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Effects of ionizing radiation on non-human biota

Hildegarde Vandenhove

Biosphere Impact Studies
Environment Health and Safety

hildegarde.vandenhove@sckcen.be

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Outline

- Why addressing impact on non-human biota
- Key elements for the non-human biota risk assessment
- Dose effects data from UNSCEAR-1996/2008
- Comparison of benchmarks
- Conclusions

Need for a system to protect environment (1/2)

- Paradigm contested: “If man is protected, the environment is protected”

Estimated dose to organism from controlled discharges of RN that would each lead to 1 mSv/a for man residing in same environment			
Radionuclide	**Dose rate (µGy/h): 1 µGy/h→ ~100 mSv/a**		
	***Plants*[a]**	***Animals*[a,b]**	***Fish*[c]**
H-3	5.8	5.8	0.59
C-14	18	11	
P-32	32	28	4.8
Co-60			0.53
Sr-90	2.0	0.042	67
Zr-95	38	2.0	
Tc-99			3.8
I-131	1.2	0.058	
Cs-137	5.4	3.1	0.72
Ra-226			3.6
U-235			2.6
U-238			4.7
Pu-239	0.023	0.00055	0.49
Am-241			0.71
	Atmospheric	**Atmospheric Farm animals**	**Aquatic**

Need for a system to protect environment (2/2)

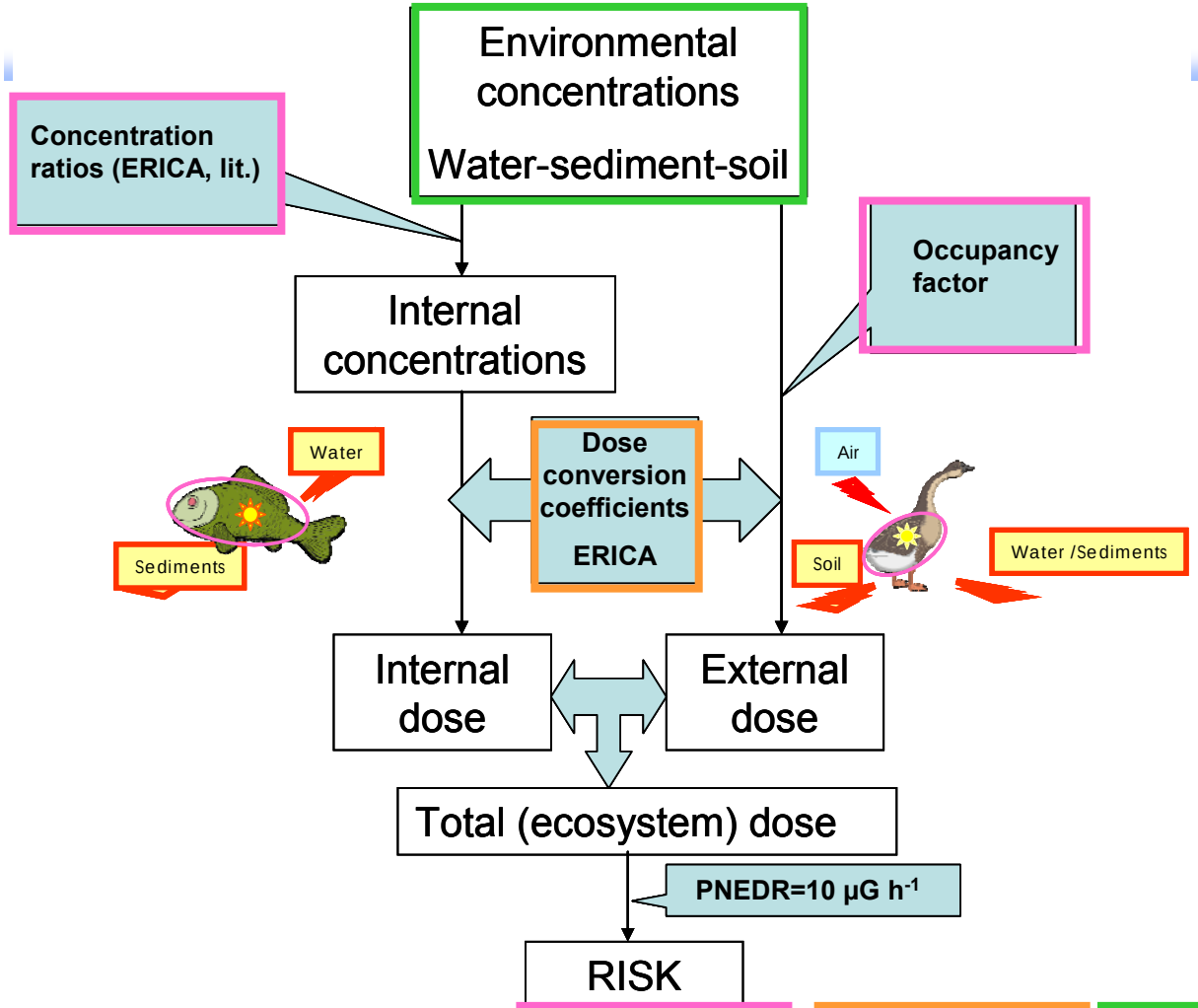
- Over last decade, considerable national and international effort
- Environmental protection now being referred to in the IAEA Fundamental Safety Principles
  - Vague terminology: Revised BSS of IAEA: "*Environmental protection should be considered*"
- Recommendations of the ICRP
- UNSCEAR
- EC-FASSET, ERICA, PROTECT
- DoE, EnvCan

Key elements in a framework for assessment of radiation effects on non-human biota

- Exposure of biota
  - Spatial and temporal variation of RN conc in environment
  - Uptake by organism
  - Non-uniform distribution in organism
- Reference organisms
  - Not possible to evaluate all biota
- Dosimetry model for reference biota
  - Absorbed dose for different geometries
  - Radiation weighing factor
- Endpoints
  - Population 'umbrella effects' – morbidity, mortality, reproduction
  - Assign reference doses
- Effects
  - Individual effect on umbrella endpoint → effect on population
  - Role of BG radiation levels
  - Natural population variability

- Earthworm/soil invertebrate
- Rat/burrowing mammal
- Bee/flying insect
- Wild grass/grass, herbs, crops
- Pine tree/tree
- Deer/herbivorous mammal
- Duck/bird
- Frog/amphibian
- Brown seaweed/macroalgae

