Noble gas dosimetry for non-human biota

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Reasons for noble gas dosimetry

- ^{85}Kr and ^{41}Ar account for approximately 75% and 10% of airborne releases for nuclear reactors
- Smaller amounts of ^{131m}Xe, ^{133}Xe and ^{88}Kr also released.
  - ^{41}Ar and ^{85}Kr contribute 80% from next-generation AP1000 reactors
  - ^{85}Kr the main radionuclide discharged from Sellafield (~ 40 PBq y^{-1}).
- For inert gases Ar and Kr plume immersion is the only concern.
- For Rn there is the problem of internal dose by the daughters.
- General drive to ensure that the environment is protected
  - Ongoing need to prove limited impact in new reactor designs
  - Compliance and public perception (birds roosting on stacks?)
  - The US NRC now includes the plume dose from noble gas emissions in assessing dose to biota for new reactor licensing

First steps in methodology development

- In previous habitat assessments, the EA (2002) suggested ^{137}Cs as an analogue for application in assessments of ^{41}Ar and ^{85}Kr, and ^{239}Pu for ^{222}Rn and its daughters.
- However, the use of such an analogue led to highly conservative dose estimates (Beresford et al., 2004).
- Produce sufficiently robust methodology to allow the calculation of Ar, Kr and Rn doses to biota without using analogues.
- Explicit approaches developed in 2003 (Ar, Kr) and 2009 (Rn) at Westlakes Scientific Consulting, UK
- The Ar and Kr method was adopted in an updated version of the EAR&D 128 methodology.
  - To date, no such approach exists in ERICA and the method remains a valid option.

Points to note

- Noble gases have a small but finite solubility in water and body fluids.
- ^{41}Ar and ^{85}Kr are inert gases and internal incorporation in animals can be neglected compared with cloud immersion.
- Noble gases are not deposited to soil (so no plant uptake, etc.).
- Will be exchanged within the air pore volume of surface soil (but small component).
- So we assume pore air concentration = ground level air concentration

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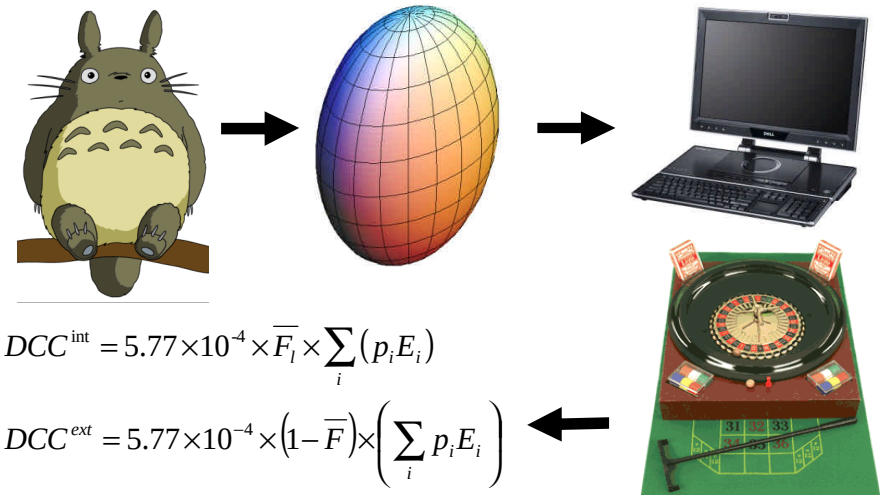
Argon and krypton methodology

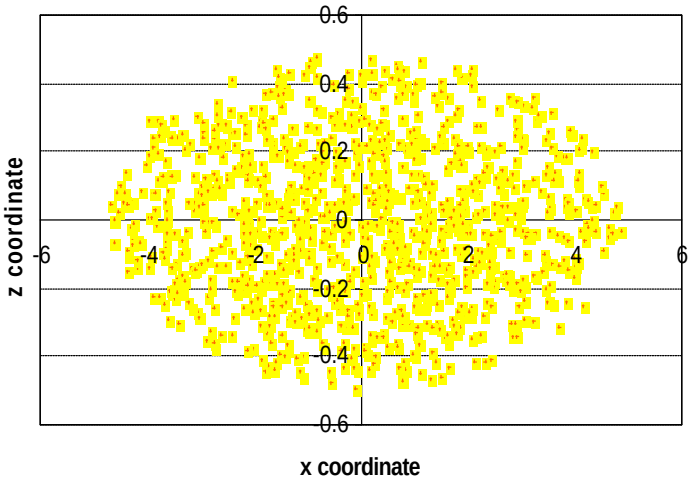
Approach

- Calculate DCC values using the EA R&D 128 ellipsoid-based Monte Carlo approach.
- Compare with human dose conv. factors (DCFs) from ICRP 72.
- Study dependence of DCC with area/volume ratio
- Incorporate methodology into R&D 128 terrestrial model.
- Update wqith ERICA geometries



$$DCC^{int} = 5.77 \times 10^{-4} \times \overline{F_l} \times \sum_i (p_i E_i)$$

$$DCC^{ext} = 5.77 \times 10^{-4} \times (1 - \overline{F}) \times \left(\sum_i p_i E_i \right)$$



DCC calculation

- Inputs: Ar and Kr in air (measured or calculated with simple semi-infinite cloud model)
- Outputs: Convert DCC in μGy h^{-1}/Bq m^{-3} instead of kg^{-1} using 1.2 kg m^{-3} air density.
- Usual approximations: equilibrium transfer, ellipsoid geometries, uniform density between organism and media, uniform distribution in organism and doses averaged for whole body.
- Species considered: all terrestrial R&D 128 + “reference man” ellipsoid defined for comparison with ICRP-72.
- Method has been recently revamped to include:
  - DCCs for the ERICA reference organisms
  - DCCs for ^{131m}Xe, ^{133}Xe and ^{88}Kr
- Paper submitted to STOTEN

Dose calculation – humans *vs*. biota

$$Dose_{ij}^{imm} = C_j \left(dcf_j^{skin} + a \times dcf_j^{imm} (1 - f_i^{ind} (1 - b)) \right) \times f_i^{occ} h_y$$

$Dose_{ij}^{imm}$	- Plume immersion dose to age group *i*, nuclide *j* (Sv y^{-1}).
dcf_j^{skin}	- Skin dose from unit air concentration, nuclide j (Sv h^{-1}/Bq m^{-3}).
C_j	- Air concentration (Bq m^{-3}).
dcf_j^{imm}	- Dose from unit air concentration, nuclide j (Sv h^{-1}/Bq m^{-3}).
a	- Multiplier to account for departure from semi-infinite plume.
b	- Multiplier to account for shielding from a building.
f_i^{ind}	- Fraction of time spent indoors during site occupancy.
f_i^{occ}	- Fraction of time spent at site (site occupancy).
h_y	- Number of hours in one year (8760 h y^{-1}).

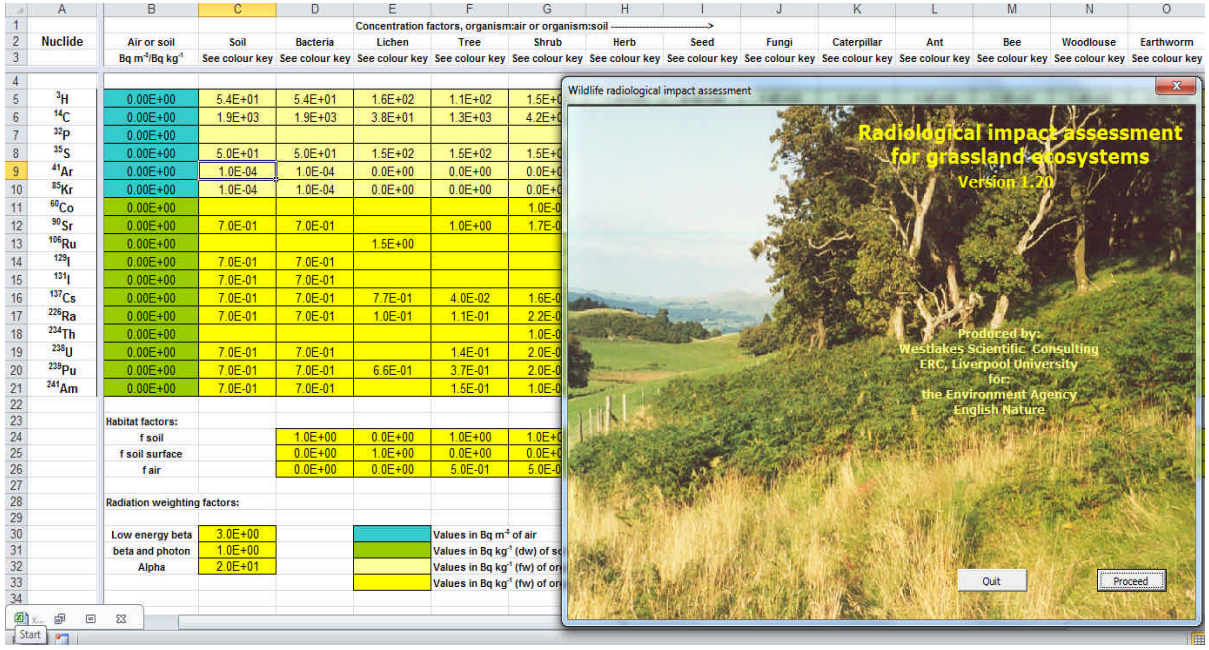
- This is a modified semi-infinite cloud model for close distances from source
- For biota we adapt tis to use a = 1, b = 0, f_i^{ind} = 0, and f_i^{occ} = 1.

