

Uncertainties in field dosimetry for non-human biota

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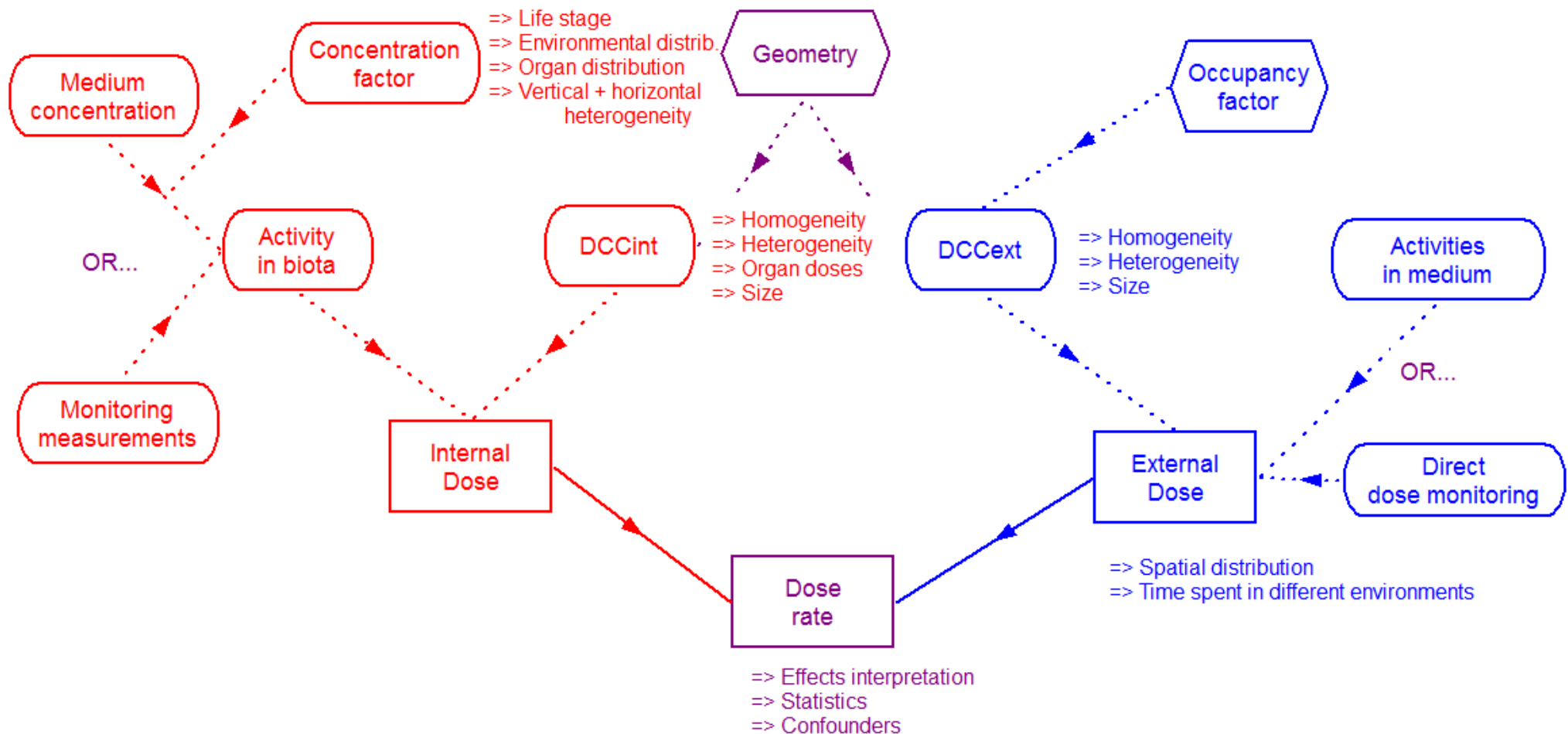
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STAR Wildlife Dosimetry Workshop, Madrid

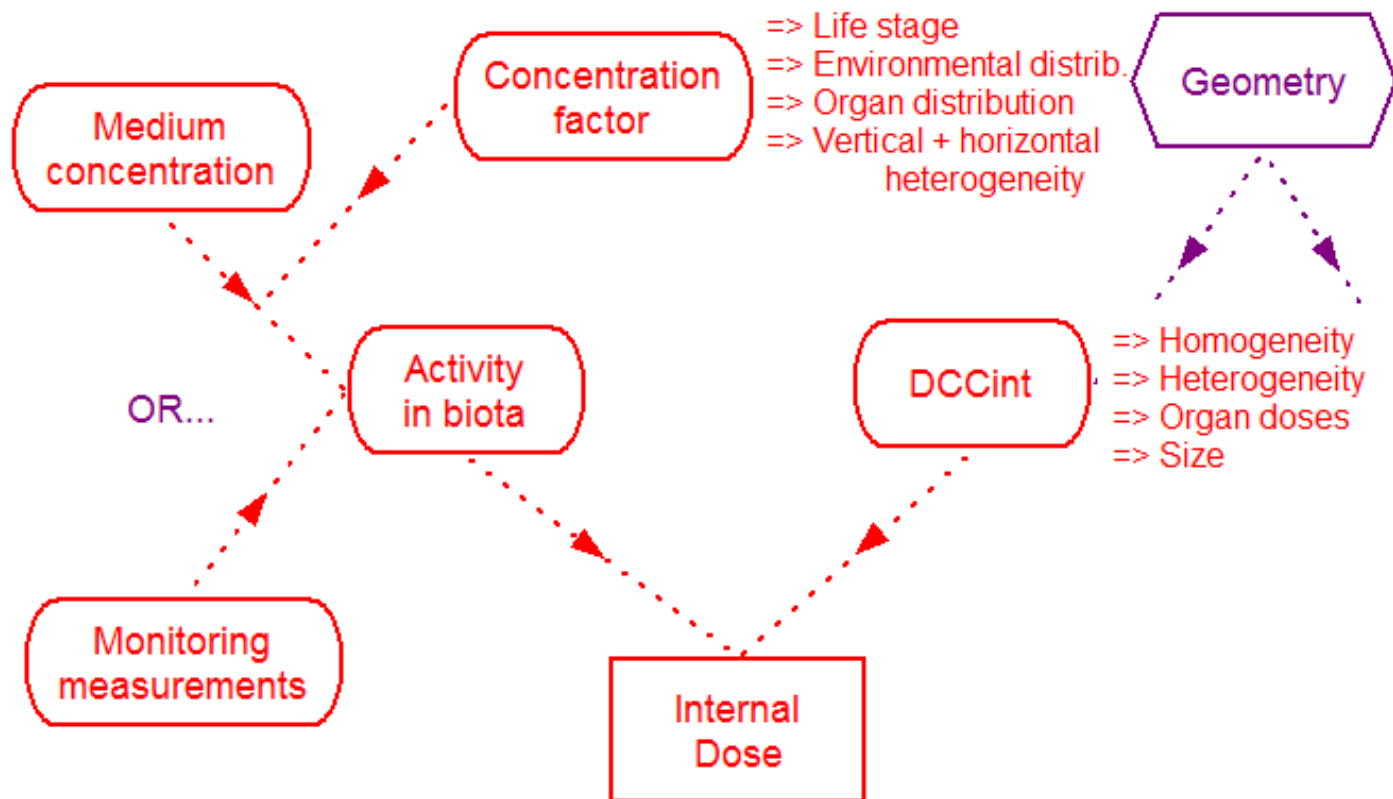
10-12 June 2014

The main components of dose

- Estimating exposure and dose to a free ranging animal is not a trivial matter.



