Biological uptake, accumulation, dose estimates and biological responses

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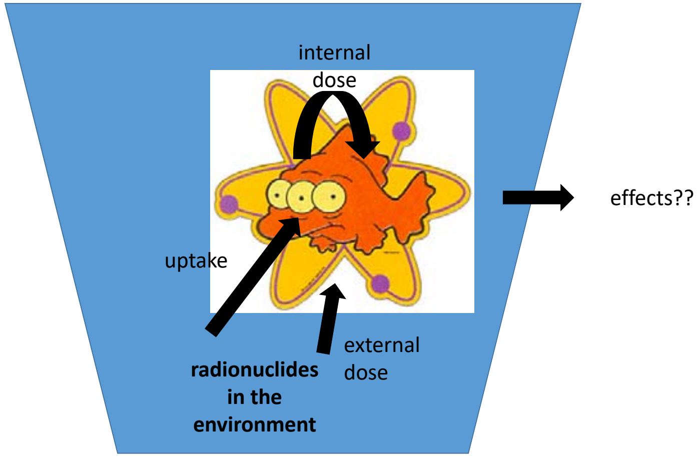
COMET

1



2

UPTAKE AND EXPOSURE

3

Concentrations of radionuclides/elements in biota depend on:

- concentrations in the environment
- concentrations in organism's food
- chemical forms of the radionuclides
- half-lives of the radionuclides
- essentiality and toxicity of the elements
- specific biological uptake and/or excretion mechanisms
- organism's behaviour
- environmental factors e.g. pH, organic matter…

Th Si C Br Dy Mn N Rb Ca

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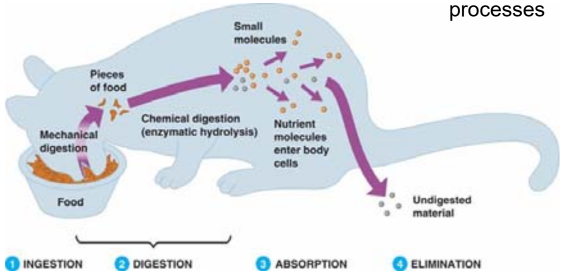
Biological processes that affect accumulation

- Inhalation
- Ingestion
- Absorption (e.g. across membranes, gills)
- Adsorption

- Excretion
- Respiration
- Photosynthesis
- Transpiration
- Other physiological processes



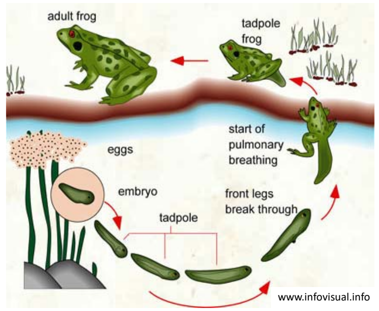
Picture from: hodnett-ap.wikispaces.com

Exposure and physiology (and lifestyle, habitat) can change during a lifecycle

HABITAT

semi-terrestrial

aquatic



PHYSIOLOGY / DIET

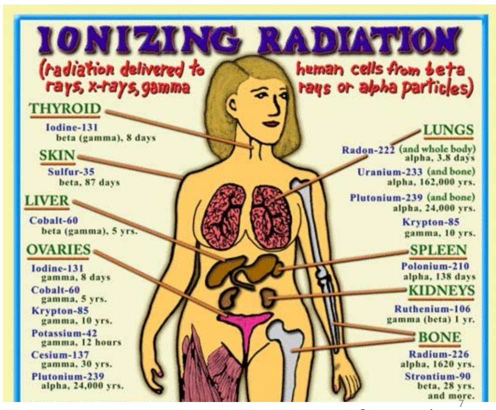
Respire through lungs. Carnivorous - eat worms, insects.

Respire through external gills, then internal gills. Eat periphyton, leaves, detritus

From Bradshaw et al (in prep)

Different radionuclides accumulate in different tissues

- Different radionuclides are preferentially taken up by different types of tissues
- Physical and biological half-lives are different for different radionuclides



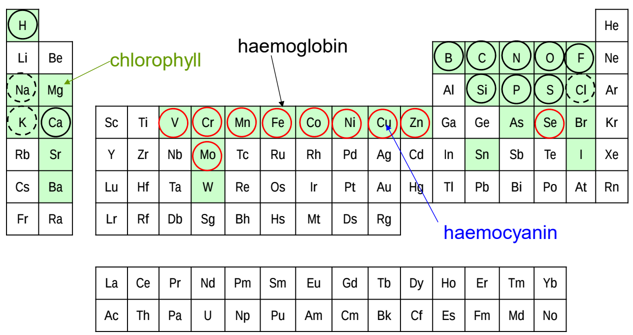
Source: scienceray.com

Essential vs non-essential elements

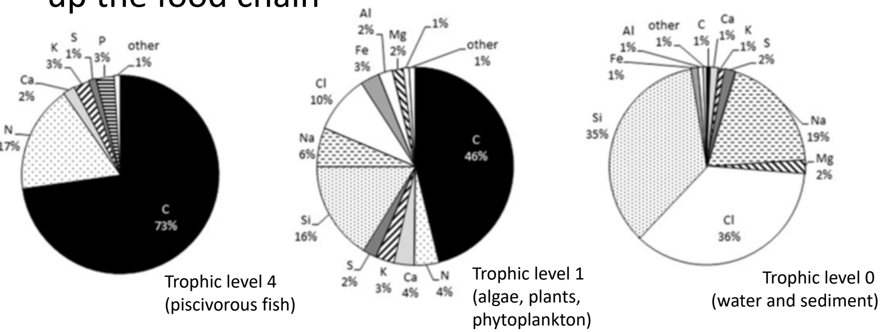
electrochemical

enzymes

structural



Relative distribution of elements / RNs changes up the food chain



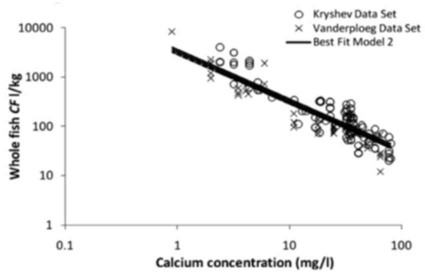
Example from a Baltic Sea ecosystem near Forsmark NPP, Sweden.

