concentrations and, for one species (frogs in Utnora), model-measurement comparisons of external dose rate in soil.

2.4 General approach taken by participants

For Steel Creek and Utnora Swamps, whole organism activity concentrations of ^{137}Cs were estimated by multiplying CRs with soil or water concentrations, given the assumptions being made for the fraction of time spent feeding in aquatic or terrestrial environments. Internal and external dose rates were estimated from assumed occupancy factors in air, on soil, in soil, on water, in water, on sediment, and in sediment, together with dose conversion coefficients

(DCCs). If default reference organisms were used, included DCCs were applied. Alternately, DCCs were calculated by the models if new geometries approximating specific organisms were considered to be required.

Two approaches were used to estimate biota concentrations of ^{14}C in Duke Swamp (Table 1): I) the specific activity approach in which the specific activity ratio (Bq ^{14}C/kg C) was assumed to be the same in the whole ecosystem. Each whole body activity concentration (Bq/kg fresh mass, FM) was estimated from a given specific activity in air (Bq/kg C) multiplied by whole body content of stable C in organisms (kg C/kg FM). II) to use the ERICA Tool default CR_{wo} (whole organism concentration ratio; Howard et al., 2013) values (Bq/kg per Bq/m^3) to convert air concentrations Bq/m^3 to organism activity concentrations (it was suggested participants used the carbon concentration in air presented in IAEA (2010) to estimate air ^{14}C concentrations). However, CR_{wo}s from the ERICA Tool were originally derived through the specific activity approach assuming carbon content of biota from Robbins (1993) and Crocker et al. (2002), as described by Brown et al. (2003).

3. Results and Discussion

3.1 Wetland assessment approaches taken by the assessors

Because none of the biota dose models used in this study were specifically developed for wetlands, only their aquatic or/and terrestrial functions were available. As a result, species from the wetlands were mainly assumed to feed in terrestrial systems by all assessors, and thus, mainly terrestrial CRs were used in predictions (Table 4). However, a few organisms were assumed to be aquatic or to occupy or feed from aquatic environments for various fractions of time (Table 4 and 5). Assessors assumed an organism to be terrestrial or aquatic according to supporting information they identified about the species.

3.2 *Predicted biota activity concentrations*

Differences in results between assessors for predicted biota activity concentrations of ^{137}Cs in Steel Creek and Utnora Swamp (Figure 4 and 5) were mainly due to differences in assumptions of transfer from terrestrial and aquatic sources and the choice of reference organism to represent wetland species. In Duke Swamp, differences in predicted activity concentrations of ^{14}C (Figure 6) mainly depended on differences in assumed carbon content of organisms.

3.2.1 Choice of ecosystem and CR_{wo}-value

In Steel Creek Swamp, the ERICA (CEH) application only used an aquatic CR_{wo} for duck and gave a lower estimated biota activity concentration, even though it was assumed to spend part of the time on land. The assessor justified this on the basis of the importance of the freshwater environment as food source for typical duck species. This resulted in a difference in predicted activity concentrations between assessors by a factor of seven for duck in Steel Creek Swamp (Figure 4). Differences between predicted activity concentrations for shrubs, frogs, and snakes were mainly caused by differences in CR_{wo} between the two databases in the ERICA Tool and TRS (IAEA, 2014), which was less than a factor of two for most organisms, although a seven-fold difference were predicted for terrestrial snake. For terrestrial reptiles, the TRS CR_{wo} value for Cs is a factor of seven lower than the ERICA CR_{wo}. Barnett et al. (2009) had previously observed errors in the derivation of the ERICA CR_{wo} for reptiles (corrected in the TRS dataset).

In Utnora Swamp the largest variation in predicted activity concentrations of ^{137}Cs was for forbs and sedges, mainly because the ERICA(CEH) application used freshwater vascular plant as reference organism (justified by the assessor on the basis of species listed for the site), and thus, water as surrounding medium. Consequently, results varied up to three orders of magnitude between assessors (Figure 5). For Moor frog, the two applications that included aquatic transfer to frog (K-Biota and ERICA (SCK•CEN) resulted in the lowest predictions.

3.2.2 Choice of reference organism

Another source of difference between predicted activity concentrations was the choice of reference organism to represent the exercise species, for example, whether to choose detritivorous or flying insect to represent beetles (in the ERICA Tool). In Steel Creek Swamp, these differences were generally less than a factor of three. However, the decision to allocate woody plants as trees or shrubs was of more consequence, as difference in CR_{wo} between trees and shrubs was more than a factor of 15 for both the ERICA Tool and TRS datasets. This resulted in a relatively large difference in predictions for willow in Steel Creek, which was represented as a tree by most assessors but as a shrub in the RESRAD-Biota application.

For Utnora Swamp, different choices of reference organism (herb/grass/shrub) to represent fern also resulted in a difference by a factor of six for fern activity concentrations between assessors.

3.2.3 ^{14}C transfer

In general, differences between assessors in predicted ^{14}C activity concentrations in biota were small for Duke Swamp, with estimated mean values varying by a factor of four or less (Figure 6). However, differences of one order of magnitude were predicted for insects largely due to varying ^{14}C approach used (Table 1) and assumed carbon content of biota. One explanation of the relatively large difference in assumed carbon content, besides choosing different reference organisms to represent species, is that it should be expressed on a fresh mass basis, and thus, assumption of water content influenced results.

3.3 Measured biota activity concentrations

When comparing predicted activity concentrations to measured values in biota, predictions between 3 times above or 3 times below the measured value may be considered good. In Steel Creek Swamp, 44% of the predictions were within the described range (Figure 4). The assessors under-predicted activity concentrations in arthropods by an order of magnitude depending upon the chosen reference organism. For example, the difference in CR_{wo} between mean arthropod and mean herbivorous arthropod in the TRS is a factor of 11. ERICA (CEH) parameterised both aphids and grasshoppers as herbivorous (lower CR_{wo}), the RESRAD-Biota application represented both groups by the overall mean arthropod, while the ERICA (SCK•CEN) and K-BIOTA applications parameterised aphids using the herbivorous CR_{wo} and grasshoppers using the overall mean arthropod value. The original data for arthropods at Steel Creek Swamp were reported on dry mass basis, so there were some uncertainties in the conversion to fresh mass.

For vertebrate species (frog, aquatic/terrestrial snake, and duck) in Steel Creek Swamp, predictions were in the same order of magnitude to measured values and 96% were within the described range (between 3:1 – 1:3; Figure 4). When estimating activity concentrations in duck, applications using partly a soil CR_{wo} and partly an aquatic CR_{wo} resulted in estimates deviating by only 20% from measured values. For vegetation, all modellers used CR_{wo}s for tree to represent alder, and all but the RESRAD-Biota application used the tree CR_{wo} for willow. This resulted in lower concentrations in alder and willow, compared to shrub species (mainly wax myrtle), which were modelled using a shrub CR_{wo}. Field data from Steel Creek Swamp, however, showed no differences between these three species (leaf samples), and the alder (*Alnus serrulata*) and willow (*Salix nigra*) species dominating the site were shrubs rather than trees.

For Utnora Swamp, for most organisms, predictions were up to two orders of magnitude higher than measured values and none were within the described range (3:1 – 1:3; Figure 5). Thus, less ^{137}Cs is taken up by organisms (spruce, fern, alder tree, forbs/sedges, moor frog) than predicted using biota dose models. The only exception was the ERICA (CEH) application that used a freshwater plant CR_{wo} as representative of forbs and sedges, which under-predicted the activity concentration by a factor of four. Possibly, this difference between predictions and measurements could be explained by the fact that ^{137}Cs has an affinity to sediment particles as exemplified by the partition coefficient, $K_{d,}$ of 2635 L kg^{-1} (defined below in section 3.5). It is likely that ^{137}Cs in Utnora Swamp is attached to particles from the upstream lake and transported by the outlet stream that floods the swamp. This has resulted in ^{137}Cs deposits located mainly in the top 10-cm of soil layers (Stark et al., 2006), possibly making it less bioavailable for deeper plant roots.