Factors affecting the internal dose



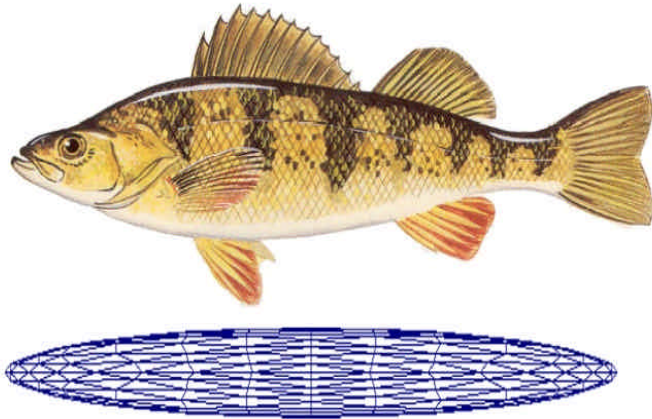
- Internal dose rate needs to be determined accurately:
- Estimate concentration of radionuclide in animal first
 - a) from activity in the medium, using transfer functions, or
 - b) from monitoring (biota captured in the field), alive or dead.
- Then calculate dose => Apply DCC – use ERICA or other tool
- Uncertainties in the determination of the activity in the biota
- Uncertainties in the internal dose conversion coefficients (DCC)
 - Impact of shape, inhomogeneous distributions / organ doses, radiation weighting factor
- Specific limitations of the assessment tools (more later)

Determination of the activity in the biota

- a) Extrapolating from medium concentration
 - Uncertainty in transfer (concentration factors)
 - Considerable variation, ranging over several orders of magnitude.
 - Different CR with different life stage
 - Overestimation of transfer in dynamic situations
- or**
- b) Direct measurement (monitoring)
 - Uncertainty in the field sampling:
 - Problems with sampling sparsity and representativeness
 - Problems with population census valuation (random mobility of biota).
 - Uncertainty in the measurements themselves
 - Problems with radiation measurements (local variations in measured background, masking by natural radionuclides).
 - Analytical and counting errors.

Dose conversion factors - impact of shape

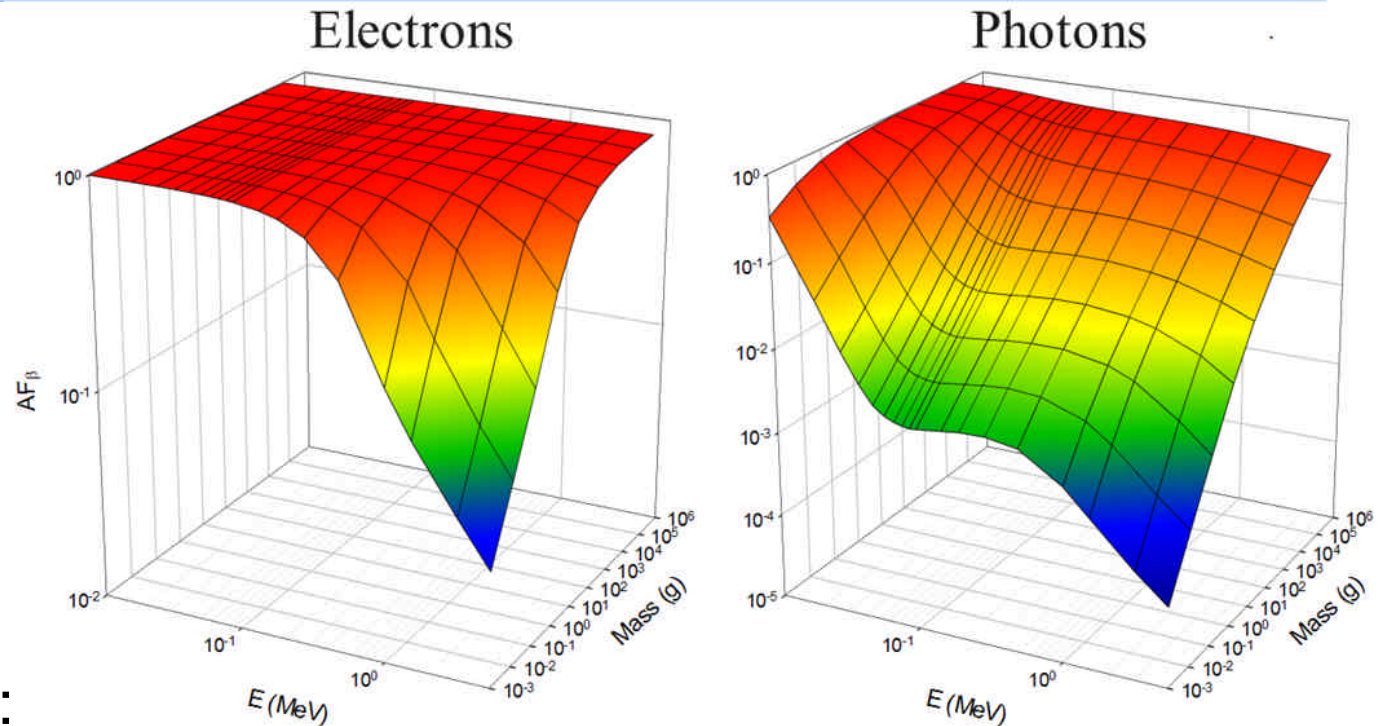
- Organism shapes approximated by ellipsoids, spheres or cylinders of stated dimensions. This is a major oversimplification of the world but use of voxel phantoms is complicated.



- Basis of the dose rate is the absorption fraction which depends on organism size and radiation type
- Dose rate averaged over organism volume immersed in uniformly contaminated medium.

