Radiation protection of the environment - some thoughts and perspectives

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Environmental protection from ionising radiation in practice (the historical view)

- End of 1990s – protection of the environment based upon human radiological protection citing (ICRP-60; para 16) :
  - *"The Commission believes that the standard of environmental control needed to protect man to the degree currently though desirable will ensure that other species are not put at risk. Occasionally, individual members of non-human species might be harmed, but not to the extent of endangering whole species or creating imbalance between species. At the present time, the Commission concerns itself with mankind's environment only…."*
- Problems ?
  - Where is the evidence ? An article of faith as oppose to a scientifically supported fact.
  - What happens in situations where there is no (environmental) connection with humans ?
  - Why is radioactivity treated in a different way to other contaminants ?
  - How can we evaluate the impact from radiaoactivity within a wider, environmental managment, context (e.g. in relation to resource management, CO_2 emissions - climate change etc.)

Reaction

- Several groups (IUR, USDoE, SSI, EA, NRPA) identified the need for a clear, structured framework to allow environmental impact assessments to be performed
- The EU accepted arguments from European institutes : supported the projects EPIC + FASSET (2000-2003) and thereafter ERICA (2003-2007)
- International Commission on Radiological Protection
  - Through the work of Committee 5 : began to reevaluate their position in relation to environmental protection of the enviironment and recommend a way forward.

ICRP environmental protection – introduction I

- New recommendations – ICRP(2007)
  - Planned, existing and emergency situations
  - all of the environment needs to be considered, including areas where humans are absent.
- Aims of environmental protection now include
  - Preventing or reducing the frequency of deleterious radiation effects to a level where they would have a negligible impact on the maintenance of biological diversity, the conservation of species, or the health and status of natural habitats, communities, and ecosystems.

ICRP, 2007. The 2007 Recommendations of the International Commission on Radiological Protection. ICRP Publication 103. Ann. ICRP 37(2–4).

ICRP environmental protection – introduction II

- ICRPs approach to environmental protection
  - Provide ”high level” guidance for demonstration of compliance corresponding with existing/emerging national and international legislation
  - Radiation one factor among many
  - Compatible with other approaches to protect the environment
  - Group biota effects in terms of early mortality, or morbidity, or reduced reproductive success.
  - Provide a framework for more applied and specific numerical approaches

↓

ICRP, 2008. Environmental Protection: the Concept and Use of Reference Animals and Plants. ICRP Publication 108. Ann. ICRP 38 (4-6).

Reference animals and plants (RAPs)

- Reference man of great utility – use similar approach for environment.
- Limited group of biota for relating exposure to dose and dose to effect for environmental situations
  - Employ derived consideration reference levels
  - Consequences for individuals or relevant populations
- Points of reference for drawing comparisons with sets of information on other organisms
- <u>Not</u> necessarily the *direct* objects of protection
  - Allows more site-specific information (e.g. secondary sets) to be compared and examined.

Criteria for selection of RAPs

- Requirements
  - To meet existing or expected legislation ➔ vertebrates, wetland habitats;
  - For environmental impact assessments ➔ animals and plants relevant to practices such as fisheries, agriculture, forestry;
  - To achieve consistency in regulatory approaches ➔ reasonable coverage of the major ecological compartments of terrestrial and aquatic ecosystems.
- Pragmatism in selecting RAPs
  - radiobiological information available; amenable to future research; typical of particular ecosystems; likely to be exposed to radiation; exposure can be modelled and life-cycle relevant for evaluating total dose and dose-effect responses; reasonable chance of identiying effects in individuals; political and public ”resonance”