For Duke Swamp, 50% of predicted activity concentrations were within the described range (3:1 – 1:3; Figure 6). Average measured values differed by less than a factor of seven from predictions, except for insects. As was seen for Steel Creek for ^{137}Cs, predicted activity concentration of ^{14}C in insects were approximately one order of magnitude higher than measured data. For small plants, predictions were close to measured values. However, for trees, all predictions were consistently higher (up to a factor of 4) than measured data. Yankovich et al. (2013a) reports that previous studies observed an exponential decrease in ^{14}C specific activity concentrations in vegetation with height above ground at this site, possibly the consequence of activity concentrations in air reducing with height as $^{14}CO_2$ and $^{14}CH_3$ disperse with distance from the source (i.e. the ground surface). Air samplers providing input air concentrations were located at ground surface, so an over-prediction in trees is not surprising.

3.4 Internal dose rates

Internal dose rates are directly proportional to biota activity concentrations and to the dose conversion coefficient, with the latter in turn depending on organism composition and dimensions and the energies of the radioactive decays considered. As a result, the spread in predictions in Steel Creek and Utnora Swamps discussed above was also manifested in corresponding internal dose rates (Figure 7 and 8).

Estimated internal dose from ^{14}C to organisms in Duke Swamp (Figure 9) show the same pattern as activity concentrations with the largest variation for insects. K-Biota assumed 50% occupancy, and 50% feeding, in aquatic environment for frog, which resulted in higher predictions than for other model applications.

3.5 External dose rates

3.5.1 Assumption of occupancy factor

Assumptions of occupancy factor for wetland organisms greatly influenced predicted external dose rates. For Steel Creek Swamp, the most obvious difference between assessors was the dominance of external dose rate in the aquatic environment for tree frog and aquatic snake for the ERICA (SCK•CEN) application (Figure 7). This difference resulted from the assumption that frogs and snakes spend time in or on bottom sediment. The sediment activity concentration was estimated by means of the default sediment-to-water partition coefficient (K_d-value) given in the ERICA-Tool (Brown et al., 2008), which is defined as:

$$Kd\ (L \cdot kg^{-1}) = \frac{Activity\ concentration\ in\ sediment\ (Bq \cdot kg^{-1}\ dry\ mass)}{Activity\ concentration\ in\ water\ (Bq \cdot L^{-1})}$$

The estimated sediment activity concentration was approximately 30 times higher than measured values. This result highlights the importance of the occupancy factor assumptions, and that default K_d values may not replicate field conditions due to a range of site-specific factors.

Regarding external dose rates to terrestrial vegetation in Steel Creek and Utnora Swamp, the RESRAD-Biota application predicted consistently higher estimates (by a factor two to three) than other applications. A key difference between RESRAD-Biota and the ERICA Tool is that the former allows plants to be located above and below the soil surface (the assessor assumed 50% occupancy in soil), whereas terrestrial plant geometries in the ERICA Tool are assumed to be on the soil surface. This likely explains most of the difference in external dose rates between the two models.

The ERICA (CEH) application that chose an aquatic vascular plant for forbs/sedges, predicted external dose rates within the range of predictions by other applications, despite different assumptions on location (Figure 8). Results from the ERICA Tool were inconsistent with those generated using other approaches, in that it models aquatic vascular plant as being 50% in and 50% above sediment, whereas terrestrial plants are modeled on the soil surface.

Carbon-14 range in tissues is very short and the dose to biota is dominated by internal dose. This means that any assumptions of occupancy within a given environment have little impact on the results.

3.5.2 Soil saturation assumptions

Another influential parameter for external dose rates in terrestrial parts of the wetland was assumptions used for soil moisture. For Steel Creek Swamp, the ERICA (ANSTO) application, and for Utnora Swamp the ERICA (eriss/ARPANSA), (ANSTO), and (CEH) applications, estimated external dose rates 10% of those predicted using other applications. These results are explained by use of the option in the ERICA Tool to define soil/sediment dry matter percentage. External dose rates are calculated by the ERICA Tool in a manner intended to be representative of exposure conditions in the field. However, soil concentration data are usually given on a dry mass basis which, for wetland soils, can be very different than field conditions. By specifying a dry matter percentage, the ERICA Tool back-calculates the fresh mass soil concentration from dry mass concentrations that are required input. The default, conservative value of dry matter percentage in the ERICA Tool is 100%, but it might be appropriate to enter lower values if *in situ* dry matter percentage is known at the site. In this scenario, a 10% soil dry matter percentage was given for Duke Swamp and was used in ERICA (ANSTO) for all wetland soils. The resulting external dose rates were a factor of ten lower than they would have been if the option to define dry matter percentage was not used. This is because in the ERICA Tool, external dose rates decreased corresponding to entered percentage.

The importance of using the dry matter percentage functionality in ERICA Tool is particularly well illustrated in our wetland scenario, where dry matter percentage is likely to be low. It highlights that input of site-specific soil dry matter percentage is either not available in some codes, or is typically not used by most practitioners. While the adjustment is easily made using the ERICA Tool, it could also be achieved using other models by making separate model runs for internal and external dose rates, using different soil activity concentrations. Code developers could improve dose estimation for wetlands by adding required functionality and clarifying instructions to users. Assessors should be aware of the DCCs being defined on a fresh soil mass basis and justify whether soil activity concentrations should be adjusted to reflect this, or if the input should be on a dry mass basis.

3.5.3 Predicted and measured external dose rates to Moor frog

For Moor frog in Utnora Swamp, predicted external dose rates varied by a factor of 10. As for other organisms, the largest difference in predictions was due to assumptions of dry matter percentage for soil. Also, some differences were due to choices of occupancy. It is evident that all models produce similar predictions for an occupancy of 100% in soil (Figure 10; but only if all modellers used the same dry matter percentage for soil). Surprisingly, in contrast to tree frog in Steel Creek Swamp, external doses from sediments is not dominating in the ERICA (SCK•CEN) application, despite an assumed occupancy of 25% in sediment. The explanation for this is that sediment concentration was derived from water concentration through a K_d value for marine ecosystems because the swamp was interpreted as being influenced by the Baltic Sea. However, in Utnora Swamp this is unlikely because a thick reed belt separates the swamp from the sea and the swamp is flooded by a freshwater stream coming from an upstream lake. An estimate based on a freshwater K_d value would have resulted in a two orders of magnitude higher sediment concentration. Estimates of external dose rate to Moor frog from a study using phantoms and thermoluminescent dosimeters (TLDs) (Stark and Pettersson, 2008) were available for comparison with predictions. Dose rate estimates from ERICA (eriss/ARPANSA) and ERICA (ANSTO), assuming 10% soil dry matter percentage, were similar to measured values (Figure 10). Soil dry matter percentage varied between 20% and 50% (Stark and Pettersson, 2008), although this information was not provided to participants. A third assessor, ERICA (CEH), estimated dose rates to Moor frog assuming 10% dry matter percentage in soil (for minimum dose) and up to 100% dry matter percentage in soil (for maximum dose), resulting in a large range. The assessors using the RESRAD-Biota and K-BIOTA models both assumed a 100% dry matter percentage in soil and predicted ranges that were approximately an order of magnitude higher than measured values.

3.6 General aspects

The models included in this exercise all consider terrestrial and freshwater ecosystems but only RESRAD-Biota, through the possibility to model riparian animals (USDoE, 2004), includes the capacity to directly assess vertebrate wetland organisms. This functionality of RESRAD-Biota was not used by any modeller in this exercise.

