

Article (refereed) - postprint

Stark, K.; Andersson, P.; Beresford, N.A.; Yankovich, T.L.; Wood, M.D.; Johansen, M.P.; Vives i Battle, J.; Twining, J.; Keum, D.-K.; Bollhofer, A.; Doering, C.; Ryan, B.; Grzechnik, M.; Vandenhove, H.. 2015. **Predicting exposure of wildlife in radionuclide contaminated wetland ecosystems.** *Environmental Pollution*, 196. 201-213.
<https://doi.org/10.1016/j.envpol.2014.10.012>

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<https://doi.org/10.1016/j.envpol.2014.10.012>

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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, ¹³⁷Cesium, ¹⁴Carbon

Capsule: Terrestrial parameters provide acceptable predictions for wetland organisms

1 **1. Introduction**

2 With a renewed interest in nuclear power in many countries (Marcus, 2008; Joskow and
3 Parsons, 2012) and with the recognition by the International Commission on Radiological
4 Protection (ICRP) for an explicit consideration of radiological protection of the environment
5 (ICRP, 2007; 2009), robust methods for assessing radiation doses and effects to wildlife are
6 becoming increasingly important. This challenging task has been addressed by radioecologists
7 by the development of a number of biota dose estimation models (see Vives i Batlle et al.,
8 2011; Beresford et al., 2009) that can be used in environmental risk assessments such as the
9 ERICA Tool (Brown et al., 2008) and RESRAD-Biota (USDoE, 2004) which are freely
10 available software. However, these models are in need of validation.

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

23 In general, current biota dose models consider three generic ecosystem types:
24 terrestrial, freshwater, and marine. Available models do not consider wetlands explicitly,
25 although, RESRAD-Biota does include an option to assess riparian animals. However, such

26 ecosystems require assessment, as numerous wetlands are protected under the RAMSAR
27 convention (Mitsch and Gosselink, 2000), support high biodiversity, and data show that some
28 are contaminated with radionuclides (see below).

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

38 This study focused on swamps in temperate/sub-tropical regions, which often
39 are wetlands that can be nutrient sinks, filtering particles from temporarily inflowing water.
40 Many radionuclides have an affinity to sediment particles and these types of wetlands may,
41 therefore, accumulate and function as sinks for such radionuclides (e.g., Walling and Bradley,
42 1988; Burrough et al., 1999; Kaplan et al., 2014).

43 The objective of this study was to investigate how current models for wildlife
44 radiation dose assessments can be applied to radionuclide contaminants (particularly ^{137}Cs and
45 ^{14}C) in wetlands. Here we report results of a model-to-model inter-comparison exercise
46 considering three wetlands. We focused on differences between how exercise participants,
47 representing ‘informed users’ and model developers (Wood et al., 2009), approached a
48 wetland scenario, to evaluate differences in predictions between different model applications
49 used to run the scenario.

50

51 **2. Methods**

52 *2.1 Biota dose models and participants*

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

63 *2.2 Description of the wetland areas*

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

68 *2.2.1 Steel Creek Swamp*

69 Steel Creek, a 20 km long creek, drains a 290 km² watershed (Figure 1) situated on the US
70 Department of Energy Savannah River Site in South Carolina, USA (N33°06'50'',
71 W81°37'50''). The creek received cooling water from nuclear reactors between 1954 and
72 1974 (Paller et al., 2008). A floodplain borders the main channel and the creek is shallow (<
73 1m) and 3 - 5 m wide. Soil was sampled down to a depth of 1 meter along three transects
74 perpendicular to the creek (Figure 1) and ¹³⁷Cs activity concentrations are available (Brisbin
75 et al, 1974a). Most of the activity was in the top 10-cm of profiles. In addition, water,

76 vegetation, amphibians, reptiles, and invertebrates activity concentrations were available
77 (RAC, 2001; Brisbin et al., 1974b; Anderson et al., 1973; Dapson and Kaplan, 1975; Table 3).

78 2.2.2 *Utnora Swamp*

79 Utnora Swamp (Figure 2) is a 0.024 km² riparian swamp next to Verkmyra Stream, which
80 flows out of Hille Lake, in the central-eastern part of Sweden (N60°46'20'', E17°16'30'').
81 The swamp received fallout following the Chernobyl accident in 1986. Verkmyra Stream
82 floods the swamp every spring, resulting in deposition of radioactive material, mainly ¹³⁷Cs
83 (Stark et al., 2006). Available samples from this area were soil/sediment profiles down to a
84 depth of 50 cm, water, vegetation, and amphibians (Stark et al., 2004; Stark unpublished data;
85 Table 3). Most of the activity (60 – 90%) in soil was found in the top 10-cm layer.

86

87 2.2.3 *Duke Swamp*

88 The Duke Swamp (Figure 3) is a 0.102 km² wetland in the Atomic Energy of Canada
89 Limited's Chalk River facility in Ontario, Canada (N46°02'40'', W77°24'40'') that receives
90 radionuclides, including ¹⁴C, through groundwater transport from a waste management area
91 situated approximately 400 m east of the swamp (Kim et al., 2011; Yankovich et al., 2008a).
92 Past assessments indicated that the primary contributor to dose to biota is likely to be ¹⁴C
93 (Zach et al. 1998) from ¹⁴C volatilised into the atmosphere rather than via direct transfer from
94 groundwater (Yankovich et al. 2013a). A detailed survey of ¹⁴C in soil to a depth of 5 cm and
95 surface vegetation had been conducted. A subset of locations was selected for detailed biota
96 sampling to obtain a range of activity concentrations across Duke Swamp. Samples included
97 in this study were of soil, air, vegetation, invertebrates, amphibians, reptiles, and rodents
98 (Yankovich et al., 2013a; Table 3).

