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Uncertainties in field dosimetry for non-human biota

Jordi Vives i Batlle

jvibatll@sckcen.be

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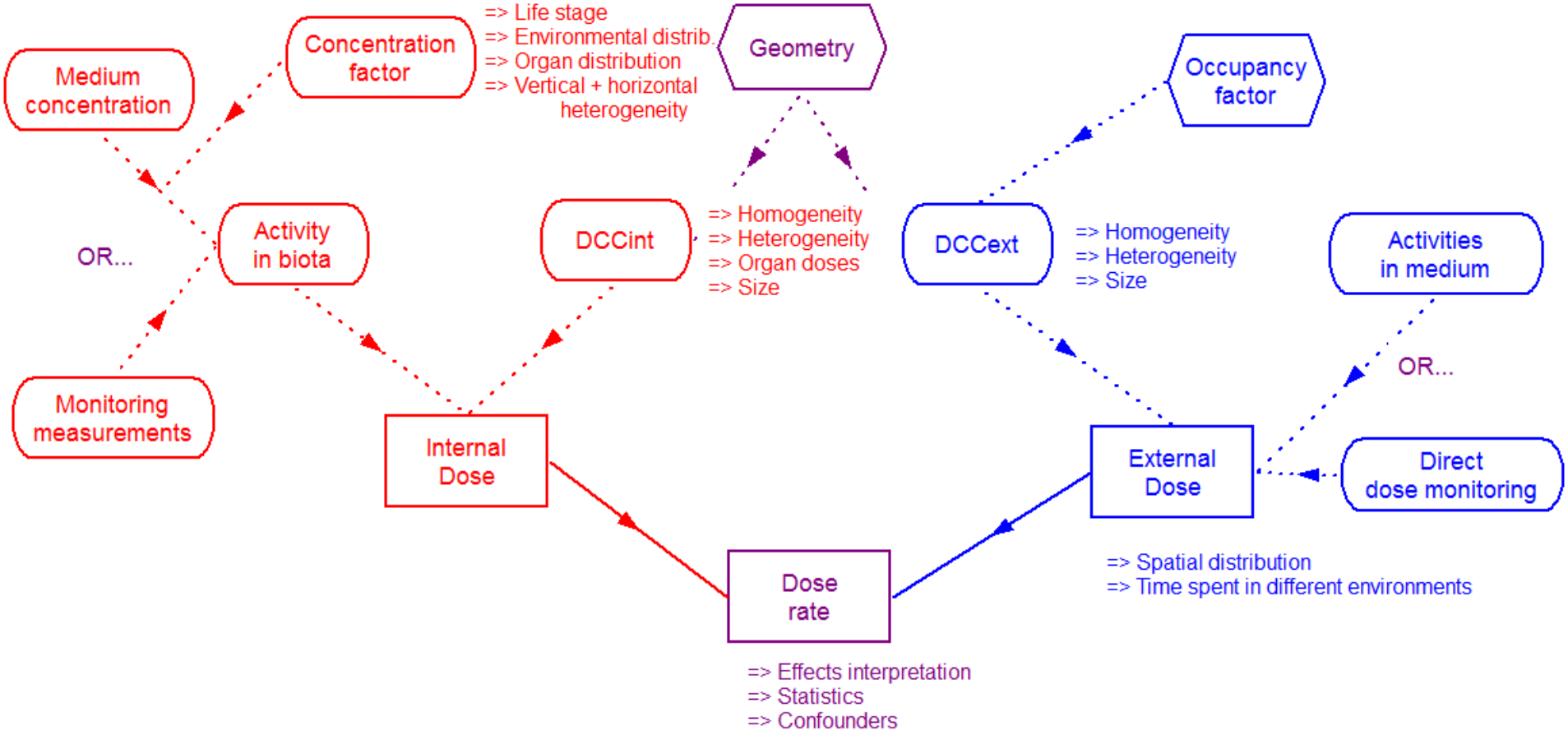
The main components of dose