As the allometric relationships presented in RESRAD-Biota are for mammals and birds, they are not applicable to the majority of vertebrates (reptiles and amphibians) considered in this study (Beresford and Vives i Batlle, 2013). For the purpose of comparison, we used the allometric relationships to make predictions for duck at Steel Creek Swamp under different assumptions of diet. We defined an organism approximating to a mallard duck (*Anas platyrynchos*) assuming: a default geometry of 4 (which is defined as a 1 kg organism); a soil geometry factor of 0.25 (representing 50% occupancy on soil for a 2π exposure geometry); a water geometry factor of 0.25; an area factor of 1 (which assumes 100% of time is spent in the assessment area); and a dry matter food intake of 72 g d^{-1} for generic birds of 1 kg live-mass (Nagy, 2001).

The geometric mean $CR_{wo\text{-}media}$ from IAEA (2014) was used to provide best estimate (Wood et al., 2013). Assuming a 100% aquatic plant diet, RESRAD-Biota predicted an activity concentration of 110 Bq kg^{-1} (FM) and total dose rate of 0.27 µGy h^{-1}. If a diet of terrestrial plants was assumed, an activity concentration of 4070 Bq kg^{-1} (FM) and dose rate of 0.97 µGy h^{-1} were estimated. Accepting that mallards are omnivorous, a diet comprising 20% aquatic benthic invertebrates, 30% aquatic plants and 50% terrestrial plants resulted in activity concentration of 2430 Bq kg^{-1}, with a dose rate of 0.68 µGy h^{-1}. Again these results highlight the importance of assumed food source for wetland organisms. Assuming a diet of 100% aquatic plants resulted in an under-estimation of uptake by one order of magnitude, while a mixture of terrestrial and aquatic food produced predictions close to measurements (Figure 4).

To assess the risk for each contaminated wetland is beyond the scope of this study but for the purpose of comparison to a screening value of 10 µGy h^{-1}, below which ecosystems are to be protected (Howard et al., 2010), all but one predicted dose in Steel Creek Swamp exceeded 10 μGy h^{-1}. For Utnora Swamp three predicted doses were above 10 μGy h^{-1}, while measurements showed that actual levels were up to two orders of magnitude lower. For Duke Swamp all predicted doses were well below the screening value.

4. Conclusions

This study highlights effects of the many aspects to consider when assessing wetlands, in particular the influence of water. To make a site-specific assessment, knowledge of seasonal water level is required, as well as habitat use and occupancy patterns of organisms during the year. Current biota dose models are not explicitly formulated for wetland conditions. Rather, doses to biota in wetlands must be estimated using terrestrial and aquatic parameters. In this respect, our scenario was well-suited to bring to light effects of different methodological assumptions. In general, using terrestrial parameters can provide acceptable and conservative predictions for wetland organisms. However, for some organisms, such as duck, a combination of terrestrial and aquatic food sources may give better predictions. Predicted biota activity concentrations and external and internal dose rates were in general within the same order of magnitude but occasionally varied up to three orders of magnitude between participants. In contrast to previous inter-comparison studies where results varied most with transfer, different choices of reference organisms and occupancy factors for wetland species resulted in largest differences in predictions (in part, because all assessors used one of two concentration ratio (CR) datasets). In addition, assumptions of food sources (terrestrial or aquatic) influenced choices of CR value. The dry matter percentage in soil influenced external doses by an order of magnitude and we recommend that soil saturation is explicitly taken into account. Also, predicted uptake of ^{137}Cs and ^{14}C in arthropods differed by an order of magnitude in comparison to measurements and we recognise a need for more field data to improve predictions.

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Table 1

Model names, and origin of model parameters used in this wetland scenario exercise.

Name of approach in this chapter	Model	Origin of transfer parameters	Origin of organism dimensions	C-14 approach
ERICA (eriss/ARPANSA)	ERICA Tool	Model default[1]	Model default	Specific activity approach
ERICA (ANSTO)	ERICA Tool	Model default	Mainly model default but also two new organism sizes from expert judgement or own data	ERICA default $CR_{wo\text{-}air}$
ERICA (CEH)	ERICA Tool	Mainly draft TRS but also ICRP derived CR for duck	Model default	Specific activity approach
ERICA (SCK•CEN)	ERICA Tool	Draft TRS	Mainly model default, but also some new organism sizes from expert judgement or own data	Specific activity approach
RESRAD	RESRAD-Biota	Draft TRS	Chosen from a set of model default organism sizes.	Specific activity approach
K-BIOTA	K-Biota	Draft TRS	Mainly from expert judgement but also ARKiv and ICRP 108	Specific activity approach

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[1] model default implying that an organism already defined in the model was used to represent the species in the scenario. Different modellers did however choose different default organisms to represent the same species.

Table 2

Input data given for a wetland assessment exercise. Mean values (minimum and maximum values within brackets) of environmental media activity concentrations measured in three wetlands; Steel Creek, Utnora, and Duke Swamp.

	^{137}Cs (Bq/kg d.w. or Bq/l)	^{14}C (Bq/kg)	^{14}C (Bq/g C)	References
Steel Creek				
soil	3500 (210-19000)	-	-	Brisbin et al., 1974a
water	0.81	-	-	RAC, 2001 – appendix K
Utnora				Stark et al., 2006; Stark, unpublished data
soil	30000 (12000-74000)	-	-	
water	0.2	-	-	
Duke				Yankovich et al 2014 ; Yankovich et al 2013a; Yankovich et al 2008a and 2008b
soil	-	7600 (310-27000)	14 (0.56-50)	
air	-	-	15 (1.1-38)	

Table 3

Summary of organisms included in the scenario (Anderson et al., 1973; Brisbin et al., 1974b; Dapson and Kaplan, 1975; RAC, 2001- Chapter 11; Stark et al., 2004; Stark unpublished data; Yankovich et al., 2013a)

Wetland	**Vegetation**	**Animal**
Steel Creek Swamp	Grasses (*Scirpus sp., Juncus sp.*), Sedges (*Andropogon sp.*), Alder tree (*Alnus serrulata*) Shrubs (*Myrica cerifera*), Willows (*Salix nigra*).	Green tree frog (*Hyla cinerea*), Aquatic snakes, Terrestrial snakes, Ducks (e.g. *Anas platyrynchos*), Spiders (Order Aranae), Beetles (Order Coleoptera), Aphids, Leafhoppers (Order Homoptera), Cicadas, Grasshoppers, Crickets (Order Orthoptera)
Utnora Swamp	Spruce (*Picea abies*), Alder tree (*Alnus glutinosa*), Fern (*Matteuccia struthiopteris*), Forbs (*Filipendula ulmaria, Urtica dioica, Scirpus sylvaticus, Lysimachia thyrsifolia*), Sedges (*Carex* sp.)	Moor frog (*Rana arvalis*)
Duke Swamp	Peat moss (*Sphagnum sp.*), Grass (e.g. *Calamagrostis sp.*), Forbs, Ferns (e.g. *Thelypteris palustris*), Cedar (*Thuja sp.*), Balsam fir (*Abies balsamea*)	Aerial insects, including deer flies (*Chrysops* spp.), horse flies (*Tabanus* spp.), other types of flies (Order Diptera), wasps (Order Hymenoptera) and moths (Order Lepidoptera), Carrion beetles (Family *Silphidae*), American bullfrog (*Rana catesbeiana*), Green frogs (*Rana clamitans*), Northern leopard frog (*Rana pipens*), Mink frog (*Rana septentrionalis*), Grey treefrog (*Hyla versicolor*), American toad (*Bufo americanus*), Common garter snake (*Thamnophis sirtalis*), Deer mice (*Peromyscus maniculatus*), Meadow vole (Microtus pennsylvanicus), Northern short-tailed shrew (*Blarina brevicauda*), White-footed mouse (*Peromyscus leucopus*)

Table 4

Concentration ratios for organism in Steel creek and Utnora Swamp as assumed by the different participants. Model applications abbreviated as e: ERICA (eriss/ARPANSA), A: ERICA (ANSTO), C: ERICA (CEH), S: ERICA (SCK•CEN), R: (RESRAD) and K: K-Biota.