99 *2.3 Input data and exercise instructions*

100 Participants were given measured activity concentrations in soil, water, and air, as available
101 for the three wetland areas (Table 2). No other parameters were specified in the scenario
102 description, although basic information for sites and a list of species to consider were
103 provided (Table 3; IAEA in press). Soil concentrations were presented on a dry mass basis;
104 hence, fresh mass concentrations had to be estimated if required. Water concentrations (only
105 available for Steel Creek and Utnora Swamps), were given for filtered water. To provide soil
106 ^{14}C concentration in Duke Swamp for those models requiring this input, available ^{14}C specific
107 activity concentrations in soil were calculated by assuming the mean soil organic matter
108 content determined for the site (95%; Yankovich et al., 2014) and an assumed carbon content
109 of soil organic matter of 58% (Brady, 1990).

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

117

118 *2.4 General approach taken by participants*

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

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

127 Two approaches were used to estimate biota concentrations of ^{14}C in Duke Swamp
128 (Table 1): I) the specific activity approach in which the specific activity ratio ($\text{Bq }^{14}\text{C}/\text{kg C}$)
129 was assumed to be the same in the whole ecosystem. Each whole body activity concentration
130 (Bq/kg fresh mass, FM) was estimated from a given specific activity in air ($\text{Bq}/\text{kg C}$)
131 multiplied by whole body content of stable C in organisms ($\text{kg C}/\text{kg FM}$). II) to use the
132 ERICA Tool default CR_{wo} (whole organism concentration ratio; Howard et al., 2013) values
133 (Bq/kg per Bq/m^3) to convert air concentrations Bq/m^3 to organism activity concentrations (it
134 was suggested participants used the carbon concentration in air presented in IAEA (2010) to
135 estimate air ^{14}C concentrations). However, CR_{wo} s from the ERICA Tool were originally
136 derived through the specific activity approach assuming carbon content of biota from Robbins
137 (1993) and Crocker et al. (2002), as described by Brown et al. (2003).

138

139 **3. Results and Discussion**

140 *3.1 Wetland assessment approaches taken by the assessors*

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

148

149 *3.2 Predicted biota activity concentrations*

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

156

157 *3.2.1 Choice of ecosystem and CR_{wo} -value*

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

170 In Utnora Swamp the largest variation in predicted activity concentrations of
171 ^{137}Cs was for forbs and sedges, mainly because the ERICA(CEH) application used freshwater
172 vascular plant as reference organism (justified by the assessor on the basis of species listed for
173 the site), and thus, water as surrounding medium. Consequently, results varied up to three

174 orders of magnitude between assessors (Figure 5). For Moor frog, the two applications that
175 included aquatic transfer to frog (K-Biota and ERICA (SCK•CEN) resulted in the lowest
176 predictions.

177

178 *3.2.2 Choice of reference organism*

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

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

190

191 *3.2.3 ^{14}C transfer*

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

199

200 3.3 Measured biota activity concentrations

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

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

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

236 For Duke Swamp, 50% of predicted activity concentrations were within the
237 described range (3:1 – 1:3; Figure 6). Average measured values differed by less than a factor
238 of seven from predictions, except for insects. As was seen for Steel Creek for ^{137}Cs , predicted
239 activity concentration of ^{14}C in insects were approximately one order of magnitude higher
240 than measured data. For small plants, predictions were close to measured values. However,
241 for trees, all predictions were consistently higher (up to a factor of 4) than measured data.
242 Yankovich et al. (2013a) reports that previous studies observed an exponential decrease in ^{14}C
243 specific activity concentrations in vegetation with height above ground at this site, possibly
244 the consequence of activity concentrations in air reducing with height as $^{14}\text{CO}_2$ and $^{14}\text{CH}_3$
245 disperse with distance from the source (i.e. the ground surface). Air samplers providing input
246 air concentrations were located at ground surface, so an over-prediction in trees is not
247 surprising.

248

249 *3.4 Internal dose rates*

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

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

259

260 *3.5 External dose rates*

261 *3.5.1 Assumption of occupancy factor*

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

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

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

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

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

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

289

290 *3.5.2 Soil saturation assumptions*

291 Another influential parameter for external dose rates in terrestrial parts of the wetland was
292 assumptions used for soil moisture. For Steel Creek Swamp, the ERICA (ANSTO)
293 application, and for Utnora Swamp the ERICA (eriss/ARPANSA), (ANSTO), and (CEH)
294 applications, estimated external dose rates 10% of those predicted using other applications.
295 These results are explained by use of the option in the ERICA Tool to define soil/sediment
296 dry matter percentage. External dose rates are calculated by the ERICA Tool in a manner
297 intended to be representative of exposure conditions in the field. However, soil concentration

298 data are usually given on a dry mass basis which, for wetland soils, can be very different than
299 field conditions. By specifying a dry matter percentage, the ERICA Tool back-calculates the
300 fresh mass soil concentration from dry mass concentrations that are required input. The
301 default, conservative value of dry matter percentage in the ERICA Tool is 100%, but it might
302 be appropriate to enter lower values if *in situ* dry matter percentage is known at the site. In
303 this scenario, a 10% soil dry matter percentage was given for Duke Swamp and was used in
304 ERICA (ANSTO) for all wetland soils. The resulting external dose rates were a factor of ten
305 lower than they would have been if the option to define dry matter percentage was not used.
306 This is because in the ERICA Tool, external dose rates decreased corresponding to entered
307 percentage.