Exposure analysis



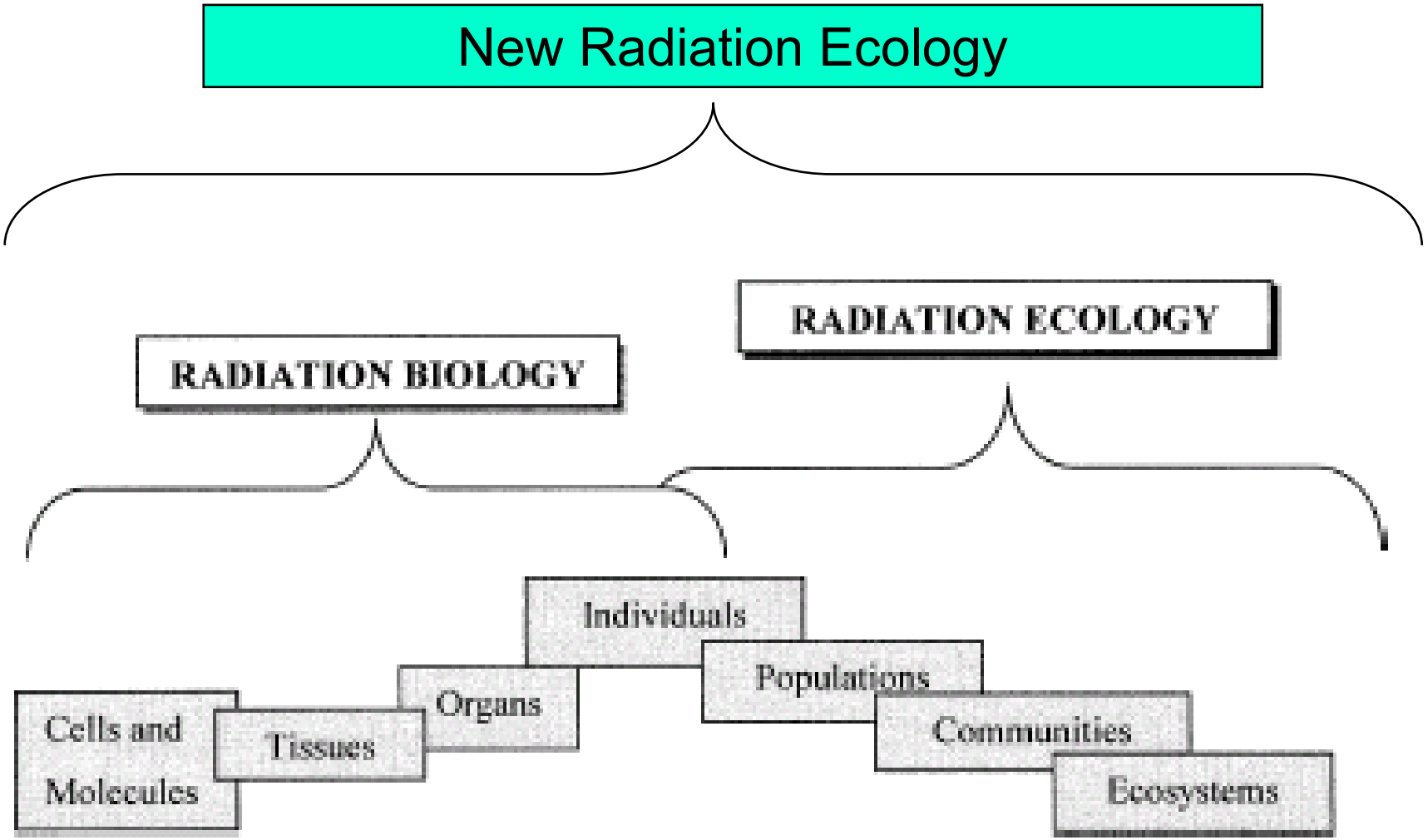
External exposure

Internal exposure

$$PEDR_{ext}(o) = OF(o,m) \times DCC_{ext}(i,o) \times C(i,m)$$

$$PEDR_{int}(o) = CR(i,o,m) \times DCC_{int}(i,o) \times C(i,m)$$

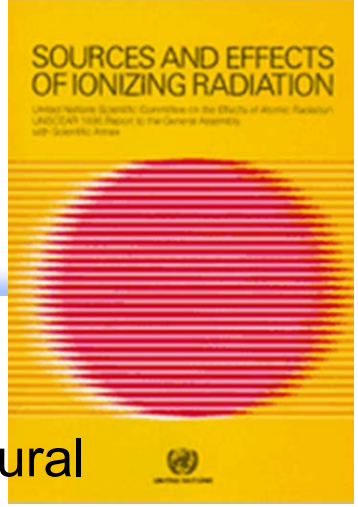
Fundamental differences between human and ecological risk assessment



Most contaminant research is not directly relevant to responses in nature

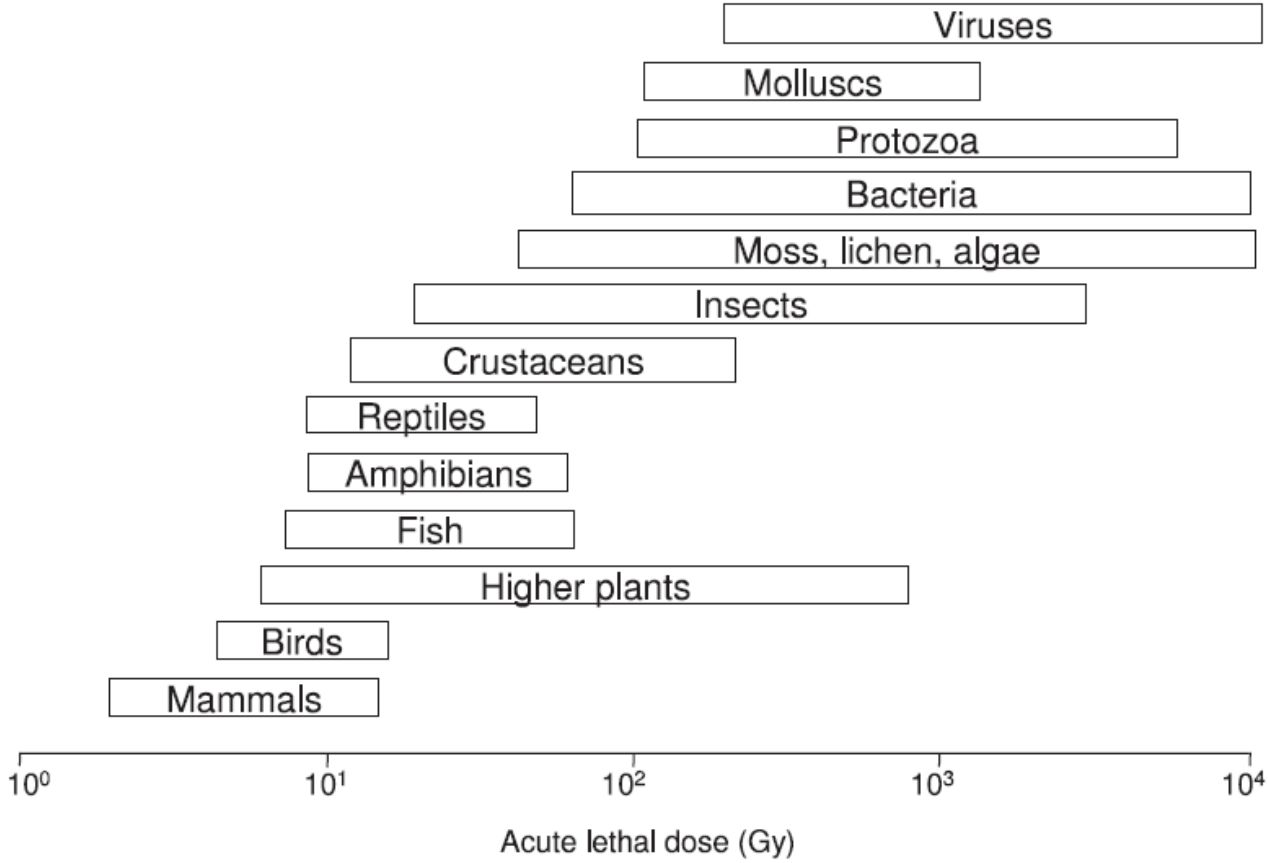
Data Exists but Least Relevant	Data Scarce but Most Relevant
Individual response	Population response
Mortality, mutation	Reproduction
Acute exposure	Chronic exposure
External gamma	Multiple exposure route
Laboratory	Field
Short-term	Long-term
Direct effects	Indirect effects
Optimal growth conditions	Sub-optimal, multiple stressors