	Terrestrial concentration ratio						Aquatic concentration ratio					
	e	A	C	S	R	K	e	A	C	S	R	K
Steel Creek												
Grasses, sedges	6.93E-01	6.93E-01	1.20E+00	1.20E+00	1.20E+00	1.80E+00						
Alder tree	1.63E-01	1.63E-01	1.40E-01	1.40E-01	1.40E-01	1.40E-01						
Shrubs	3.97E+00	3.97E+00	2.30E+00	2.30E+00	2.30E+00	2.30E+00						
Willows etc	1.63E-01	1.63E-01	1.40E-01	1.40E-01	2.30E+00	1.40E-01						
Green treefrog	5.37E-01	5.37E-01	4.40E-01	4.40E-01	4.40E-01	4.40E-01				3.10E+03		3.00E+03
Aquatic snakes		5.37E-01	5.20E-01	5.20E-01	5.80E-01	5.20E-01	9.30E+03	9.30E+03	4.00E+03	4.00E+03		4.00E+03
Terrestrial snakes	3.59E+00	3.59E+00	5.20E-01	5.20E-01	5.80E-01	5.20E-01						
Ducks (ringneck, mallard)	7.50E-01	7.50E-01		5.70E-01	6.70E-01	5.70E-01	3.00E+03		4.40E+02	4.00E+03		2.00E+03
Spiders	5.51E-02	5.51E-02	3.00E-02	3.00E-02	3.00E-02	3.00E-02						
Beetles	5.51E-02	1.34E-01	1.10E-01	9.00E-02	1.10E-01	2.50E-01						
Aphids, leafhoppers, cicadas	5.51E-02	5.51E-02	9.80E-03	9.80E-03	1.10E-01	9.80E-03						
Grasshoppers, crickets	5.51E-02	1.34E-01	9.80E-03	1.10E-01	1.10E-01	1.10E-01						
Utnora												
Spruce	1.63E-01	1.63E-01	1.50E-01	1.50E-01	1.40E-01	1.40E-01						
Fern	6.93E-01	3.97E+00	1.20E+00	1.20E+00	1.20E+00	1.10E+00						
Alder tree	1.63E-01	1.63E-01	1.40E-01	1.40E-01	1.40E-01	1.40E-01						
Forbs, sedges	6.93E-01	6.93E-01		1.20E+00	1.20E+00	1.10E+00			3.12E+02			
Moor frog	5.37E-01	5.37E-01	4.40E-01	4.40E-01	4.40E-01	4.40E-01				8.40E+01		3.00E+03

Table 5

Occupancy factors for organism in Steel creek and Utnora Swamp as assumed by the different participants. Model applications abbreviated as e: ERICA (eriss/ARPANSA), A: ERICA (ANSTO), C: ERICA (CEH), S: ERICA (SCK•CEN), R: (RESRAD) and K: K-Biota.

	In air						On soil						In soil						On water						In water						On sediment						In sediment					
	e	A	C	S	R	K	E	A	C	S	R	K	e	A	C	S	R	K	e	A	C	S	R	K	e	A	C	S	R	K	e	A	C	S	R	K	e	A	C	S	R	K
Steel Creek																																										
Grasses, sedges							1	1	1	0.75	0.5	1				0.25	0.5																									
Alder tree							1	1	1	0.75	0.5	1				0.25	0.5																									
Shrubs							1	1	1	0.75	0.5	1				0.25	0.5																									
Willows etc							1	1	1	0.75	0.5	1				0.25	0.5																									
Green treefrog	1							1	0.95	0.25		0.5					0.5						0.5				0.05	0.25		0.5										0.5		
Aquatic snakes								0.5	0.75	0.25	0.3	0.5					0.2		0.5		0.25		0.5		0.5	0.5		0.25		0.5				0.5								
Terrestrial snakes							1	1	1	1	0.3	1					0.6						0.1																			
Ducks (ringneck, mallard)	0.25						0.5	1	0.5	0.5		0.75					0.5		0.25		0.5	0.5							0.5	0.25												
Spiders	0.5	0.5					0.5	0.5	1	1							1																									
Beetles							1		1							1	1																									
Aphids, leafhoppers, cicadas	1								1							1	1																									
Grasshoppers, crickets	0.5			0.5			0.5		1	0.5							1																									
Utnora																																										
Spruce							1	1	1	0.75	0.5					0.25	0.5																									
Fern							1	1	1	0.75	0.5					0.25	0.5																									
Alder tree							1	1	1	0.75	0.5					0.25	0.5																									
Forbs, sedges							1	1		0.75	0.5					0.25	0.5																1									
Moor frog							0.66	1	0.95	0.5	0.3	0.5	0.34				0.5						0.2				0.05	0.25		0.5										0.25		

Figures captions

Fig. 1. Location of Steel Creek on the Savannah River Site in South Carolina (Brisbin et al.,1974a); the soil sampling transects are represented by the three lines with letter.

Fig. 2. The Utnora Swamp in Sweden. Grey areas indicate wetland areas. Samples included in this scenario are taken in areas indicated by the letters A and B, next to Verkmyra Stream (Stark et al., 2006).

Fig. 3. Duke Swamp with sampling points indicated by sample ID (Yankovich et al., 2008a). The sampling points that are included in this exercise are marked with an ellipse.

Fig. 4. Mean measured and predicted biota whole organism activity concentrations of ^{137}Cs in Steel Creek Swamp (Anderson et al., 1973; Brisbin et al., 1974b; Dapson and Kaplan, 1975; RAC, 2001- Chapter 11). Organisms included from left to right: treefrog, alder tree, duck, aphids and cicadas, shrub, willow, aquatic/terrestrial snake, spider, beetles, grasshoppers and crickets, and grasses. A range with 3 times above (3:1) and 3 times below (1:3) the mean measured values is indicated.

Fig. 5. Mean measured and predicted biota whole organism activity concentrations of ^{137}Cs in Utnora Swamp (Stark et al., 2004; Stark unpublished data). Organisms included from left to right: spruce, alder tree, forbs and sedges, fern, and frog. A range with 3 times above (3:1) and 3 times below (1:3) the mean measured values is indicated.

Fig. 6. Mean measured and predicted whole biota activity concentrations of ^{14}C in Duke Swamp (Yankovich et al., 2013a). Organisms included from left to right: insect, rodent, frog, tree, small plant, and snake. A range with 3 times above (3:1) and 3 times below (1:3) the mean measured values is indicated.

Fig. 7. Estimated internal and external radiation dose rates (µGy/h) from ^{137}Cs to organisms in Steel Creek Swamp.

Fig. 8. Estimated internal and external radiation dose rates (µGy/h) from ^{137}Cs to organisms in Utnora Swamp.

Fig. 9. Estimated external and internal radiation dose rates (µGy/h) from ^{14}C to organisms in Duke Swamp.

Fig. 10. Estimated and measured external radiation dose rates (µGy/h) from ^{137}Cs to moor frog in Utnora Swamp assuming 100% occupancy in soil. Measurements were done using frog phantoms (Stark and Pettersson, 2008). Bars are representing the range (min-max) and the points are representing mean values.