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

318

319 *3.5.3 Predicted and measured external dose rates to Moor frog*

320 For Moor frog in Utnora Swamp, predicted external dose rates varied by a factor of 10. As for
321 other organisms, the largest difference in predictions was due to assumptions of dry matter
322 percentage for soil. Also, some differences were due to choices of occupancy. It is evident

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

344

345 *3.6 General aspects*

346 The models included in this exercise all consider terrestrial and freshwater ecosystems but
347 only RESRAD-Biota, through the possibility to model riparian animals (USDoE, 2004),

348 includes the capacity to directly assess vertebrate wetland organisms. This functionality of
349 RESRAD-Biota was not used by any modeller in this exercise.

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

360 The geometric mean $\text{CR}_{\text{wo-media}}$ from IAEA (2014) was used to provide best
361 estimate (Wood et al., 2013). Assuming a 100% aquatic plant diet, RESRAD-Biota predicted
362 an activity concentration of 110 Bq kg^{-1} (FM) and total dose rate of $0.27 \mu\text{Gy h}^{-1}$. If a diet of
363 terrestrial plants was assumed, an activity concentration of 4070 Bq kg^{-1} (FM) and dose rate
364 of $0.97 \mu\text{Gy h}^{-1}$ were estimated. Accepting that mallards are omnivorous, a diet comprising
365 20% aquatic benthic invertebrates, 30% aquatic plants and 50% terrestrial plants resulted in
366 activity concentration of 2430 Bq kg^{-1} , with a dose rate of $0.68 \mu\text{Gy h}^{-1}$. Again these results
367 highlight the importance of assumed food source for wetland organisms. Assuming a diet of
368 100% aquatic plants resulted in an under-estimation of uptake by one order of magnitude,
369 while a mixture of terrestrial and aquatic food produced predictions close to measurements
370 (Figure 4).

371 To assess the risk for each contaminated wetland is beyond the scope of this
372 study but for the purpose of comparison to a screening value of $10 \mu\text{Gy h}^{-1}$, below which

373 ecosystems are to be protected (Howard et al., 2010), all but one predicted dose in Steel Creek
374 Swamp exceeded $10 \mu\text{Gy h}^{-1}$. For Utnora Swamp three predicted doses were above $10 \mu\text{Gy h}^{-1}$,
375 while measurements showed that actual levels were up to two orders of magnitude lower.
376 For Duke Swamp all predicted doses were well below the screening value.

377

378 **4. Conclusions**

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

397 magnitude in comparison to measurements and we recognise a need for more field data to
398 improve predictions.

399

400 **Acknowledgements**

401 This study was produced under IAEA's EMRAS II programme.

402

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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-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

¹model 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.

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17 **Table 2**

18 Input data given for a wetland assessment exercise. Mean values (minimum and maximum
19 values within brackets) of environmental media activity concentrations measured in three
20 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
<i>Steel Creek</i>				
soil	3500 (210-19000)	-	-	Brisbin et al., 1974a RAC, 2001 – appendix K
water	0.81	-	-	
<i>Utnora</i>				
soil	30000 (12000-74000)	-	-	Stark et al., 2006; Stark, unpublished data
water	0.2	-	-	
<i>Duke</i>				
	-	7600 (310-27000)	14 (0.56-50)	Yankovich et al 2014 ; Yankovich et al 2013a; Yankovich et al 2008a and 2008b
soil air	-	-	15 (1.1-38)	

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36 **Table 3**

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

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

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45 **Table 4**

46 Concentration ratios for organism in Steel creek and Utnora Swamp as assumed by the
47 different participants. Model applications abbreviated as e: ERICA (eriss/ARPANSA), A:
48 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
<i>Steel Creek</i>																																										
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	0.5	0.5	0.5	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																													
<i>Utnora</i>																																										
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		

1 **Figures captions**

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

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

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

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

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

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

23 **Fig. 7.** Estimated internal and external radiation dose rates ($\mu\text{Gy/h}$) from ^{137}Cs to organisms in
24 Steel Creek Swamp.

25 **Fig. 8.** Estimated internal and external radiation dose rates ($\mu\text{Gy/h}$) from ^{137}Cs to organisms in
26 Utnora Swamp.

27 **Fig. 9.** Estimated external and internal radiation dose rates ($\mu\text{Gy/h}$) from ^{14}C to organisms in
28 Duke Swamp.