UNSCEAR 1996

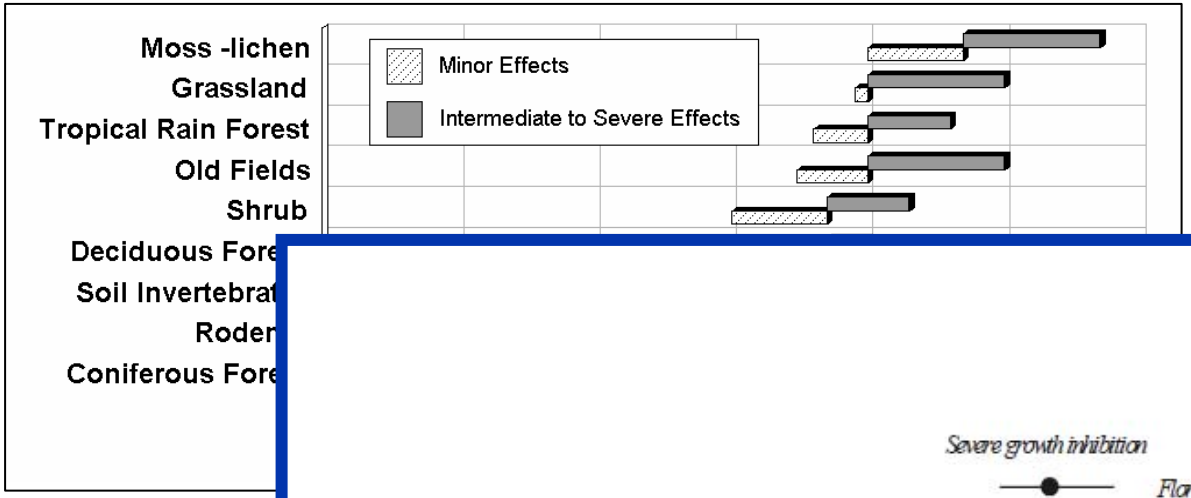


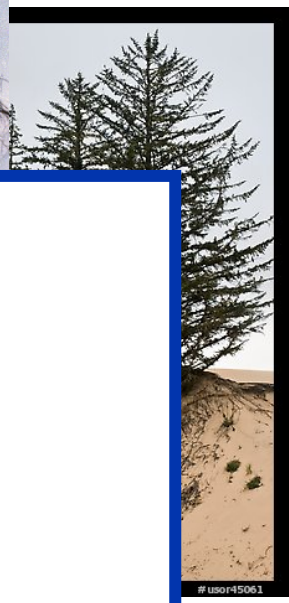
- Aim: to review and summarize information on
  - exposures of organisms in their natural habitats to the natural radiation background, to radionuclides released into the environment in a controlled manner from industrial activities, and to radionuclides released as a consequence of accidents; and
  - the responses of plants and animals, both as individuals and as populations, to acute and chronic irradiation
- Endpoints
  - Mortality: affecting age distribution, death rate, density
  - Fertility and fecundity: affecting birth rate, age distribution, #, density
  - Induction of mutations: affecting birth rate and death rate
- Reproduction more sensitive than mortality

A wide range of sensitivities



Effects on plants: acute exposure





- Acute
- Pine m

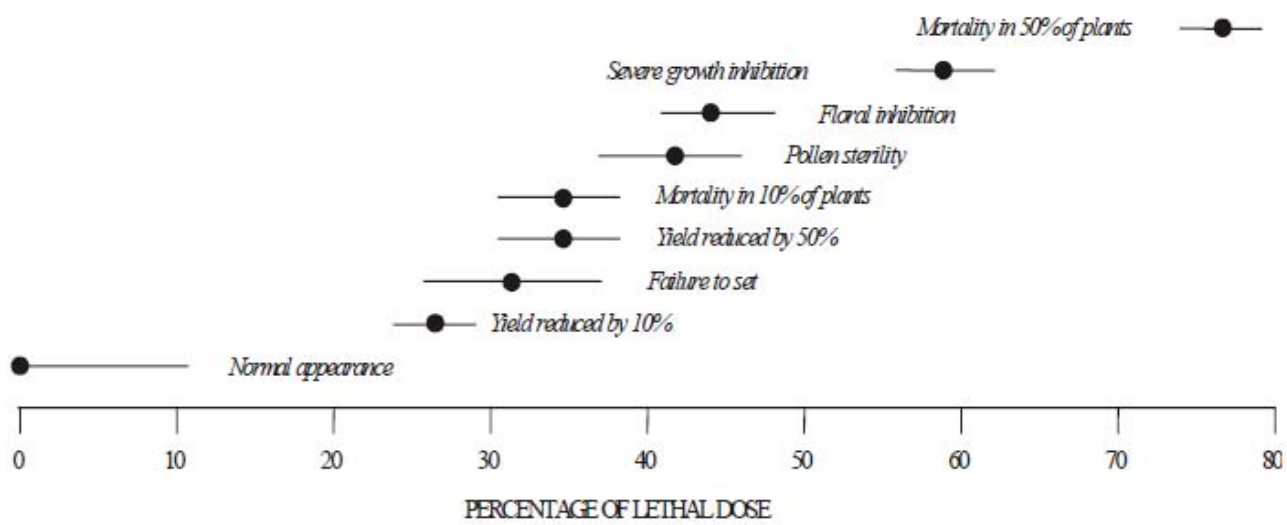


Figure X. General range of response to radiation by herbaceous plants in comparison with lethal dose (LD_{100}) [S3].

Effects on plants

- Effects of chronic irradiation of the most sensitive plants evident at 1000–3000 µGy/h
- Specific changes noted at 400–2000 µGy/h

- Committee suggested:

  chronic dose rates at or below 400 µGy/h should have only slight effects in sensitive plants but would be unlikely to produce any significant deleterious effects in the wider range of plants present in natural plant communities.

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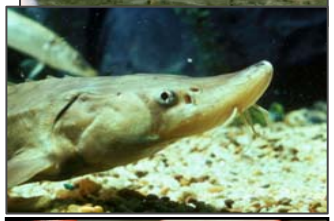
Effects on terrestrial animals

- Sensitivity
  - Large mammals>small mammals=birds>reptiles >invertebrates
- Acute lethal doses (LD50/30)
  - 6-10 Gy for small mammals
  - 1.5–2.5 Gy for larger animals and domesticated livestock
- Chronic exposure
  - Dose rates below 400 µGy/h to most exposed members of population (and, hence, with correspondingly lower average dose rates to the whole population) unlikely to seriously affect their mortality
  - Reproductive capacity more sensitive to radiation effects than mortality
    →Dose rates less than 40 µGy/h to most exposed individual in population unlikely to have impact on the overall reproductive capacity of a mammalian population

Effects on aquatic organisms






- Fish most sensitive, developing embryos in particular
- Acute lethal doses (LD50)
  - Marine invertebrates: >100 Gy
  - Fish: 10-25 Gy
  - Fish embryos: 0,16 Gy (Salmon)
- Chronic exposure
  - No effect of dose rates of 10 000–30 000 µGy/h on mortality or of 3200–17 000 µGy/h on reproductive capacity for snails, marine scallops, clams and crabs
  - 1000 µGy/h no effect of reproduction of fish

  →dose rates up to 400 µGy/h to a small proportion of the individuals in aquatic populations (and, hence, with correspondingly lower average dose rates to the whole population) would not have any detrimental effects at the population level

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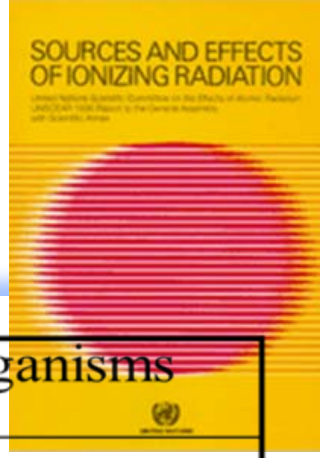
UNSCEAR 1996 in summary



Terrestrial plants	Terrestrial animals	Aquatic organisms
Chronic dose rates <400 µGy/h would have effects, although slight, in sensitive plants but would be unlikely to have significant deleterious effects in the wider range of plants present in natural plant communities	For most sensitive animal species, mammals, little indication that dose rates of 400µGy/h to the most exposed individual would seriously affect mortality. For dose rates up to an order of magnitude less (40-100 µGy/h), the same statement could be made with respect to reproductive effects.	For aquatic organisms, maximum dose rates of 400 µGy/h to a small proportion of the individuals, and, therefore, a lower average dose rate to the remaining organisms would not have any detrimental effects at the population level

400 µGy/h	400 µGy/h mortality 40 µGy/h reproduction	400 µGy/h

UNSCEAR 1996 → 2008
No change in guidance values

- *Overall conclusions 1996*: chronic dose rates of less than 100 μGy h^{-1} to the most highly exposed individuals would be unlikely to have significant effects on most terrestrial animal communities and that maximum dose rates of 400 μGy h^{-1} to a small proportion of the individuals in aquatic populations of organisms would not have any detrimental effect at the population level

- *2008*: The Committee considers that data developed since its 1996 report do not support changes to its previous conclusions of the values of nominal chronic dose-rates below which direct effects on non-human species are unlikely at the population level

Some conclusions by the Chernobyl Forum Expert Group on Environment

- Numerous acute adverse effects in the biota located in areas of higher exposure (up to few tens of km from the release point).
  Both individual and population effects caused by radiation-induced cell death observed in plants and animals:
  - increased mortality of coniferous plants, soil invertebrates and mammals
  - reproductive losses in plants and animals
  - chronic radiation sickness of animals (mammals, birds, etc.).
- Beyond exclusion zone, no acute radiation-induced effects on biota reported
- No adverse radiation effect reported in plants and animals exposed to a cumulative dose <0.3 Gy during the first month after accident (i.e. <10 mGy/d)
- By the next growing season following the accident, population viability of plants and animals substantially recovered as a result of the combined effects of reproduction and immigration.
  Few years needed for recovery from major radiation induced adverse effects in plants and animals.