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



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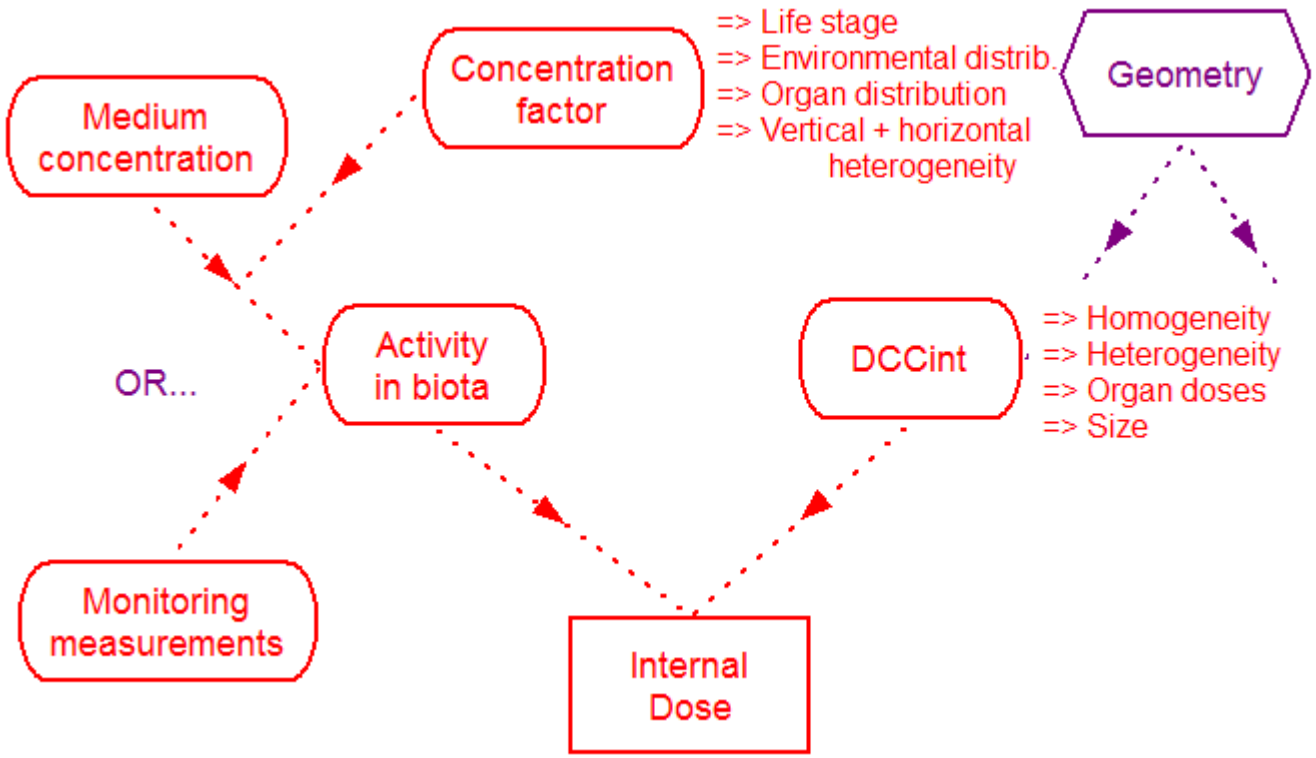
Factors affecting the internal dose



Internal dosimetry – key issues

- 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

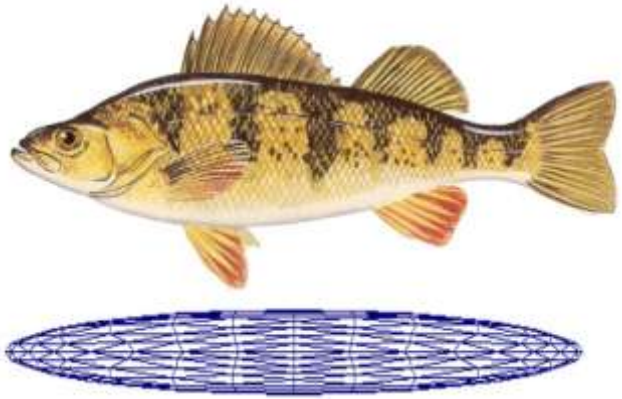
- a) Extrapolating from medium concentration
  - Uncertainty in transfer (concentration factors)
    - considerable variation, ranging over several orders of magnitude.
  - Different CR with different life stage
  - Overestimation of transfer in dynamic situations

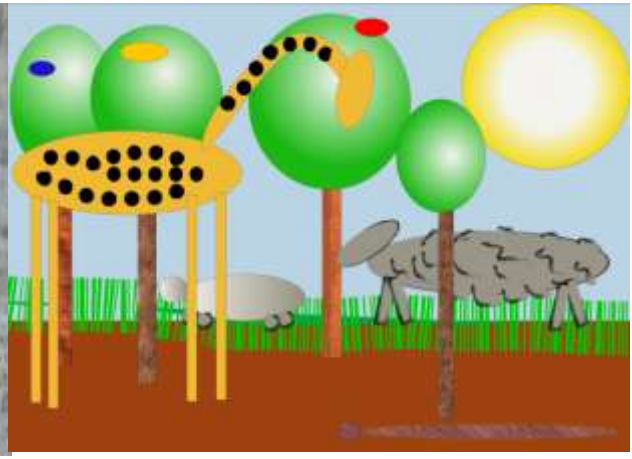
or

- 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.