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

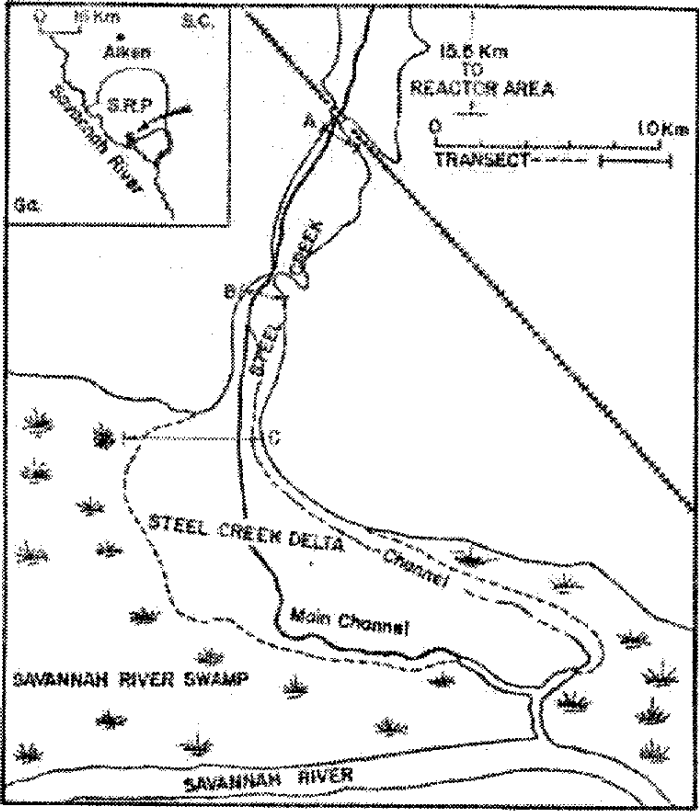
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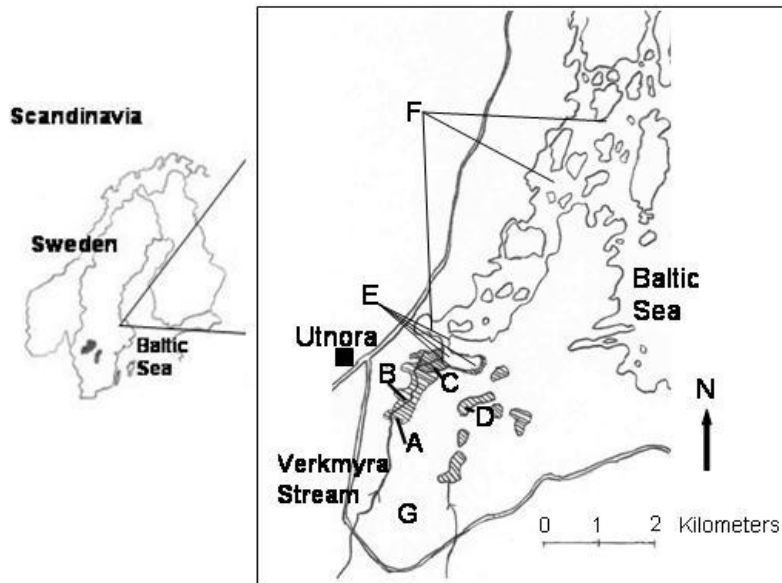
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Figure 1.