With the removal of humans, wildlife around Chernobyl are flourishing

48 endangered species listed in the international Red Book of protected animals and plants are now thriving in the Chernobyl Exclusion Zone

Russian Boar

Wolves

Prejevalsky Horses

ICRP-108 (2008) (1/3)
DCRL-Derived Consideration Reference Levels

- Very much based on human system of protection
- 12 reference animals and plants (RAPS) selected for which information on effects was collected
- Criteria for selection somewhat arbitrary based on global occurrence, plants and animals, terrestrial and aquatic, different habitats
- Endpoints: mortality, morbidity, reduced reproductive success, chromosomal damage
- Establishment of Derived Consideration Reference Levels (DCRLs) for each of the RAPs based on expert judgement

ICRP-108 (2/3)
DCRL-Derived Consideration Reference Levels

- DCRL: intended to serve as points of reference in assessing the potential effects of ionizing radiation on non-human biota

- DCRL can be considered as a band of dose rate within which there is likely to be some chance of deleterious effects of ionising radiation occurring to individuals of that type of Reference Animal or Plant

- Not clear how effects on individual level can be extrapolated to effects at population levels
  - → DCRL only refer to individual level

ICRP-108 (3/3)
DCRL-Derived Consideration Reference Levels

RAPs	DCRL-range	Description
Deer	4-40 µGy/h	Very low probability of effects
Rat	4-40 µGy/h	Very low probability of effects
Duck	4-40 µGy/h	No information
Frog	40-400 µGy/h	No positive 'effect' information
Trout	40-400 µGy/h	Possible reduced reproductive success
Flatfish	40-400 µGy/h	Possible reduced reproductive success due to reduced fertility in males
Bee	400-4000 µGy/h	No information
Crab	400-4000 µGy/h	No information
Earthworm	400-4000 µGy/h	Effects unlikely
Pine tree	4-40 µGy/h	No information
Wild grass	40-400 µGy/h	No information
Brown seaweed	400-4000 µGy/h	Potential effects on growth rate and reproductive success

Species Sensitivity Distribution approach to derive SV
Cfr TGD Approach for Chemicals

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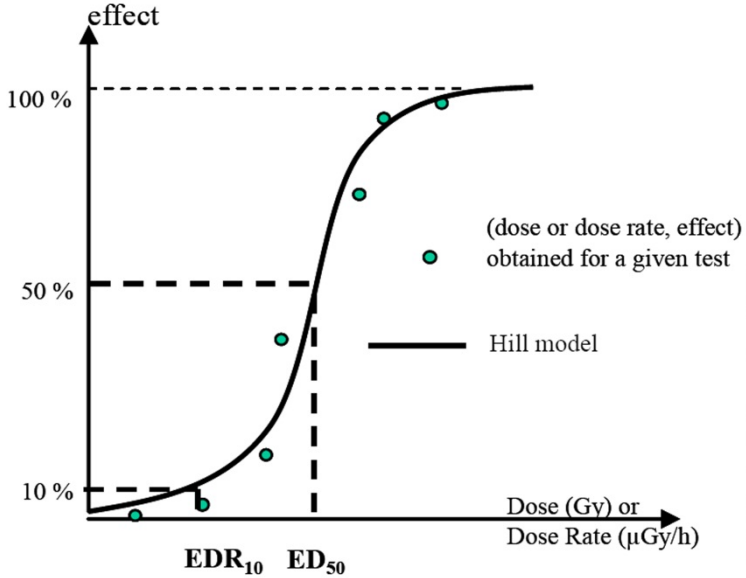
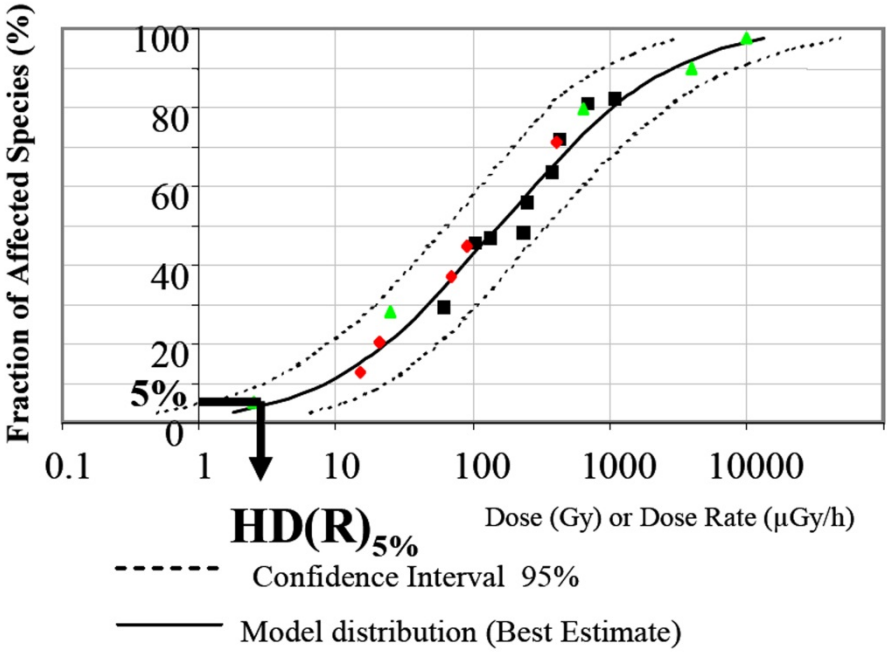
FREDERICA
Radiation Effect Database

Endpoints: morbidity, mortality, reproductive capacity



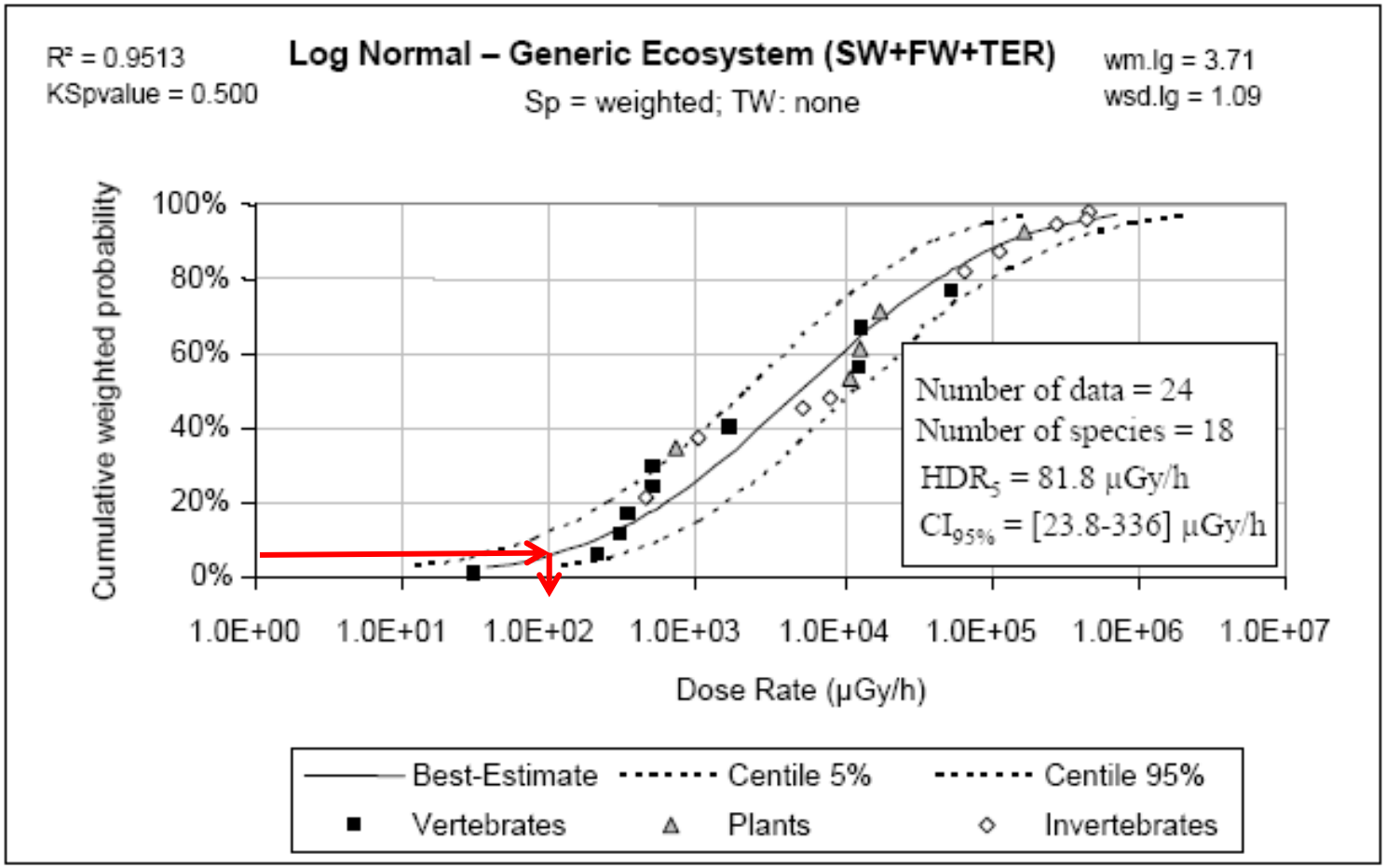
EDR_{10}: Effective dose rate causing 10 % effect
ED_{50}: Effective dose causing 50% effect