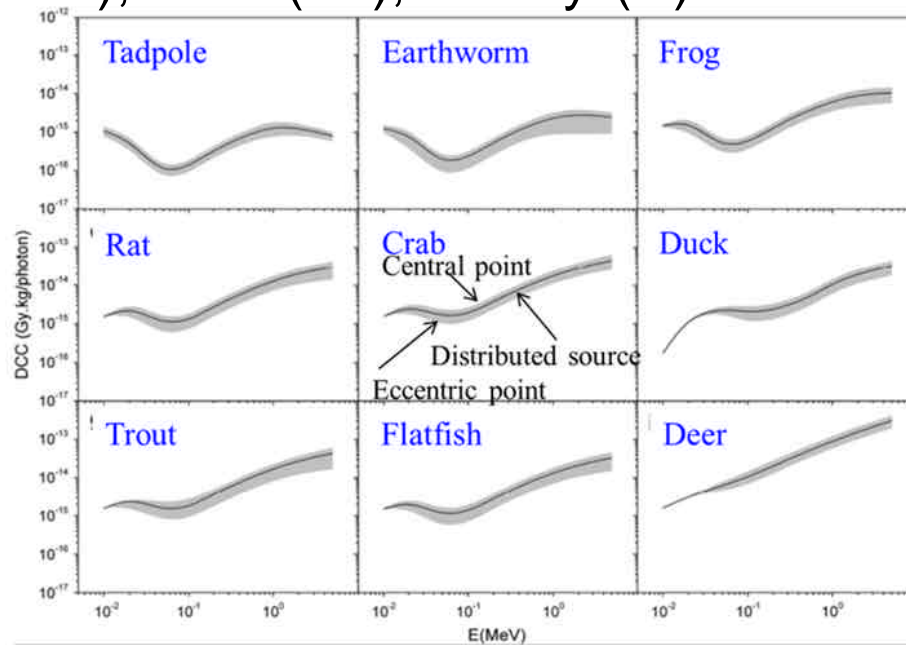
Dose conversion factors - impact of shape (2)

- Internal exposure increases with energy, but...
- **Relatively little impact of size**
- Mass ratio fox/woodlouse = 39000
- Ratio of exposures:
 - Factor 3 for low energy photons
 - Factor 2 for high energy photons
- Cause: relatively low range - most internal radiation self-absorbed
 - U-238: α -emitter: range in tissue: ca. 0.1 mm
 - Sr-90/Y-90: β -emitter: range in tissue: few mm
 - Co-60: γ -emitter: range in tissue: ca. 1000 mm



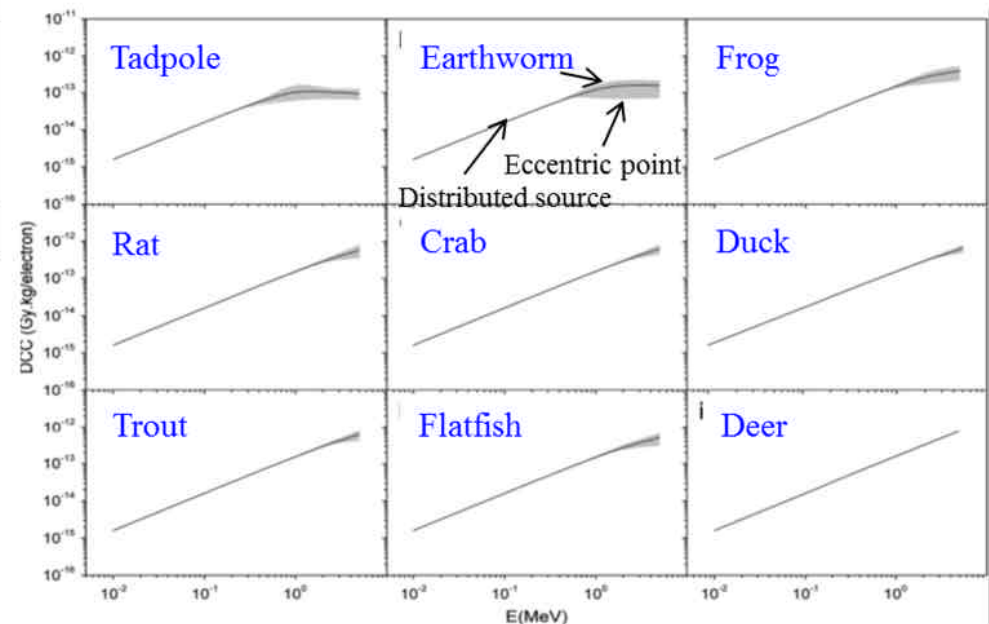
DCC - inhomogeneous distributions

Only a few nuclides homogeneously distributed: ^3H , ^{14}C , ^{40}K , ^{137}Cs . Many concentrate in specific organs e.g. Green gland (Tc), Thyroid (I), Bone (Sr, Ra), Liver (Pu), Kidney (U).



For electrons, the uncertainties are negligible below certain energies, dependent on the size of the organisms.

Gómez-Ros et al. (2009) showed that whole body DCC uncertainties due to inhomogeneous nuclide distribution are $< 30\%$ for photons and electrons for all considered organisms.



- Ratio of the average dose rates organ/whole body is proportional to the whole body/organ mass ratio.
- Conditions for this to be true:
 - Absorbed fraction should be close to 1
 - Alpha-particles and electrons,
- For photons, the approximation is not so accurate due to the penetration of the emitted photon (from the considered organ) into the surrounding tissue.
- Key parameter the range of the photon in tissue (depends on energy).

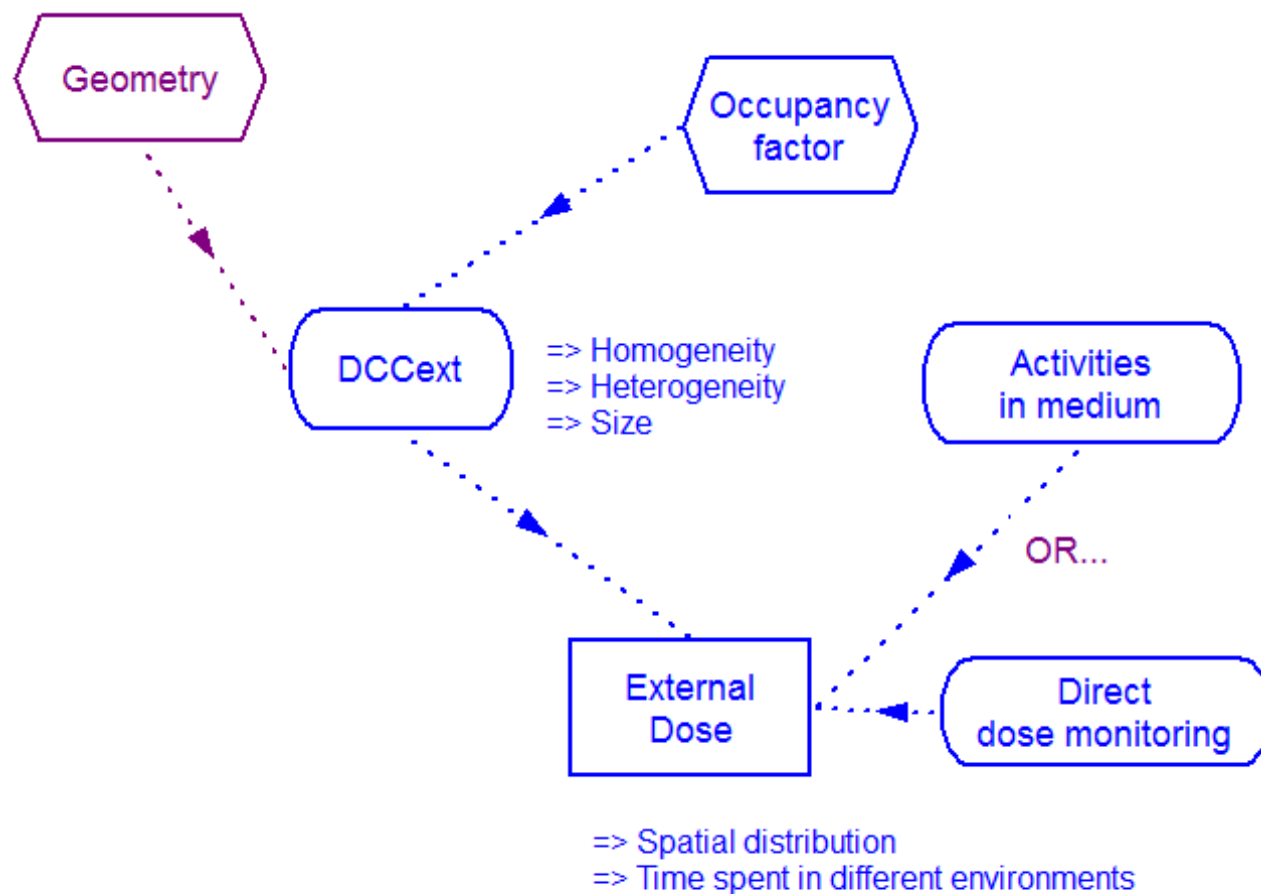
Impact of the radiation weighting factor