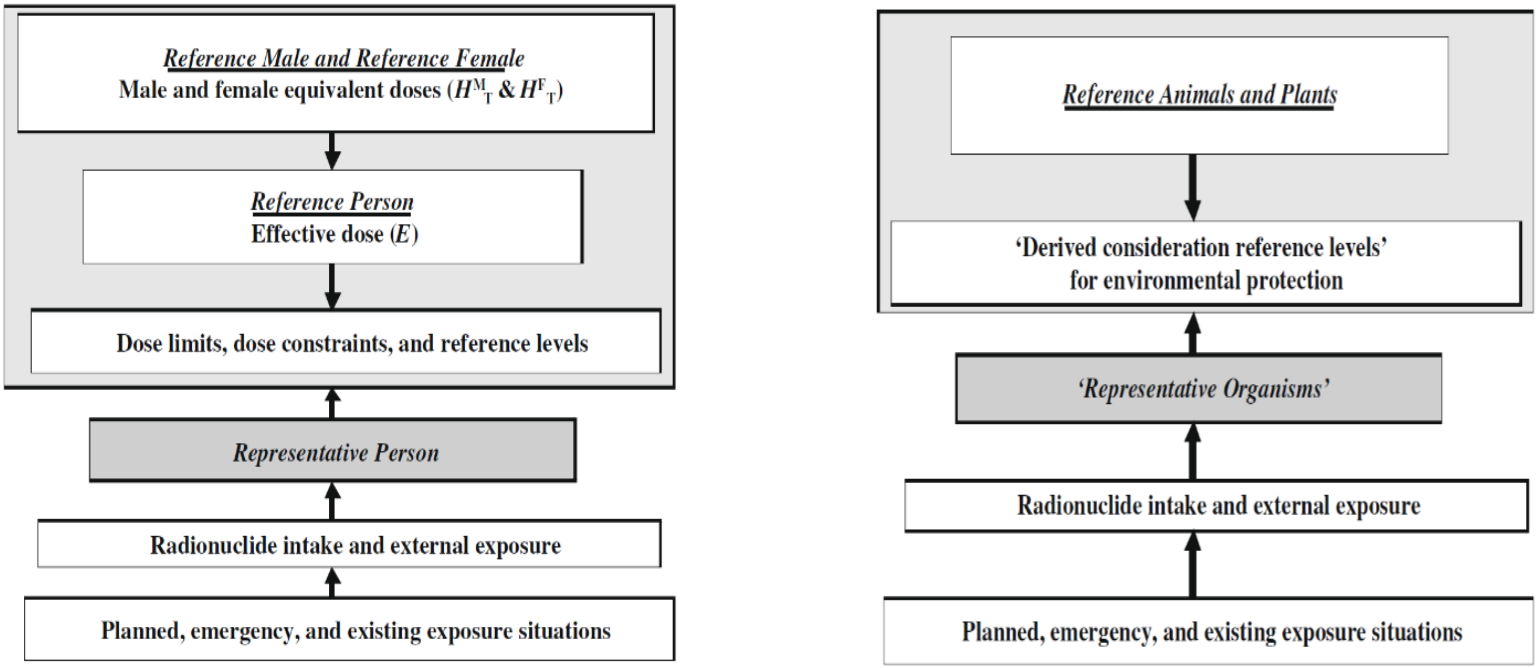
RAP definition

- ***A Reference Animal or Plant is a hypothetical entity, with the assumed basic biological characteristics of a particular type of animal or plant, as described to the generality of the taxonomic level of Family, with defined anatomical, physiological, and life-history properties, that can be used for the purposes of relating exposure to dose, and dose to effects, for that type of living organism.***

RAP selection

	Legislation relating to wildlife protection	Use in toxicity testing	Human resource	Data on radionuclide accumulation	Data on radiation effects	Amenable to further study
Deer	+		++	+	+	+
Rat	+	+++		++	+++	+++
Duck	+++		+	+	+	+++
Frog	++		+	+	+	++
Trout	++	+++	+++	+	+++	+++
Flatfish		+	+++	+++	++	++
Bee	+	+	++	++	+	+++
Crab		+	+++	+++	+	++
Earthworm		+++		++	+	+++
Pine tree	+		+++	++	+++	+++
Grass		+	+++	++	+++	+++
Seaweed			+	+++	+	++

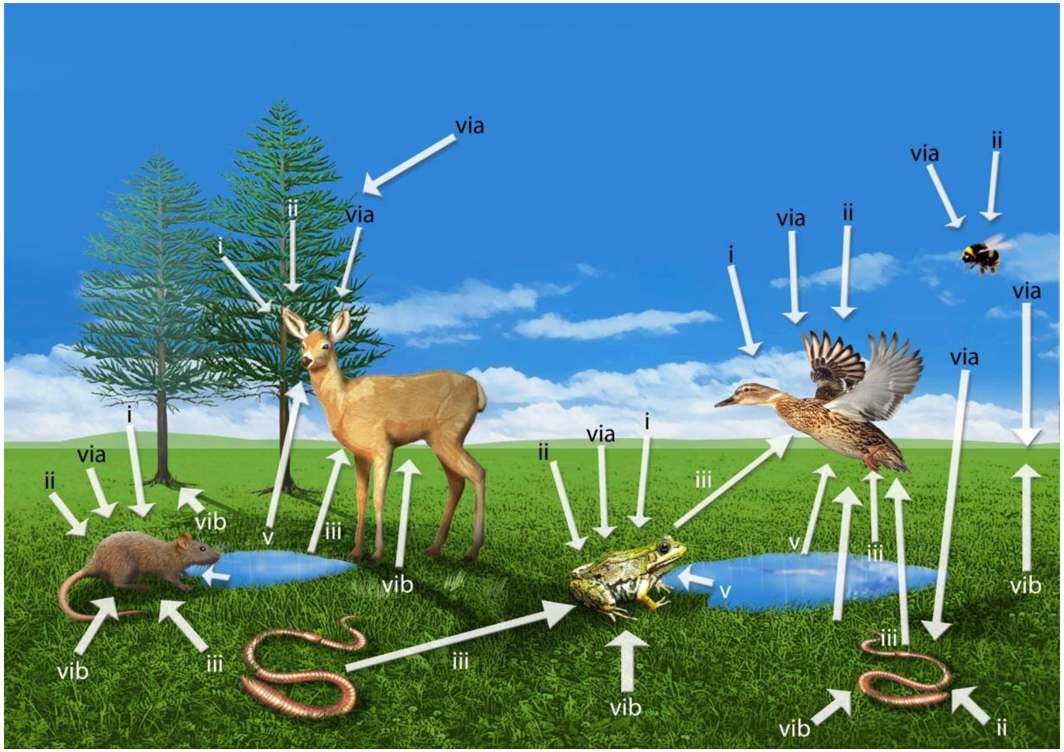
The parallel systems for radiological protection of man and the environment



Pathways of exposure

- Useful to consider 'sources'
  - indicates any physical entity or procedure that results in a potentially quantifiable radiation dose.
- Types of exposure situation
  - Planned
  - Emergency
  - Existing

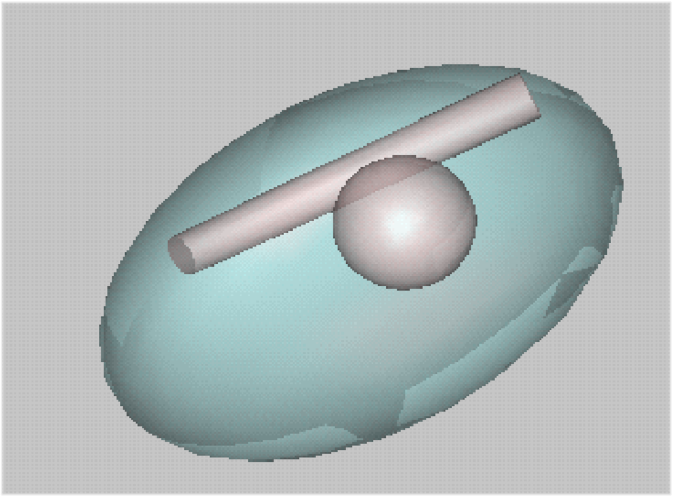
Exposure pathways



- Fig. 1.3 Terrestrial exposure pathways; i) Inhalation of particles or gases ii) Contamination of fur/feathers/skin iii) Ingestion lower trophic levels v) Drinking contaminated water vi) External exposure through a) air or b) soil