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43 **Figure 2.**

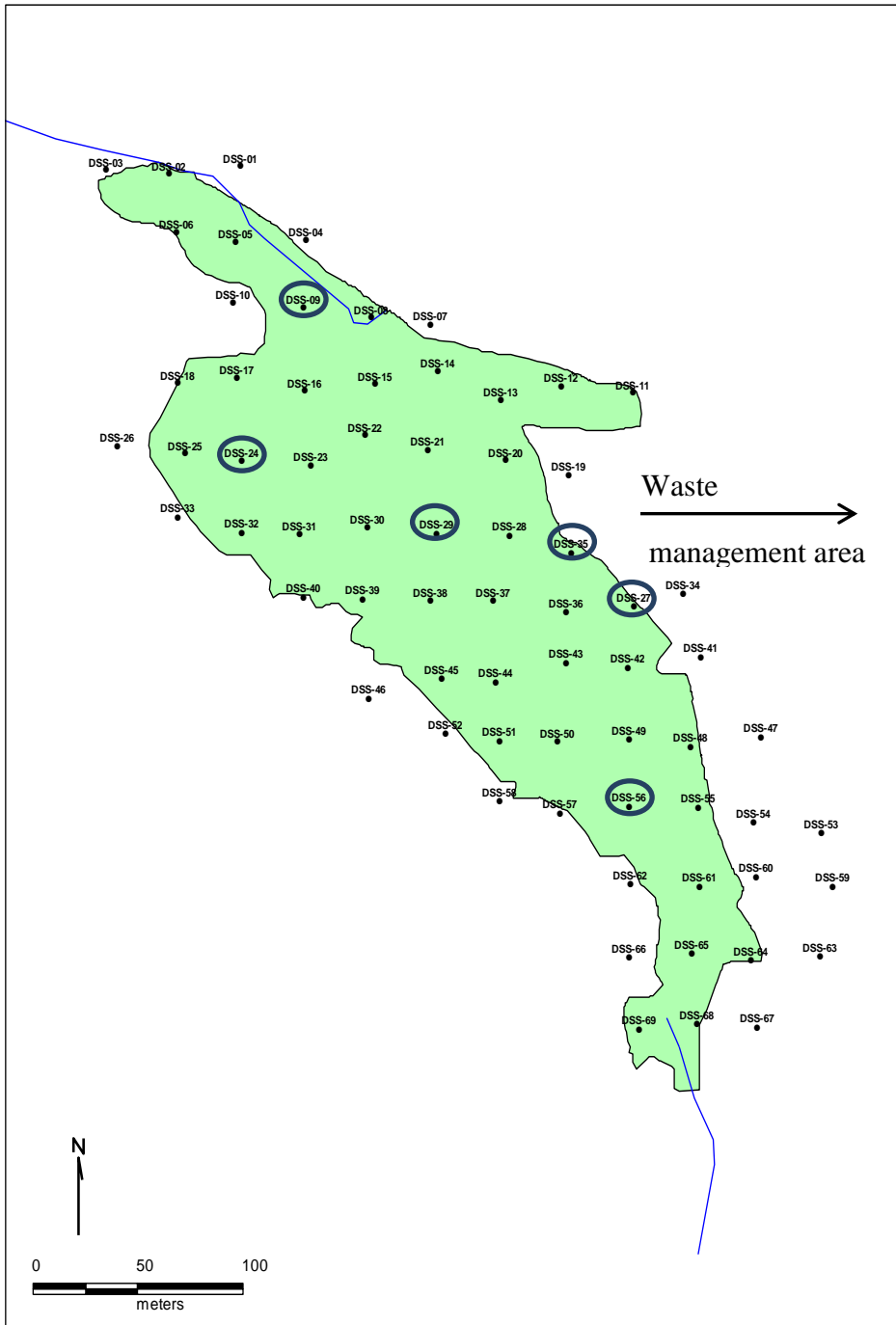
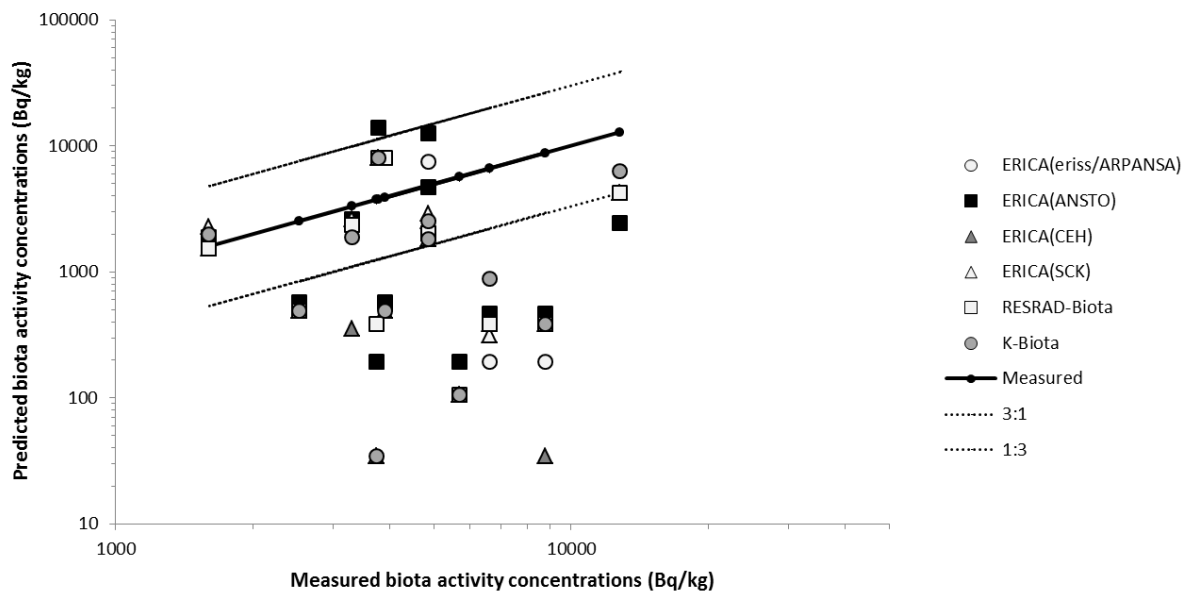


Figure 3.



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50 **Figure 4.**

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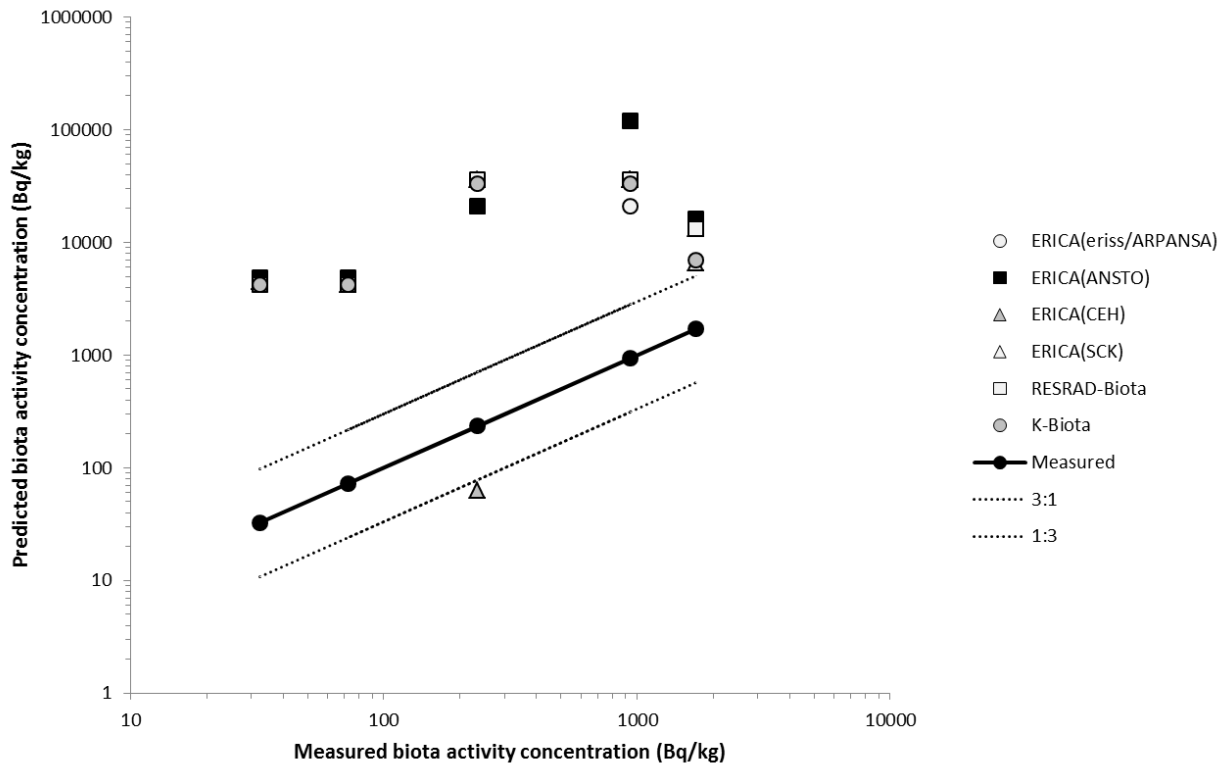
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70 **Figure 5.**