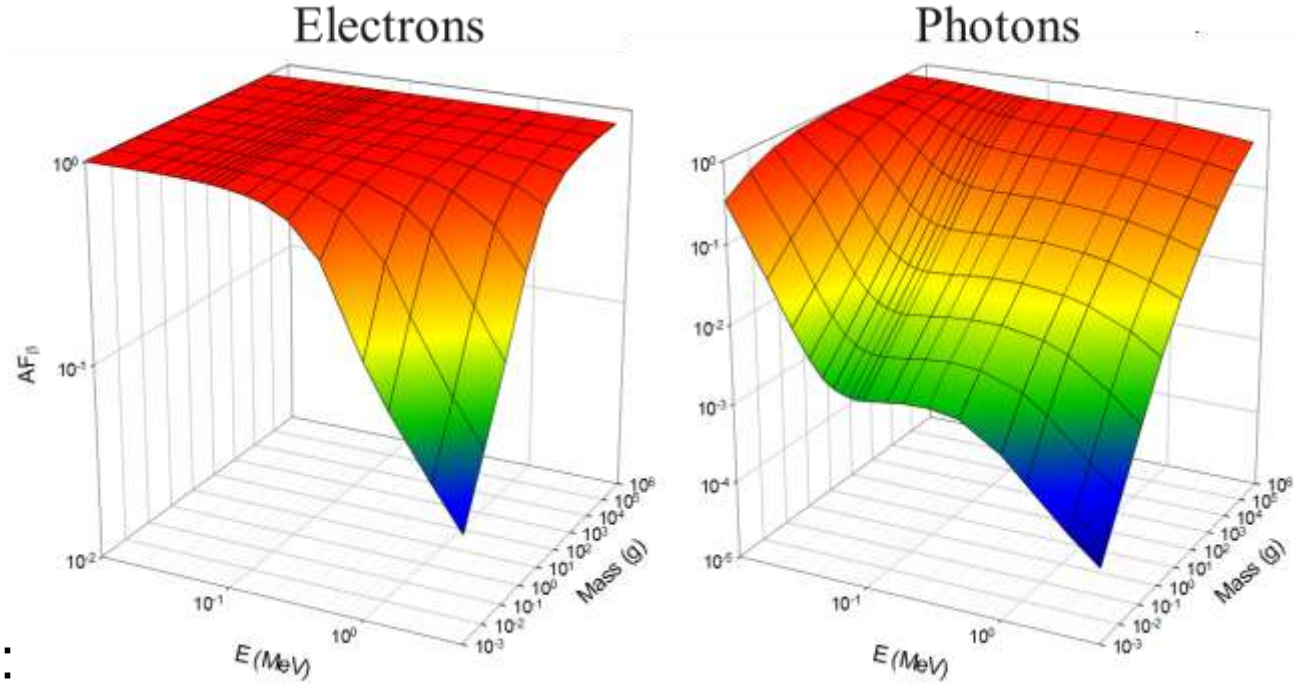




- Basis of the dose rate is the absorption fraction which depends on organism size and radiation type
- Dose rate averaged over organism volume immersed in uniformly contaminated medium.

Dose conversion factors - impact of shape (2)

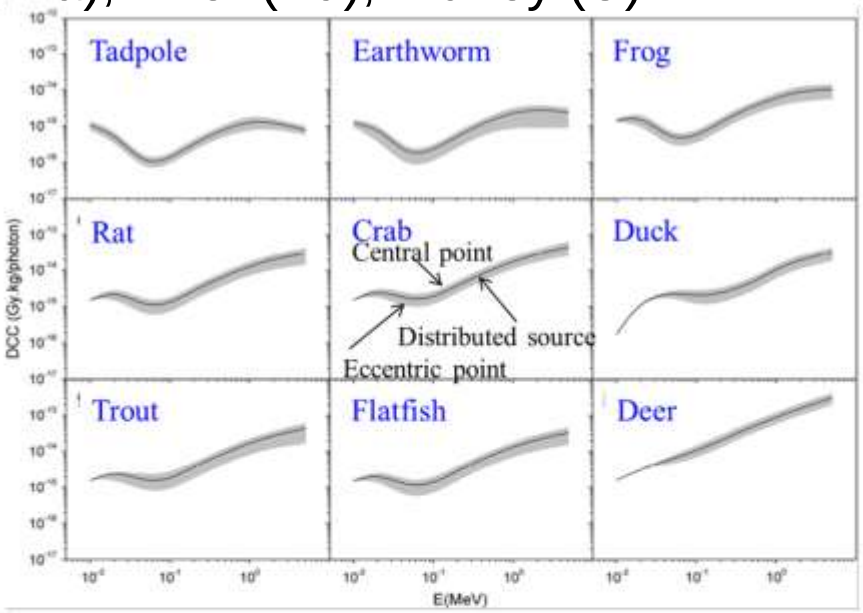
- Internal exposure increases with energy, but…
- Relatively little impact of size
- Mass ratio fox/woodlouse = 39000
- Ratio of exposures:
  - Factor 3 for low energy photons
  - Factor 2 for high energy photons



- 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

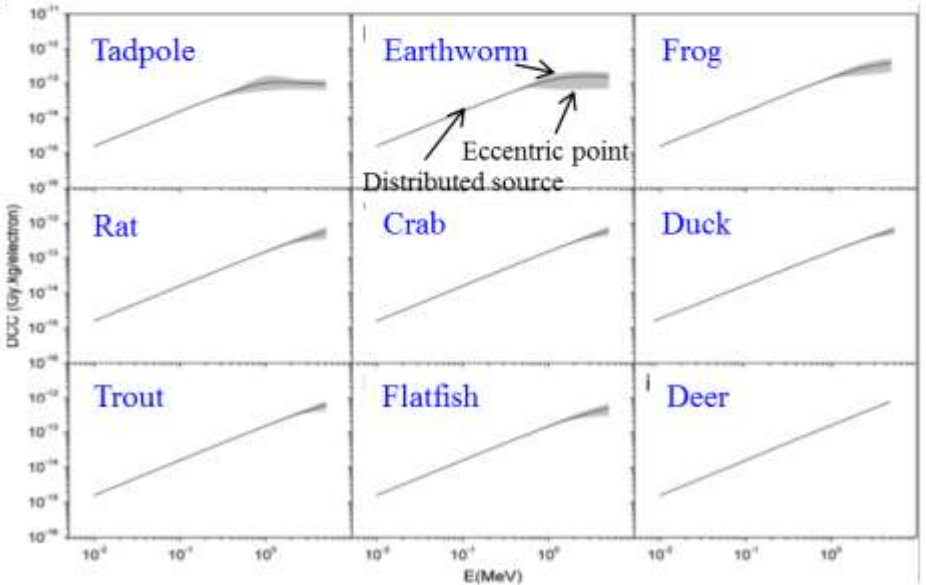
DCC - inhomogeneous distributions

Only a few nuclides homogeneously distributed: ^{3}H, ^{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).



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.

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



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DCC – Approach for organ doses

- 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).

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Impact of the radiation weighting factor

- Equiv. dose = absorbed dose × radiation weighting factor
- Need to make allowance of such factors as LET or RBE
- No firm consensus for RWF
  - 1 for γ and > 10keV β radiation
  - 3 for $\leq$ 10keV 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 $\leq \times 2 - 5$.