HDR_5: Hazardous dose rate affecting 5% of the species at 10% level



One symbol per trophic level : EDR_{10} (chronic exposure) or ED_{50} (acute exposure)

ERICA proposes 1 screening value for terrestrial, freshwater and marine ecosystems in case of chronic exposure



HDR_5= 81.8 µGy/h, SF=5→SV= 10 µGy/h

Screening dose rate: to screen out sites of no concern

Background radiation exposure for wildlife (UNSCEAR, 1996; 2008)

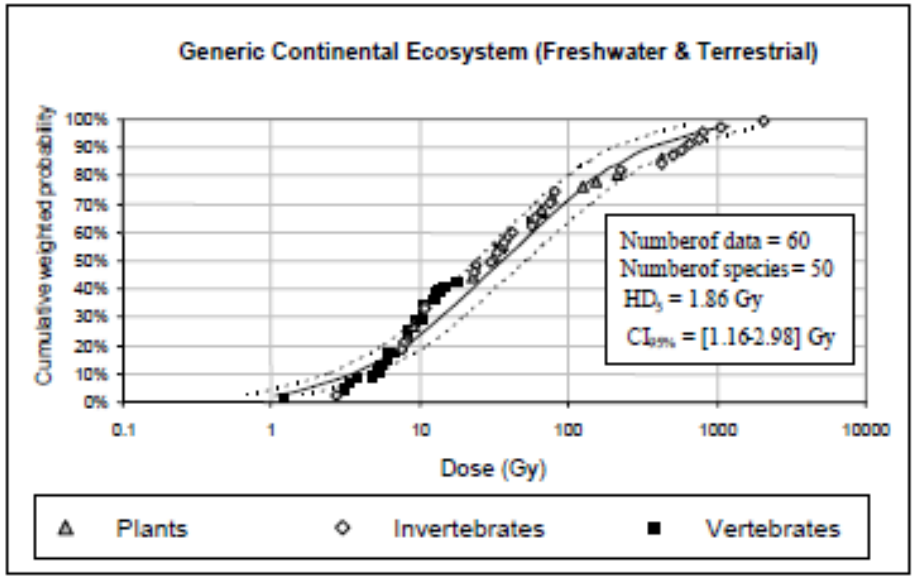
terrestrial and aquatic plants – 0.02 - 0.7 µGy/h;

terrestrial animals (mammals) - 0.01-0.44 µGy/h

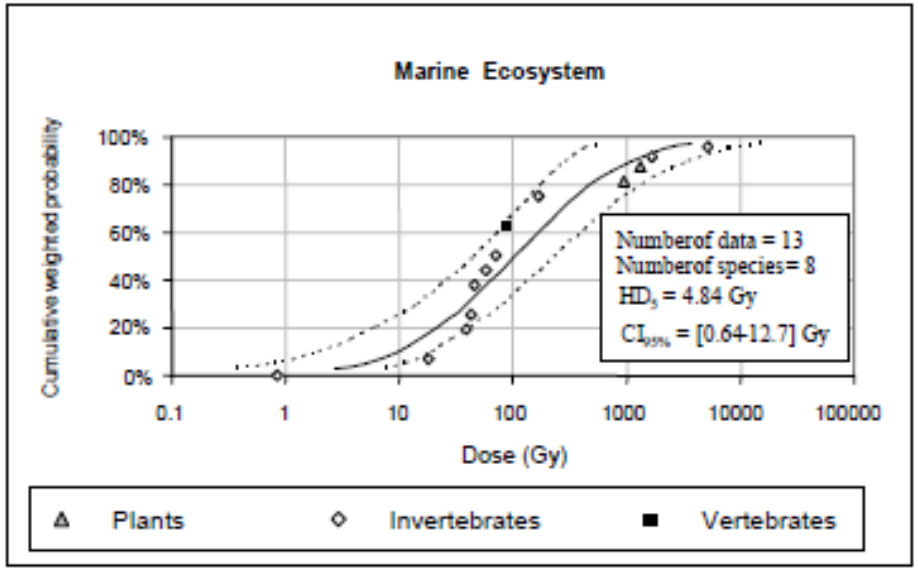
freshwater organisms – 0.022-0.18 µGy/h

Derived screening dose rate (10 µGy/h) is more than 10 times these background values

Acute exposure: Predicted No Effect Dose



HD_5= 1.86 Gy
SF=5→SV= 300 mGy



HD_5= 4.84 Gy
SF=5→SV= 900 mGy

The EC-PROTECT approach

- Globally same approach as for ERICA
- But, only reproductive endpoints (generally most sensitive and population relevant) and lowest endpoint per species for construction of SSD
- HDR_5 = 17 µGy/h, SF = 2→SV = 10 µGy/h
  (20 EDR_{10} values to produce SSD)
- Organism group specific SVs

	SV	N	Lowest EDR_{10}	Approach
Vertebrates	**2**	9	3.6	SSD
Invertebrates	**200**	7	1030	SSD
Plants	**70**	4	710	SF (=10)

Benchmarks compared

	UNSCEAR 1996/2008	IAEA 1992	ICRP 2008	ERICA 2006	PROTECT 2008
Terrestrial				10	10
Plants	400	400			70
Reference Pine tree			4-40		
Reference Wild grass			40-400		
Animals	40	40			
Mammals					2
Reference Deer			4-40		
Reference Rat			4-40		
Birds					2
Reference Duck			4-40		
Invertebrates					200
Reference Bee			400-4000		
Reference Earthworm			400-4000		
Aquatic	400	400		10	10
Freshwater organisms					
Invertebrates					200
Vertebrates					2
Reference Frog			4-40		
Reference Trout			40-400		
Marine organisms					
Reference Brown Seaweed			40-400		
Reference Crab			400-4000		
Reference Flatfish			40-400		

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	UNSCEAR 1996/2008	IAEA 1992	ICRP 2008	ERICA 2006	PROTECT 2008
Terrestrial				10	10
Plants	400	400			70
Reference Pine tree			4-40		
Reference Wild grass			40-400		
Animals	40	40			
Mammals					2
Reference Deer			4-40		
Reference Rat			4-40		
Birds					2
Reference Duck			4-40		
Invertebrates					200
Reference Bee			400-4000		
Reference Earthworm			400-4000		
Aquatic	400	400		10	10
Freshwater organisms					
Invertebrates					200
Vertebrates					2
Reference Frog			4-40		
Reference Trout			40-400		
Marine organisms					
Reference Brown Seaweed			40-400		
Reference Crab			400-4000		
Reference Flatfish			40-400		