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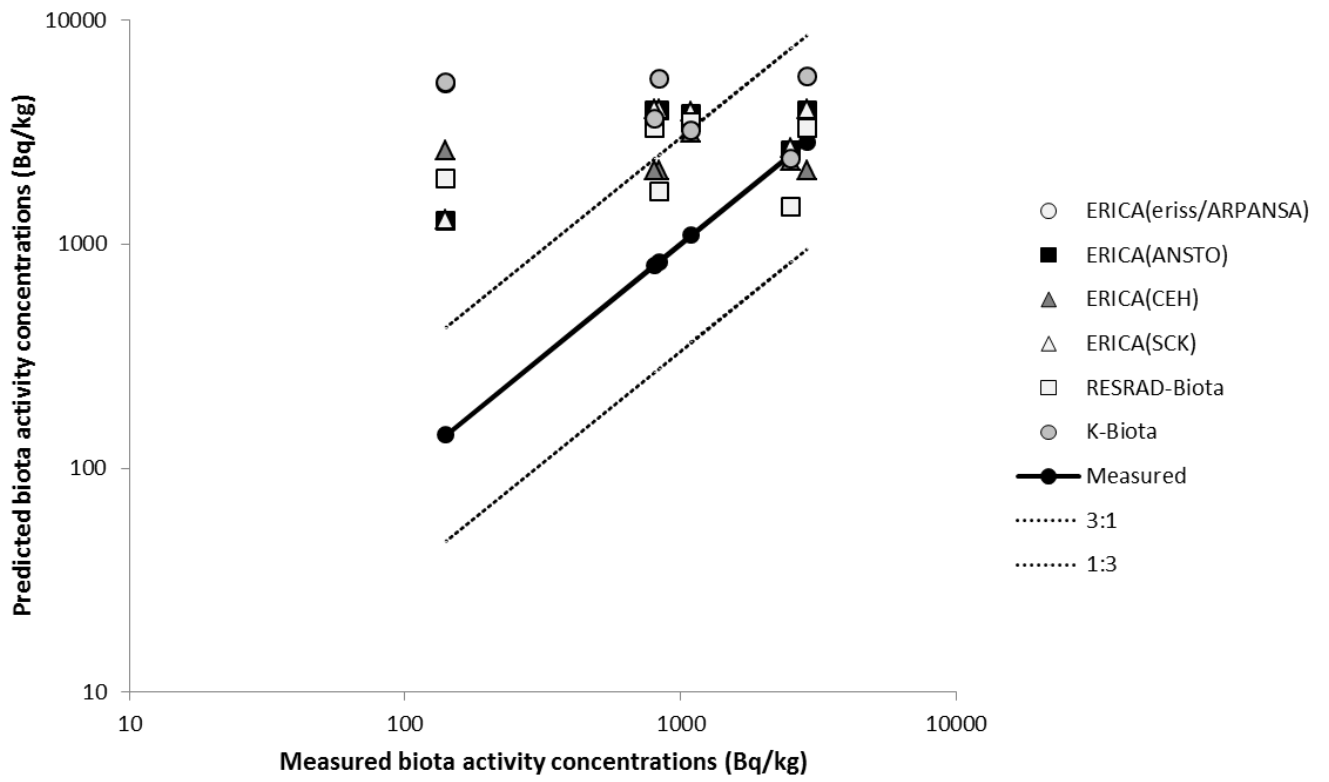
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79 **Figure 6.**