Ecodosimetry

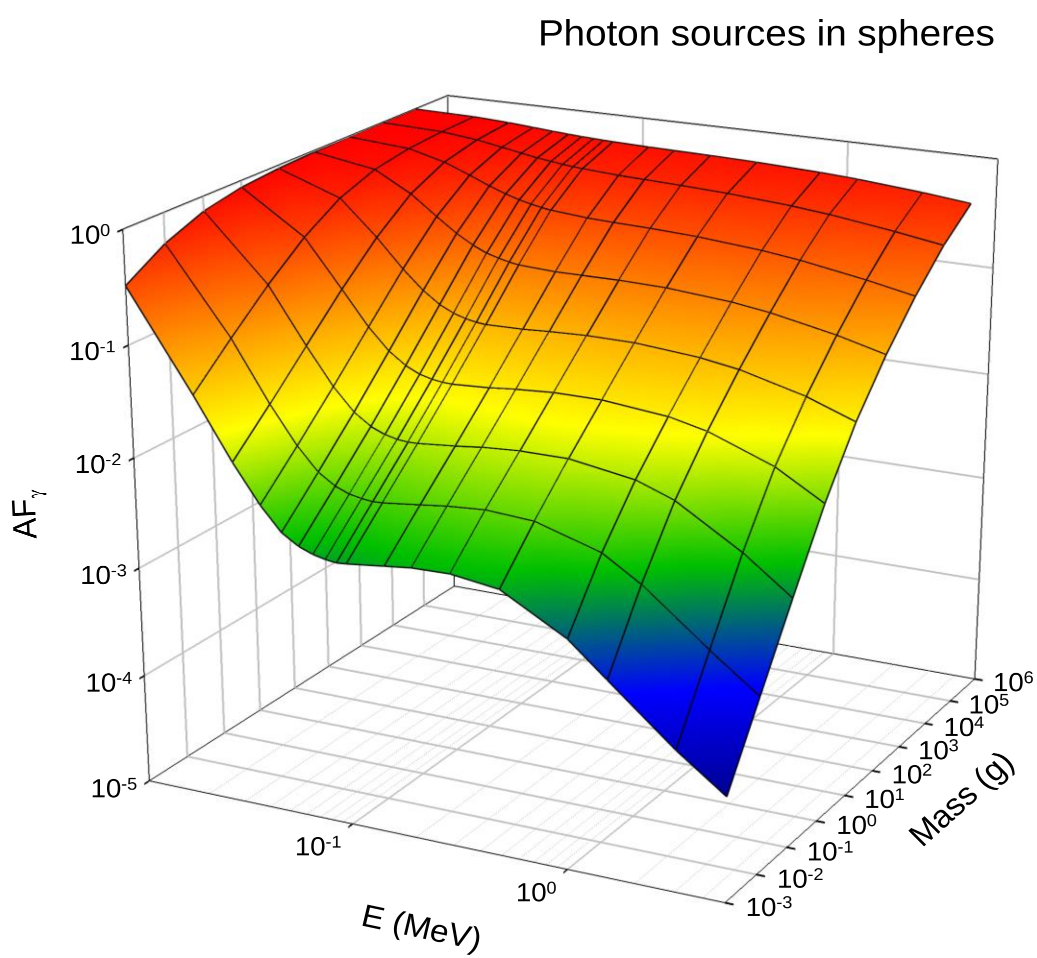
•Methodology used for ICRP's "Reference animals and plants."



$$\phi = \frac{\text{photon energy absorbed by target}}{\text{photon energy emitted by source}}$$

- Data pertaining to absorbed fractions (ϕ) have been calculated using Monte Carlo radiation tranport models for
  - a) Spherical and elliptical forms in water (9 shapes)
  - b) masses in the range from 1 mg to 1 tonne
  - c) photon/electron energies in the range from 10 keV to 5 MeV

Results: Photon ϕ (sphere)



ϕ is a function of

- **Energy**
- **Mass**

Large mass and low energy

ϕ ➔ 1.

Small mass, and High energy,

ϕ ➔ 0

Dosimetry

•Internal DCC

$$DCC_T^{\text{int}} = 5.75 \times 10^{-4} \cdot \sum_i \Phi_T(E_i) \cdot E_i \cdot y_i$$

Ei is the energy of component <i> of emitted radiation (MeV); *yi* is the yield of emitted radiation of energy Ei (dis-1); *ΦT(Ei)* is the absorbed fraction in the target for energy Ei; 5.75×10^{-4} is the factor to account for conversions of MeV to Joules and seconds to hours

•External DCC (where density differences between media are small)

$$DCC_T^{ext} = 5.75 \times 10^{-4} \cdot \sum_i (1 - \Phi_T(E_i)) \cdot E_i \cdot y_i$$

•For terrestrial – explicit MC simulations for selected ”target-source configurations”

Note on DCCs

- We also calculate **weighted total dose rates** (in µGy/h)
- **Radiation weighting factors** (dimensionless):

$$DCC_{int} = wf_{low\beta} \cdot DCC_{int,low\beta} + wf_{\beta+\gamma} \cdot DCC_{int,\beta+\gamma} + wf_{\alpha} \cdot DCC_{int,\alpha}$$

$$DCC_{ext} = wf_{low\beta} \cdot DCC_{ext,low\beta} + wf_{\beta+\gamma} \cdot DCC_{ext,\beta+\gamma}$$

Where:
wf = weighting factors for various components of radiation (low beta, $\beta + \gamma$ and alpha)
DCC = dose conversion coefficients in µGy/h per Bq/L or kg

Radiation weighting factors

- For humans, α-rad ”weighting” factor = 20 but this value is specific to stochastic effects.
- For plants and animals more emphasis placed upon ’endpoints’ that are relevant for the integrity of the population – mortality, morbidity, reproduction effects
- Based upon (Relative Biological Effectiveness) RBE studies –

$$RBE = \frac{\text{Absorbed dose of reference radiation required to produce a given biological effect}}{\text{Absorbed dose of specified radiation required to produce the same effect}}$$

- RBE is dependent upon dose-rate, species, endpoint studied etc.
- Statistical treatment of data ➔
  - circa 4 = reference value for alpha radiation weighting factor
  - Chambers et al. (2006) – up to 10 for deterministic, population relevant endpoints.