- Benchmarks indicative of different organisms groups
  - UNSCEAR (and IAEA) refer to the most exposed individual rather than the population as a whole
  - ICRP suggest values for smaller groups
  - ERICA/PROTECT SV intended to protect generic ecosystems
- Lowest dose rates quoted broadly comparable but between approaches

Different organism groups indicated as being the most radiosensitive

Protective dose rates for a similar organism group differ

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Conclusions

- Different international initiatives to derive environmental radiation protection benchmarks
- Benchmarks difficult to compare as they are stated to be indicative for different organism groups
  - May lead to confusion
- Need to derive robust, ecosystem screening values based on dose and effects assessment under realistic chronic exposure conditions

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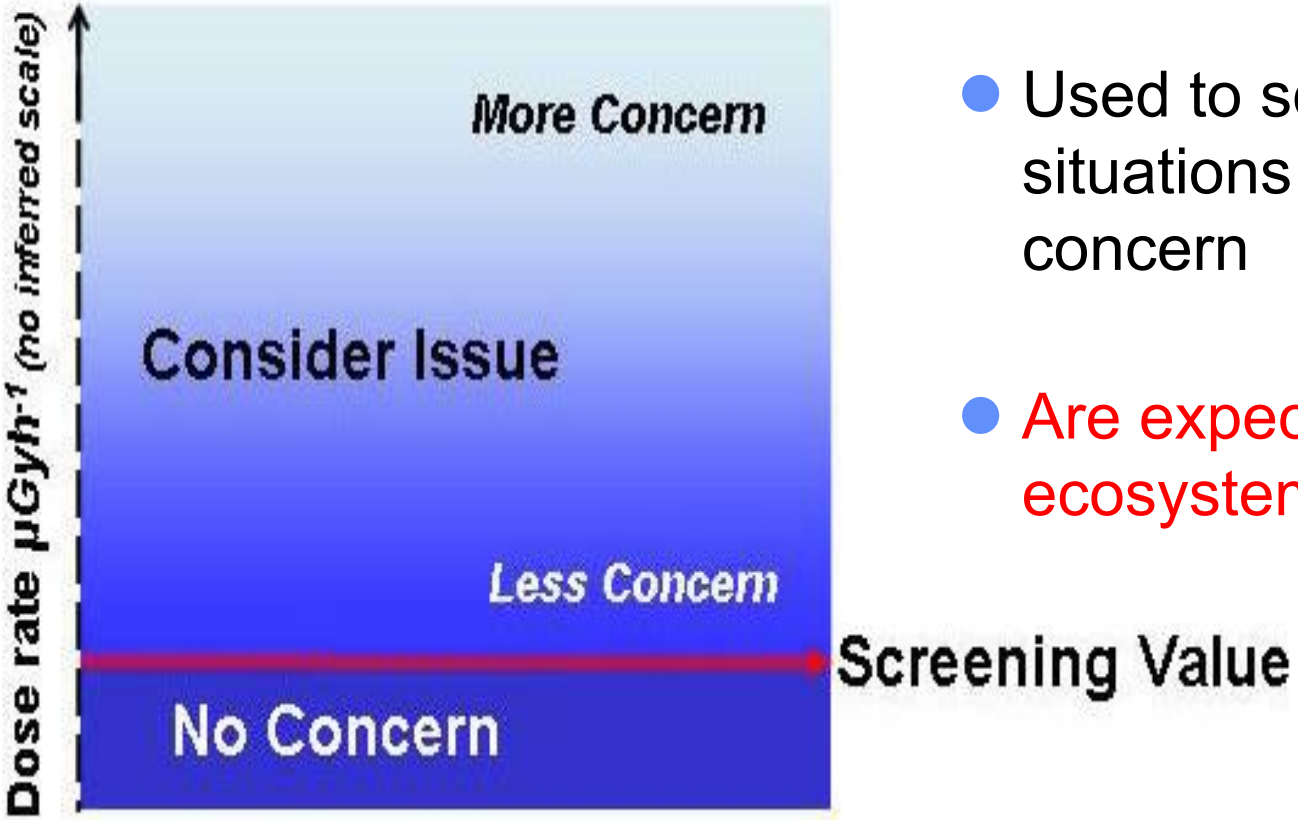
Benchmark values derived are screening values



- Used to screen out situations of no regulatory concern
- Are expected to protect ecosystems

EC-PROTECT
Action Values?

	EDR10	EDR25	EDR50
HDR5	17	65	233
HDR10	51	166	514
HDR20	189	514	1340
HDR50	2304	4499	8368

All values µGy/h

Chernobyl accident

- Initial phase: Mo-99, Te/I-132, Xe-133, I-131, Ba/La-144
  - Gamma dose up to 20 Gy/d
  - For surface tissues (needles, buds) additional dose from bèta radiation
  - High doses to thyroids of animals
- Second phase – summer autumn
  - 10 % of initial values
- Third and continuing phase
  - 1 % of initial values mainly due to Cs-137

Zones and corresponding damage to coniferous forest in area around Chernobyl

Zone and classification	*External gamma dose (mGy)*	*Exposure rate* (μGy/h)	*Internal dose to needles (mGy)*
Conifer death (4 km^2); Complete death of pines; partial damage to deciduous trees	over 80 000–100 000	over 5000	over 100 000
Sublethal (38 km^2); Death of most growth points, partial death of coniferous trees, morphological changes to deciduous trees	10 000–20 000	2000-5000	50 000–100 000
Medium damage; (120 km^2); Suppressed reproductive ability, dried needles, morphological changes	4 000–5 000	500-2000	20 000–50 000
Minor damage; Disturbances in growth, reproduction and morphology of coniferous trees	500–1 200	<200	<10 000

Effects on terrestrial animals

- Soil invertebrates: accident at most sensitive stage (out of winter dormancy, reproduction) ~30 Gy
  - Reproduction impeded but recovered after 1 year, but species diversity declined
  - Only 10 y after accident diversity recovered
- Rodents population
  - Decreased 2-10 fold during first 5 months since dose:
    - 12-110 Gy-gamma,
    - 0.6-4500 Gy-bèta
  - Recovery due to immigration
  - Pre-implantation death: 2-3 fold vs control
- Farm animals
  - High thyroid dose (> 180 Gy)→ reproductive failure
  - Recovered after 1989