Bradshaw et al (2012) Ecosystems 15: 591–603

Analogues / competing ions

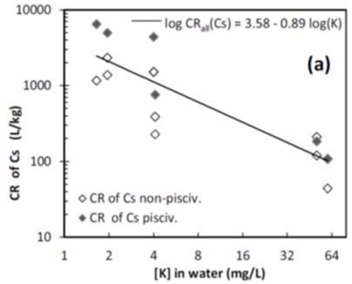
(CF, CR = ratio of element in fish: water)

Sr and Ca



Smith et al (2009) JER 100: 950–954

Cs and K

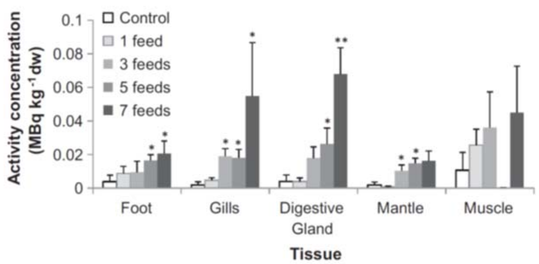


Konovalenko et al (2016) JER 160: 64-79

Examples of tissue-specific accumulation

- In fish:
  - Up to 95% of Sr-90 is found in the bony parts of fish (skeleton, fins, skin) due to its similar bioaccumulation to Ca
  - Cs-137 tends to accumulate in K-rich tissues, such as muscle; soft tissues account for up to 99%

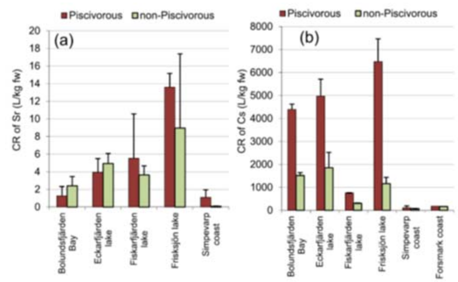
Blue mussels fed phytoplankton containing H-3

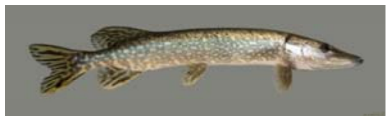


Jaeschke & Bradshaw (2013) JER 115: 28-33

Trophic transfer / biomagnification

- Biomagnification = increasing concentrations higher up the food chain
- Most radionuclides do not biomagnify
- Some evidence that ^{137}Cs can biomagnify





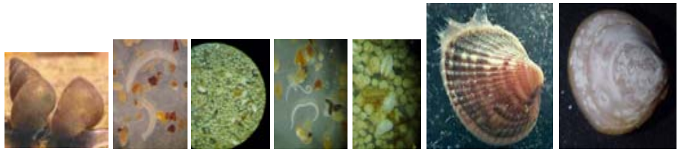
Cs BMFs = 2 - 5.6

Konovalenko et al (2016) JER 160: 64-79

We can’t measure everything! So we usually simplify

Uptake and doses to organisms are usually estimated in a rather generalised way, e.g. based on:

- activity concentrations in the surrounding environment,
- bioconcentration factors, transfer factors
- reference organisms
- organism geometry



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K_d and transfer coefficients

- **K_d** is the solid/liquid partition coefficient, also known as distribution coefficient

$$= \frac{\text{concentration in sediment or particles}}{\text{concentration in dissolved phase}}$$

- **Transfer Coefficients** (also known as Concentration Factors, Concentration Ratios, Bioconcentration Factors, Bioaccumulation Factors...)

$$= \frac{\text{concentration in biota}}{\text{concentration in medium (water, soil etc)}}$$

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Using K_ds: pros and cons

- Easy – just **measure the concentration in the water or sediment or soil**
- Assume equilbrium (but this is rarely the case)
- Don’t take into account biological processes
- Vary widely with time, space, type of organism, element...
- Lack of data means extrapolation necessary (between types of organism, elements, ecosystems...)

Concentration in water (mg/L)

x

K_d (mg/kg)/(mg/L)

=

Concentration in sediment (mg/kg)

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Using CRs: pros and cons

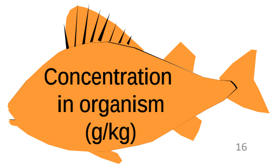
- Easy – just **measure the concentration in the medium**
- Assume equilbrium (but this is rarely the case)
- Don’t take into account biological processes
- Vary widely with time, space, type of organism, element...
- Lack of data means extrapolation necessary (between types of organism, elements, ecosystems...)

Concentration in water (mg/L)

x

CR (mg/kg)/(mg/L)

=



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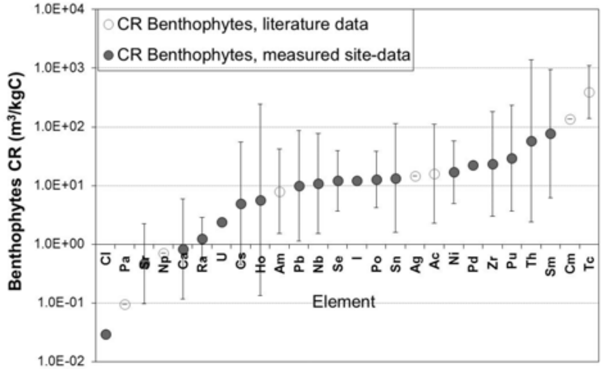
CR variability: using literature values can introduce uncertainty