Problems when using assessment tools

- 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.

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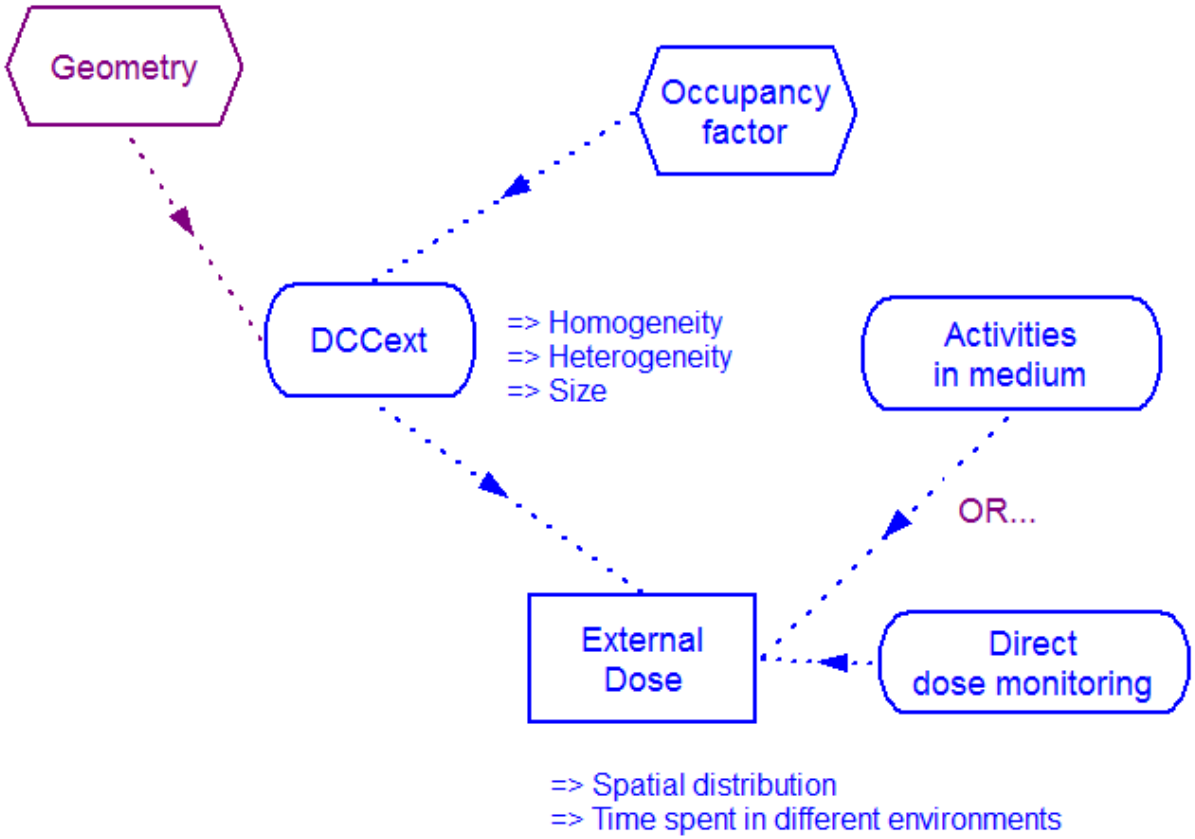
Factors affecting the external dose