Chambers D, Osborne R, Garva A. 2006. Choosing an alpha radiation weighting factor for doses to non-human biota. J. Environ. Radioactivity, 87(1):1-14.

Effects of radiation and its relevance to RAPs

- Large data base on the effects of radiation on plants and animal – regularly reviewed (e.g. UNSCEAR)
- More systematic approach ➔ FREDERICA database*.
- For individual studies, enormous variation in
  - range of individual species studied
  - mode of exposure,
  - dose rates and
  - selection of 'biological effects' recorded.

*Copplestone, D., Hingston, J.L., Real, A., 2008. The development and purpose of the FREDERICA radiation effects database. Journal of Environmental Radioactivity 99, 1456-1463.

General observations – effects data

- For the higher vertebrates,
  - There is little difference in response across a range of dose rates for mammals,
  - Similar response for birds (although data insufficient in this case to draw conclusions)
- For the lower vertebrates,
  - Generalisations are difficult because allowance has not usually been made for their lower metabolic rates
  - If this fact accounted for, differences between higher and lower vertebrates may be less than it appears to be.
- Invertebrates more radioresistant than vertebrates
  - Mechanistic understanding missing
  - Eggs and larvae have usually been found to be more radiosensitive,
- Trees and plants
  - Long time scales required for study (for effects to appear)
  - Few controlled experiments and little data on which tissues have received dose
  - No clear information on differences in effects of radiation on plant and animal cells
- WHAT CAN BE DONE WITH THIS INFORMATION IN A STRUCTURED WAY ?

Derived Consideration Reference Levels

- Practical means required to make environmental management decisions and judgements based on knowledge of effects of radiation on different types of biota
- Useful comparator might be natural background
  - Additional doses that were e.g. fractions of normal background dose rates might be unlikely to cause concern, whereas dose rates that were very much higher, and in the region of expected effects, would need to be considered further
  - bands of dose rates based on natural background ➔ Derived consideration Reference levels
  - Point of reference to summarise what is know about effects on RAPs
  - Used in conjunction with other relevant information, e.g. area affected
- Information on natural background
  - Typical background dose-rates cited from published works

DCRL values

- Extreme simplification of existing data
- Start point to stimulate development
- Derived Consideration Levels highlighted in yellow
- Dose-rates > 1 Gy d^{-1} not relevant for environmental management but considered for completeness

Dose rate (mGy d^{-1})	Reference Deer	Reference Rat	Reference Duck
>1000	Mortality from haemopoietic syndrome [1 to 8 Gy $LD_{50/30}$]	Mortality from haemopoietic syndrome in adults [6 to 10 Gy $LD_{50/30}$] and [1 Gy LD_{50}] for embryos	Mortality in adults [9 Gy $LD_{50/60}$]; and [9 to13Gy LD_{50}] for eggs.
100 - 1000	Reduction in lifespan due to various causes.	Reduction in lifespan due to various causes.	Potential lethal effects on hatchlings.
10 - 100	Increased morbidity. Possible reduced lifespan. Reduced reproductive success.	Increased morbidity. Possible reduced lifespan. Reduced reproductive success.	Increased morbidity.
1 - 10	Potential for reduced reproductive success due to sterility of some adult males.	Potential for reduced reproductive success due to reduced fertility in males and females.	Potential for reduced reproductive success due to reduced hatchling viability.
0.1 - 1	Very low probability of effects	Very low probability of effects	No information
0.01 – 0.1	No observed effects.	No observed effects.	No information
< 0.01	Natural background	Natural background	Natural background

DCRLs - Matters for consideration

- DCRLs NOT intended to be dose limits
  - Values greater than DCRLs not necessarily to be considered as environmentally damaging
  - Values less than DCRLs not necessarily to be considered safe.
  - DCRLs are the starting points to consider such conclusions in the light of the local legislation and local situation.
- Management – use other information to justify action, e.g.
  - Exposure situation (existing, planned, emergency)
  - Area where dose-rates occur
  - Time over which dose-rates occur etc. etc.
- Issues
  - Not considered appropriate to simplify tables
  - Precautionary factors (e.g. safety factors) might be applied but at least can be related to tables
  - Link between protection of individuals versus populations : still very uncertain

UNSCEAR

- UNSCEAR 2008 report to the General Assemby with scientific Annexes, Volume II.
- Annex E. Effects of ionizing radiation on non-human biota

- Available from :
  - http://www.unscear.org/docs/reports/2008/11-80076_Report_2008_Annex_E.pdf

UNSCEAR Conclusions - I

- Unlikely that radiation exposures causing only minor effects on the most exposed individual would have any significant effect on the population.
- Reproductive effects sensitive to exposures cf. mortality
- Mammals most sensitive animal organism
- Chernobyl zone research has added to the knowledge base from the earlier general review of 1996

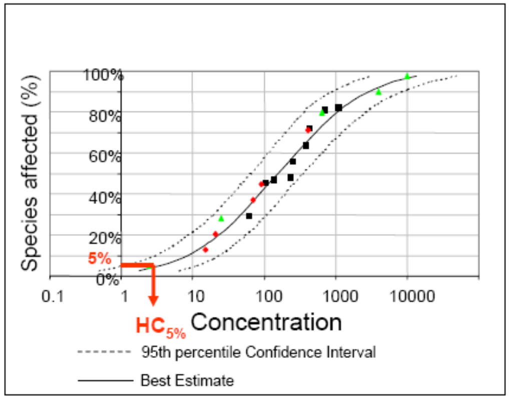
Category	*Dose rate (µGy/h)*	*Effects*	*Endpoint*	*Reference*
Plant	100–1 000	Reduced trunk growth of pine trees	Morbidity	[W4]
	400–700	Reduced numbers of herbaceous plants	Morbidity	[G26]
Fish	100–1 000	Reduction in testis mass and sperm production, lower fecundity, delayed spawning	Reproduction	[H11, K16, N1]
	200–499	Reduced spermatogonia and sperm in tissues	Reproduction	[C11]

UNSCEAR Conclusions - II

- Earlier review (1996) :
  - Chronic dose rates of less than 100 µGy/h to the most highly exposed individuals would be unlikely to have significant effects on most terrestrial communities and a maximum dose rate of 400 µGy/h to any individual in aquatic populations would be unlikely to have any detrimental effects at the population level.
  - Where a significant part of incremental exposure comes from high-LET radiation, it is considered necessary to account for the different RBE of the radiation.