- Equiv. dose = absorbed dose \times radiation weighting factor
- Need to make allowance of such factors as LET or RBE
- **No firm consensus for RWF**
 - 1 for γ and $> 10\text{keV}$ β radiation
 - 3 for $\leq 10\text{keV}$ β radiation
 - 10 for α (non stochastic effects) vs. 20 for humans (stochastic)
- Low β component different from 1.
 - Assumes that the experimental RBEs for tritium represent LET values for low energy β 's (conservative - uncertainty $\leq \times 3$).
- The α component has been variously proposed as ranging between 5 (UNSCEAR 1996) and 50 (Brown et al., 2003)
 - 10 commonly used for NHB, with an uncertainty between $\leq \times 2 - 5$.

- Plant geometries in ERICA are unrealistic:
 - They do not really represent whole-organisms.
 - Grass geometry taken from the ICRP.
 - Excludes 'in soil' dose rates, considers only dose above ground.

=> Create a surrogate organism to represent the plant (e.g. leaf) and compare DCC values to the default grass.
- Size interpolation within predefined mass range:
 - 0.0017 to 550 kg for animals on soil.
 - 0.0017 to 6.6 kg in soil; 0.035 to 2 kg for birds; 10^{-6} to 10^3 kg for aquatic organisms.
 - Small errors incurred when out of range - consult Table 10 of ERICA help file.

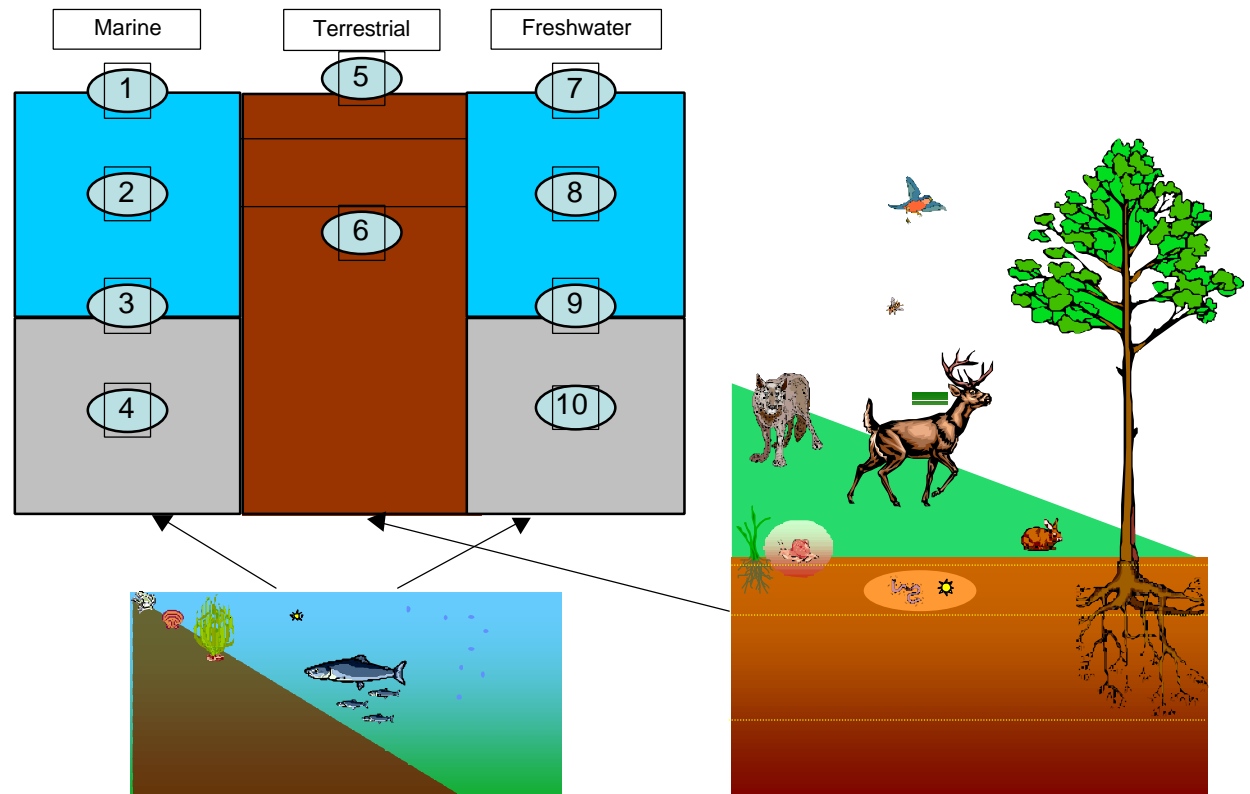
Factors affecting the external dose



- External dose rate also needs to be determined accurately:
 - Option 1: Start from activity in the medium, then calculate external dose using a model that takes into account occupancy in areas of different radiation level (air, on soil, in soil...) => ERICA tool.
 - Option 2: Attach dosimeter to measure external dose to animal in natural state (Woodhead, 1984 - plaice tagged with dosimeters; Beresford et al. 2008 terrestrial TLD study).
 - Option 3: Use hand-held dosimeters & assume same dose for biota (more risky – detector does not travel with the animal).
- Organism geometry effects
 - Absorbed fraction (external) = $1 - \text{Absorbed fraction (internal)}$
 - As in internal dose, there is an assumption of ellipsoidal shape that introduces an error
 - Organism size at different life stages could have a large influence on external dose

Known limitations of the ERICA approach

- Limitations of the ERICA approach due to dosimetry assumptions: skin/fur, biota in bordering environments (mixed terrestrial, aquatic, aerial scenarios e.g. seabird on land, etc).