DCCs FOR Ar, Kr and Xe (ERICA organisms)

Radionuclide	Amphibian	Annelid	Arthropod Detritivorous	Bird	Detritivorous Invertebrate	Flying insects	Grasses & Herbs	Lichen & bryophytes	Mammal – large	Mammal – small	Mollusc – Gastropod	Reptile	Tree
^{41}Ar (7.613E-02 days)													
Dpuc(int) low beta	7.6E-11	7.6E-11	7.6E-11	7.6E-11	7.6E-11	7.6E-11	7.6E-11	7.6E-11	7.6E-11	7.6E-11	7.6E-11	7.6E-11	7.6E-11
Dpuc(int) beta plus photon	2.3E-04	1.9E-04	1.5E-04	2.8E-04	1.5E-04	1.8E-04	1.9E-04	1.1E-04	5.0E-04	2.5E-04	2.0E-04	2.4E-04	4.1E-04
Dpuc(int) photon	2.1E-05	8.9E-06	3.4E-06	6.9E-05	3.4E-06	5.8E-06	8.4E-06	2.1E-06	2.9E-04	4.3E-05	7.9E-06	3.1E-05	2.0E-04
Dpuc(ext) low beta	1.5E-15	5.0E-15	1.8E-14	1.0E-15	2.0E-14	8.0E-15	5.5E-15	3.3E-14	2.1E-16	6.7E-16	3.8E-15	1.3E-15	3.1E-16
Dpuc(ext) beta plus photon	5.9E-04	6.2E-04	6.6E-04	5.3E-04	6.6E-04	6.4E-04	6.2E-04	7.1E-04	3.1E-04	5.6E-04	6.2E-04	5.8E-04	4.0E-04
Dpuc(ext) photon	5.8E-04	5.9E-04	5.9E-04	5.3E-04	5.9E-04	5.9E-04	5.9E-04	6.0E-04	3.1E-04	5.5E-04	5.9E-04	5.7E-04	4.0E-04
^{85}Kr (3.913E+03 days)													
Dpuc(int) low beta	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Dpuc(int) beta plus photon	1.1E-04	1.1E-04	9.9E-05	1.2E-04	9.8E-05	1.1E-04	1.1E-04	8.4E-05	1.2E-04	1.2E-04	1.1E-04	1.1E-04	1.2E-04
Dpuc(int) photon	4.1E-08	1.7E-08	6.3E-09	1.3E-07	6.3E-09	1.1E-08	1.6E-08	4.0E-09	5.8E-07	8.4E-08	1.5E-08	6.1E-08	4.0E-07
Dpuc(ext) low beta	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Dpuc(ext) beta plus photon	3.2E-06	8.0E-06	1.9E-05	1.7E-06	1.9E-05	1.1E-05	8.2E-06	3.4E-05	5.7E-07	2.0E-06	6.9E-06	2.7E-06	8.5E-07
Dpuc(ext) photon	9.9E-07	1.0E-06	1.0E-06	8.9E-07	1.0E-06	1.0E-06	1.0E-06	1.0E-06	4.5E-07	9.4E-07	1.0E-06	9.7E-07	6.3E-07
^{88}Kr (1.18E-01 days)													
Dpuc(int) low beta	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Dpuc(int) beta plus photon	7.9E-04	4.8E-04	2.8E-04	1.1E-03	2.8E-04	3.9E-04	4.8E-04	1.6E-04	1.7E-03	1.0E-03	5.2E-04	8.9E-04	1.5E-03
Dpuc(int) photon	4.0E-05	1.7E-05	6.5E-06	1.3E-04	6.5E-06	1.1E-05	1.6E-05	3.9E-06	5.4E-04	8.2E-05	1.5E-05	5.8E-05	3.7E-04
Dpuc(ext) low beta	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Dpuc(ext) beta plus photon	1.5E-03	1.8E-03	2.0E-03	1.2E-03	2.0E-03	1.9E-03	1.8E-03	2.2E-03	6.6E-04	1.3E-03	1.8E-03	1.4E-03	8.5E-04
Dpuc(ext) photon	1.1E-03	1.2E-03	1.2E-03	1.1E-03	1.2E-03	1.2E-03	1.2E-03	1.2E-03	6.4E-04	1.1E-03	1.2E-03	1.1E-03	8.1E-04
^{134m}Xe (1.19E+0.1 days)													
Dpuc(int) low beta	1.8E-06	1.8E-06	1.8E-06	1.8E-06	1.8E-06	1.8E-06	1.8E-06	1.8E-06	1.8E-06	1.8E-06	1.8E-06	1.8E-06	1.8E-06
Dpuc(int) beta plus photon	6.6E-05	6.4E-05	6.1E-05	6.9E-05	6.1E-05	6.3E-05	6.4E-05	5.6E-05	7.3E-05	6.8E-05	6.4E-05	6.7E-05	7.1E-05
Dpuc(int) photon	1.7E-06	7.9E-07	3.6E-07	3.8E-06	3.6E-07	5.6E-07	7.6E-07	2.3E-07	7.5E-06	2.9E-06	7.7E-07	2.1E-06	6.4E-06
Dpuc(ext) low beta	3.8E-11	1.3E-10	4.5E-10	2.6E-11	5.0E-10	2.0E-10	1.4E-10	8.4E-10	5.1E-12	1.7E-11	9.8E-11	3.3E-11	7.6E-12
Dpuc(ext) beta plus photon	8.1E-06	1.0E-05	1.4E-05	5.7E-06	1.4E-05	1.1E-05	1.0E-05	1.8E-05	1.8E-06	6.6E-06	9.9E-06	7.6E-06	3.0E-06
Dpuc(ext) photon	7.6E-06	8.5E-06	9.0E-06	5.5E-06	9.0E-06	8.8E-06	8.6E-06	9.1E-06	1.8E-06	6.4E-06	8.6E-06	7.2E-06	2.9E-06
^{133}Xe (5.25E+00 days)													
Dpuc(int) low beta	1.2E-06	1.2E-06	1.2E-06	1.2E-06	1.2E-06	1.2E-06	1.2E-06	1.2E-06	1.2E-06	1.2E-06	1.2E-06	1.2E-06	1.2E-06
Dpuc(int) beta plus photon	6.4E-05	6.2E-05	6.0E-05	6.7E-05	6.0E-05	6.1E-05	6.2E-05	5.7E-05	7.8E-05	6.6E-05	6.2E-05	6.4E-05	7.4E-05
Dpuc(int) photon	2.1E-06	8.8E-07	3.7E-07	5.6E-06	3.7E-07	6.0E-07	8.4E-07	2.3E-07	1.6E-05	3.9E-06	8.3E-07	2.8E-06	1.2E-05
Dpuc(ext) low beta	2.5E-11	8.5E-11	3.0E-10	1.7E-11	3.3E-10	1.3E-10	9.3E-11	5.5E-10	3.4E-12	1.1E-11	6.4E-11	2.2E-11	5.0E-12
Dpuc(ext) beta plus photon	2.0E-05	2.1E-05	2.3E-05	1.6E-05	2.3E-05	2.2E-05	2.1E-05	2.6E-05	5.0E-06	1.8E-05	2.1E-05	1.9E-05	9.1E-06
Dpuc(ext) photon	1.9E-05	2.1E-05	2.1E-05	1.6E-05	2.1E-05	2.1E-05	2.1E-05	2.1E-05	5.0E-06	1.8E-05	2.1E-05	1.9E-05	9.1E-06

Implementation in EA R&D 128

- Introduction of two new radionuclides (^{41}Ar and ^{85}Kr);
- Inclusion of the ^{41}Ar and ^{85}Kr DCCs converted to µGy h^{-1}/Bq kg^{-1} of air;



- Simple modifications to the code necessary to accommodate the fact that ^{41}Ar and ^{85}Kr (like ^{3}H, ^{14}C, ^{32}P and ^{35}S, already in model) derive from a concentration in air rather than in soil, and
- Small changes in coding to include doses from immersion of organisms in air in the calculation.

Concentration ratio approach

- Internal dose negligible: default Ar and Kr CRs for all organisms set to 0.
- Although no deposition, some migration into soil pores possible leading to a transfer factor.
  - Assume pore air is at the same concentration as ground level air concentrations
  - assume a free air space of 0.15 v:v, bulk density for soil of 1500 kg m-3, so free air space = 0.15/1500 = 10^{-4} m^3 kg^{-1}. Thus Bq m^{-3}(air) × 10^{-4} = Bq kg^{-1} (wet soil).
  - A TF of 10^{-4} is therefore specified as a default for air (Bq m^{-3}) to soil (Bq kg^{-1} wet).

Occupancy factors

- For plants and fungi occupancy factors are changed to 1.0 soil, 0.5 air (instead of 0).
- Soil, bacteria and earthworms are assumed to reside only in the subsurface soil and are exposed only to ^{41}Ar and ^{85}Kr in the air pore spaces.
- External DCCs for fungi are those calculated for bacteria (i.e. infinite medium DCCs). Internal DCCs are those calculated for the dimensions of the fruiting body.

Dose calculation formulae

- The R&D 128 spreadsheet uses the following formulae for <u>all</u> radionuclides whose concentration is referenced to air: ^{3}H, ^{14}C, ^{32}P, ^{35}S, ^{41}Ar and ^{85}Kr.

$$(\text{Soil conc})_{nuclide} = (\text{Air conc, Bq m}^{-3})_{nuclide} \times CR^{\text{soil}}_{nuclide}$$

$$(\text{Air conc, Bq kg}^{-1})_{nuclide} = (\text{Air conc, Bq m}^{-3})_{nuclide} / 1.2$$

$$(\text{Internal dose})_{nuclide,organism} = (\text{Air conc})_{nuclide} \times CR^{\text{organism}}_{nuclide} \times DCC^{\text{internal}}_{nuclide,organism}$$

$$(\text{External dose})_{nuclide,\ organism} = (Soil\ \ dose + Immersion\ \ dose)$$

$$(Soil\ \ dose) = DCC^{\text{external}}_{nuclide,organism} \times$$

$$\left[(\text{Soil conc})_{nuclide} \times \left(\begin{array}{l} \left(fsoil_{organism} + fsoilsur_{organism} / 2 \right) \\ + \ fair_{organism} \times (\text{reduction factor})_{\text{radiation type}} \end{array} \right) \right]$$

$$(Immersion\ \ dose) = DCC^{\text{external}}_{nuclide,organism} \times (\text{Air conc, Bq kg}^{-1})_{nuclide} \times$$

$$(fair_{organism} + fsoilsur_{organism} / 2)$$

- Where the reduction factor is the modifier for dose to organisms in air is received from exposure to soil: 0 for α and low-energy β radiation and 0.25 for high energy $\beta+\gamma$ radiation.

Comparison with human dosimetry (ICRP 72)

Source	Description	DCC (mSv h^{-1} per Bq m^{-3}) ^{41}Ar	^{85}Kr
Human dosimetry	External γ DCF[1]	2.20E-04	4.73E-07
	Skin (β) DCF[2]	8.69E-07	4.44E-07
	Total (β+γ) DCF	2.21E-04	9.17E-07
Monte Carlo calculation	External DCC[3]	2.03E-04	3.89E-07

- [1]Data from ICRP 72 (1996). [2]Data from Simmonds *et al.* (1995). [3]Geometry-corrected as ½ × external DCC (beta plus photon) values for the "human geometry" above.
- ICRP 72 ^{85}Kr immersion dose rate is 9.2×10^{-13} Sv h^{-1} per unit air conc.
- This is an effective dose (includes skin dose with a weighted by 1%). From the EU methodology (Simmonds *et al.* 1995), the weighted beta dose rate to skin is given as 4.44×10^{-13} Sv h^{-1}.
- Assuming that only the skin receives beta dose, the dose rate due to gamma is therefore $9.17 \times 10^{-13} - 4.4 \times 10^{-13} = 4.73 \times 10^{-13}$ Sv h^{-1}.