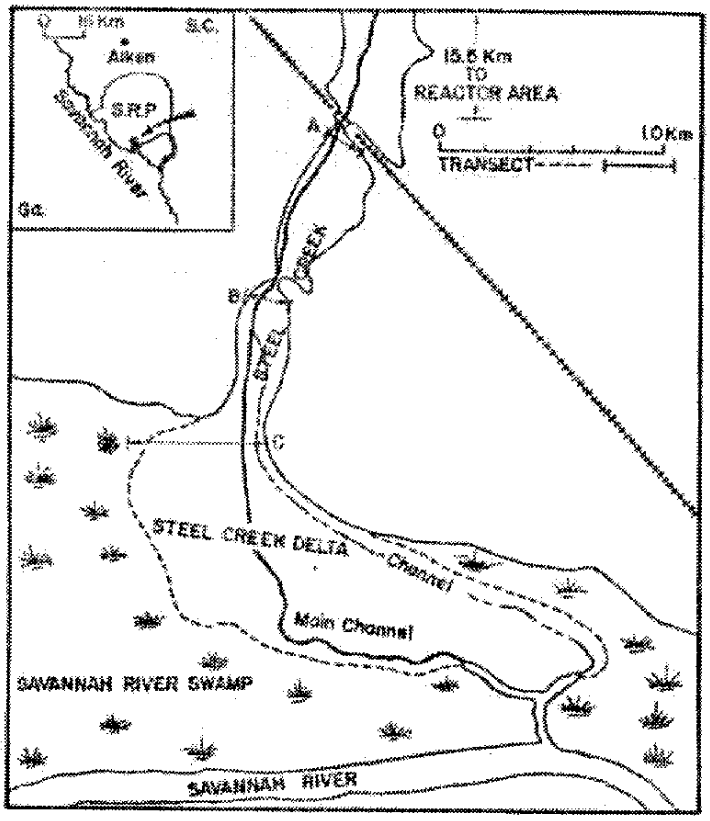

0
16 Km
S.C.
Aiken
S.R.P
Savannah River
Ga.
15.5 Km
TO
REACTOR AREA
0
1.0 Km
TRANSECT
A
CREEK
B
STEEL
C
STEEL CREEK DELTA
Channel
Main Channel
SAVANNAH RIVER SWAMP
SAVANNAH RIVER

Figure 1.

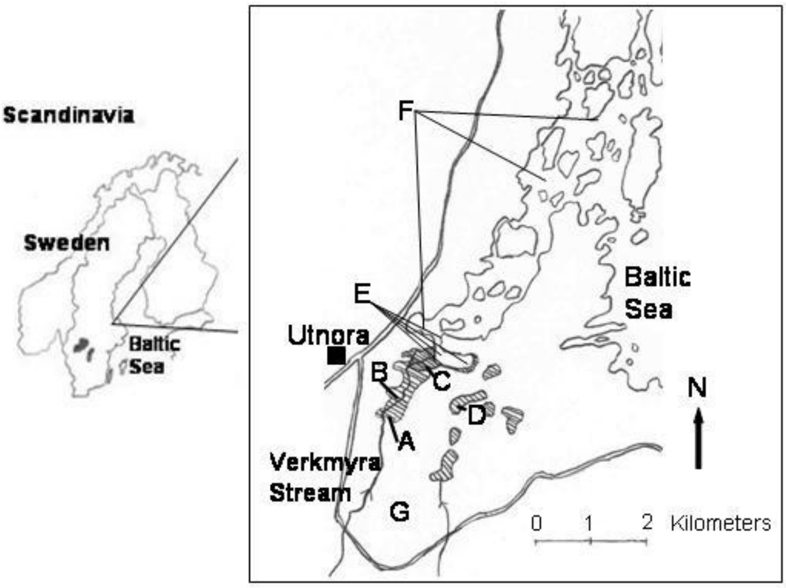

Scandinavia
Sweden
Baltic Sea
F
E
Utnora
B
C
D
A
Verkmyra Stream
G
Baltic Sea
N
0 1 2 Kilometers

Figure 2.

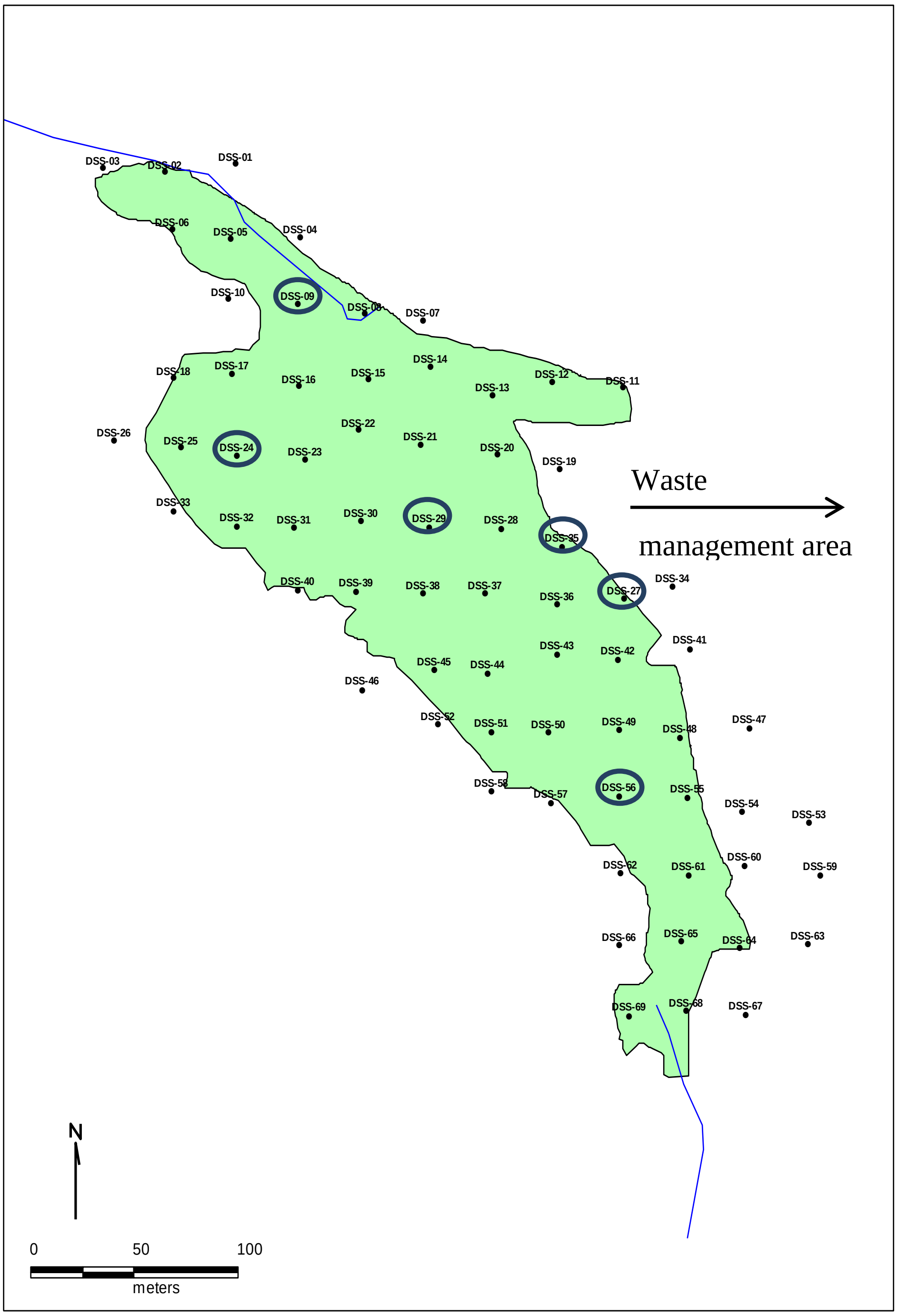

DSS-03
DSS-02
DSS-01
DSS-06
DSS-05
DSS-04
DSS-10
DSS-09
DSS-08
DSS-07
DSS-14
DSS-18
DSS-17
DSS-16
DSS-15
DSS-12
DSS-11
DSS-13
DSS-22
DSS-26
DSS-25
DSS-24
DSS-23
DSS-21
DSS-20
DSS-19
Waste management area
DSS-33
DSS-32
DSS-31
DSS-30
DSS-29
DSS-28
DSS-35
DSS-40
DSS-39
DSS-38
DSS-37
DSS-36
DSS-27
DSS-34
DSS-41
DSS-43
DSS-42
DSS-45
DSS-44
DSS-46
DSS-52
DSS-51
DSS-50
DSS-49
DSS-48
DSS-47
DSS-58
DSS-57
DSS-56
DSS-55
DSS-54
DSS-53
DSS-62
DSS-61
DSS-60
DSS-59
DSS-66
DSS-65
DSS-64
DSS-63
DSS-69
DSS-68
DSS-67
N
0
50
100
meters

Figure 3.