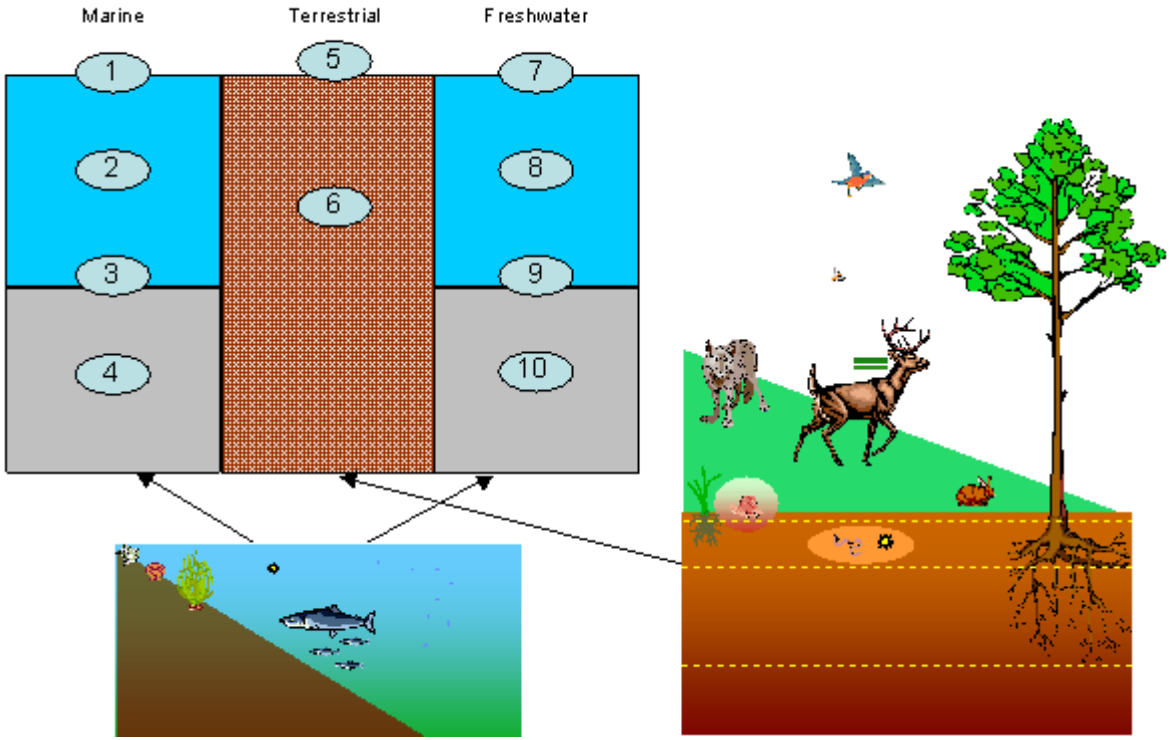


External dosimetry – key issues

- 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 – 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 asumptions: skin/fur, biota in bordering environments (mixed terrestrial, aquatic, aerial scenarios e.g. seabird on land, etc).



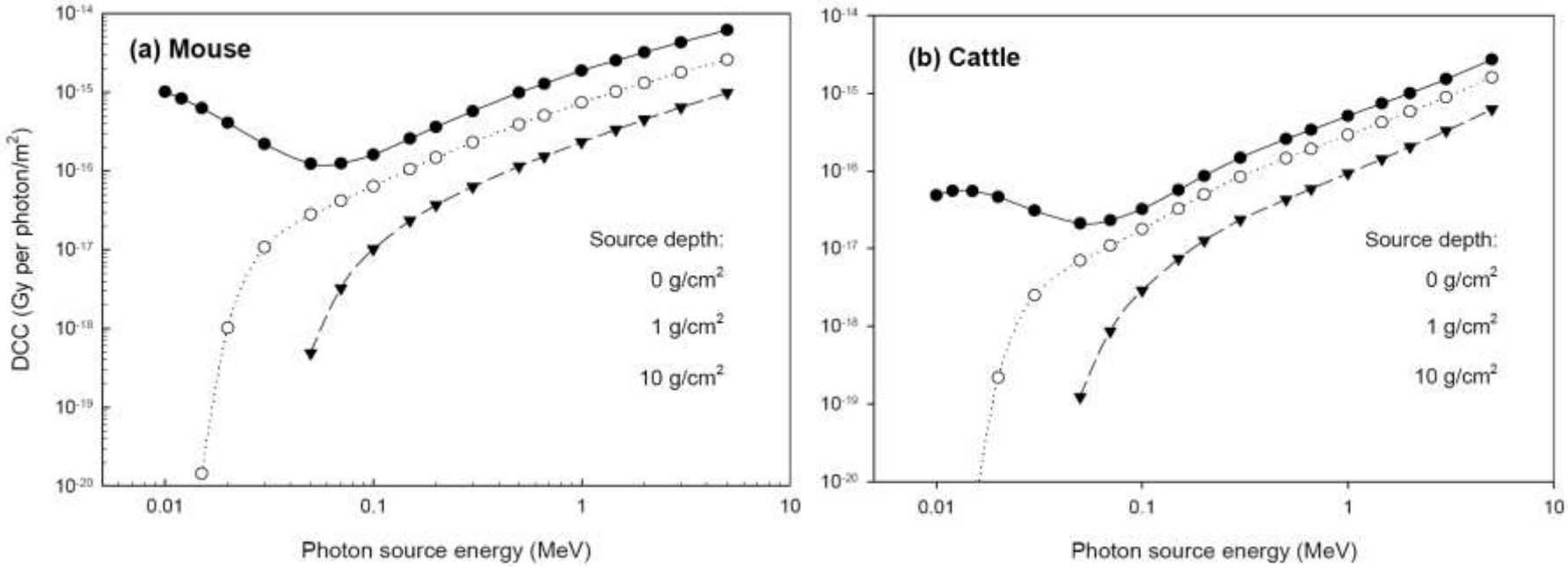
- Ignores life stage-based occupancy differences e.g. bird (flying) versus egg (on tree/nest).

External dosimetry – key issues (2)

- 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 (≤ × 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.



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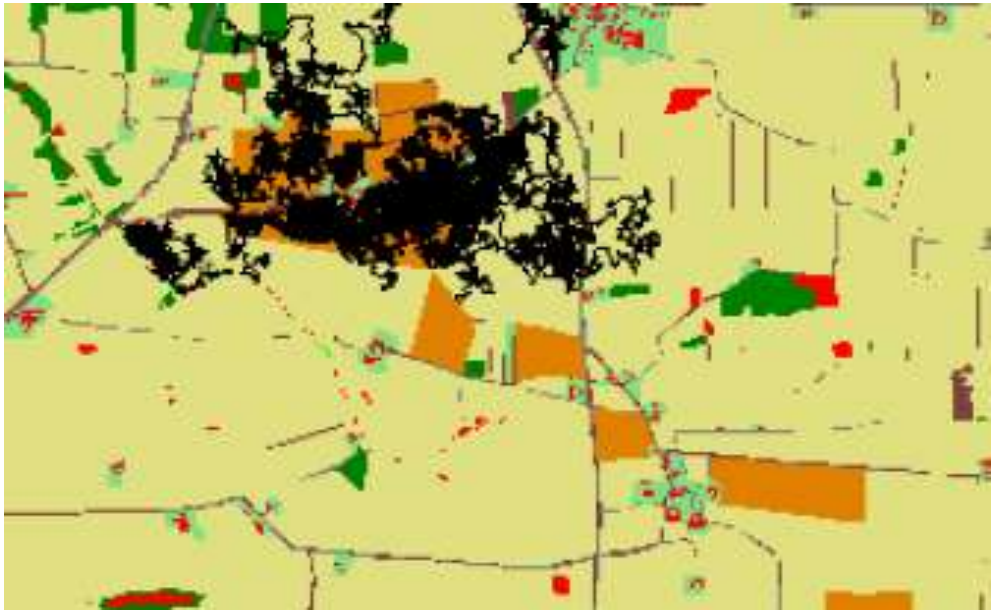
Issues with spatial distribution

- 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.