Aquatic organisms: in cooling pond 6.5 PBq alpha+bèta activity released

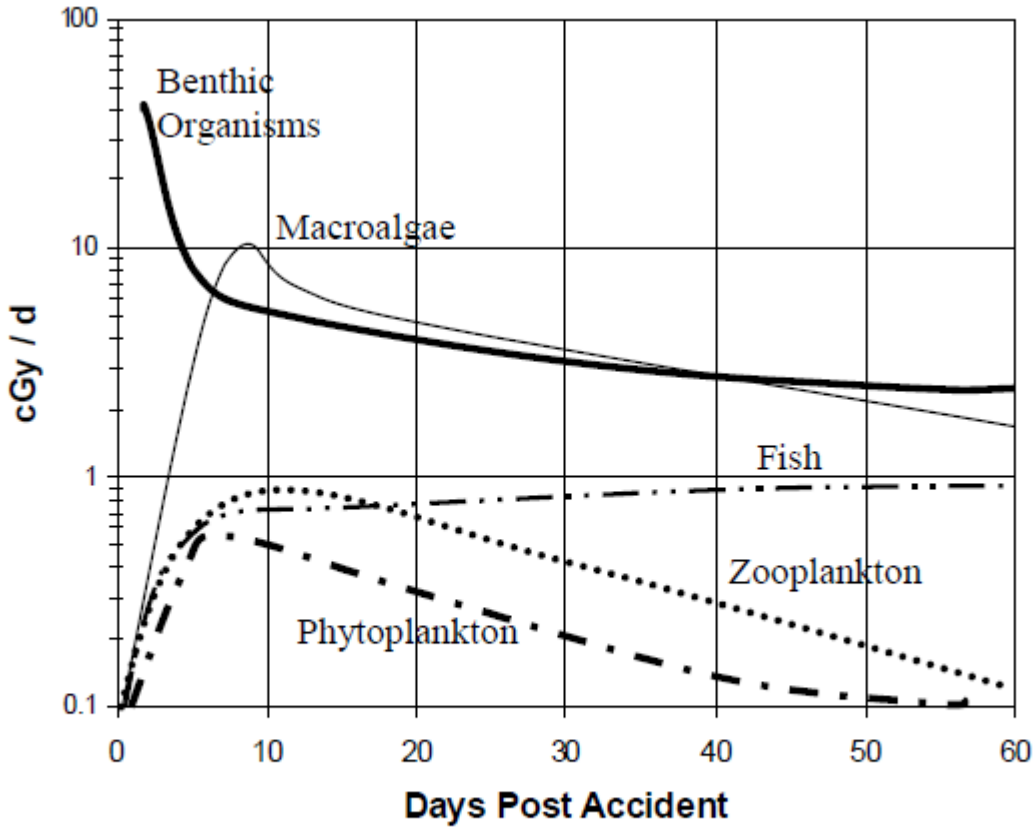
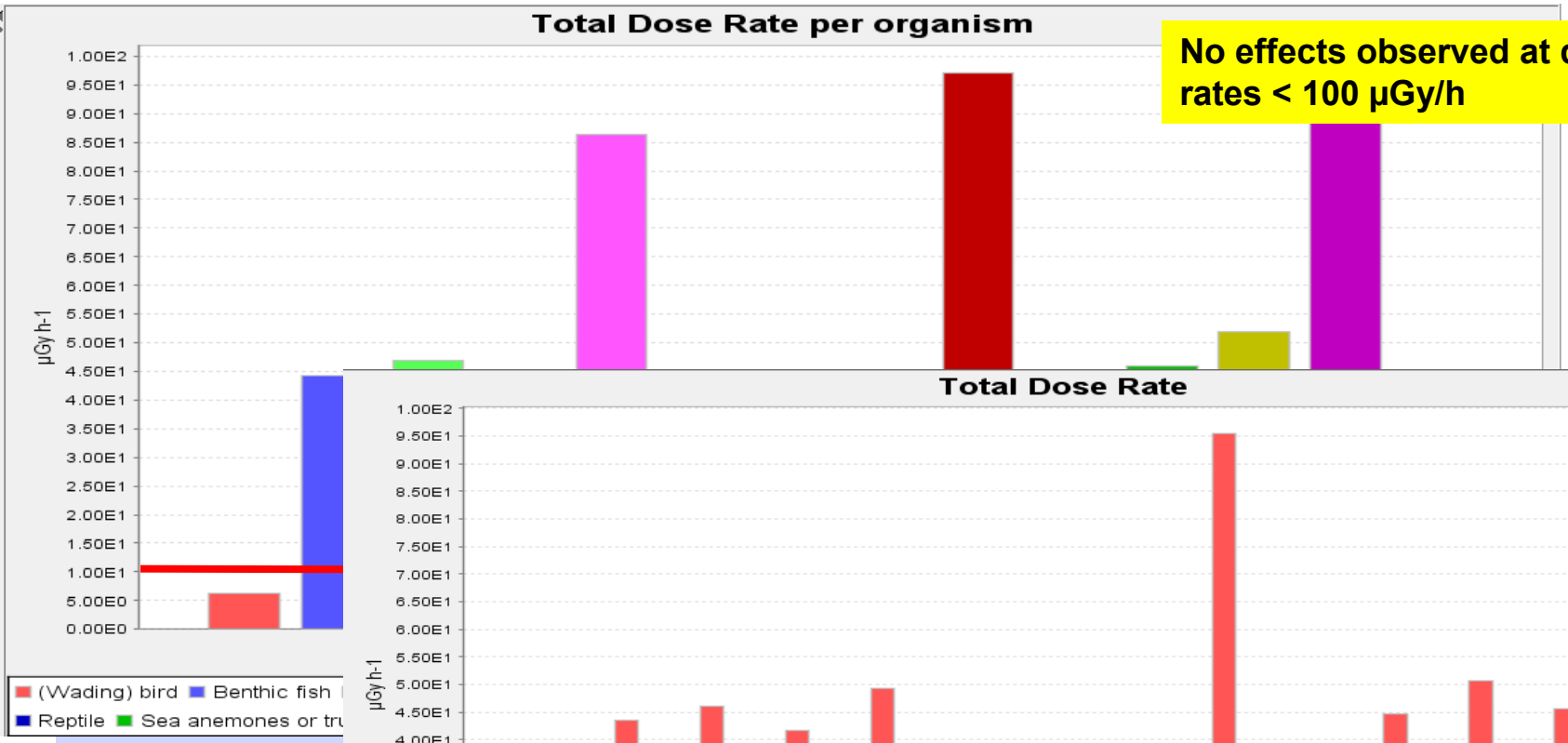
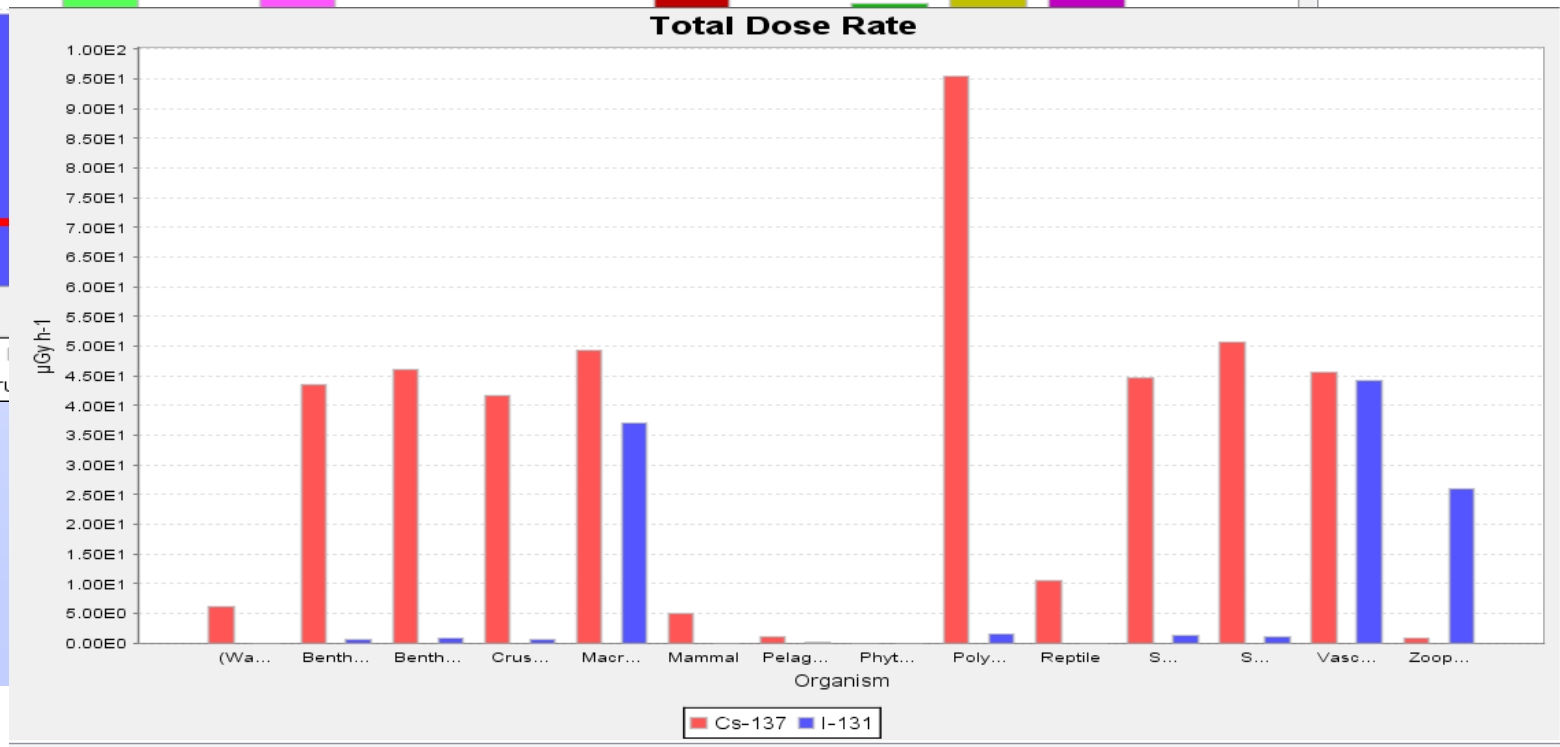