Konovalenko et al (2014) JER 133: 48-59

DOSE

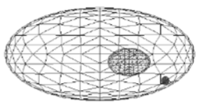
Dose estimates

- Dose = <u>mean energy absorbed per unit **volume**</u>
  mass of that volume

=> so geometry is important

- Unit for absorbed dose is Gray (Gy) (= Joule/kg)

=

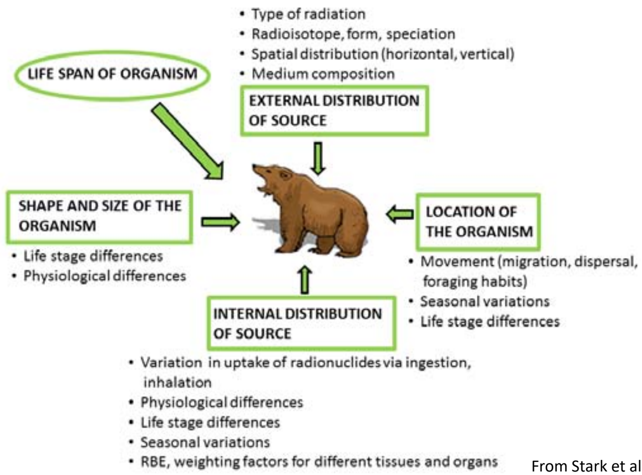


- Dose (Gy) vs dose rate (Gy/y)

- external and internal dose
- risk assessments
- science

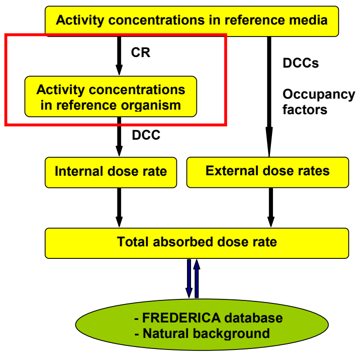
Parameters affecting radiation dose to wildlife in a site contaminated with radionuclides

But again - we usually simplify!



From Stark et al (in prep).

ERICA Tool (Environmental Risk from Ionising Contaminants: Assessment and Management)



- Models transfer through the environment
- Estimates doses to biota from internal and external distributions of radionuclides
- Estimates the significance of the dose-rates received by organisms
- Also used in research

See Brown et al (2008) JER 99: 1371-1383 for more details

Examples of reference organisms

(ICRP* "Reference Animals and Plants" (RAPs) in red)

Terrestrial		*Marine*		*Freshwater*	
Soil Invertebrate	Earthworm	Phytoplankton		Phytoplankton	
Detritivorous invertebrate		Macroalgae	B. seaweed	Vascular plant	
Flying insects	Bee	Vascular plant		Zooplankton	
Gastropod		Zooplankton		Insect larvae	
Lichen & bryophytes		Polychaete worm		Bivalve mollusc	
Grasses & Herbs	Grass	Bivalve mollusc		Gastropod	
Shrub		Crustacean	Crab	Crustacean	
Tree	Pine	Benthic fish	Plaice	Benthic fish	
Mammal	Deer & Rat	Pelagic fish		Pelagic fish	Trout
Bird	Duck	(Wading) bird		Bird	Duck
Bird egg		Mammal		Mammal	
Reptile		Reptile		Amphibian	Frog
Amphibian	Frog	Sea anemones/true corals			

*International Commission on Radiological Protection

Criteria for selection

- Reasonable amount of existing radiobiological data
- Represent a range of
  - taxa
  - ecosystems/habitats
  - life cycles
- Exposure can be modelled using relatively simple geometry
- ....etc

Radionuclides in ERICA cover known / expected sources:

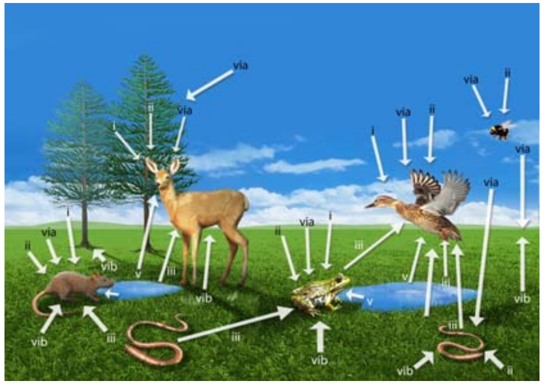
- TENORM (technologically enhanced naturally occurring radioactive materials)
- Routine releases (reprocessing, power production)
- Accidents
- High level waste repositories

Ag	Silver
Am	Americium
C	Carbon
Cd	Cadmium
Ce	Cerium
Cl	Chlorine
Cm	Curium
Co	Cobalt
Cs	Caesium
Eu	Europium
H	Tritium
I	Iodine
Mn	Mangenese
Nb	Niobium
Ni	Nickel
Np	Neptunium
P	Phosphorus
Pb	Lead
Po	Polonium
Pu	Plutonium
Ra	Radium
Ru	Ruthenium
S	Sulphur
Sb	Antimony
Se	Selenium
Sr	Strontium
Tc	Technetium
Te	Tellurium
Th	Thorium
U	Uranium
Zr	Zirconium

Exposure pathways in ERICA

Example from terrestrial ecosystems:

- Inhalation of particles or gases
- Contamination of fur/feathers/skin
- Ingestion of lower trophic levels
- Drinking contaminated water
- External exposure through air or soil

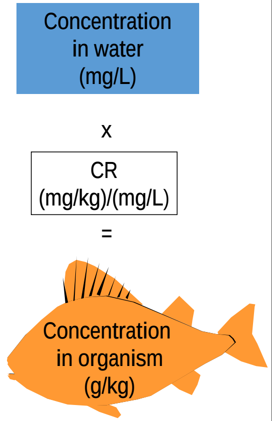


Biological transfer in ERICA

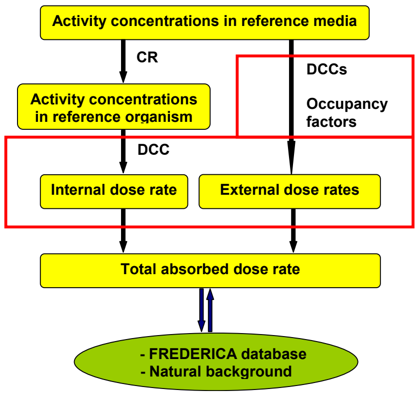
CR = concentration in biota / concentration in medium (water, soil etc)