UNSCEAR Conclusions - III

- In addition to new data from Chernobyl, new analyses methods such as **Species Sensitivity Distributions** have been applied. However, UNSCEAR considered that ‘*insufficient data are available for the application of such methods*’ (for the purposes of UNSCEAR as oppose to deriving e.g. benchmarks)



Species Sensitivity Distribution. The example shows the five percent protection level and the corresponding HC5 (Hazardous Concentration 5%) used to determine the PNEC.

- Acknowledgement regarding the new information concerning pathways of exposure and dosimetry since the previous report in 1996. **Opportunities remain to improve our understanding of the relationship between the levels of radioactivity in the environment and the potential effects for biota residing in that environment.**

UNSCEAR Conclusions - IV

- Based on current knowledge – no change to previous (1996) conclusion (on impacts of chronic dose-rates on populations) but
  - Where specific effects data of high enough quality on specific species and endpoints : these should be used.
  - Very limited data from many taxa. This requires extrapolation from one biological group to another and therefore is associated with substantial uncertainty
  - Requirement to understand chronic effects over generations, multistressor situations and extrapolations from molecular to cellular to higher levels of biological organisation.

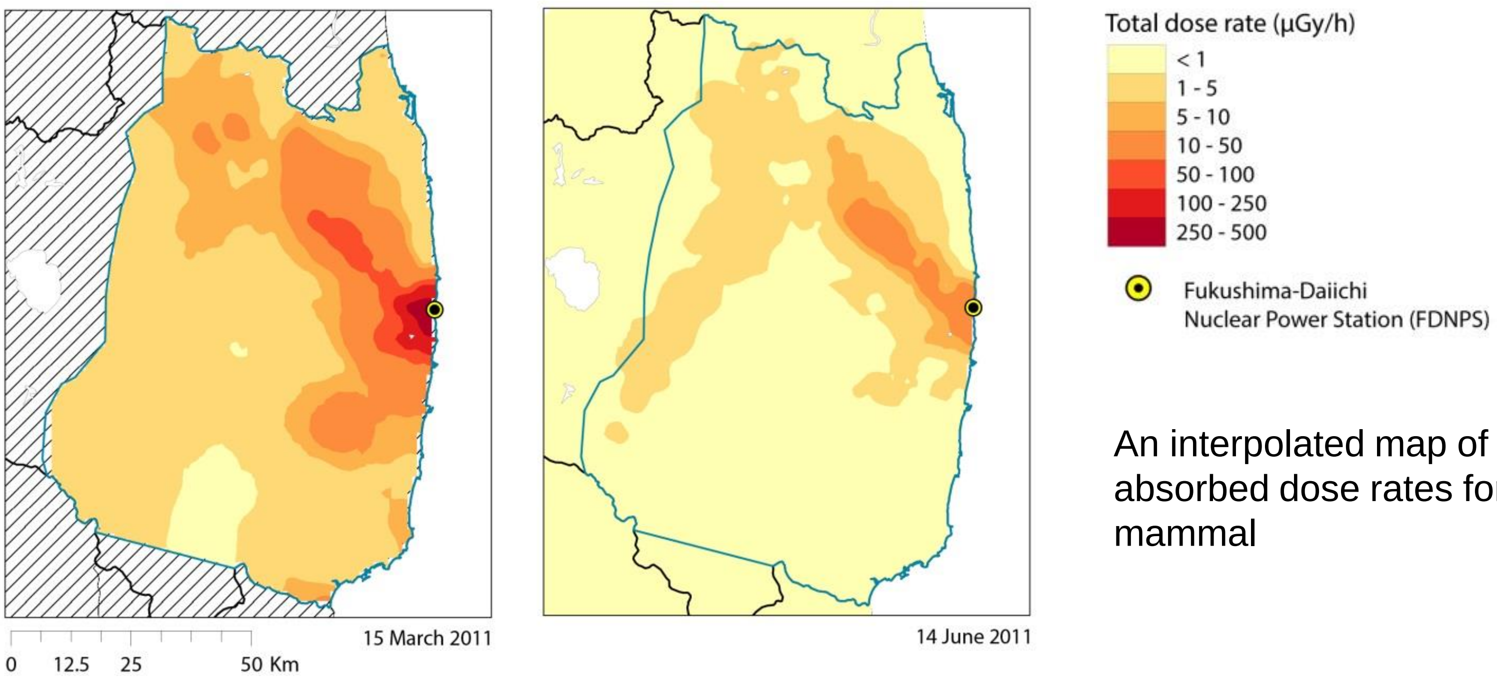
UNSCEAR-2013 : Fukushima impacts

- **The generic methodology has been developed based around Reference organisms and the ERICA integrated Approach**

Table 1. List of organisms selected by UNSCEAR (2008) for assessing exposures

Earthworm/soil invertebrate	**Rat/burrowing mammal**	**Bee/above ground invertebrate**
Wildgrass/grasses,herbs and crops	**Pine tree/tree**	**Deer/herbivorous mammal**
Duck/bird	**Frog/amphibian**	**Brown Seaweed/macroalgae**
Trout/pelagic fish	**Flatfish/benthic fish**	**Crab/crustacean**