Conceptual difference human vs. biota

- Human DCFs are calculated for a plume emitting "from above", i.e., over a 2π (semi-infinite) geometry.
- Biota DCCs, are calculated assuming that the medium envelops the organism (infinite) geometry.
- This is not an inconsistency in so far as it is recognised that the human DCFs and biota DCCs refer to two different geometry definitions.
- Having corrected biota DCCs by a factor of 0.5, we should obtain identical results for ^{41}Ar and about a half different for ^{85}Kr.

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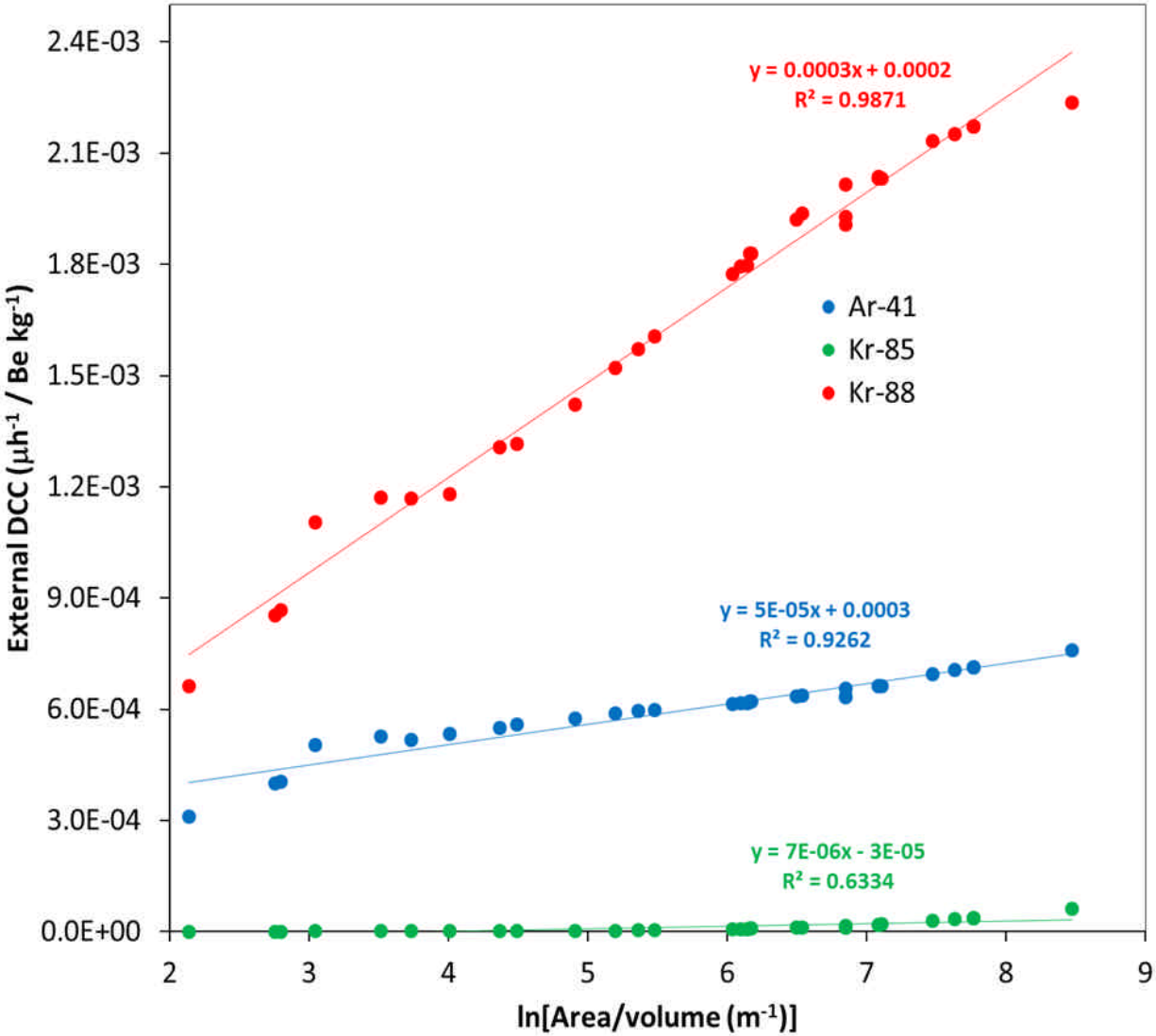
Comparison results

- For ^{41}Ar, only 0.25% of the total biota DCC arises from β-radiation.
- For Kr, the β- component is significantly higher.
- For γ-rays, both methods (DCF and DCC) give the same result for Kr.
- However, for ß-radiation, the DCC method undershoots for Kr.
- Explanation: The DCC method averages the external dose over the whole volume, whereas the DCF method averages over an outer layer.
- The averaging method makes little difference for small organisms and significant difference for large organisms like a human.
- Hence, the "1% of skin dose" component of the human DCF (4.7×10^{-5} µSv h^{-1} per Bq m^{-3}) should resemble the DCC for a very small organism (divided by geometry factor of 2).
- Examination of a suitable small organism ("germinating seed") confirms this. ß DCC = $6.1 \times 10^{-5}/2 = 3.1 \times 10^{-5}$ µSv h^{-1} per Bq m^{-3}.
- The two values are less than 35% different; this provides assurance that ignoring density differences has not introduced significant errors.

Relationship between DCC and organism size

- Select area/volume as the sizing variable.
- DCCs increase with larger area (more surface to absorb) and decrease with larger volume (averaging into larger organism).
- Predicted Ar and Kr DCCs of 2.6 $\times 10^{-4}$ and 6.4 $\times 10^{-7}$ µGy h^{-1}/ Bq m^{-3}, similar to explicitly calculated values.



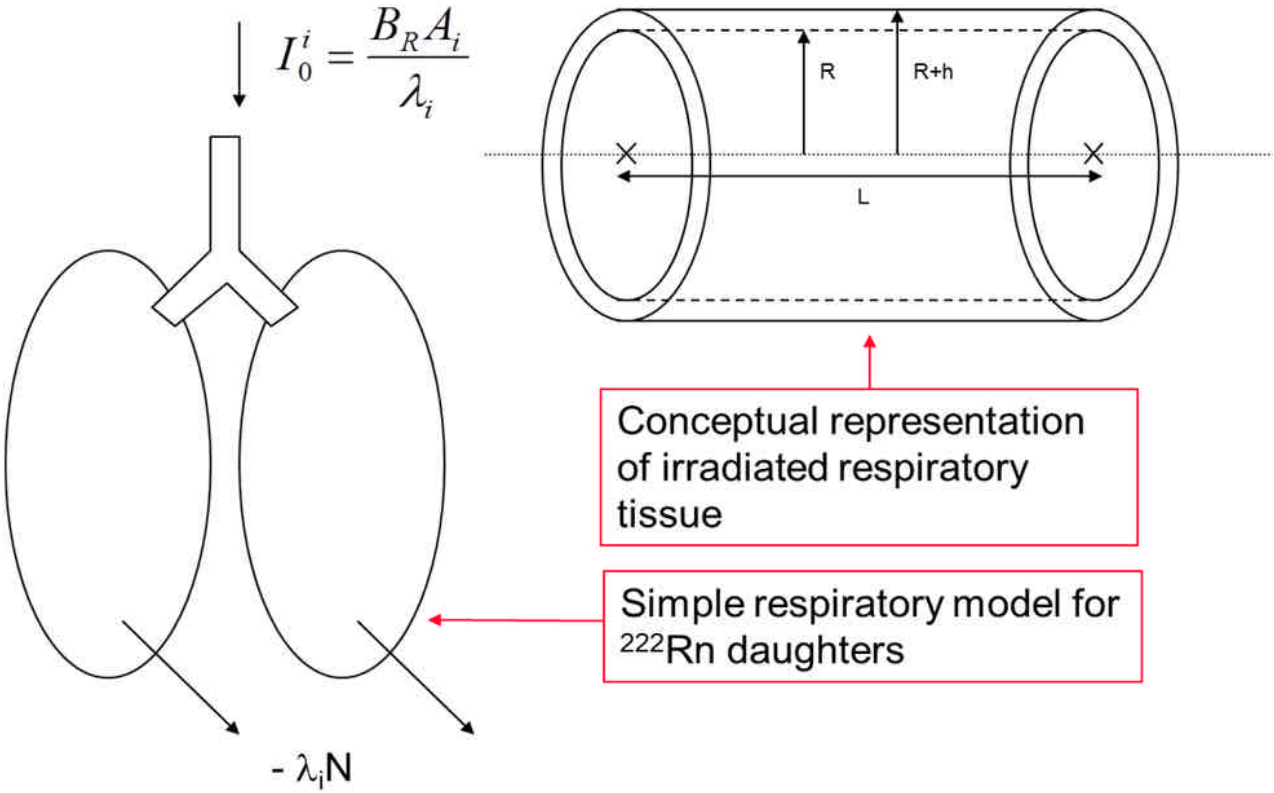
Using ^{85}Kr as an analogue for other Kr and Xe

- Previous statement that other Xe and Kr isotopes can be modelled using ^{85}Kr as a surrogate (Copplestone et al., 2010).
- We tested this assumption by calculating DCCs for ^{131m}Xe, ^{133}Xe and $^{88}Kr(+^{88}Rb)$ explicitly.
- The DCCs for ^{88}Kr can vary significantly with respect to ^{85}Kr: by a factor between 10 and 300 (β-radiation > 10 keV) and between 1200 and 1400 (γ-radiation).
- The corresponding factor ranges of variation for ^{131m}Xe and ^{133}Xe are 0.2 - 3800 and 4 – 20, respectively; similar for both radionuclides.
- The main sources of difference are therefore (a) the larger amount of γ-emissions of ^{88}Kr (52 vs. 1 for ^{85}Kr and 10 for the Xe isotopes), and (b) the stronger high-energy β-component of the Xe isotopes.
- The ^{85}Kr analogue approximation is therefore not valid for ^{88}Kr.
- For Xe, it is only valid for small organisms – not for birds, mammals and trees.

Radon – allometric model

Basis of the approach

- A model based on allometrically derived respiration rates and target tissue masses, designed for calculating ^{222}Rn daughter dose rates to sensitive tissues and the whole body of terrestrial animals and plants.