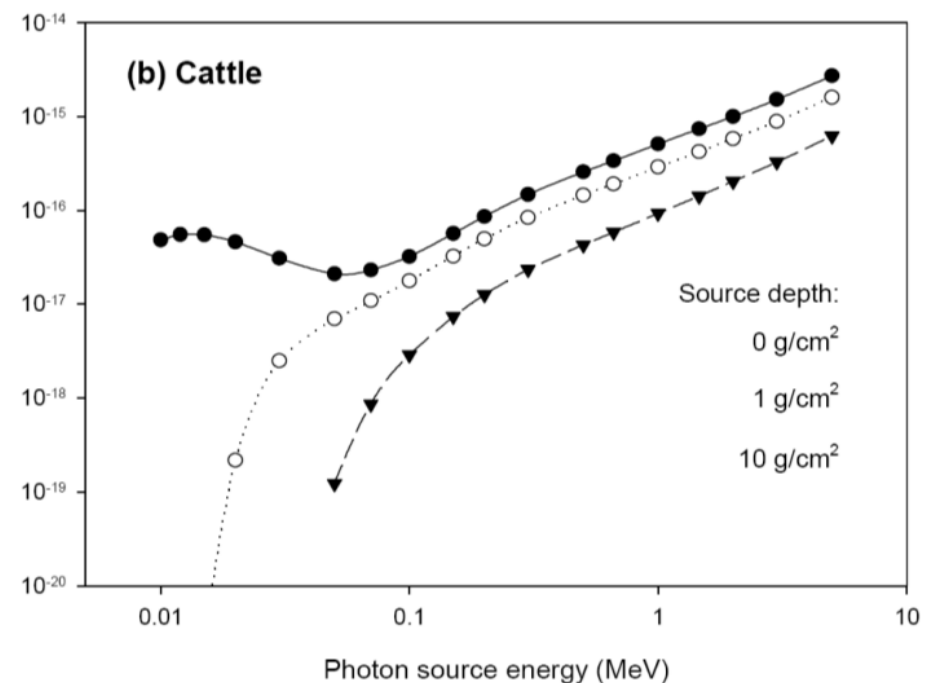
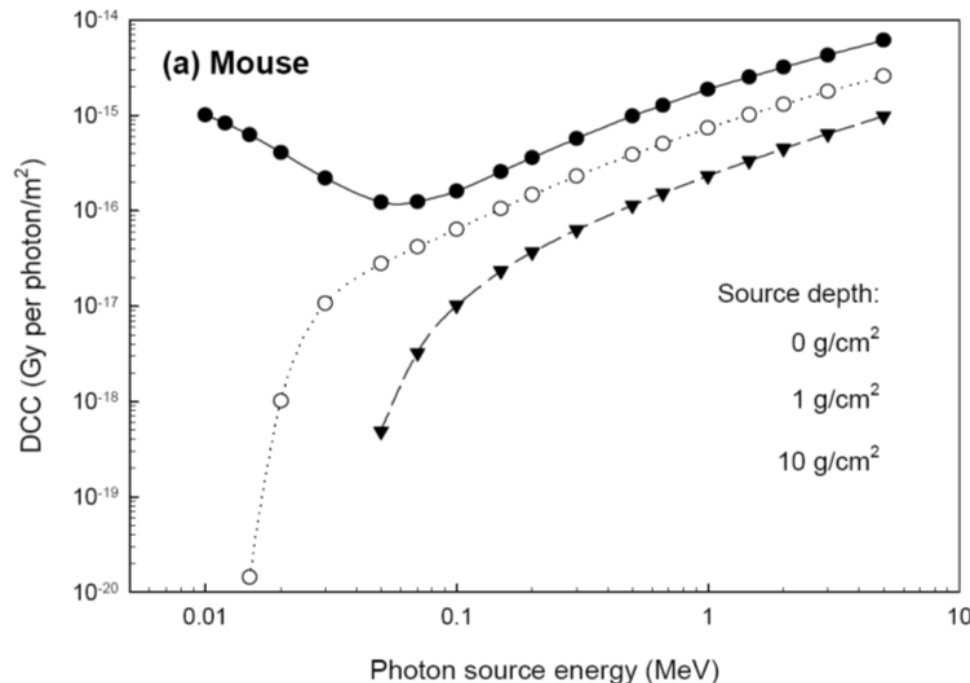


- Ignores life stage-based occupancy differences e.g. bird (flying) versus egg (on tree/nest).

- Source – target geometry effects
 - Geometry-related uncertainties for birds due to flying height, egg on nest vs. flying bird, etc.
 - DCC's for a fixed soil/sediment contamination depth.
 - Depth profiles seldom considered (Timms et al., 2004).
 - Assumption that source term is a smooth plane (Eckerman et al., 1993)
 - Rarely the case in terrestrial habitats ($\leq \times 2$ uncertainty).
- Occupancy – related effects
 - Uncertainty in organisms with different life stages
 - Varying external exposures for different life stages with different occupancy
 - Some aquatic organisms may be surrounded by sediment during certain life stages (frog vs. tadpole)
 - Limits on what organisms appear under some ecosystems:
 - cannot calculate DCC for marine bird in air (do bird on water or sediment)

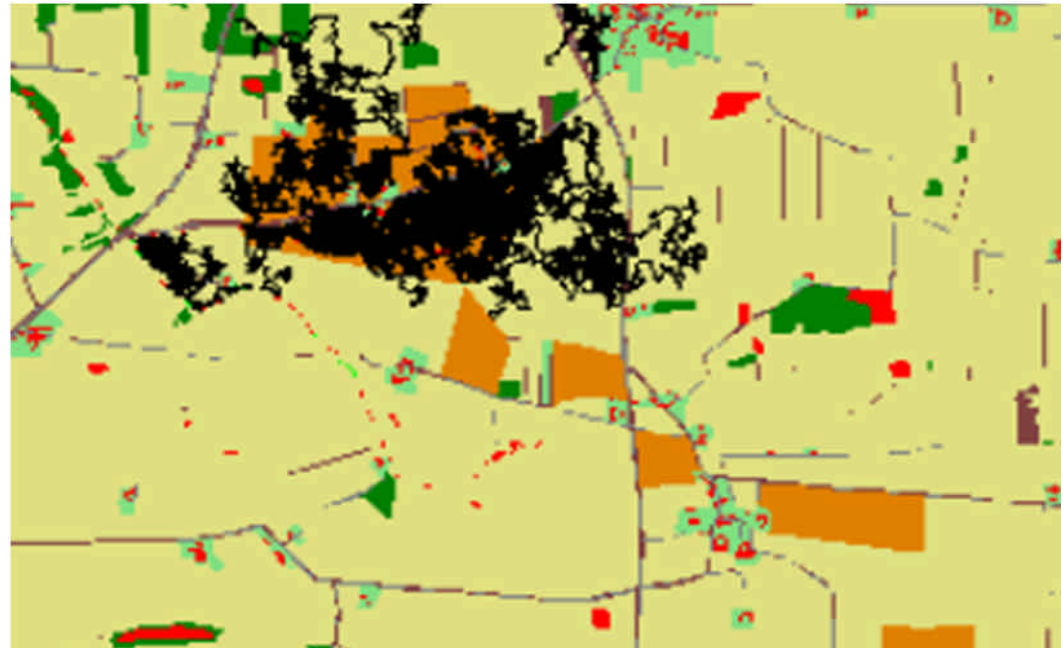
Effect of source depth

- Thin coverage of source has an impact.
 - No appreciable difference between assuming radioactivity distributed (a) within the first 50 cm of soil; or (b) to infinite depth.
 - At < 10 cm depth there would be an effect for high-energy photons.
 - Surface roughness can be important.
- Similar effect for small and large animals.