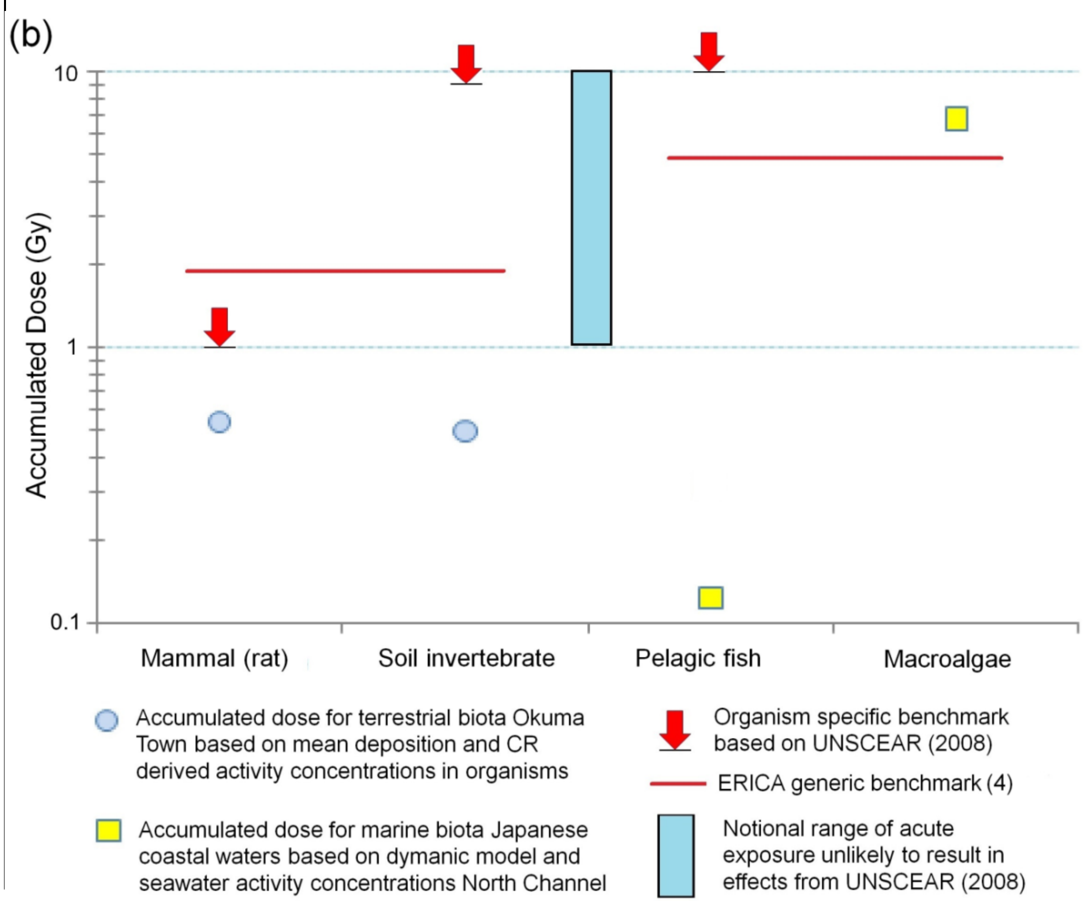
Dose rates in terrestrial ecosystems



An interpolated map of weighted absorbed dose rates for a large mammal

- These dose rates do not include some of the very short-lived radionuclides that were present in fallout from the middle of March 2011. Initial analyses suggest that the primary radionuclides contributing to dose at this time were ^{132}I and ^{132}Te.
- Dose rates to organisms are augmented considerably by including these short-lived radionuclides. For soil dwelling organisms (mammal/rat and soil invertebrate) dose rates, potentially approached 1 mGy/h for a short duration.

Cumulative dose during the first 90 days after the accident in terms of acute exposure benchmarks.



Environmental Science & Technology LETTERS

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Assessment of Fukushima-Derived Radiation Doses and Effects on Wildlife in Japan

P. Strand,[†] T. Aono,[‡] J. E. Brown,[*,†] J. Garnier-Laplace,[§] A. Hosseini,[†] T. Sazykina,[‖] F. Steenhuisen,[⊥] and J. Vives i Batlle[@]

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Conclusions from UNSCEAR 2013 Report

- **Intermediate Phase after the accident** : Dose Rates for biota from terrestrial ecosystems may have exceeded the benchmark level of 100 µGy/h for limited periods. However, effects on populations were considered unlikely although changes in biomarkers for certain biota, especially mammals, could not be excluded. Calculated doses to marine biota indicated no effect, other than possibly transiently very close to discharge points (FDNPP port)

- **Late phase after the accident** : Potential risk for individuals of certain species, especially mammals, may exist in areas with relatively high deposition. Nevertheless, population effects for terrestrial biota were considered unlikely:- Estimated exposures for both marine and freshwater biota fell well below the benchmarks where such effects were considered likely.

- The possibility of effects on biota are geographically limited. In areas outside the most contaminated areas, the potential for (population) effects on biota were considered negligible.

REVIEW OF DEVELOPMENTS SINCE THE 2013 UNSCEAR REPORT - I

- Exposures derived for non-human biota in recent studies [e.g. F2, K10] generally corresponded closely to the estimates made in the 2013 Fukushima report.
- An exception possibly existed for the marine environment where elevated concentrations in benthic marine fish were found to persist [S4].

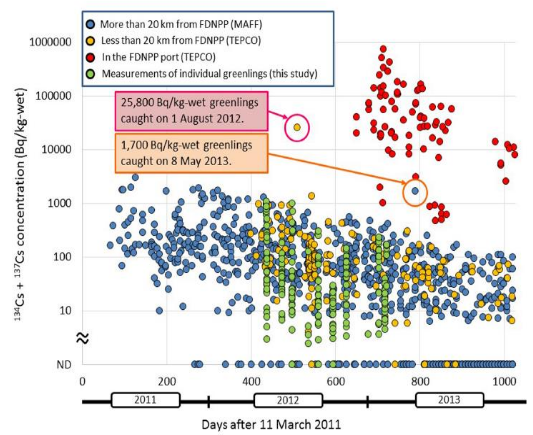


Figure 2 | Temporal trends of radiocesium concentrations ($^{134}Cs + ^{137}Cs$) for greenlings caught within and more than 20 km from the Fukushima Daiichi Nuclear Power Plant (FDNPP) port are shown. Tokyo Electric Power Corporation (TEPCO) has been monitoring marine products within 20 km of the FDNPP since April 2012.