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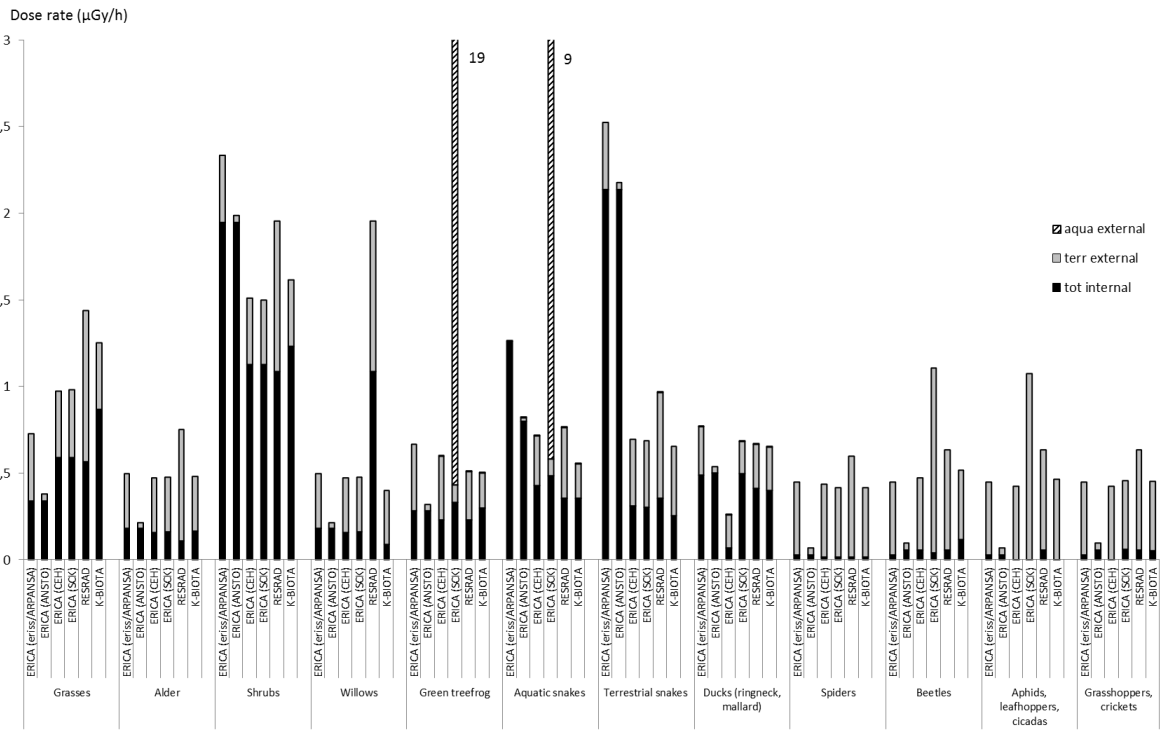
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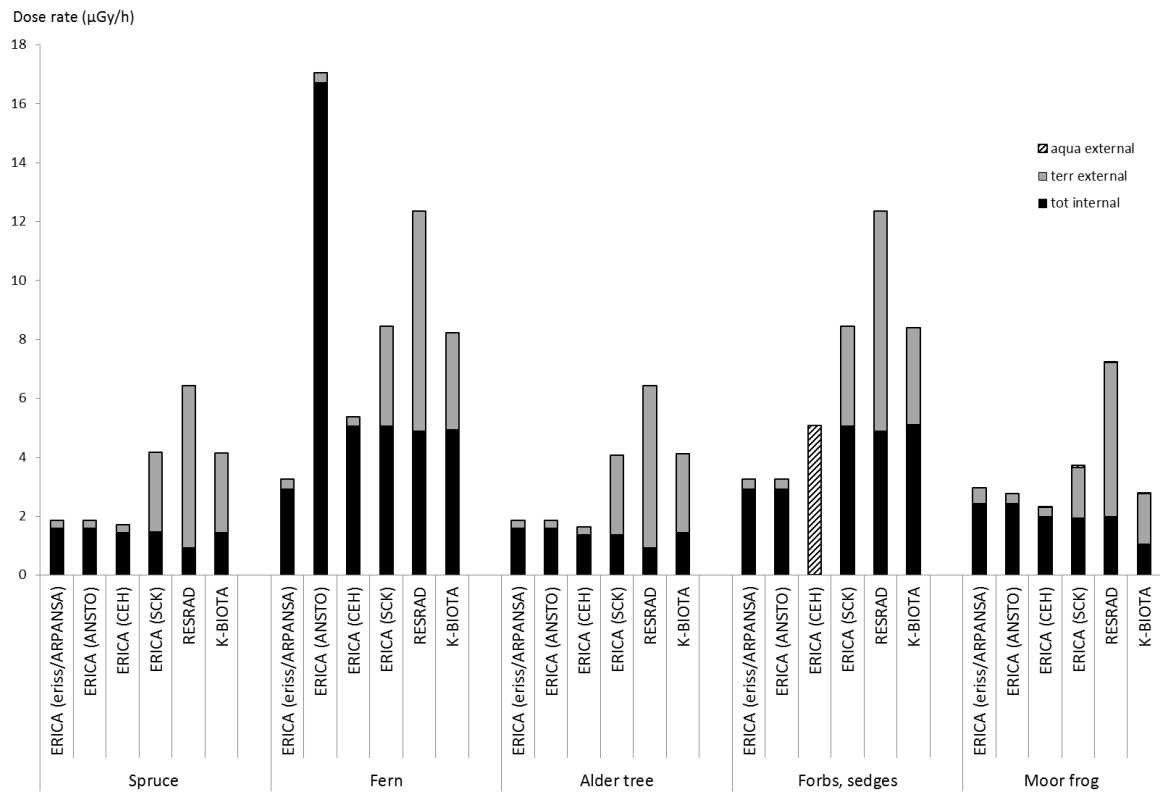
Figure 7.

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Figure 8.