Problem formulation

- Model the input of a constant flow of atoms into a compartment with continuous decay, with these two fluxes in equilibrium.
- Assume that the compartment is 100% efficient at trapping the material, i.e. no particles escape by exhalation and decay is the only source of removal.
- The input flow I_0^i equals the specific activity × breathing rate / decay constant (in order to convert disintegrations per unit time to particles).

$$I_0^i = \frac{B_R A_i}{l_i}$$

i: Index labelling the radionuclide: 1 to 5 for ^{222}Rn, ^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po;
A_i: Activity of radionuclide *i* [Bq m^{-3}] = A_1 (secular equilibrium)
BR: Breathing rate [m^3 s^{-1}] = tidal volume (V_T) × breathing frequency (ν_R)
l_i: Decay constant of radionuclide *i* [s^{-1}].

- From here the DCC is:

$$DCC = \frac{\dot{D}}{A_{Rn}} = \frac{B_R D_P^a}{M_T} = 5.54 \times 10^{-9} \frac{B_R}{M_T}$$

- Where D_a^p is the potential α-energy per Bq activity of the short-lived radon daughters in secular equilibrium

Allometric scaling

- Many biological parameters relating to organism structure relate to metabolism and scale according to the Brody-Kleiber law:

$$Y = A \times M^{b},\ b = 0.75$$

- Other parameters scale on the basis of surface exchange, like radiation flux and heat transfer:

$$S \propto r^{2} and\ M \propto V \propto r^{3} \Rightarrow S \propto M^{\frac{2}{3}} and\ \frac{S}{V} \propto M^{-\frac{1}{3}}$$

- For this study we use the following relationships:

$$B_R(M) = A_{BR} M^{B_{BR}} = (8.7 \pm 4.4) \times 10^{-6} M^{0.76 \pm 0.02}$$

$$M_L(M) = A_{LM} M^{B_{LM}} = (1.28 \pm 0.72) \times 10^{-2} M^{1.02 \pm 0.03}$$

- M is the mass in kg and B_R is the ventilation rate in $m^3\ h^{-1}$.

Allometric scaling

Breathing rate comparison using different allometric formulae

Organism	Reference	Measured BR ($m^3 s^{-1}$)	Predicted BR ($m^3 s^{-1}$) Ref. Man	DOE (1992)	Peters (1983)	This work
Man	Reference man	3.34E-04	3.33E-04	1.41E-04	1.88E-04	2.20E-04
Rat	Hofmann *et al*. (1992)	3.90E-06	5.58E-06	2.23E-06	2.76E-06	3.49E-06
Oryzomys	Drew & Eisenbud (1966)	6.67E-07	1.97E-06	7.78E-07	9.07E-07	1.22E-06

Base and exponent of the allometric formulae for ^{222}Rn daughter DPUCs (internal α irradiation)

Parameter	B	TB	L	WB
Base A	5.14E-04	5.55E-05	3.77E-06	4.83E-08
Exponent B	9.63E-02	9.63E-02	-2.57E-01	-2.37E-01

Animal DCCs

- Simple power functions for DPCCs in μGy h^{-1} per Bq m^{-3}:

$$DCC_B = F_U R_{WF}^{\alpha} \left(\frac{D_P^{\alpha} A_{BR}}{r_T h_T S_B^{RM}} M_{RM}^{2/3} \right) M^{B_{BR} - \frac{2}{3}}$$

$$DCC_{TB} = F_U R_{WF}^{\alpha} \left(\frac{D_P^{\alpha} A_{BR}}{r_T h_T S_{TB}^{RM}} M_{RM}^{2/3} \right) M^{B_{BR} - \frac{2}{3}}$$

$$DCC_L = F_U R_{WF}^{\alpha} \left(\frac{D_P^{\alpha} A_{BR}}{A_{LM}} \right) M^{B_{BR} - B_{LM}}$$

$$DCC_{WB} = F_U R_{WF}^{\alpha} \left(D_P^{\alpha} A_{BR} \right) M^{B_{BR} - 1}$$

This approach is only recommended for mammals. Applicability to other animals with structurally simpler respiratory systems (birds, reptiles, amphibians and insects) is conjectural and likely over-conservative.

F_U: Unit conversion factor (3.6×10^9 μGy h^{-1} per Gy s^{-1});
BR: Gross extrapolation to the bronchial epithelium (airway generations 1 - 8);
TB: Full tracheobronchial epithelium (generations 1 - 15); L: Full lung; WB: Whole body;
$A_{BR}(A_{LM})$, $B_{BR}(B_{LM})$: Base and exponent of the allometric formulae for breathing rate & lung mass;
S_{TB}^{RM} and S_B^{RM} : surface area of the tracheobronchial tree or the bronchial epithelium;
R_{wf}^{α}: Radiation weighting factor for α-energy (default = 20).

Approximation for plants

- The rate of resource use in plants = A x $M^{3/4}$, though isometric respiration rates have also been suggested.
- We calculated a breathing rate relationship for plants from whole plant respiration:
  - Use respiration rate (net CO_2 efflux in nmol CO_2 s^{-1}) = $1.19 \times M^{1.02}$ from Reich et al. (2005).
  - Apply conversion factor of 2.5×10^3 mols of air per mols of CO_2
  - Apply a generic wet: dry mass ratio of 5 and a molar volume of 22.4 l STP.
  - This is the largest potential source of uncertainty in this calculation.

$$BR_{PLANT}(m^3 s^{-1}) = 1.95 \times 10^{-4} M(kg)^{1.02} = A_{PL} M^{B_{PL}}$$

  - Justification: dry air contains approximately 0.04% carbon dioxide. The partial pressure of carbon dioxide in dry air at sea level is, therefore, 4×10^{-4} Pa. One mol of air will have 4×10^{-4} mols of CO_2 in it; hence there are $1 / 4 \times 10^{-4} = 2.5 \times 10^3$ mols of air per mol of CO_2.

Approximation for plants

- Ellipsoid with axes L, a, a: $V_{ellipsoid} = \frac{1}{6} pLa^2$
- 'Equivalent' cylinder radius: $R = \frac{a}{\sqrt{6}}$
- The target tissue is the space between the two interlocking cylinders of radii *R* and *R* + h_T and length *L*, with mass:

$$m_T \approx \sqrt{\frac{2}{3}} p r a L h_T = 2\sqrt{6}\,\frac{h_T}{a} M$$

- Where M is the total mass of the organism.
- Assume that assume that the whole plant is a surface exchanging gases with the atmosphere.
- Give doses a factor of < 5 of what would have been obtained using the allometric formulae for animals.

Plant DCCs

- Simple power functions for DPCCs in µGy h^{-1} per Bq m^{-3}:

$$DCC_{PLANT\ TISSUE} = F_U R_{WF}^a D_P^a \frac{A_{PL} a M^{B_{PL}-1}}{2\sqrt{6} h_T}$$

$$DCC_{WHOLE\ PLANT} = F_U R_{WF}^a D_P^a A_{PL} M^{B_{PL}-1}$$

D_P^a: Potential α-energy factor 5.54×10^{-9} J Bq^{-1};

A_{PL}: Allometric base for breathing rate in plants, 1.95×10^{-4} m^3 s^{-1} calculated by Vives i Batlle et al. (2012) based on previous data (Reich et al., 2005) and based on net CO_2 efflux data;

a: Minor axis of the ellipsoid representing the plant in m (if the two minor axes of the geometry are dissimilar then the average is taken);

h_T: Depth of sensitive tissue = 5.5×10^{-5} m;

F_U: Unit conversion factor (3.6×10^9 µGy h^{-1} per Gy s^{-1});

R_{wf}^a: Radiation weighting factor for α-energy (default = 10).

Dose calculation formulae (again)

- Applicable to all radionuclides whose concentration is referenced to air - that is, ^{3}H, ^{14}C, ^{32}P, ^{35}S, ^{41}Ar, ^{85}Kr and ^{222}Rn:

$$(\text{Internal dose}, m\text{Gy h}^{-1})_{nuclide,organism} = \left(\text{Air conc, Bq m}^{-3}\right)_{nuclide} \times$$
$$\times (DCC, m\text{Gy Bq}^{-1}\text{ h}^{-1}\text{ m}^{3})^{\text{internal}}_{nuclide,organism}$$

$$(\text{External dose})_{nuclide,\ organism} = (Soil\ dose + Immersion\ dose)$$

$$(Soil\ dose) = (\text{Air conc, Bq m}^{-3})_{nuclide} \times (CR,\ m^{3}kg^{-1})^{\text{soil}}_{nuclide} \times$$
$$\times (DCC, m\text{Gy Bq}^{-1}\text{ h}^{-1}\text{ m}^{3})^{\text{external}}_{nuclide,organism} \times$$
$$1.2\ kg\ m^{-3} \times \left[\left(\begin{array}{l}\left(fsoil_{organism} + fsoilsur_{organism}/2\right) \\ + fair_{organism} \times (\text{reduction factor})_{\text{radiation type}}\end{array}\right)\right]$$

$$(Immersion\ dose) = (\text{Air conc, Bq m}^{-3})_{nuclide} \times (DCC, m\text{Gy Bq}^{-1}\text{ h}^{-1}\text{ m}^{3})^{\text{external}}_{nuclide,organism} \times$$
$$\times (fair_{organism} + fsoilsur_{organism}/2)$$

- Where the reduction factor is the modifier for dose to organisms in air is received from exposure to soil: 0 for α and low-energy β radiation and 0.25 for high energy $\beta+\gamma$ radiation

Internal DCCs for Rn (ERICA organisms)

Animals

Organism	M (kg)	a (m)	b (m)	c (m)	f (m^3 s^{-1})	DCC_B	DCC_{TB}	DCC_L[a]	DCC_{WB}
Amphibian (ICRP Frog)	3.1E-02	8.0E-02	3.0E-02	2.5E-02	5.9E-07	1.3E+01	1.4E+00	3.1E-01	3.7E-03
Reptile (FASSET snake)	7.4E-01	1.2E+00	3.5E-02	3.5E-02	6.3E-06	1.6E+01	1.7E+00	1.3E-01	1.7E-03
Mammal (ICRP Rat)	3.1E-01	2.0E-01	6.0E-02	5.0E-02	3.2E-06	1.5E+01	1.6E+00	1.6E-01	2.1E-03
Mammal (ICRP Deer)	2.5E+02	1.3E+00	6.0E-01	6.0E-01	6.9E-04	3.8E+01	4.1E+00	4.0E-02	5.6E-04
Bird (ICRP Duck)	1.3E+00	3.0E-01	1.0E-01	8.0E-02	9.4E-06	1.7E+01	1.9E+00	1.2E-01	1.5E-03
Mammal (FASSET Marine)	1.8E+02	1.8E+00	4.4E-01	4.4E-01	5.4E-04	3.6E+01	3.8E+00	4.2E-02	5.9E-04
Reptile (ICRP Marine Turtle)	1.4E+02	8.5E-01	3.9E-01	8.0E-01	4.3E-04	3.4E+01	3.7E+00	4.4E-02	6.2E-04
Mammal (FASSET Freshw.)	3.9E+00	3.3E-01	1.5E-01	1.5E-01	2.3E-05	2.0E+01	2.1E+00	8.9E-02	1.2E-03