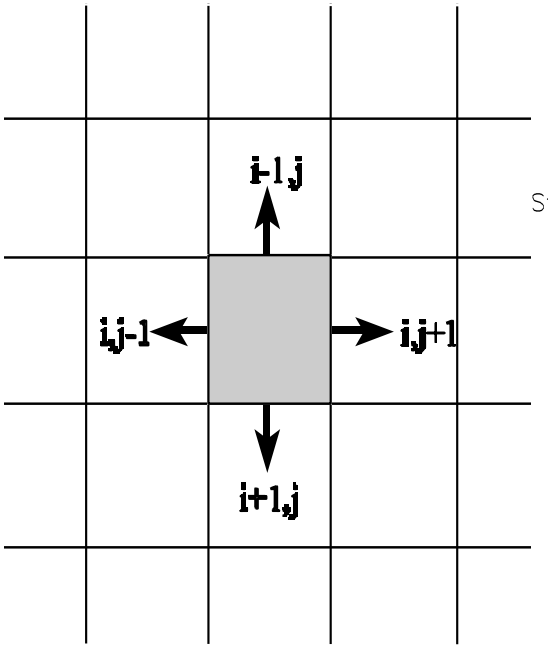


Field voles in agricultural landscape using SmallSteps model (http://www.wageningenur.nl/en/show/GridWalkSmallSteps.htm)

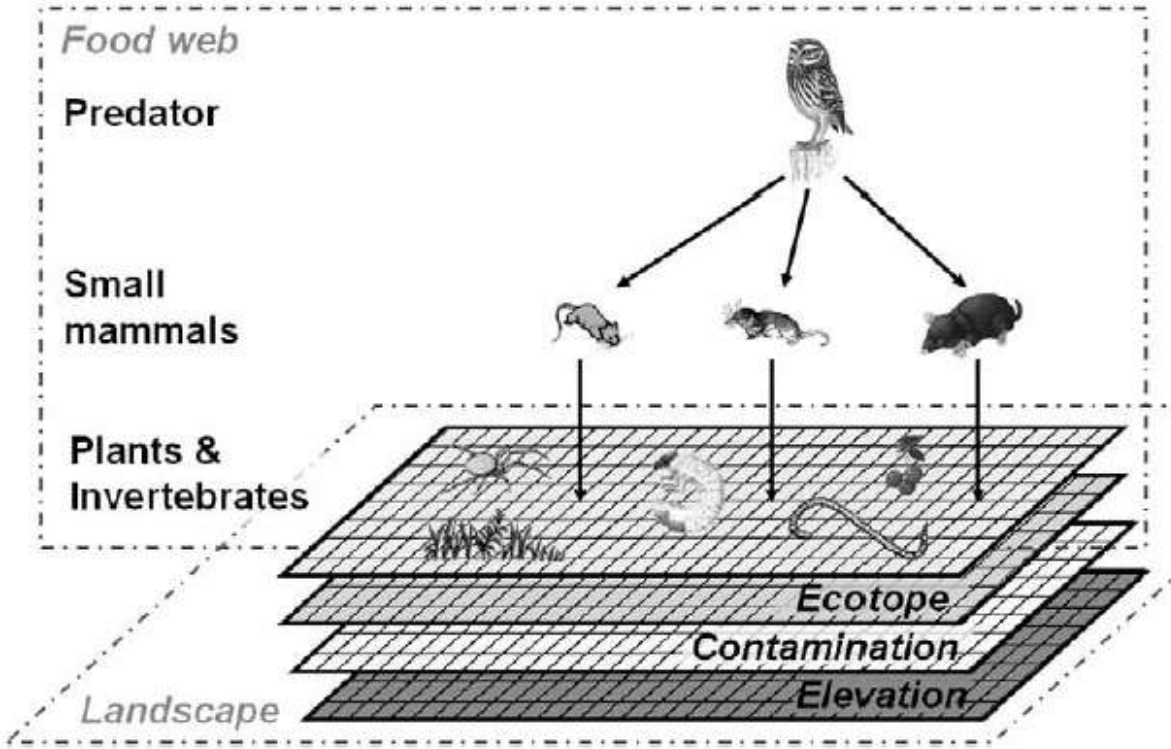
- Some individuals may be exposed to contaminants out of a larger population due to their erratic wandering and foraging patterns in regions more contaminated than others (affects internal dose also).