Issues with spatial distribution

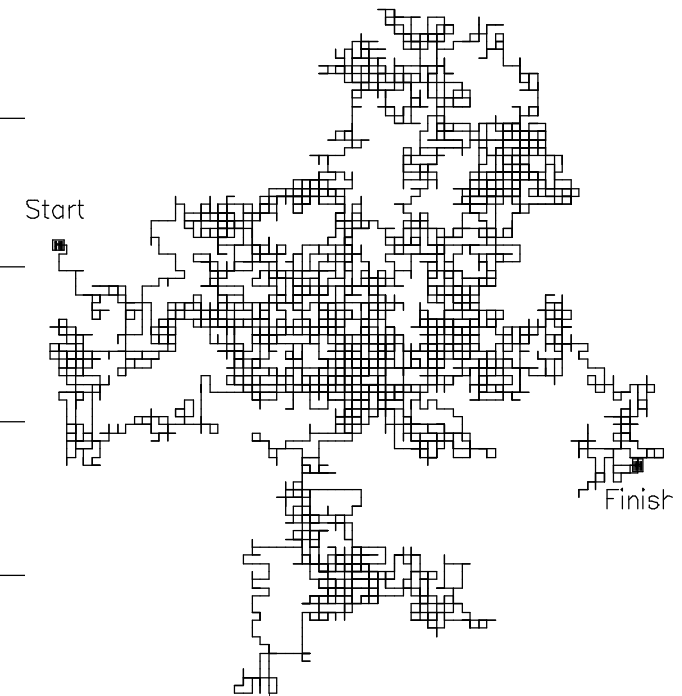
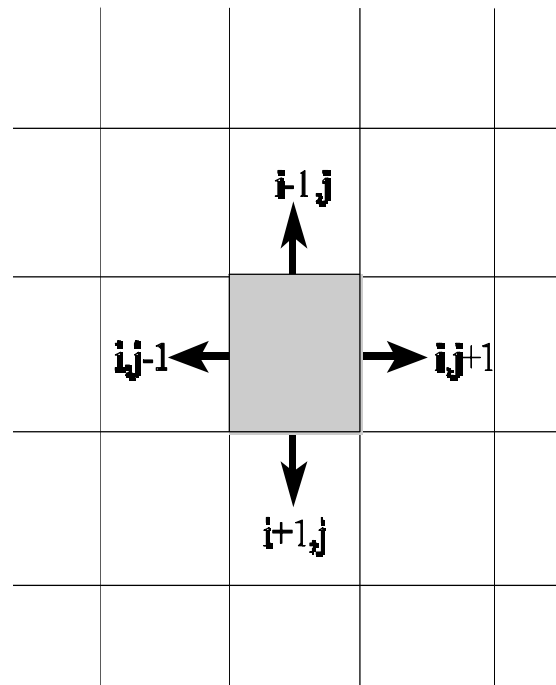
- Spatial issues in field dose estimation
 - Need to account for the time animals spend in environments (temporal component) that vary significantly in contaminant levels (spatial component).
 - Averaging regions of high spatial variability can blur conclusions about the temporal variability of dose.
- Some individuals may be exposed to contaminants out of a larger population due to their erratic wandering and foraging patterns in regions more contaminated than others (affects internal dose also).



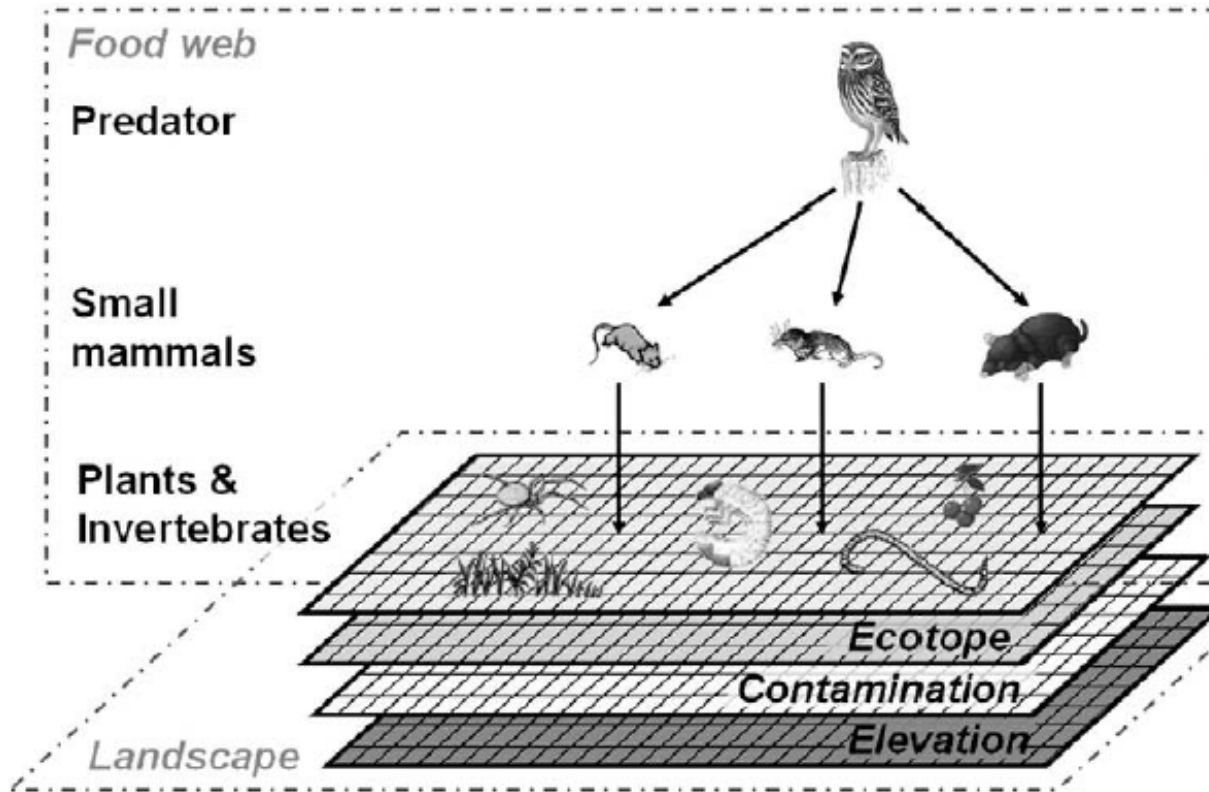
Field voles in agricultural landscape using SmallSteps model
(<http://www.wageningenur.nl/en/show/GridWalkSmallSteps.htm>)

An option – random walk modelling

- An organism's mobility in a heterogeneously contaminated area leads to variation in exposure observed between individuals.
- This can be captured in random or quasi-random walk models
 - Simulate behaviour and movement of organisms in space
 - Determine what individuals of a particular population are more at risk, rather than treating all them as having had the same exposure.
 - Can take into account multiple stressors in a multi-species setting.