Simplification! But the approach

- uses empirical information and can therefore be considered to represent in situ conditions
- is easily understood
- is consistent with human impact assessment methodology



Estimating doses to biota in ERICA



Dose Conversion Coefficients (DCC) are used to derive

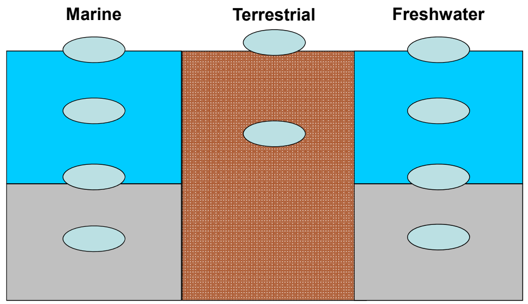
- internal dose rates
- external dose-rates (using "occupancy factors")

They are based on geometry

DCC = Dose-rate (µGy/h) per activity concentration (Bq/kg fresh mass)

Occupancy factors

= Fraction of time spent by organism at different locations within its habitat



Example: the Reference Duck

Default values can be changed to measured values, if available

- Assumed to have the characteristics of a typical urban/rural duck:
- Lays 10 elliptical eggs at one day intervals, incubation 30d
- Nestlings spend equal time on the ground and on the water and fledge at 60d
- Juvenile stage 1 y, then breed
- Breed annually for 10 years
- Equal sex ratio
- Adult = ellipse (30x10x8cm), 1.26kg

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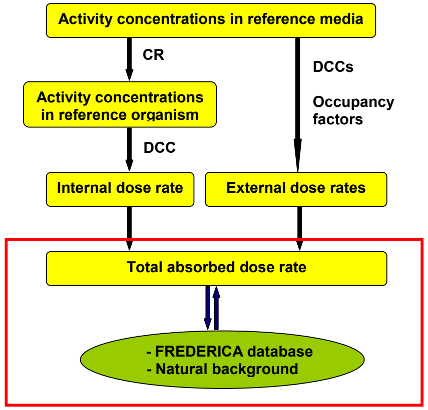
Estimating probability of effects in ERICA



- Compare calculated total dose rates to the effects database FREDERICA
- Compare calculated total dose rates to the screening levels (DCRLs)

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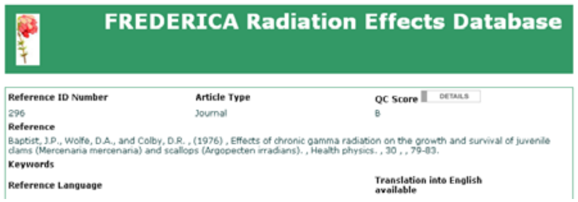
Estimate probability of effects for a given dose

www.frederica-online.org


FREDERICA Radiation Effects Database

Reference ID Number: 296
Article Type: Journal
QC Score: B (DETAILS)
Reference
Baptist, J.P., Wolfe, D.A., and Colby, D.R. , (1976) , Effects of chronic gamma radiation on the growth and survival of juvenile clams (Mercenaria mercenaria) and scallops (Argopecten irradians). , Health physics. , 30 , , 79-83.
Keywords
Reference Language
Translation into English available

- Large literature review : >1200 references; circa 30 000 data
- Various animal and plant categories
- Different endpoints : mortality, morbidity, reproduction, mutation
- Acute and chronic exposure data but focus on chronic (environmentally relevant) data.
- Data is quality controlled

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Derived Consideration Reference Levels (DCRLs)

= band of dose rate within which there is some chance of deleterious effect from ionizing radiation occurring to individuals of the RAP

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

possible action needed

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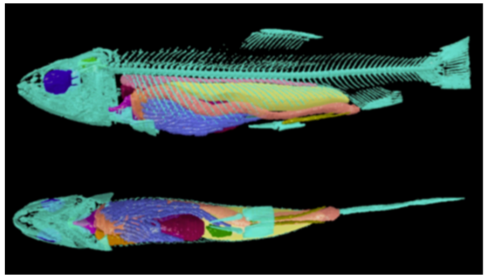
More exact/detailed dose estimates (e.g. in research)

- Voxel models
  - detailed computerized phantoms compiled from (e.g. CT scan)
  - depict the internal anatomy of an organism
  - 3D geometrical and tissue information used in dose calculations



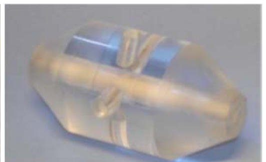
Rainbow trout (Ruedig et al 2014)

Comparing voxel and simple models

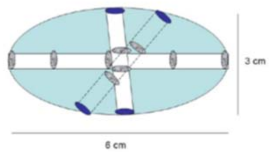
- voxel-calculated and ellipsoid-calculated dose rates compared for seven heterogeneously distributed radionuclides
  - 14C, 36Cl, 60Co, 90Sr, 131I, 134Cs, 137Cs, 210Po.
- methodologies agreed within a factor of 2-3
- ellipsoidal models for these 3 RAPs were generally conservative compared to the voxel model
  - OK for regulatory purposes
  - For regulatory work, voxel models are unnecessarily complex.
- but contribution of cross-irradiation (between organs) to total dose not fully understood / quantified and may not be adequate in simpler models