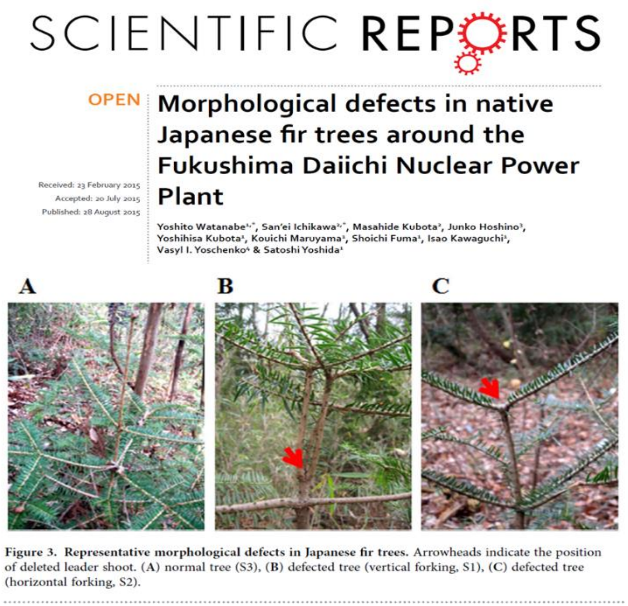
F2: Fujiwara, K., T. Takahashi, P. Nguyen et al. Uptake and retention of radio-caesium in earthworms cultured in soil contaminated by the Fukushima nuclear power plant accident. J Environ Radioact 139: 135-139 (2015).

K10 : Kubota, Y., H. Takahashi, Y. Watanabe et al. Estimation of absorbed radiation dose rates in wild rodents inhabiting a site severely contaminated by the Fukushima Dai-ichi nuclear power plant accident. J Environ Radioact 142: 124-131 (2015).

S4 : Shigenobu, Y., K. Fujimoto, D. Ambe et al. Radiocesium contamination of greenlings (Hexagrammos otakii) off the coast of Fukushima. Sci Rep 4: 6851 (2014).

REVIEW OF DEVELOPMENTS SINCE THE 2013 UNSCEAR REPORT - II

- Morphological abnormalities observed in some but not other studies.
  - Matsushima et al. [2015] observed no clear abnormalities in the gonadal tissues of frogs, collected from sites with elevated radionuclide levels



SCIENTIFIC REPORTS

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Morphological defects in native Japanese fir trees around the Fukushima Daiichi Nuclear Power Plant

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Yoshito Watanabe[1,*], San'ei Ichikawa[2,*], Masahide Kubota[2], Junko Hoshino[3], Yoshihisa Kubota[1], Kouichi Maruyama[1], Shoichi Fuma[1], Isao Kawaguchi[1], Vasyl I. Yoschenko[4] & Satoshi Yoshida[1]

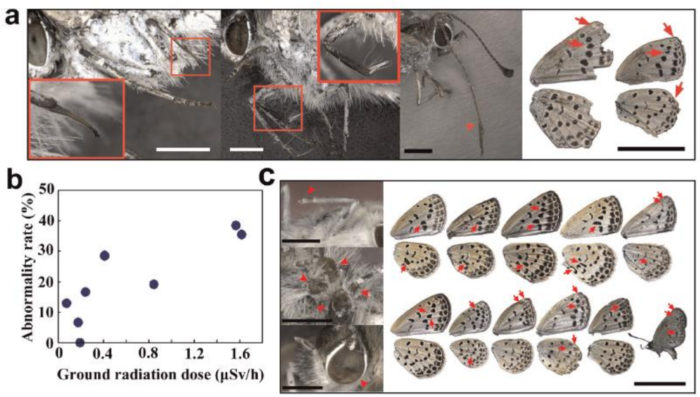
Figure 3. Representative morphological defects in Japanese fir trees. Arrowheads indicate the position of deleted leader shoot. (A) normal tree (S3), (B) defected tree (vertical forking, S1), (C) defected tree (horizontal forking, S2).

- Watanabe et al. [2015] showed that Japanese fir tree populations near FDNPS exhibit a significantly increased number of morphological defects, compared to a control population far from FDNPS.
- Accumulated doses to vegetation in areas with relatively high deposition densities were estimated for the 2013 report. The estimated doses for trees were similar to those at which disturbances in growth, reproduction and morphology of conifers had been observed following the Chernobyl accident.

Matsushima, N., S. Ihara, M. Takase et al. Assessment of radiocesium contamination in frogs 18 months after the Fukushima Daiichi nuclear disaster. Sci Rep 5: 9712 (2015).

REVIEW OF DEVELOPMENTS SINCE THE 2013 UNSCEAR REPORT - III

- Further details have been published which add support to some original studies where substantial (population relevant) effects have been observed in the field :
  - Several publications by Mousseau and Møller [e.g. M10] provided additional information on their original studies by, inter alia, presenting more details on the statistical models applied and dismissing the influence of certain confounding factors, such as the effect of the tsunami itself.
  - Several publications [e.g. H7] provided a comprehensive defence of an earlier publication cited in the 2013 Fukushima report concerning the impacts of radionuclide releases on the Pale Grass Blue Butterfly.



a) Representative morphological abnormalities of the field-caught individuals.
(b) Scatter plot of ground radiation dose and abnormality rate of the field-caught adults.
(c) Representative abnormalities in the F1 generation.