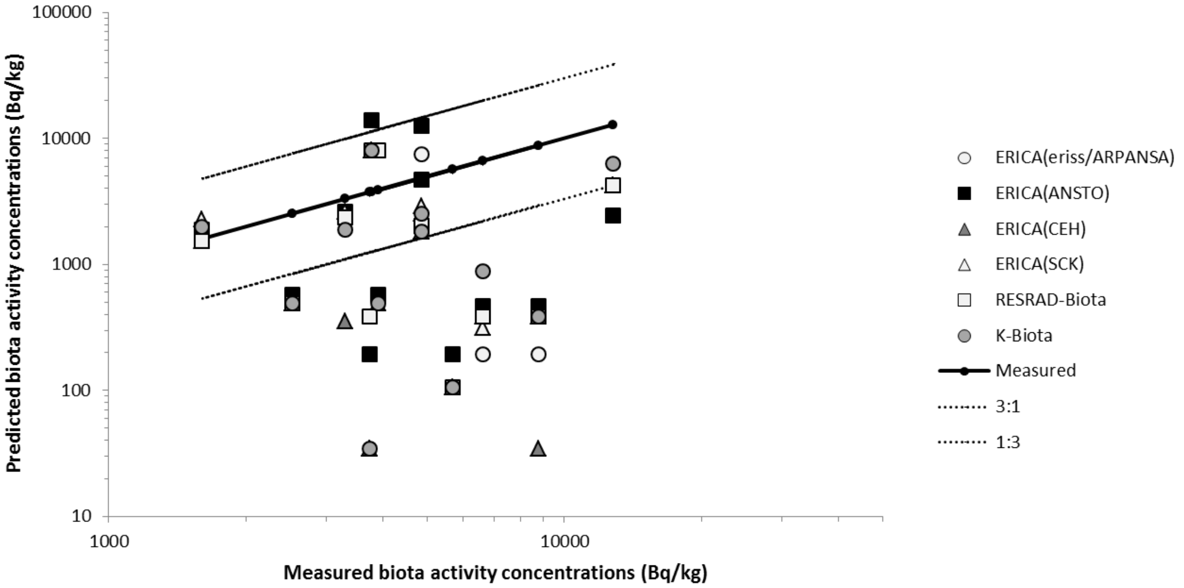
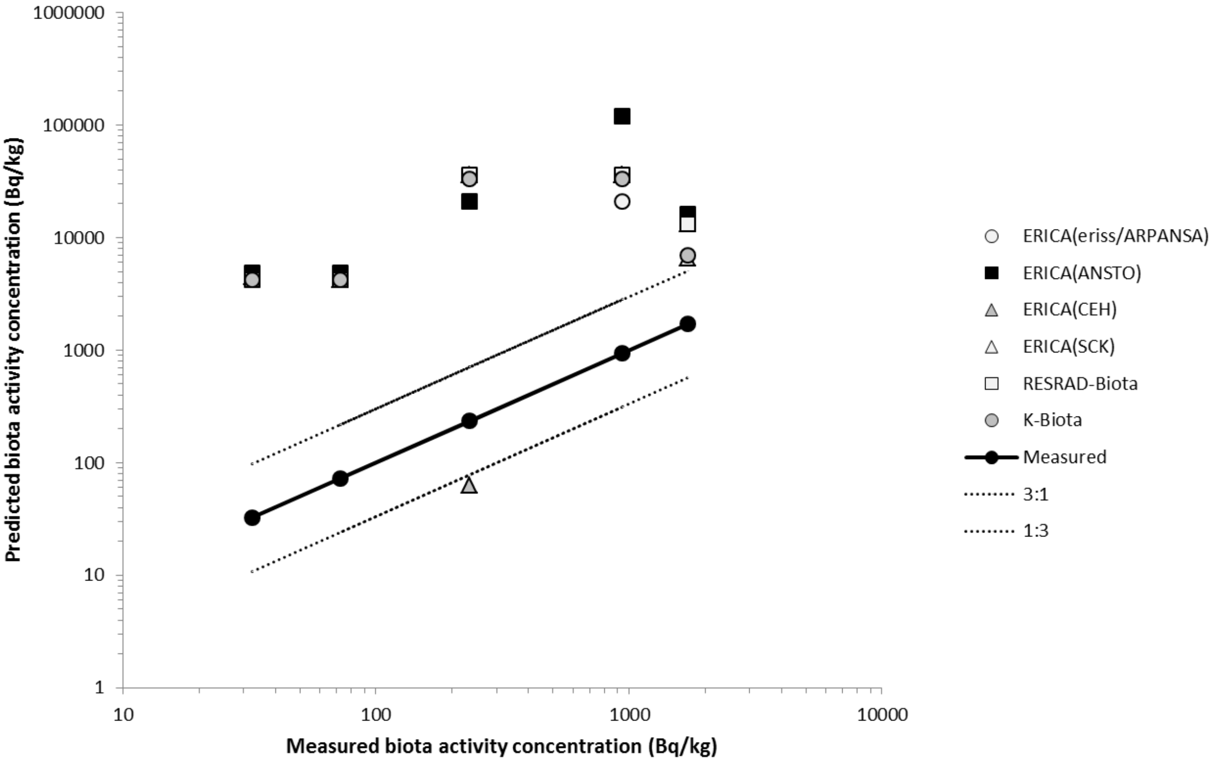

100000
10000
1000
100
10
1000
10000
Predicted biota activity concentrations (Bq/kg)
Measured biota activity concentrations (Bq/kg)
ERICA(eriss/ARPANSA)
ERICA(ANSTO)
ERICA(CEH)
ERICA(SCK)
RESRAD-Biota
K-Biota
Measured
3:1
1:3

Figure 4.



Predicted biota activity concentration (Bq/kg)
1000000
100000
10000
1000
100
10
1
10
100
1000
10000
Measured biota activity concentration (Bq/kg)
○ ERICA(eriss/ARPANSA)
■ ERICA(ANSTO)
▲ ERICA(CEH)
△ ERICA(SCK)
□ RESRAD-Biota
● K-Biota
Measured
3:1
1:3

Figure 5.