Ruedig et al (2015) JER 140: 70-77

Dosimeters in the field



Frog 'phantom' with TLDs



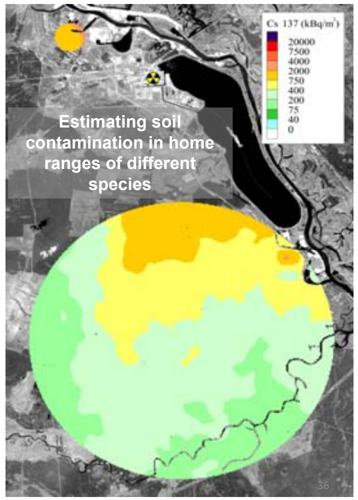
Measured dose for 90 days:
The measured doses were lower than the calculated doses
- Measured doses: 0.026 ± 0.003 mGy/d
- Modelled dose range: 0.017-0.128 mGy/d

Stark and Pettersson (2008) Rad Env Biophys 47:481-9

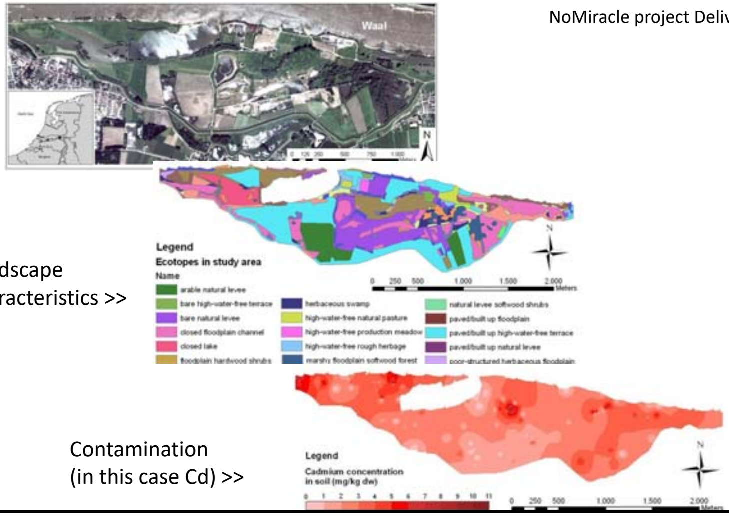
Photo: Lavrans Skuterud

Dose estimates using more detailed spatial and temporal information

- Dose usually estimated to
  - Maximally exposed individual or
  - 'Average' member of the population
- Simplistic animal-environment interaction
  - 'Average' media
  - At best - approximate time spent in different zones (habitat utilisation)

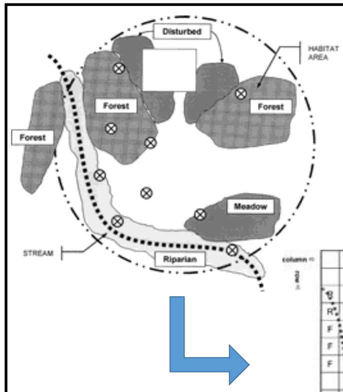


NoMiracle project Deliverable 4.2.1

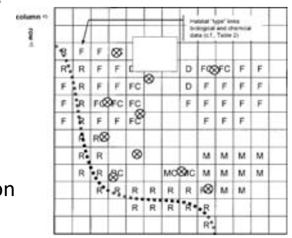


Landscape characteristics >>

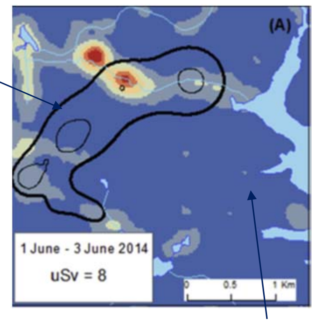
Contamination (in this case Cd) >>



Modelling habitat utilisation
Hope (2005) Hum Ecol Risk Ass 11: 539-565



Area where an adult wild pig spent 95% of its time



Cs-137 contamination from aerial survey

Measuring habitat utilisation and dose: wild pigs with GPS dosimeters in Belarussia
Hinton et al (2015) JER 145: 58-65

EFFECTS

Mechanisms of toxicity and detoxification

Ionising radiation — *direct effect* → Structural damage of DNA and other molecules in cell

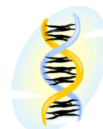
indirect effect ↓

Spallation of water in cytoplasma, production of free radicals

$H_2O \rightarrow H_2O^+ \rightarrow H^+ + OH^*$

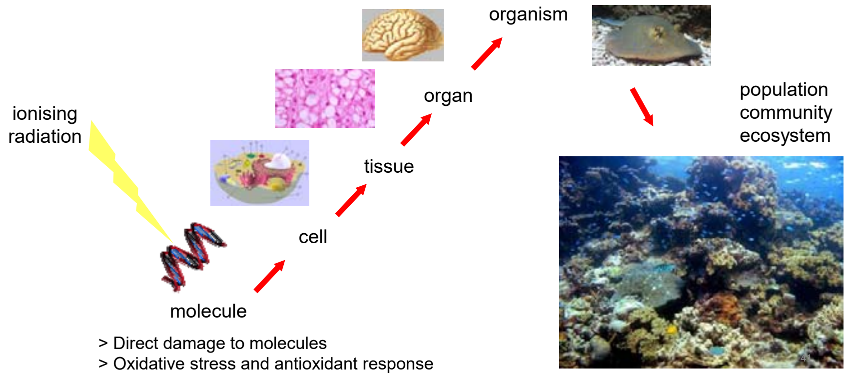
$H_2O \rightarrow e^- + H_2O^+ \rightarrow H_2O^- \rightarrow OH^- + H^*$