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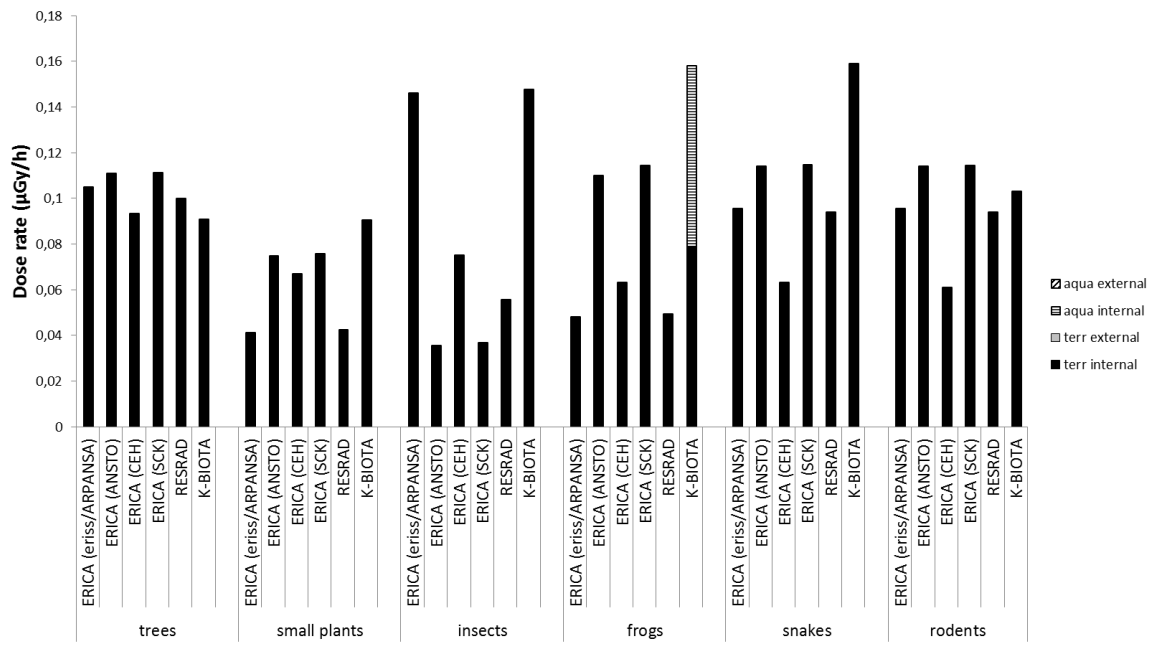
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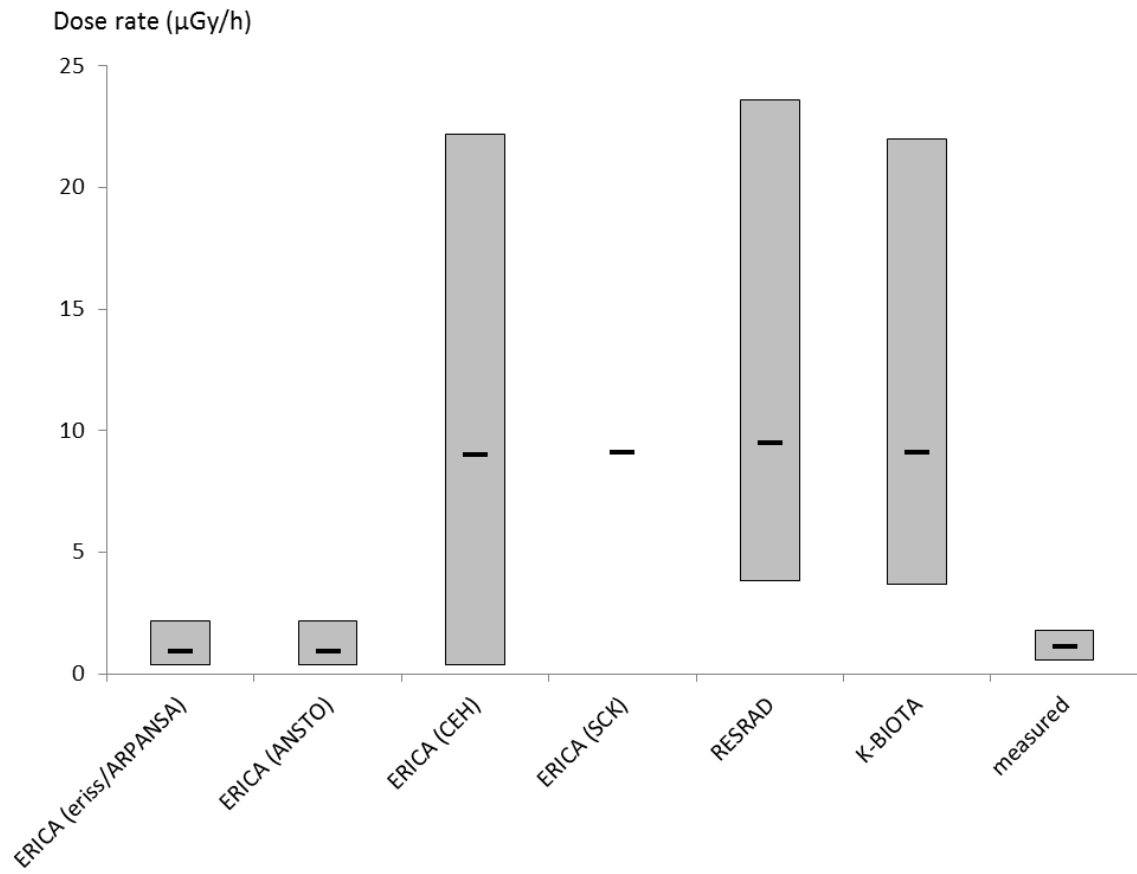
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110 **Figure 9.**

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115 **Figure 10.**

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