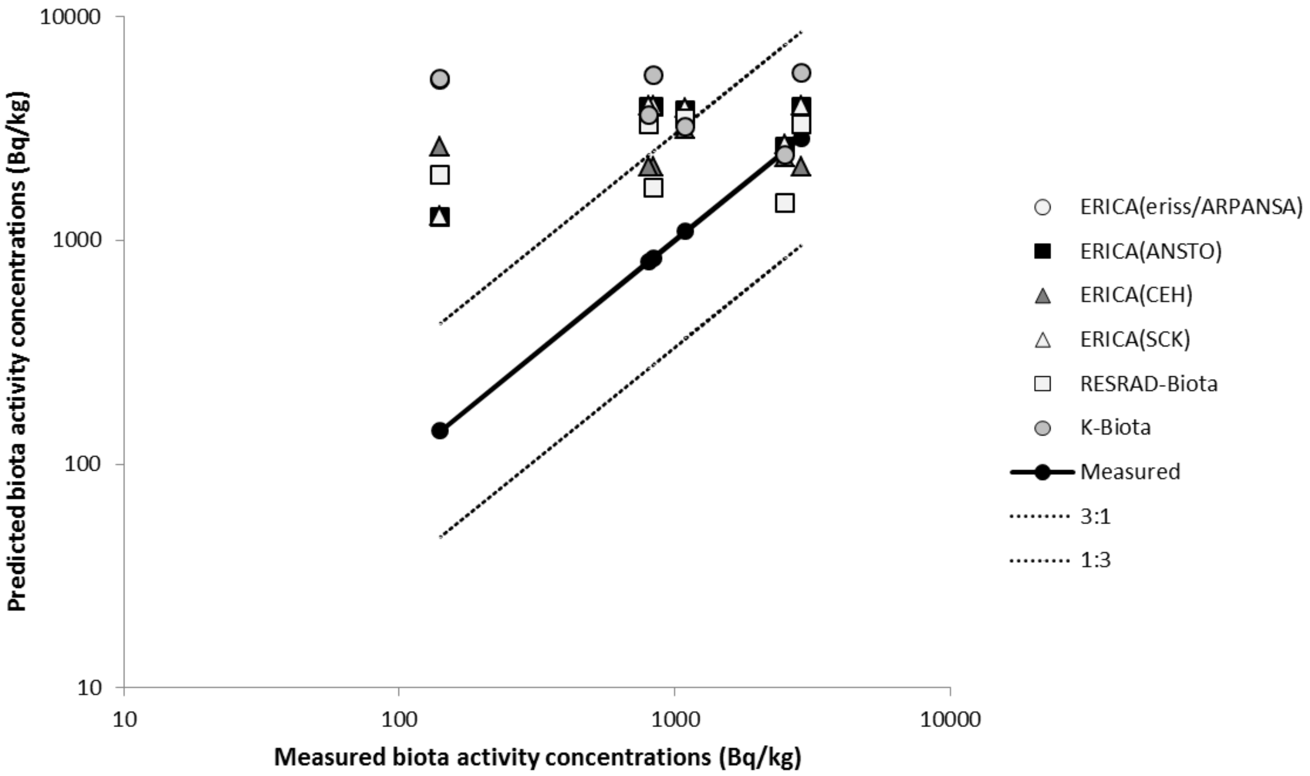

Predicted biota activity concentrations (Bq/kg)
10000
1000
100
10
10
100
1000
10000
Measured biota activity concentrations (Bq/kg)
ERICA(eriss/ARPANSA)
ERICA(ANSTO)
ERICA(CEH)
ERICA(SCK)
RESRAD-Biota
K-Biota
Measured
3:1
1:3

Figure 6.

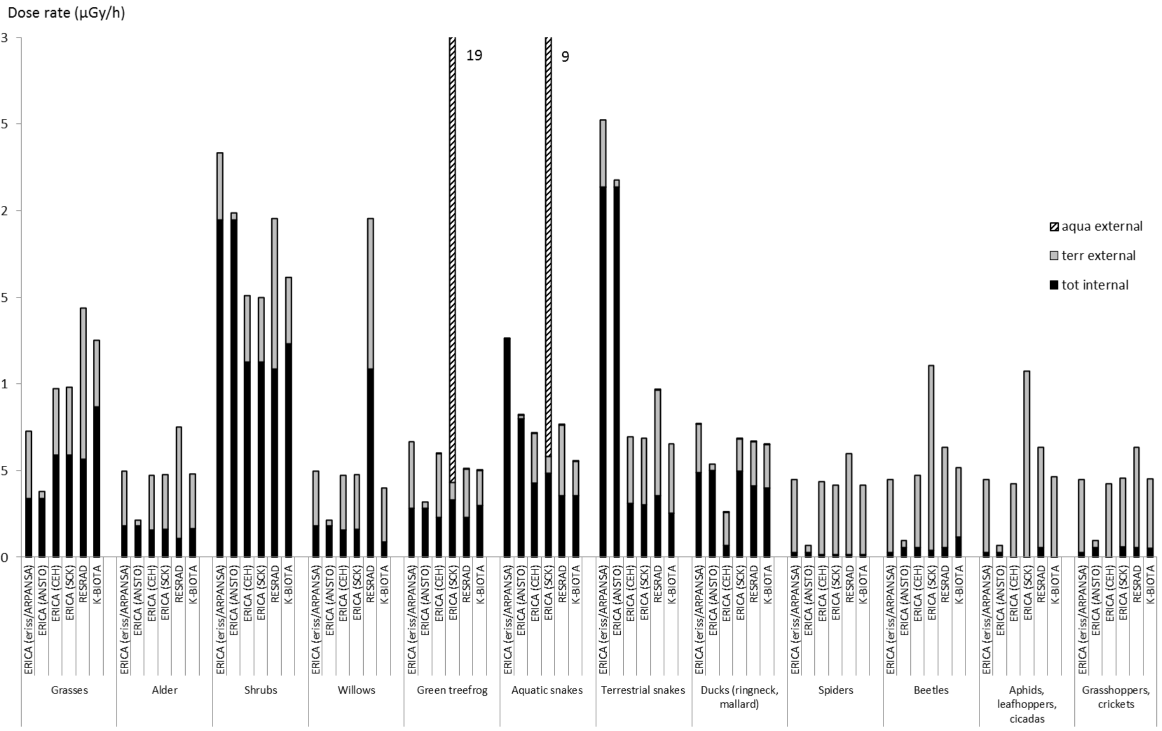

Dose rate (µGy/h)
3
2,5
2
1,5
1
0,5
0
19
9
aqua external
terr external
tot internal
ERICA (eriss/ARPANSA)
ERICA (ANSTO)
ERICA (CEH)
ERICA (SCK)
RESRAD
K-BIOTA
Grasses
Alder
Shrubs
Willows
Green treefrog
Aquatic snakes
Terrestrial snakes
Ducks (ringneck, mallard)
Spiders
Beetles
Aphids, leafhoppers, cicadas
Grasshoppers, crickets

Figure 7.

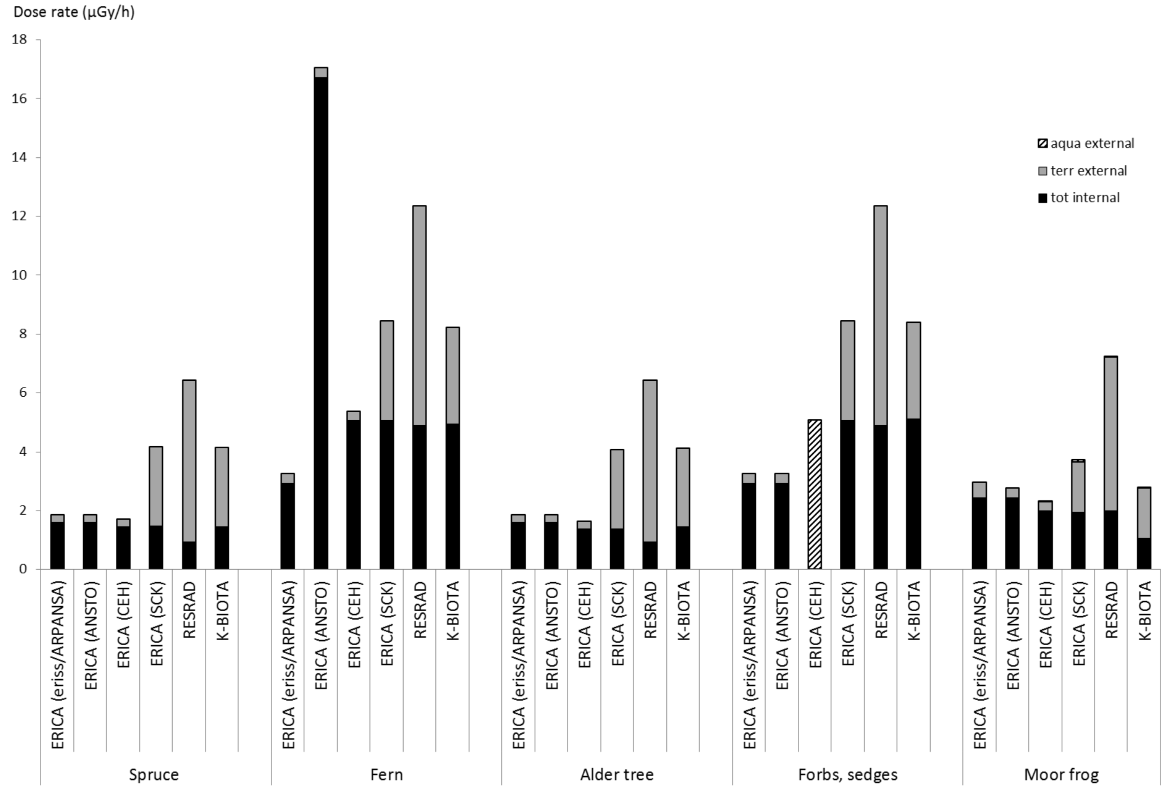

Dose rate (µGy/h)
0
2
4
6
8
10
12
14
16
18
aqua external
terr external
tot internal
ERICA (eriss/ARPANSA)
ERICA (ANSTO)
ERICA (CEH)
ERICA (SCK)
RESRAD
K-BIOTA
Spruce
Fern
Alder tree
Forbs, sedges
Moor frog

Figure 8.