Plants

Organism	M (kg)	a (m)	b (m)	c (m)	f (m^3 s^{-1})	DCC_{TISS}	DCC_{WB}
Lichen & bryophytes (ICRP Bryophite)	1.1E-04	4.0E-02	2.3E-03	2.3E-03	1.8E-08	2.8E-01	3.2E-02
Grasses & Herbs (ICRP Wild grass)	2.6E-03	5.0E-02	1.0E-02	1.0E-02	4.5E-07	1.3E+00	3.5E-02
Tree (ICRP Pine tree)	4.7E+02	1.0E+01	3.0E-01	3.0E-01	1.0E-01	4.9E+01	4.4E-02

External DCCs for Rn (ERICA organisms)

Organism	DCC ext (mGy h^{-1} per Bq m^{-3})		
	b < 10 keV	b > 10 keV + g	a
Amphibian (ICRP Frog)	4.6E-11	7.8E-04	0.0E+00
Reptile (FASSET snake)	3.3E-11	7.6E-04	0.0E+00
Mammal (ICRP Rat)	4.2E-11	7.3E-04	0.0E+00
Mammal (ICRP Deer)	4.0E-12	3.8E-04	0.0E+00
Bird (ICRP Duck)	2.6E-11	6.9E-04	0.0E+00
Mammal (FASSET Marine)	4.0E-13	4.3E-04	0.0E+00
Reptile (ICRP Marine Turtle)	9.3E-13	4.2E-04	0.0E+00
Mammal (FASSET Freshwater)	3.5E-12	6.4E-04	0.0E+00
Lichen & bryophytes (ICRP Bryophite)	1.2E-09	9.9E-04	0.0E+00
Grasses & Herbs (ICRP Wild grass)	1.7E-10	8.5E-04	0.0E+00
Tree (ICRP Pine tree)	3.6E-12	5.1E-04	0.0E+00

Validation of the Rn approach

Model validation with data from MacDonald and Laverock (1998)

Organism	Mass (kg)	DCC (mGy Bq^{-1} s^{-1} m^3)				Dose rate (mGy h^{-1})		% diff.
		B	TB	L	WB	Calculated	From paper	
Mole	4.00E-02	3.77E-04	1.85E-05	8.63E-06	1.04E-07	596	451	32
Pocket gopher	2.00E-01	4.41E-04	2.05E-05	5.71E-06	7.07E-08	854	702	22
Ground squirrel	5.00E-01	4.81E-04	2.17E-05	4.51E-06	5.69E-08	311	268	16
Ground hog	3.00E+00	5.72E-04	2.44E-05	2.85E-06	3.72E-08	132	125	6
Badger	8.00E+00	6.29E-04	2.59E-05	2.21E-06	2.95E-08	90	89	1

Additional comparison with Hofmann *et al*. (2006) and Harley (1988)

Organism	M (kg)	Source	DCC (nGy Bq^{-1} h^{-1} m^3) [a]	
			Reported	Calculated
Rat	0.3	Hofmann *et al.* (2006)	13.5 ± 12.5	76
Rats	0.35	Harley (1988)	10.3 ± 2.5	76

[a]Using the conversion 1 WLM = 6.3×10^5 Bq h m^{-3} (ICRP, 1978)

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Validation of the Rn approach

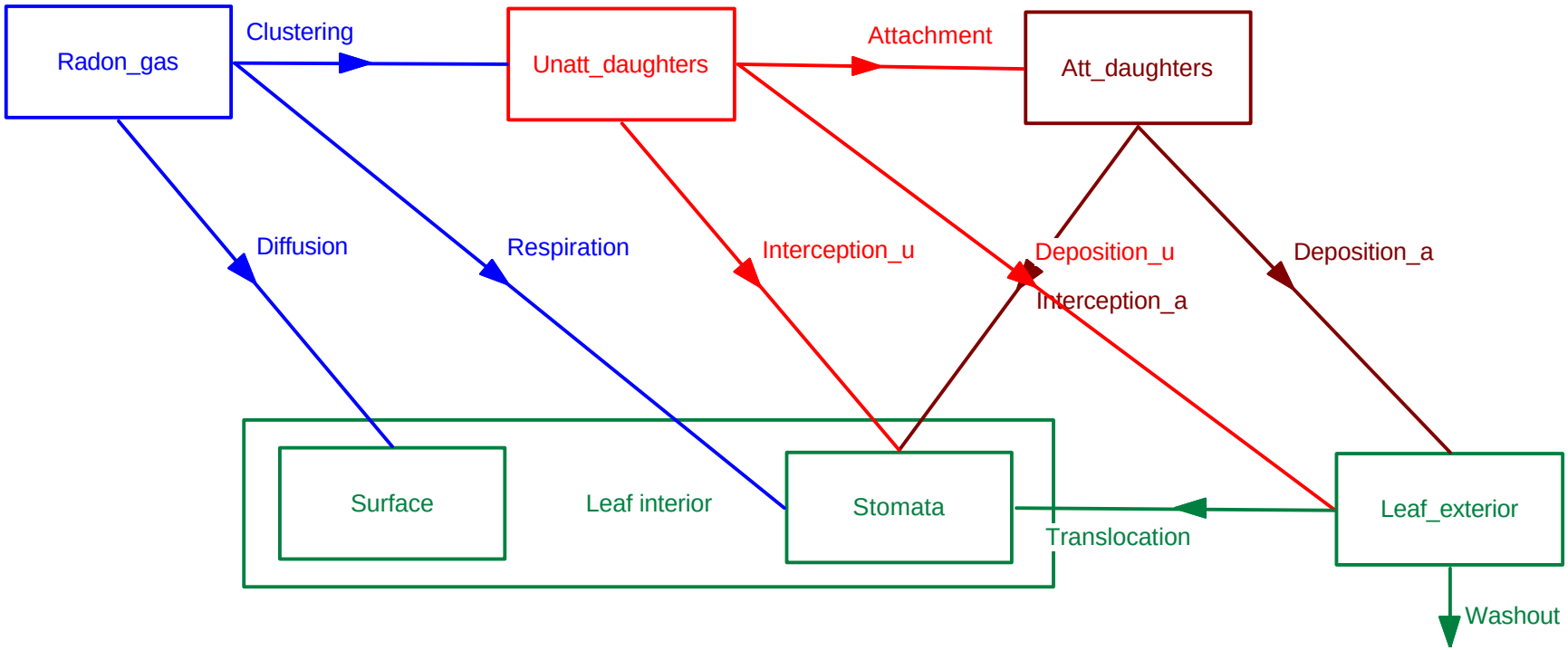
- Good agreement with McDonald ad Laverock (1998).
- Additional comparison with rat DCCs for the tracheobronchial tree by is problematic as reported sources they use a full respiratory model:
  - Predicting significant fractions of the radon daughters removed by the nasal passages.
  - Including lung clearance processes, resulting in transport from the alveolar region to the bronchial area, with associated decay included in transit.
  - The models consider atmospheres with various assumptions of equilibrium resulting in varying particle size, $F < 1$ and f_P values.
  - As a result, ours is a conservative approximation.

Radon – advanced plant model

Model description

- We developed (using ModelMaker) a compartment model representing:
  - Aerosol: free, unattached and attached fractions of ^{222}Rn, ^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po
  - Plant uptake: surface interception of unattached and attached daughters, diffusion of radon through stomata, permeation of radon through plant epidermis.
  - Plant turnover: translocation of deposited activity from plant surface to plant interior
- We derived DCCs for internal, surface and external exposure as a function of plant surface area and steady-state concentration at ground level.

Conceptual model



- Each sub-model contains the decay chain of radon: $^{222}Rn \Rightarrow {}^{218}Po \Rightarrow {}^{214}Pb \Rightarrow {}^{214}Bi \Rightarrow {}^{214}Po$.
- Exchange rates link individual compartments across sub-models, with rate constants linked to the parameter set.

Processes considered

- ^{222}Rn diffusion via stomata and permeation via epidermis (Free fraction to plant interior sub-models).
- ^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po interception through stomata (Unattached and attached fractions to plant interior sub-models).
- ^{218}Po, ^{214}Pb, ^{214}Bi, ^{214}Po aerosol deposition (Unattached and attached fractions to plant surface sub-models).
- Translocation of deposited ^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po (plant surface to plant interior)

Basic equations and parameters

Deposition flux: $f = A_{Rn}\,(Bq\,m^{-3}) \times \frac{1}{l\,(s^{-1})} \times v_d\,(m\,s^{-1})$

Deposition rate: $= \frac{v_d\,S_A}{V_G}$

Deposition velocity:

$$v_d^{unatt} = A_{unatt} e^{l_L B_{unatt}} \quad A_{unatt} = 2.1\times10^{-3}\,m.s^{-1},\ B_{unatt} = 1.04,\ r^2 = 0.998$$

$$v_d^{att} = A_{att} e^{l_L B_{att}} \quad A_{att} = 1.89\times10^{-5}\,m.s^{-1},\ B_{att} = 1.18,\ r^2 = 0.997$$

Diffusion through stomata: $-\frac{dN}{dt} = \frac{DA}{l_s}(c_{out} - c_{in})$ with D the diffusion coefficient

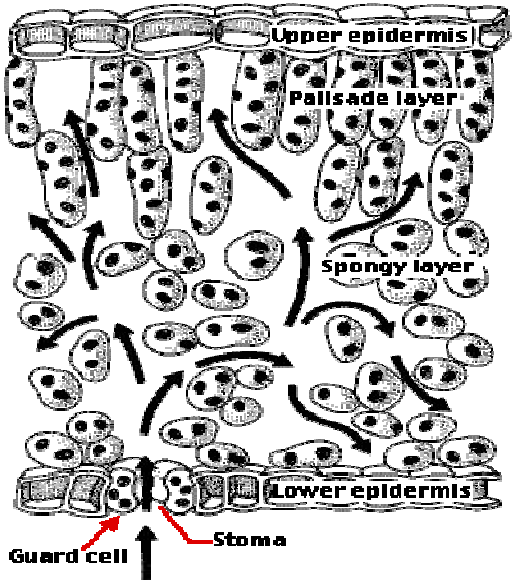
Permeation through leaf walls: $\frac{dN}{dt} = \frac{-KS}{w}(c_{in} - c_{out})$ with K the permeability