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

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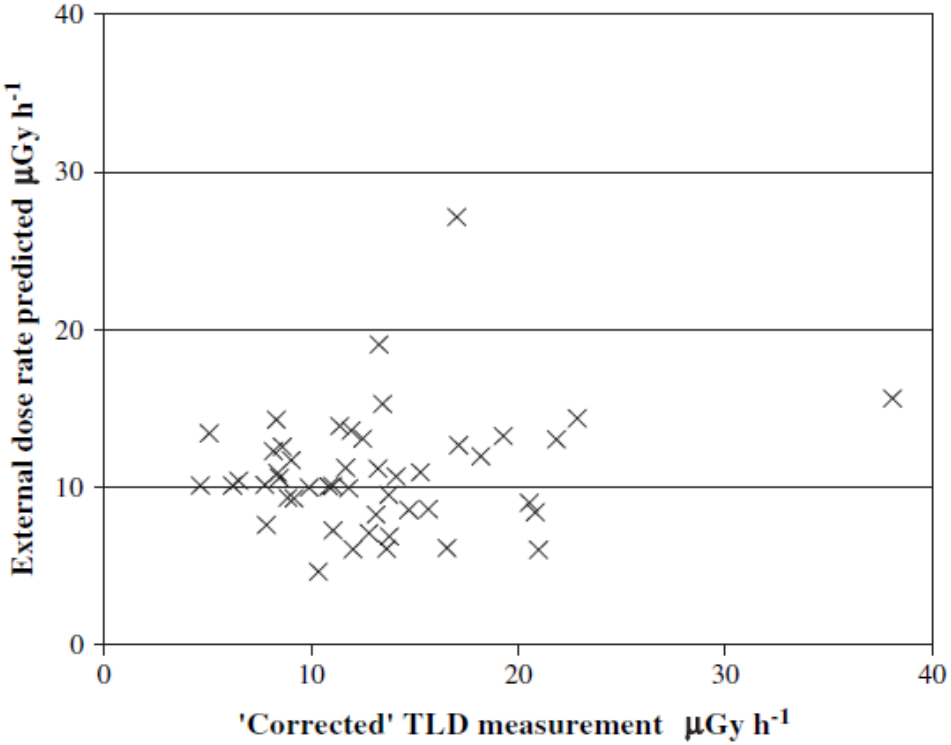
Issues with direct dose measurement

Internal 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 ≤ × 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 (≤ × 2).

External dose measurement

- 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.
- Internal dose cannot be measured but derives from activity.
- 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.

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Internal versus external dose comparison

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

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

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

- Hence the internal and external dose rates are:

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

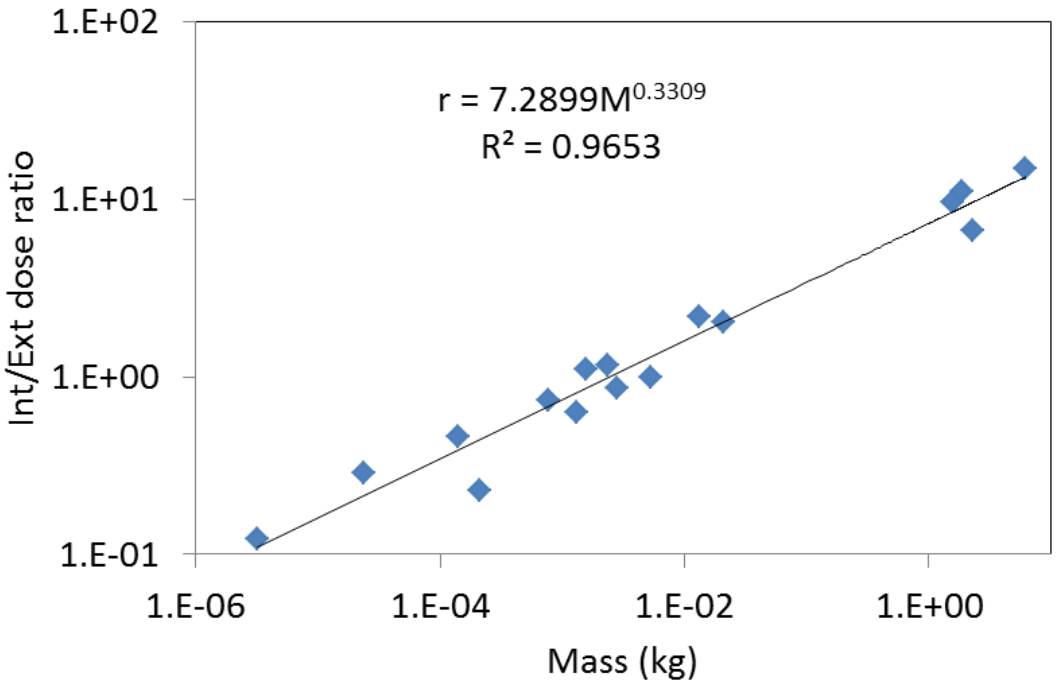
$$D_{external}(Gy\,s^{-1}) = 5.77 \times 10^{-4} \times (1 - AF) \times C_{medium} \times f_{occ}$$

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

- Where we assume CF scales allometrically as CF = a × 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)

Species	Mass (kg)	r
Grass seed	3.1E-06	1.2E-01
Ant	2.4E-05	2.8E-01
Woodlouse	1.4E-04	4.6E-01
Plant root	2.1E-04	2.3E-01
Caterpillar	7.7E-04	7.4E-01
Lichen	1.3E-03	6.3E-01
Bee	1.6E-03	1.1E+00
Fungi	2.4E-03	1.2E+00
Worm	2.8E-03	8.7E-01
Moss	5.2E-03	9.9E-01
Bird egg	1.3E-02	2.2E+00
Mouse	2.1E-02	2.0E+00
Pheasant	1.6E+00	9.7E+00
Rabbit	1.9E+00	1.1E+01
Grass snake	2.3E+00	6.7E+00
Fox	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.

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Attempted quantification of uncertainties

Attempt at evaluation 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 ≤ ± 25%
  - External dose rates ≤ ± 120%
- For the assumption of the homogeneous distribution, the estimation of the internal exposure is pretty accurate (10-20 %)

Attempt at evaluation of uncertainties (2)

- 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).