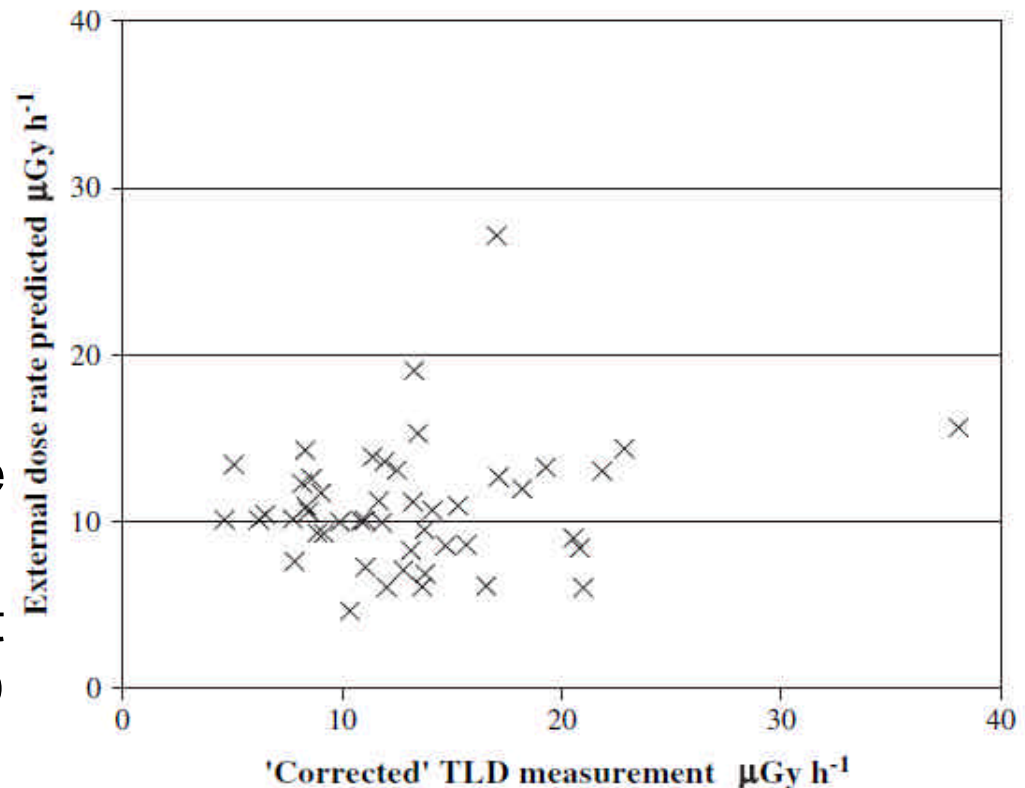
Example – EcoSpace (Loos et al., 2010)



- Represents movement & food intake over raster map
- Accumulation of contamination over time
- Feeding relationships between species
- Calculates lifetime exposure to a contaminant
- Can include different life stages with different exposure routes
- Predictions for Cd accumulation agree Dutch site field data
- Applicable to variability in Chernobyl and Fukushima fauna

Issues with direct dose measurement

- Limited number of studies reporting direct measurement
- Attaching TLDs to small mammals at Chernobyl (Beresford et al., 2008)
 - Related the TLD reading to the estimated whole-body dose.
 - External dose predicted was at worst $\leq \times 3$ lower than the TLD measurement.
 - Moderately good estimate of external and internal dose using ERICA (1 order of magnitude or less)
 - Difference in agreement between sites relate to soil type variations.
 - Air-kerma gives a fairly good approximation of external dose ($\leq \times 2$).



- Radiation-related issues to be considered:
 - α and β -emitters difficult to measure may be 'accidentally' neglected.
 - Additional shielding e.g. from snow, soil litter, etc. for β and low γ -energy emitters needs to be considered.
 - Elevation correction for external dose to plants and birds with respect to dose at ground surface is important.
 - 'False positives' in TLD measurements – setting baseline
- Radiation measured by hand-held dosimeter probably less good estimate of external dose than animal-borne dosimeter.
- Contrasting internal versus external dose pathways
 - Intercalibration of handheld monitor, TLD, gamma spectrometers
 - Need to factorise random mobility for animals who nest or get their food from locations different to that in which they are sampled.

Internal versus external dose comparison

- Radionuclide: Cs-137 (γ -emitter, ~ 0.7 MeV)
- DCC's for internal and external depend on absorbed fraction AF:

$$DCC_{\text{int}} (\text{Gy s}^{-1} / \text{Bq kg}_{\text{org}}^{-1}) = 5.77 \times 10^{-4} \times AF$$

$$DCC_{\text{ext}} (\text{Gy s}^{-1} / \text{Bq kg}_{\text{medium}}^{-1}) = 5.77 \times 10^{-4} \times (1 - AF)$$

- Hence the internal and external dose rates are:

$$D_{\text{internal}} (\text{Gy s}^{-1}) = 5.77 \times 10^{-4} \times AF \times C_{\text{medium}} \times CF$$

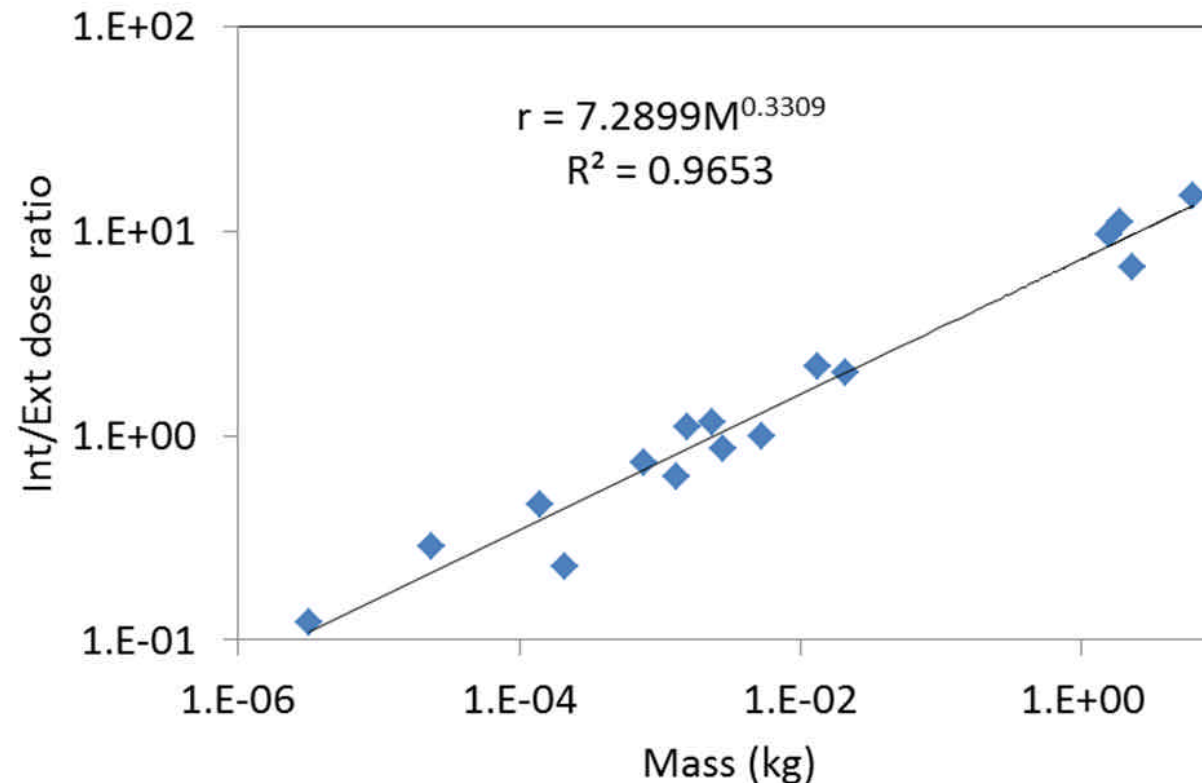
$$D_{\text{external}} (\text{Gy s}^{-1}) = 5.77 \times 10^{-4} \times (1 - AF) \times C_{\text{medium}} \times f_{\text{occ}}$$

$$D_{\text{internal}} / D_{\text{external}} = \frac{AF \times CF}{(1 - AF) f_{\text{occ}}} = \frac{a}{f_{\text{occ}}} \frac{AF \times M^b}{(1 - AF)}$$