Transfer factor: $TF = \frac{a_i^{\text{int}}}{a_{Rn}^{ext}} = a_i^{\text{int}} \left(\frac{N_{Rn}^{ext}}{hS_A} \right)^{-1}$

Dosimetry:

$$H_i^j\Big|_{\text{int}} = a_i^{\text{int}} E_i AF_i(E_i) \equiv a_i^{\text{int}} DCC_i^{\text{int}};\ H_i^j\Big|_{ext} = \frac{a_i^{ext}}{r_{air}} E_i\left(1 - AF_i(E_i)\right) \equiv \frac{a_i^{ext}}{r_{air}} DCC_i^{ext}$$

Parameter	Value
Duration of day	8.6×10^4 s
Activity of ^{222}Rn in atmosphere, A_{Rn}	1 Bq m^{-3}
Air column surface area, S_A	1 m^2
Height of radon mixing layer above soil, h	2 m
Air density, r_{air}	1.2 kg m^{-3}
Radon diffusion coefficient, D	1.1×10^{-5} m^2 s^{-1}
Clustering rate, r_{clust}	2.3 s^{-1}
Attachment rate, r_{att}	2×10^{-2} s^{-1}
Internal exposure DCCs for ^{222}Rn, ^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po (total, unweighted)	3.2×10^{-3}, 3.5×10^{-3}, 7.9×10^{-5}, 6.6×10^{-5}, 4.4×10^{-3} µGy h^{-} / Bq kg^{-1}
Surface deposition DCCs for ^{222}Rn, ^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po (total, unweighted)	3.2×10^{-3}, 3.5×10^{-3}, 7.9×10^{-5}, 6.6×10^{-5}, 4.4×10^{-3} µGy h^{-} / Bq kg^{-1}
External exposure DCCs for ^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po (total, unweighted)	1.7×10^{-3}, 8.1×10^{-5}, 7.9×10^{-5}, 2.2×10^{-3} µGy h^{-1} / Bq kg^{-1}
Decay constants for ^{222}Rn, ^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po, l_i	2.1×10^{-6}, 3.7×10^{-3}, 4.3×10^{-4}, 5.9×10^{-4}, 4.2×10^3 s^{-1}
Potential alpha energy per unit activity weighting factors for ^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po	1.05×10^{-1}, 5.16×10^{-1}, 3.79×10^{-1}, 6×10^{-8}
Permeability constant for Rn in plant epidermis, K	1.25×10^{-11} m^2 s^{-1}
Leaf area index, l_L	2
Porosity of substomatal cavity, g	0.35
Leaf thickness, L	2.5×10^{-4} m
Plant density, r_P	10^3 kg m^{-3}
Stomata density, n_s	3×10^8 m^{-2}
Width of epidermis ≈ stomatal length, l_s	2.5×10^{-5} m
Stomata surface area (maximum)	4.9×10^{-10} m^2
Exponential fit parameters for unattached deposition velocity, A_{unatt}, B_{unatt}	2.1×10^{-3} m s^{-1} 1.04
Exponential fit parameters for attached deposition velocity, A_{att}, B_{att}	1.89×10^{-5} m s^{-1} 1.18



Plant leaf geometries

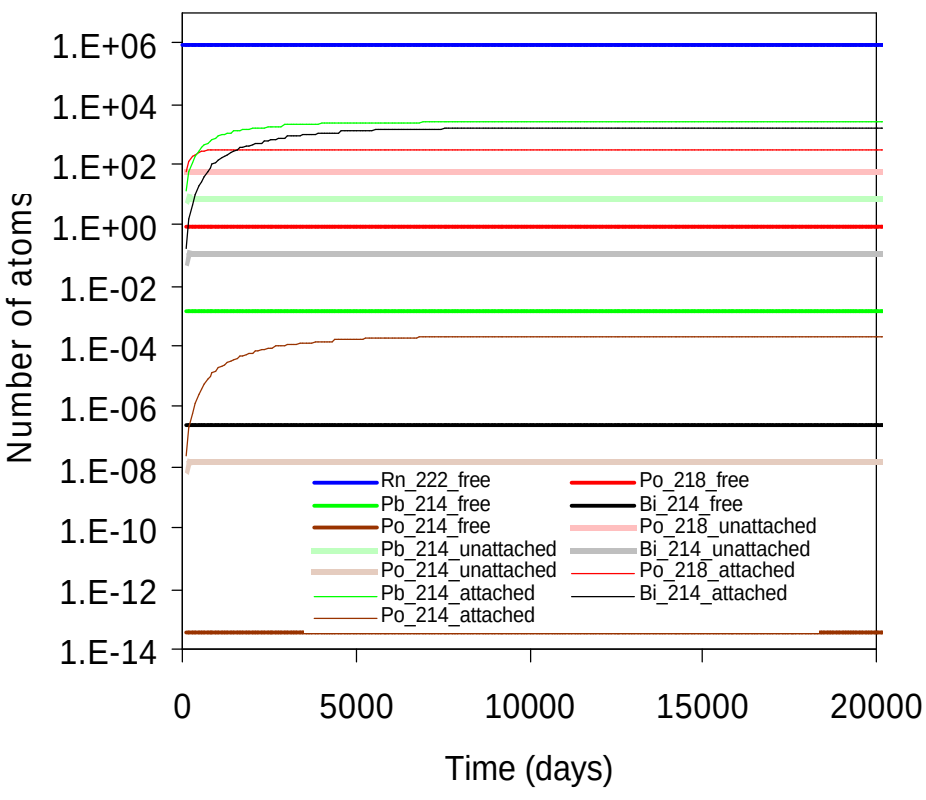
Deposition velocity values for different types of surface

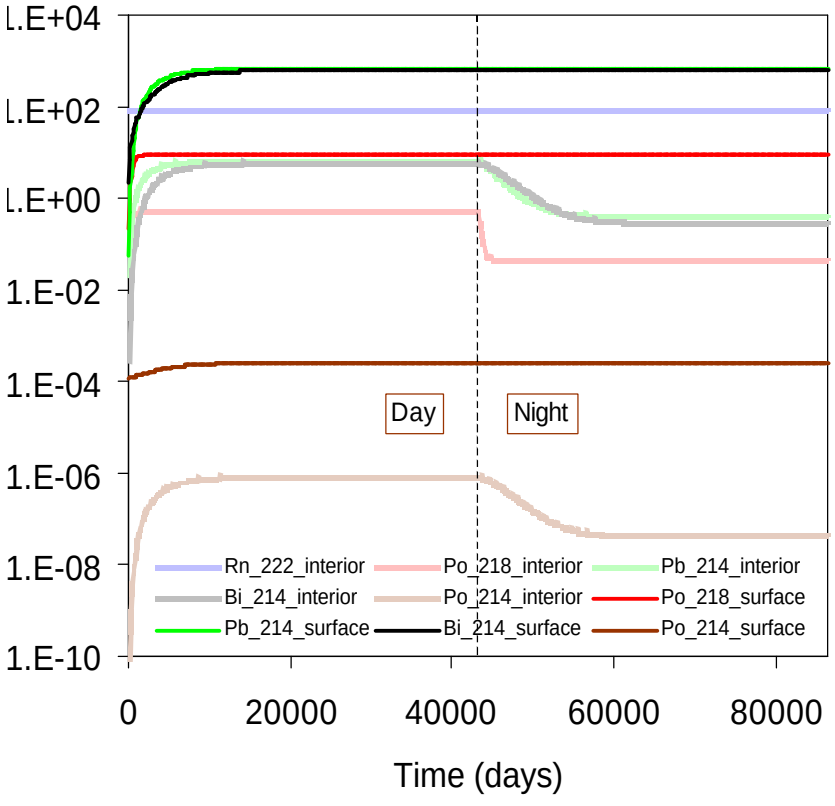
Surface	l_L	v_d^U **(m s^{-1})**	v_d^A **(m s^{-1})**
Soil	0	2×10^{-3}	2×10^{-5}
Grass	2.5	3.20×10^{-2}	3.10×10^{-4}
Wheat	4.2	1.57×10^{-1}	2.90×10^{-3}

Examples of (perennial) plant leaf geometries covering a wide size range

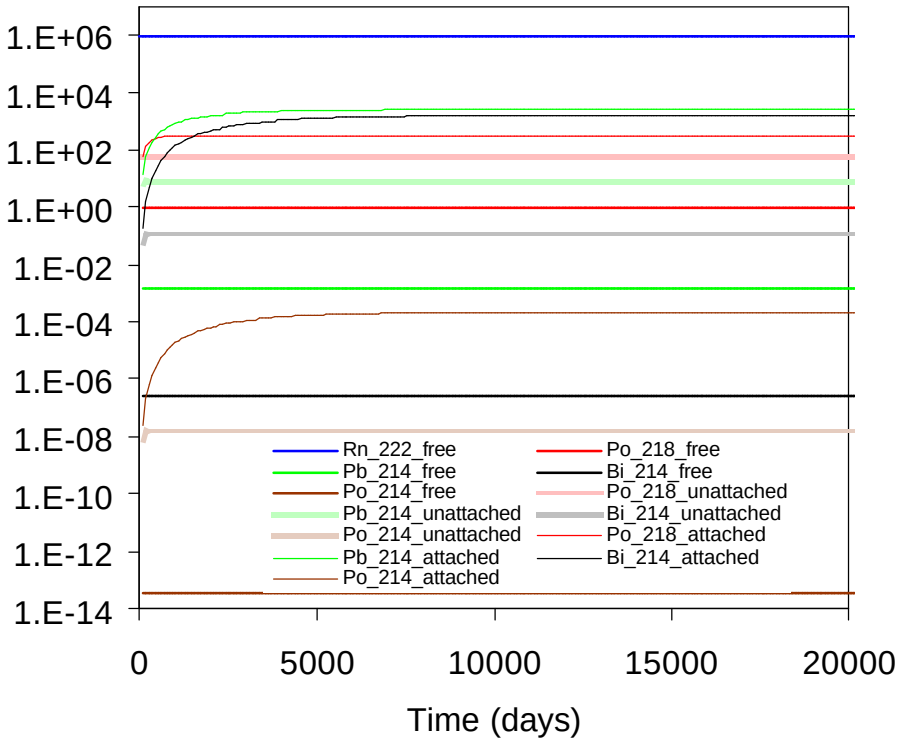
Leaf type	**Major axis a (m)**	**Major axis b (m)**	**Minor axis c (m)**	**Area (m^2)**	**Volume (m^3)**	**Mass (kg)**
Tiny	1.5×10^{-2}	5.0×10^{-3}	2.5×10^{-4}	1.2×10^{-4}	9.8×10^{-9}	9.8×10^{-6}
Small	6.0×10^{-2}	3.5×10^{-2}	2.5×10^{-4}	3.3×10^{-3}	2.8×10^{-7}	2.8×10^{-4}
Medium	1.3×10^{-1}	5.5×10^{-2}	2.5×10^{-4}	1.1×10^{-2}	9.4×10^{-7}	9.4×10^{-4}
large	1.2×10^{-1}	1.1×10^{-1}	2.5×10^{-4}	2.0×10^{-2}	1.7×10^{-6}	1.7×10^{-3}