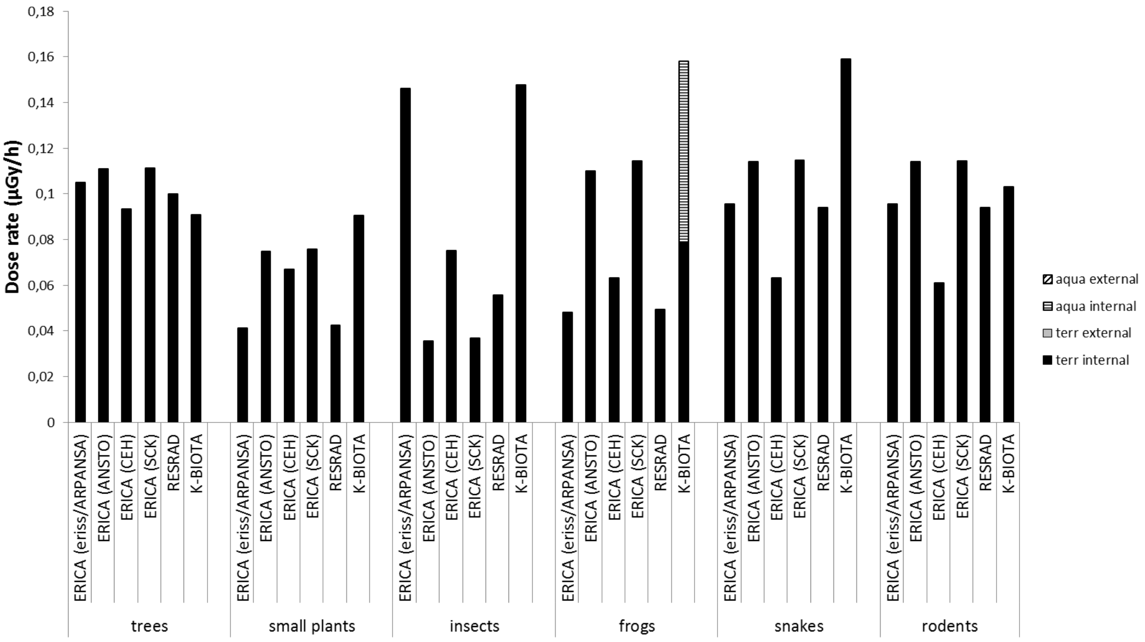

0,18
0,16
0,14
0,12
0,1
0,08
0,06
0,04
0,02
0
Dose rate (µGy/h)
aqua external
aqua internal
terr external
terr internal
ERICA (eriss/ARPANSA)
ERICA (ANSTO)
ERICA (CEH)
ERICA (SCK)
RESRAD
K-BIOTA
trees
ERICA (eriss/ARPANSA)
ERICA (ANSTO)
ERICA (CEH)
ERICA (SCK)
RESRAD
K-BIOTA
small plants
ERICA (eriss/ARPANSA)
ERICA (ANSTO)
ERICA (CEH)
ERICA (SCK)
RESRAD
K-BIOTA
insects
ERICA (eriss/ARPANSA)
ERICA (ANSTO)
ERICA (CEH)
ERICA (SCK)
RESRAD
K-BIOTA
frogs
ERICA (eriss/ARPANSA)
ERICA (ANSTO)
ERICA (CEH)
ERICA (SCK)
RESRAD
K-BIOTA
snakes
ERICA (eriss/ARPANSA)
ERICA (ANSTO)
ERICA (CEH)
ERICA (SCK)
RESRAD
K-BIOTA
rodents

Figure 9.

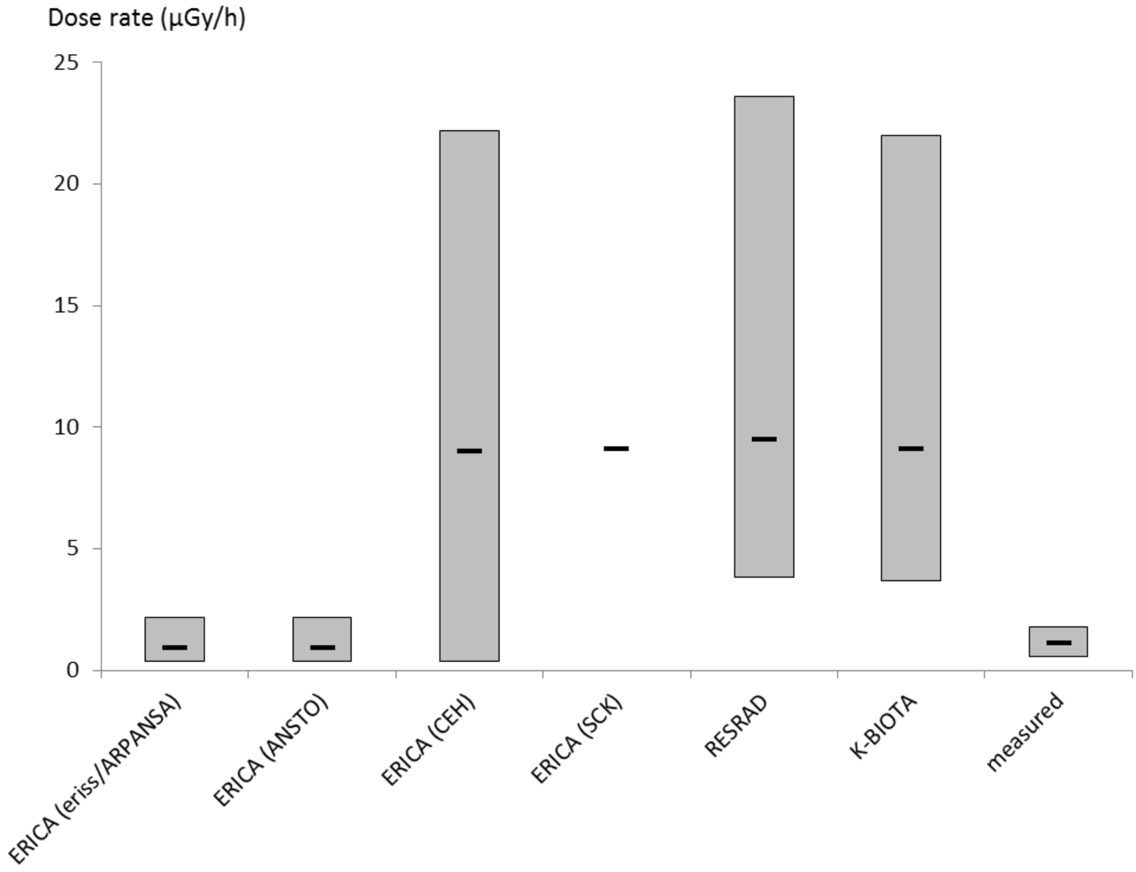

Dose rate (µGy/h)
25
20
15
10
5
0
ERICA (eriss/ARPANSA)
ERICA (ANSTO)
ERICA (CEH)
ERICA (SCK)
RESRAD
K-BIOTA
measured

Figure 10.