oxidative stress / antioxidant response



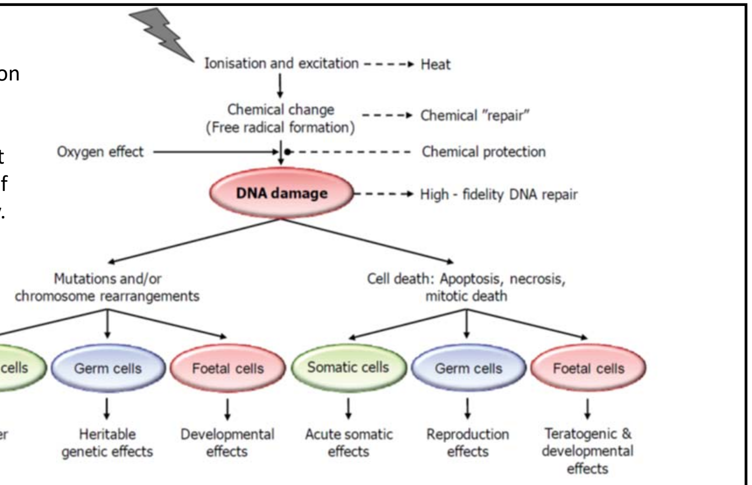
- DNA repair mechanisms
- Defective repair, Mutation
- Direct cell-death

From molecule to ecosystem



> Direct damage to molecules
> Oxidative stress and antioxidant response

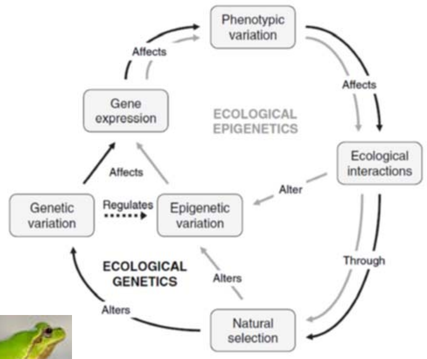
Interaction of ionising radiation with biological tissues and the subsequent development of radiation injury.



From Hertel-Aas (2014), adapted from Little (2003) and UNSCEAR (2006).

Epigenetic and transgenerational effects

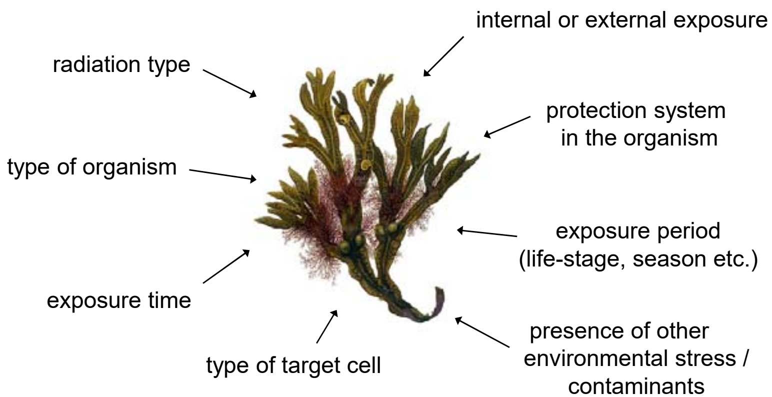
- "DNA makes RNA makes protein"
- Epigenetics = heritable changes in gene function that cannot be explained by changes in DNA sequence
- DNA and the proteins that are involved in its replication and transcription, can play an important role in adaptation both within and across generations.
- Can cause heritable changes



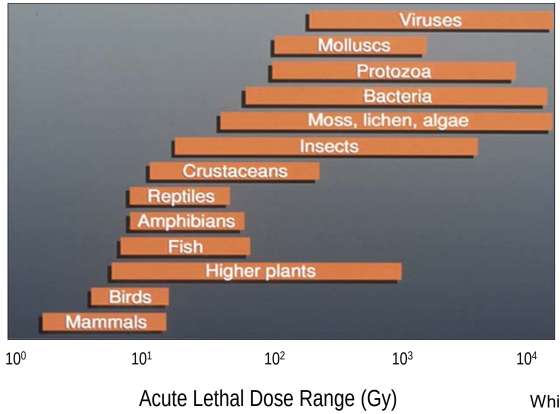
COMET: studies on frogs, earthworms, nematodes, Arabidopsis in Chernobyl and Fukushima affected areas

(From COMET Deliverable 4.1, Bossdorf et al., 2008)

Effects of radiation in organisms depend on:



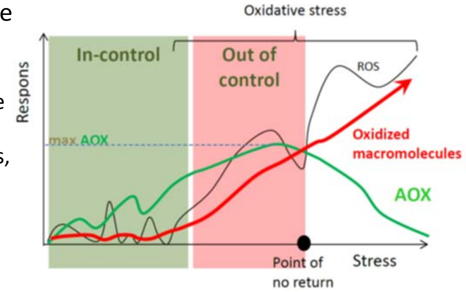
Sensitivity to radiation of various taxa



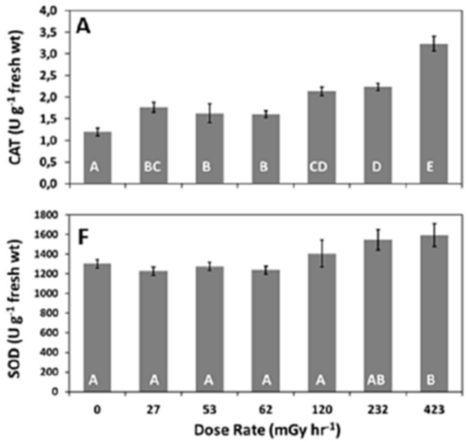
Whicker & Schultz (1982)

Radiation-induced oxidative stress

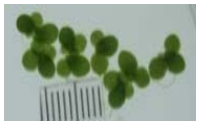
- Oxidative stress is common in nature
- There are many antioxidative defence (AOX) mechanisms to neutralize 'reactive oxygen species (ROS):
  - enzymes like catalase (CAT), superoxide dismutase (SOD) etc.
  - metabolites like glutathione, flavonoids, phenolic compounds and carotenoids
- But with with excess stress AOX mechanisms are not sufficient and ROS damages cells