<u>Transfer</u>

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

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Interpretation issues

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Uncertainty in results interpretation

- Nature adding very large variation to all things in the field, leading to low levels of statistical confidence 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).

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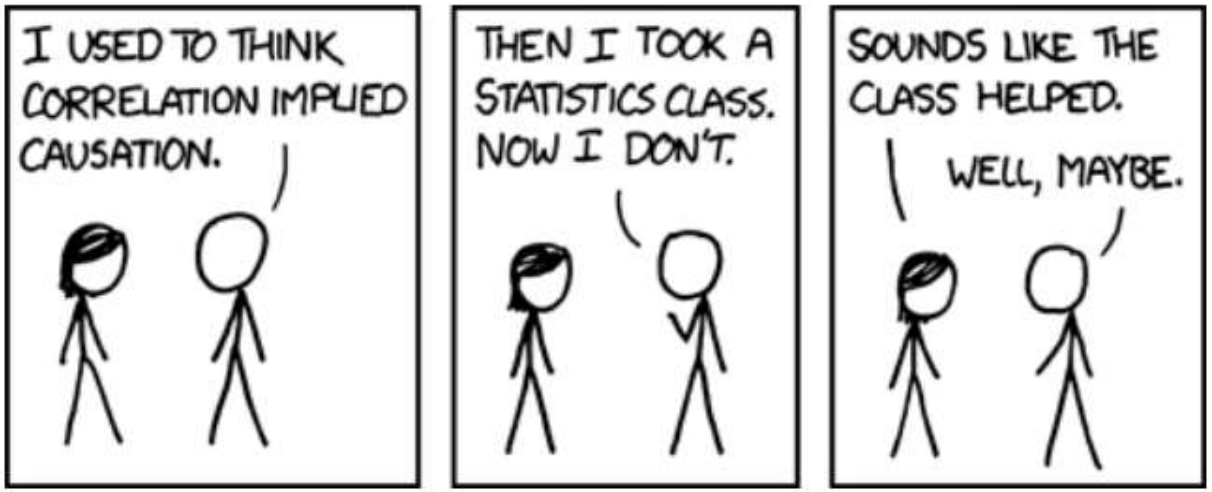
Uncertainty in results interpretation (2)

- 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).



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Conclusions

- 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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References

- Beresford, N.A., Barnett, C.L., Brown, J., Cheng, J.J., Copplestone, D., Filistovic V., et al. (2008). Inter-comparison of models to estimate radionuclide activity concentrations in non-human biota. Radiation and Environmental Biophysics 491-514.
- Beresford, N.A., Gaschak, S., Barnett, C.L., Howard, B.J., Chizhevsky, I., Strømman, G., Oughton, D.H., Wright, S.M., Maksimenko, A. and Copplestone, D. (2008). Estimating the exposure of small mammals at three sites within the Chernobyl exclusion zone – a test application of the ERICA Tool. Journal of Environmental Radioactivity 99: 1496–1502.
- Brown J., Gomez-Ros J.-M., Jones, S.R., Pröhl, G., Taranenko, V., Thørring, H., Vives i Batlle, J. and Woodhead, D, (2003) Dosimetric models and data for assessing radiation exposures to biota. FASSET (Framework for Assessment of Environmental Impact) Deliverable 3 Report under Contract No FIGE-CT-2000-00102, G. Pröhl (Ed.).
- Gómez-Ros, J.M., Pröhl, G., Ulanovsky, A. and Lis, M. (2008). Uncertainties of internal dose assessment for animals and plants due to non-homogeneously distributed radionuclides. Journal of Environmental Radioactivity 99(9): 1449-1455.
- Mohammadi, A., Kinase, S. and saito, K. (2011). Comparison of Photon and Electron Absorbed Fractions in Voxel-Based and Simplified Phantoms for Small Animals. Progress in Nuclear Science and Technology 2:365-368.
- Timms, D.N., Smith, J.T., Cross, M.A., Kudelsky, A.V., Horton, G. and Mortlock, R. (2004) A new method to account for the depth distribution of radiocaesium in soils in the calculation of external radiation dose rate. Journal of Environmental Radioactivity, 72, 323-334.
- Ulanovsky, A. and Pröhl, G. (2006) A practical method for assessment of dose conversion coefficients for aquatic biota. Radiation and Environmental Biophysics 45: 20 -214.

References

- Vives i Batlle, J., Barnett, C.L., Beaugelin-Seille,r K., Beresford, N.A., Copplestone, D., Horyna, J., et al. (2011). Absorbed dose conversion coefficients for non-human biota: an extended inter-comparison of data. Radiation and Environmental Biophysics 50: 231-251.
- Vives i Batlle, J., Wilson, R.C., Watts, S.J., Jones, S.R., McDonald, P. and Vives-Lynch, S. Dynamic model for the assessment of radiological exposure to marine biota. Journal of Environmental Radioactivity 2008; 99(11): 1711-1730.
- Vives i Batlle, J., Jones, S.R. and Gómez-Ros, J.M. (2004) A method for calculation of dose per unit concentration values for aquatic biota. Journal of Radiological Protection 24(4A): A13-A34.
- Vives i Batlle, J., Jones, S.R. and Copplestone, D. (2008) Dosimetric Model for Biota Exposure to Inhaled Radon Daughters. Environment Agency Science Report – SC060080, 34 pp.
- Woodhead, D.S. (1984) Contamination due to radioactive materials. In: Kinne O (ed) Marine ecology, vol v, part 3: pollution and protection of the seas – radioactive materials, heavy metals and oil. Wiley, New York, NY, pp 1111–1287.