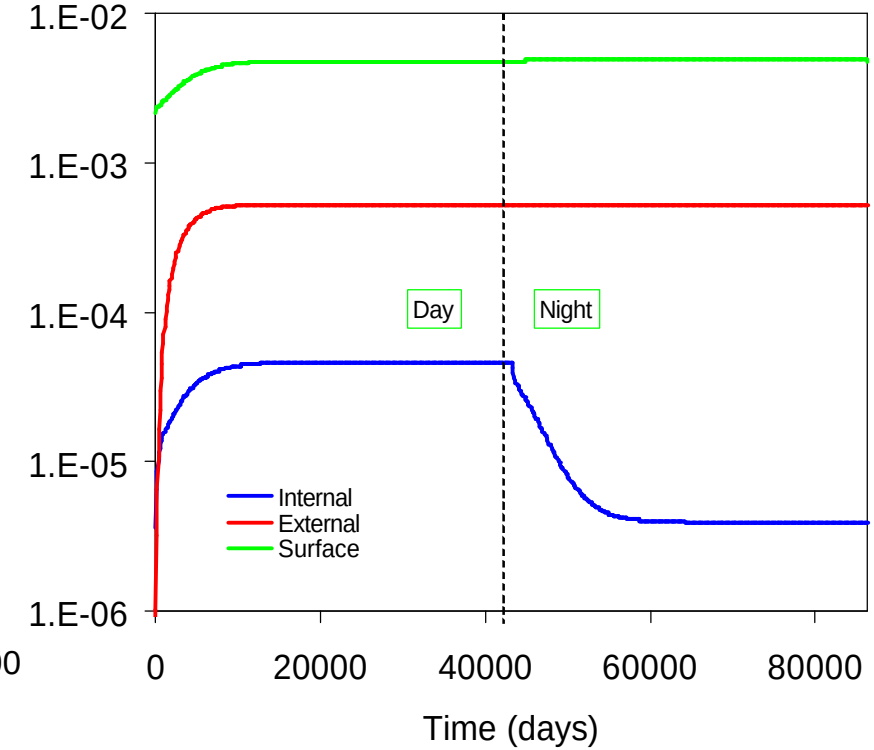
Model output



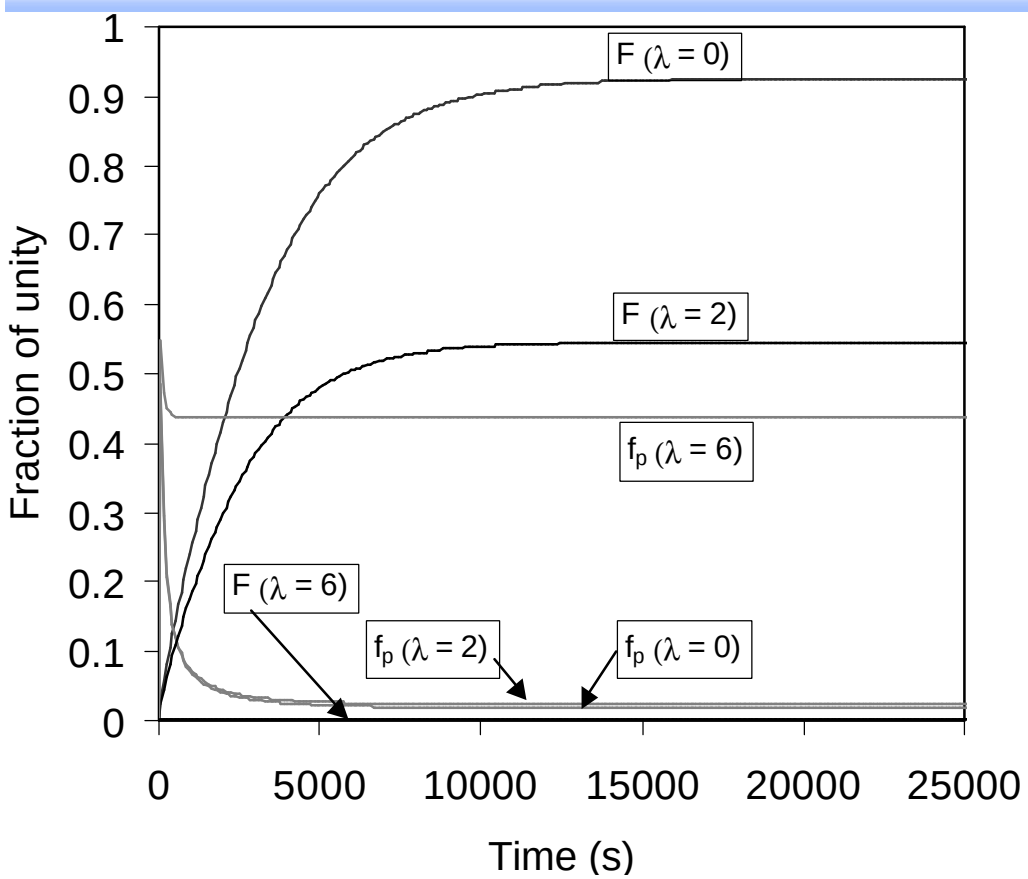


Model output





Equilibrium factor F and f_p



$$F = \frac{C_{Eq}}{C_0} = \frac{0.105\,A(^{218}Po) + 0.516\,A(^{214}Pb) + 0.379\,A(^{214}Bi) + 6\times10^{-8}\,A(^{214}Po)}{A(^{222}Rn)}$$

$$f_p = \frac{0.105\,A_{unatt}(^{218}Po) + 0.516\,A_{unatt}(^{214}Pb) + 0.379\,A_{unatt}(^{214}Bi) + 6\times10^{-8}\,A_{unatt}(^{214}Po)}{A(^{222}Rn)\times F}$$

DCCs for plant leaf geometries

Internal DCC (total), mGy h^{-1}/Bq kg^{-1}						
Nuclide	**Tiny leaf**	**Small leaf**	**Medium leaf**	**Large leaf**	**Average**	**± S.D.**
^{222}Rn	3.2E-03	3.2E-03	3.2E-03	3.2E-03	3.2E-03	1.6E-10
^{218}Po	3.5E-03	3.5E-03	3.5E-03	3.5E-03	3.5E-03	0.0E+00
^{214}Pb	7.6E-05	7.9E-05	8.0E-05	8.0E-05	7.9E-05	1.7E-06
^{214}Bi	5.8E-05	6.8E-05	6.9E-05	6.9E-05	6.6E-05	5.1E-06
^{214}Po	4.4E-03	4.4E-03	4.4E-03	4.4E-03	4.4E-03	0.0E+00
Surface DCC (total), mGy h^{-1}/Bq kg^{-1}						
^{222}Rn	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.6E-03	1.4E-09
^{218}Po	1.7E-03	1.7E-03	1.7E-03	1.7E-03	1.7E-03	3.3E-09
^{214}Pb	3.2E-06	1.1E-04	1.1E-04	1.1E-04	8.1E-05	5.2E-05
^{214}Bi	5.0E-07	1.0E-04	1.0E-04	1.1E-04	7.9E-05	5.2E-05
^{214}Po	2.2E-03	2.2E-03	2.2E-03	2.2E-03	2.2E-03	9.5E-11
External DCC (total), mGy h^{-1}/Bq kg^{-1}						
^{222}Rn	2.3E-07	2.3E-07	2.3E-07	2.3E-07	2.3E-07	1.6E-10
^{218}Po	7.0E-09	7.0E-09	7.0E-09	7.0E-09	7.0E-09	3.2E-11
^{214}Pb	2.4E-04	2.3E-04	2.3E-04	2.3E-04	2.3E-04	1.7E-06
^{214}Bi	1.2E-03	1.1E-03	1.1E-03	1.1E-03	1.1E-03	5.1E-06
^{214}Po	4.8E-08	4.8E-08	4.8E-08	4.8E-08	4.8E-08	1.9E-11

More results

Transfer factors (m^3 kg^{-1}) for radon products in plants

Transfer factor type	Time	^{218}Po	^{214}Pb	^{214}Bi	^{214}Po
Plant surface	Day	6.68E-02	5.82E-01	7.18E-01	2.09E+00
	Night	6.70E-02	5.84E-01	7.20E-01	2.09E+00
Plant interior	Day	3.84E-03	5.89E-03	6.92E-03	6.92E-03
	Night	3.50E-04	3.50E-04	3.50E-04	3.50E-04

Comparison with allometric method

Modelling approach	Organism	Time	DPURn (mGy h^{-1} per Bq m^{-3}) Internal	Surface	Int + surf	External	Total
New model	Plant leaf	Night	3.9E-06	4.8E-03	4.8E-03	5.3E-04	5.3E-03
	Plant leaf	Day	4.6E-05	4.8E-03	4.9E-03	5.3E-04	5.4E-03
Allometric	Fungi	All	N/A	N/A	3.9E-03	8.9E-04	4.3E-03
	Herb	All	N/A	N/A	3.9E-03	1.1E-03	4.4E-03
	Lichen	All	N/A	N/A	3.9E-03	9.7E-04	4.4E-03
	Seed	All	N/A	N/A	3.9E-03	1.2E-03	4.5E-03
	Shrub	All	N/A	N/A	3.9E-03	1.1E-03	4.4E-03
	Tree	All	N/A	N/A	3.9E-03	1.1E-03	4.4E-03
	Average	All	N/A	N/A	3.9E-03	1.0E-03	4.4E-03