Source: Sara Furuhagen, Stockholm University



An example:
Lemna minor
(lab experiment)



Van Hoeck et al (2015) JER 150: 195-202

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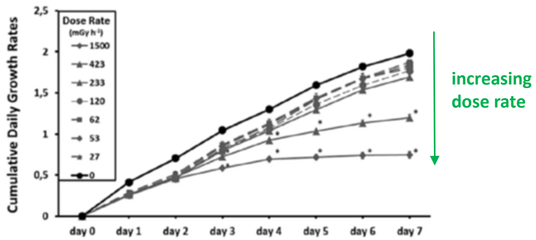
Individual and population level effects

- Individual-level effects
  - e.g. effects on growth, behaviour, feeding rates, respiration, mortality



Van Hoeck et al (2015)
JER 150: 195-202

- Effects on individual reproduction are important – they affect populations

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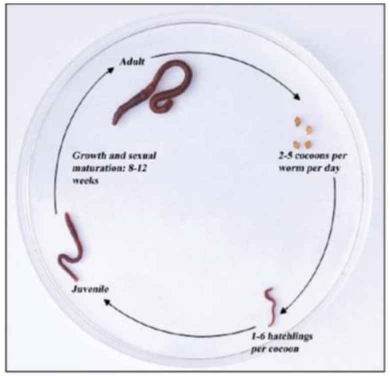
Reproductive effects

- Reproductive endpoints can be very sensitive, maybe because cells are actively dividing (developing embryos are also very sensitive)
- There may be effects on:
  - Production of germ cells
  - Transfer of genome to offspring
  - Decreased hatchability
  - Early death of embryos, via induction of mutations in germ cells
  - Etc...



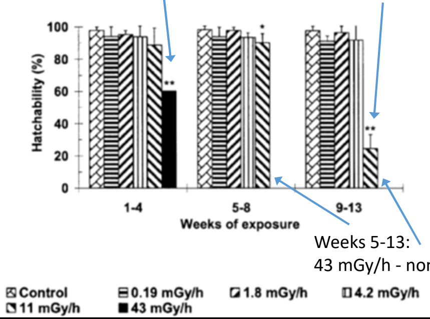
Eisenia fetida. Source: Hertel-Aas (2014)

Eisenia fetida exposed to gamma radiation for 2 generations (F0 and F1).
(Hertel Aas et al (2007) Rad Res **168**, 515–526

<u>F0: cocoon hatchability</u>

Weeks 1-4:
60% at 43 mGy/h

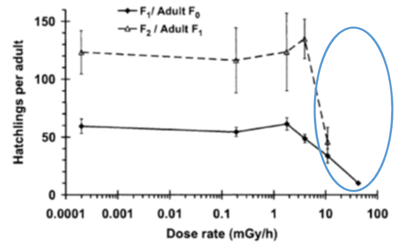
Weeks 9-13:
25% at 11 mGy/h



Weeks 5-13:
43 mGy/h - none hatched

<u>Number of F1 hatchlings per adult F0</u>

At 11 and 43 mGy/h, number of hatchlings was significantly lower than in the control.



Reproductive effects in Chernobyl pine trees

First few years after the accident:

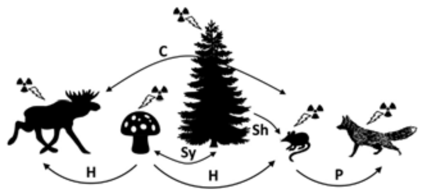
- Did not bear seeds for 5–7 years, reduced number of seeds per cone, increased fraction of hollow seeds
- micro- and macrosporification, gametogenesis and early embryogenesis of pine – showed as disorders of seed-buds for two generations
- partial female sterility - reduced gametophyte and embryonic survival of seed-buds

Source: Vasyl Yoschenko

Geras'kin et al (2008) Environment International 34: 880–897

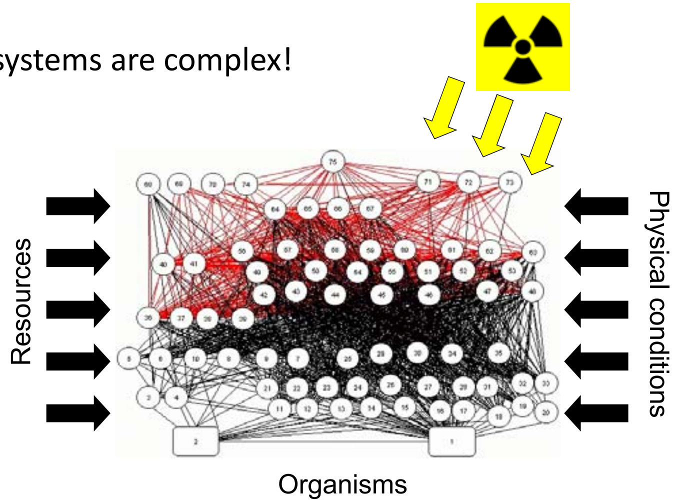
What about communities and ecosystems?

- Most studies are done on single species
- In reality individuals or species do not exist in isolation
- Interactions between species, populations, biotic-abiotic => non-linearity
  - Indirect effects
  - Feedbacks
- effects at ecosystem level may be hard to predict from effects on individual species
- may over- or under-estimate effects / risk



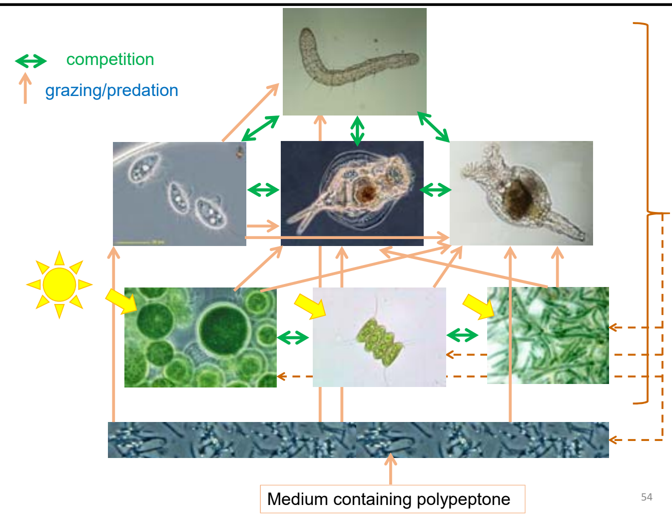
Bradshaw et al (2014)
C = competition, P = predation, H = herbivory , Sy = symbiosis , Sh = shelter