M10 : Mousseau, T.A. and A.P. Moller. Genetic and ecological studies of animals in Chernobyl and Fukushima. J Hered 105(5): 704-709 (2014).
H7 : Hiyama, A., C. Nohara, W. Taira et al. The Fukushima nuclear accident and the pale grass blue butterfly: evaluating biological effects of long-term low-dose exposures. BMC Evol Biol 13: 168 (2013).

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The impact of the Fukushima nuclear accident on marine biota: Retrospective assessment of the first year and perspectives

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UNSCEAR United Nations Scientific Committee on the Effects of Atomic Radiation

DEVELOPMENTS SINCE THE 2013 UNSCEAR

UNSCEAR United Nations Scientific Committee on the Effects of Atomic Radiation

DEVELOPMENTS SINCE THE 2013 UNSCEAR REPORT ON THE LEVELS AND EFFECTS OF RADIATION EXPOSURE DUE TO THE NUCLEAR ACCIDENT FOLLOWING THE GREAT EAST-JAPAN EARTHQUAKE AND TSUNAMI

A 2016 white paper to guide the Scientific Committee's future programme of work

…ENCE FOR INFORMED DECISION-MAKING

Journal of Environmental Radioactivity 169-170 (2017) 159–173

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On the divergences in assessment of environmental impacts from ionising radiation following the Fukushima accident

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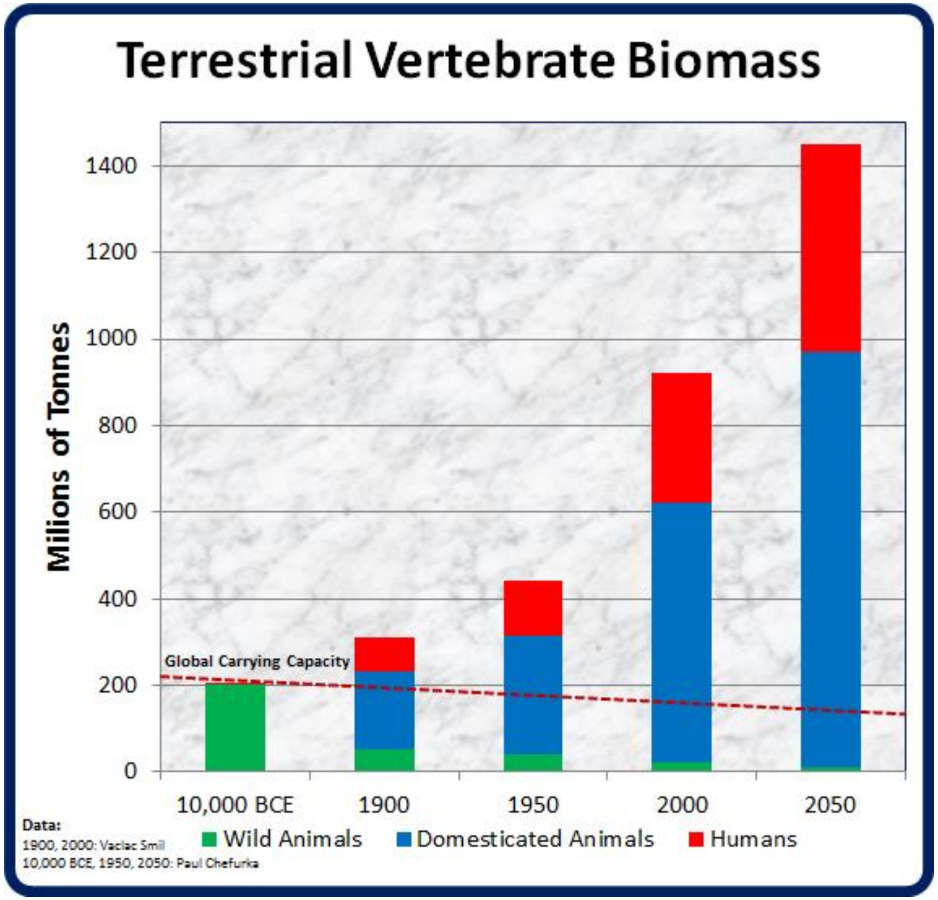
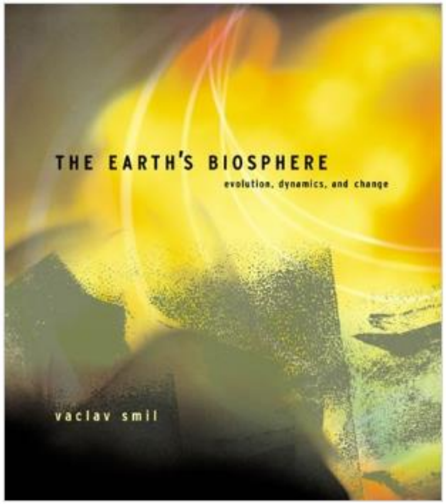
Summary and challenges ahead

- Apart from (a few, controversial) studies reporting severe population impacts, UNSCEAR's 2013 assessment (on non-human biota) is broadly supported by much of the new information that has since been published.
- There are challenges in relation to how dose-rates are interpreted, and, in particular, whether it is sufficient to focus on endpoints that do not take full account of the complexity of ecosystem interactions.
  - under real conditions, exposure to stressors might potentially trigger non-linear changes in ecosystem function and structure that cannot be predicted from effects on individual organisms.
  - There remains a clear requirement for follow-up studies investigating the dose response at high levels of biological organization (e.g. population) that take due account of biota interactions within ecosystems ➔ <u>**Ecosystem Approach**</u>
  - Field studies, tailored to analyse the impacts of exposure to ionizing radiation on populations of wild organisms interacting under the conditions prevalent within contaminated ecosystems, are required. Such studies would need to be multidisciplinary, involving not just radio-ecologists and radiation specialists but also ecologists, population biologists and geneticists.

What are we really protecting ?



Internet source but includes Data from ecological scientist Vaclav Smil "Harvesting the Biosphere"



- For regulation we need a simple (but not simplistic) system that combines well with existing human radiological protection