Example of application: Rn in burrowing mammals

Radon field studies

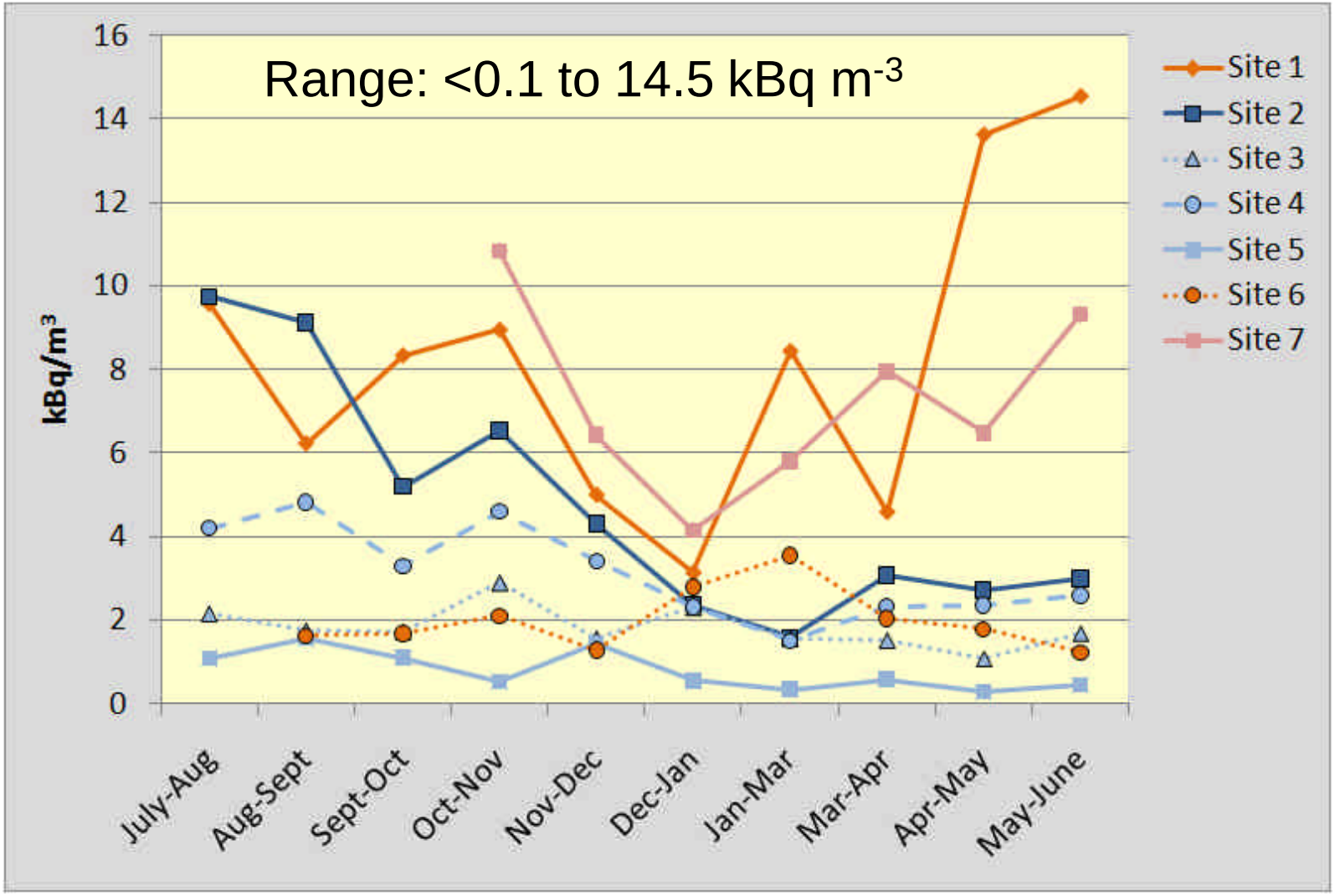
- Available dose rate estimates for ^{222}Rn:
  - One study in area of 'Rn rich soils' in Canada
  - Whole body dose rate >100 mGy y^{-1} for small burrowing animals (*c.* 10µGy h^{-1})
  - So Dose rate similar to *predicted no effect dose*
- So Beresford et al. (2012) delivered an estimation of ^{222}Rn dose rates to burrowing mammals at sites in the United Kingdom
- Dose rates calculated from measured field soil gas concentration, using the allometric methodology described previously
  - Assuming an equilibrium factor F = 0.8
  - Assuming an a-radiation weighting factor of 10
- 7 woodland, scrub and pasture sites selected to have range in potential Rn soil gas concentrations

Approach

- Make artificial burrows
- Use passive detectors developed by NRPB and SSI to measure soil gas ^{222}Rn activity concentration
- Sites across gradient of expected ^{222}Rn concentrations

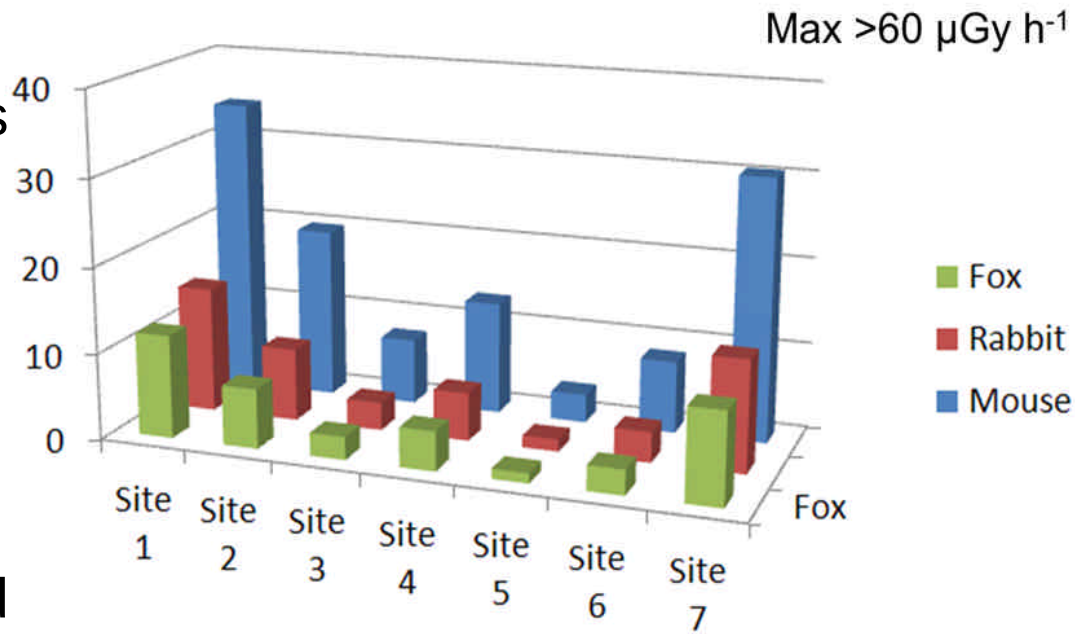
- Detector placed in approximately 10-cm diameter perforated land-drainage tubing = ‘artificial burrow’
- Tube (c.1.2 m) open ended on surface detector 50 cm below soil surface (surface length c.1 m). 3 per site
- Detector changed every 4-6 weeks (summer 2009 - summer 2010)

Measured ^{222}Rn concentrations in soil gas



Weighted dose rates

- Dose rate from ^{222}Rn to burrowing mammals likely to be at least 10 times higher than previously considered natural exposure sources (^{40}K, Th/U series).
- In many areas likely to considerably exceed predicted no-effect dose rate benchmarks.



Organism (geometry)	DCC (µGy h^{-1} per Bq m^{-3})
Mouse	2.6E-3
Rabbit	8.2E-4
Fox	9.1E-4

Conclusions

Conclusions

Argon and krypton (xenon)

- Ar and Kr dosimetry now codified into EA R&D 128 terrestrial spreadsheet.
- The R&D 128 DCC methodology for biota is consistent with the standard methodology for humans, the two only differences being:
  - External DCCs calculated for infinite geometry vs. DCFs for semi-infinite geometry (DCC correction factor of 0.5).
  - DCC method averages doses over whole volume - makes most difference in nucs. where external ß-component predominates over γ, and (progressively) as the organism becomes larger.

Radon (allometric model)

- Radon dosimetry codified into DCCs for internal -irradiation arising from exposure of animals and plants to short-lived ^{222}Rn daughters.
- The ^{222}Rn DCCs can be used to produce an assessment in the normal way, using atmospheric radionuclide versions of the standard EA R&D 128 / ERICA formula for gaseous radionuclides.

Conclusions

Radon (advanced plant model)

- The predominant component of dose is surface-deposited ^{214}Po and (to a lesser extent) ^{218}Po activity.
- Less important are ^{214}Bi external exposure and ^{214}Po internal exposure.
- Doses to plant surface tissue are x 10 higher than the surface deposition dose averaged to the whole plant.
- Differences with respect to the allometric model due to combination of surface and internal dose and the equilibrium factor of 1 in the latter.

Radon exposures in mammals

- Radon levels in burrows exceeding background levels and no-effects benchmarks for non-human biota.
- Advised benchmark dose rates need to be better put into context with background dose rates, including exposure to ^{222}Rn, for credibility
- Context will be determined by the purpose of the benchmark and the assessment level.

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Perspectives for future work

- Integrate Ar, Kr, Rn assessment in a single tool (or incorporate into ERICA).
- Conduct assessments for new nuclear reactors including exposure to birds roosting in stacks.
- Perform additional investigations of allometric radon dosimetry for insects and plants.
- Seek evidence for dose rates that would cause stochastic effects in the lung using more detailed lung modelling (if appropriate).
- Consider how to extend the dose assessment for ^{226}Ra in soil.
- Consider developing similar approach to calculate thoron doses.
- Review benchmark values in context of background and radon levels in the natural environment.

Published papers

- Vives i Batlle, J., Jones, S.R. and Copplestone, D. (2014). A methodology for the assessment of doses to terrestrial biota arising from external exposure to ^{41}Ar, ^{83,88}Kr and ^{1321,133}Xe. *Science of the Total Environment* (submitted).
- Beresford, N.A., Barnett, C.L., Vives i Batlle, J., Potter, E.D., Ibrahimi, Z.-F., Barlow, T.S., Schieb, C., Jones, D.G. and Copplestone, D. (2012). Exposure of burrowing mammals to ^{222}Rn. *The Science of the Total Environment* **431**: 252-261.
- Vives i Batlle, J., Copplestone, D. and Jones, S.R. (2012). Allometric methodology for the assessment of radon exposures to wildlife. *Science of the Total Environment*. **427-428**: 50–59
- Vives i Batlle, J., Smith, A., Vives-Lynch, S., Copplestone, D., Strand, T., Proehl, G. and Brown, J. (2011) Model-derived dose rates per unit concentration of radon in air in a generic plant geometry. *Radiation and Environmental Biophysics* **50**(4): 513-529.
- 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.

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