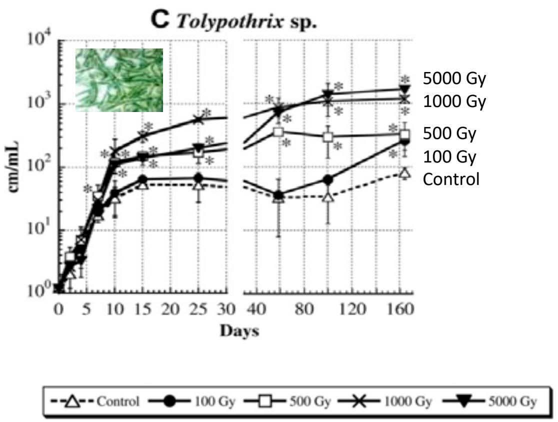
Ecosystems are complex!



Effects of acute gamma irradiation on community structure of the aquatic microbial microcosm

Fuma et al (2010) JER 101: 915-922





Conclusion:

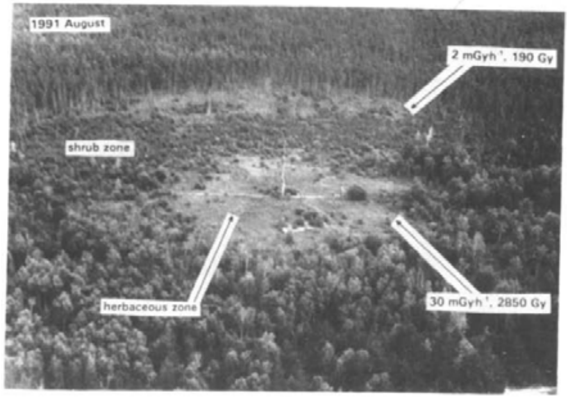
- Radiation is good for *Tolypothrix*?!?

  or
- *Tolypothrix*'s predators (rotifers) and/or competitors (other microalgae) are negatively affected?

Indirect effects are not just caused by species interactions

- They may be mediated by environmental changes
- Effects on organisms affects abiotic components which in their turn affect organisms
  - particularly via keystone species or ecosystem engineers
- e.g. light penetration, temperature, nutrient concentrations, soil moisture, pH, O2…

Evidence from the field



14y chronic gamma irradiation of boreal forest, Canada
Amiro and Sheppard (1994)

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Acute (8 day) high dose exposure, South Urals area – mixed pine and birch

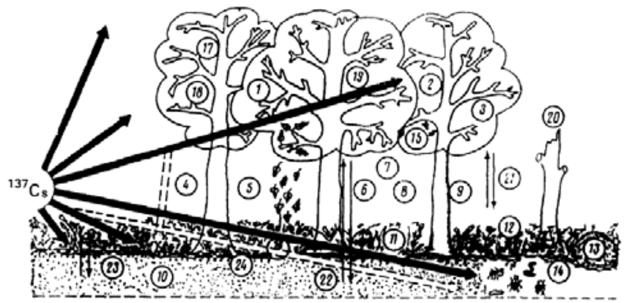

Fig. 2. General scheme illustrating major primary and secondary radiation reactions in the forest biogeocenosis. **1**, phenology; **2**, growth of the tip and side branches; **3**, leaf fall; **4**, precipitation; **5**, wind speed; **6**, temperature; **7**, light under canopy; **8**, humidity; **9**, annual wood ring; **10**, soil temperature; **11**, biomass and yield of grass seeds; **12**, structure and phenology of grass cover; **13**, ants; **14**, meso- and microfauna of soils; **15**, insects in canopy; **16**, forest litter; **17**, yield and quality of tree seeds; **18**, cytogenetic properties of buds and pollen; **19**, biomass of above ground parts of plants; **20**, damage and death of trees; **21**, tree and herb relations; **22**, tree and soil relations; **23**, grass and soil relations; **24**, yield and quantity of seeds in litter.

Alexakhin et al. (1994) Science of the Total Environment 157: 357-369

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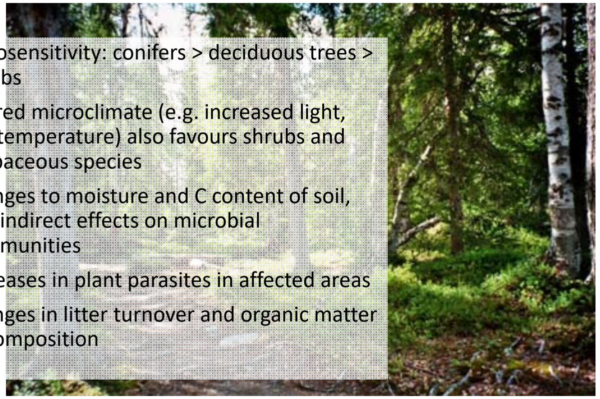
Ecosystem effects in forest field studies



- radiosensitivity: conifers > deciduous trees > shrubs
- altered microclimate (e.g. increased light, soil temperature) also favours shrubs and herbaceous species
- changes to moisture and C content of soil, and indirect effects on microbial communities
- increases in plant parasites in affected areas
- changes in litter turnover and organic matter decomposition

(note – external doses only)

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Take home message:

Don't forget the biology and ecology!

www.radioecology-exchange.org