- Where we assume CF scales allometrically as $CF = a \times M^b$. For ^{137}Cs this is $a = 63.1$ and $b = -0.021$ (taken from marine).
- Assumes equilibrium!

Internal versus external dose comparison (2)

Mass (kg)	r
3.1E-06	1.2E-01
2.4E-05	2.8E-01
1.4E-04	4.6E-01
2.1E-04	2.3E-01
7.7E-04	7.4E-01
1.3E-03	6.3E-01
1.6E-03	1.1E+00
2.4E-03	1.2E+00
2.8E-03	8.7E-01
5.2E-03	9.9E-01
1.3E-02	2.2E+00
2.1E-02	2.0E+00
1.6E+00	9.7E+00
1.9E+00	1.1E+01
2.3E+00	6.7E+00
6.1E+00	1.5E+01



- For biota > 100 g internal dose clearly dominates over external.
- Assessment not possible on the basis of external dose only.
- Especially true if the internal dose arises from radionuclides incorporated at large distances from sampling point.

Attempted quantification of uncertainties

- Overall uncertainty difficult to quantify due to imponderables such as spatial variability, mixed environments, shielding, etc.
- Studies within the EMRAS project – intercomparison of models to estimate radionuclide activity concentrations in non-human biota.
- Within the whole dose assessment, uncertainties associated with the dosimetry are much less than that associated with transfer.

Dosimetry

- Inter-model variability of dose conversion factors for ERICA vs other approaches (Vives i Batlle et al., 2011):
 - Internal dose rates $\leq \pm 25\%$
 - External dose rates $\leq \pm 120\%$
- For the assumption of the homogeneous distribution, the estimation of the internal exposure is pretty accurate (10-20 %)

- Impact of organ doses and inhomogeneous distributions not more than 30% (Gomez-Ros et al. 2008).
- Impact of the shape is little unless for extreme shapes e.g. very long or thin organisms (Ulanovsky, 2006).
 - Up to 25% for frog (Mohammadi et al., 2011).

Transfer

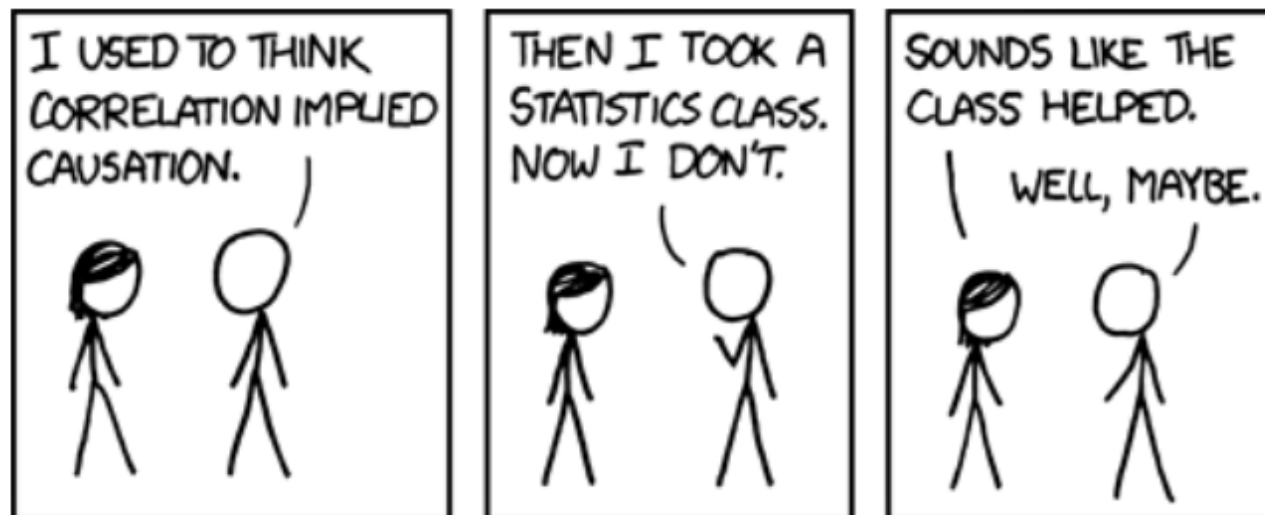
- Uncertainty in transfer factors is large: \leq factor of $\times 10$ or more if transfer factors are used.
- This can be reduced to \leq factor of $\times 2$ if transfer estimated with a dynamic model.
- This compares with residual uncertainty of $\leq 60\%$ for a monitoring-based assessment
- On top of all this there is an added layer of interpretation issues

Interpretation issues

- Nature adding very large variation to all things in the field, leading to low levels of statistical confidence, which can rarely be achieved with small sample sizes.
- Interpret cautiously effects appearing over a narrow contaminant range where there is large spatial variability in background.
- Avoid problems with 'low-number statistics'.
- Higher chance to capture damage/stressed animals can lead to overestimation of morphological effects for small sample numbers.
- Different life stages of organisms can show distinct variations in radiosensitivity at the same dose level (ICRP Committee 5 publication).

Uncertainty in results interpretation (2)

- Correlation does not necessarily equate to causation; particularly if confounding variables are not accounted or the dosimetry is not adequate).
 - Need for controls in correlative studies
 - Confounding factors when examining dose-response relationships not included in the statistical design (interaction with other pollutants / biological agents, manmade ecosystem changes e.g. abandoning contaminated land, radio-adaptation).



- Uncertainties in radionuclide concentration in biota (transfer) affect dose calculations severely – for many CR's there are no data.
- Uncertainties in the dose calculation part (organism shape, modelling the dose, inhomogeneous distributions & other simplifications) are controllable and generally we tread on safe ground because they are well studied (exceptions notwithstanding).
- Uncertainties in field operations are potentially the most misleading: instrument calibration, issues of spatial distribution, need to combine correctly internal vs. external dose, and statistical issues.
- Radiation effects estimation adds a final layer of uncertainty due to risks of selective sampling and confounding factors in causation.
- Extreme care required in field dosimetry studies - attribute cause to effect only when all other potential explanations have been eliminated.
- Results must ultimately make scientific sense and have a proper mechanistic explanation (correlation vs. causality).

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