Figure XI. The dynamics of absorbed dose rate to organisms within the Chernobyl nuclear power plant cooling pond during the first 60 days following the accident.
Data are model results based on concentrations of radionuclides in the water column and lake sediments

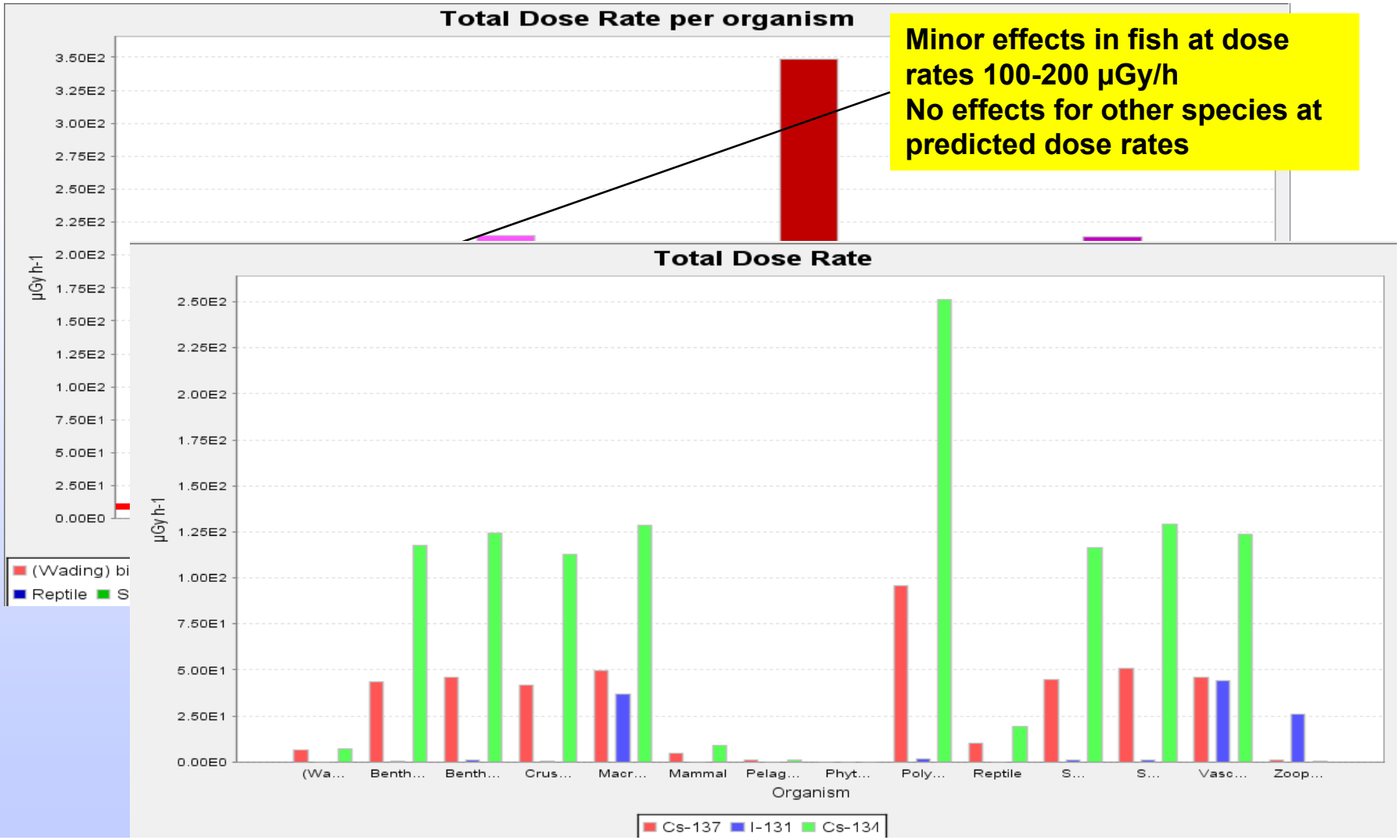
Marine exposure: Cs-137 and I-131



No effects observed at dose rates < 100 µGy/h

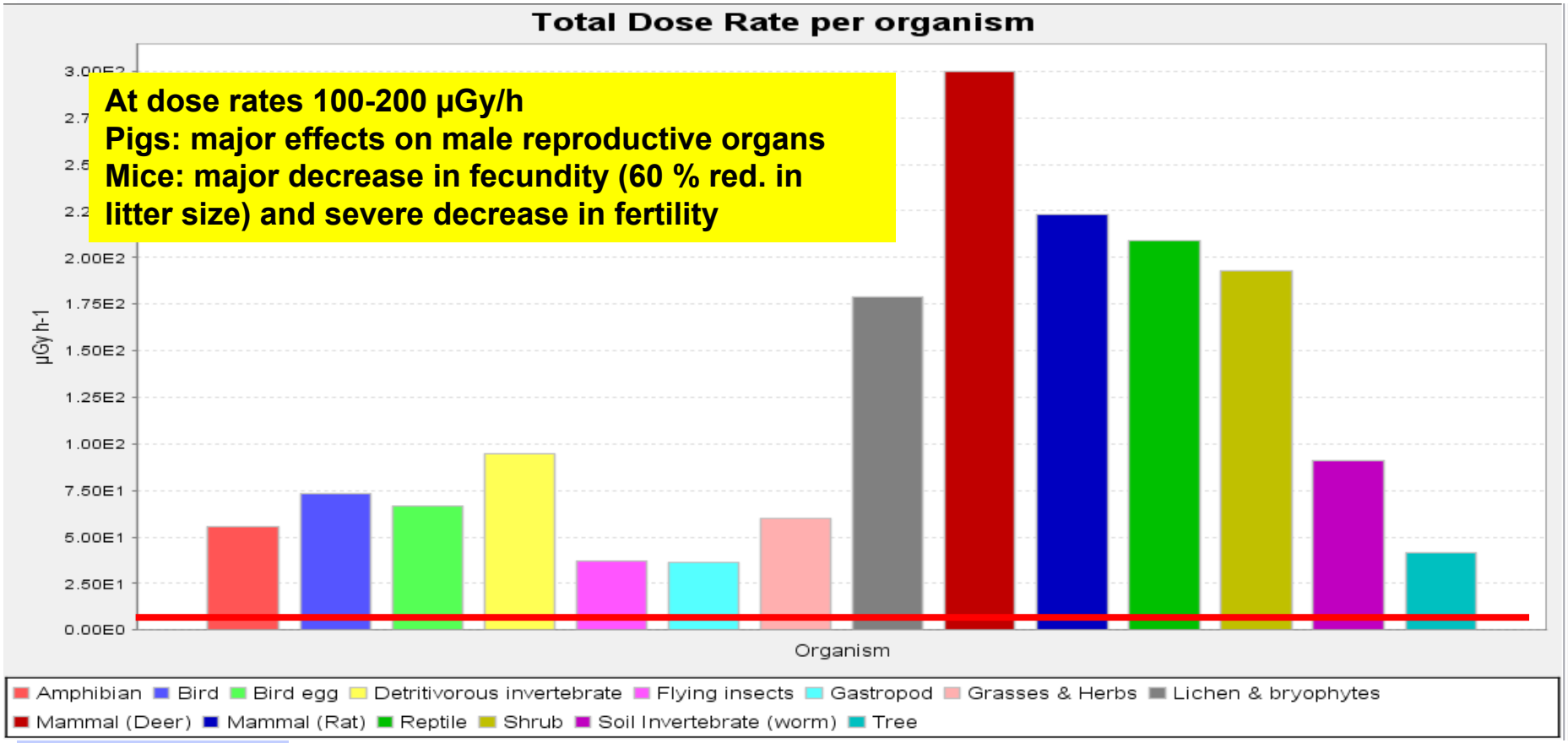


Marine exposure: Cs-137/134 and I-131



Minor effects in fish at dose rates 100-200 µGy/h
No effects for other species at predicted dose rates

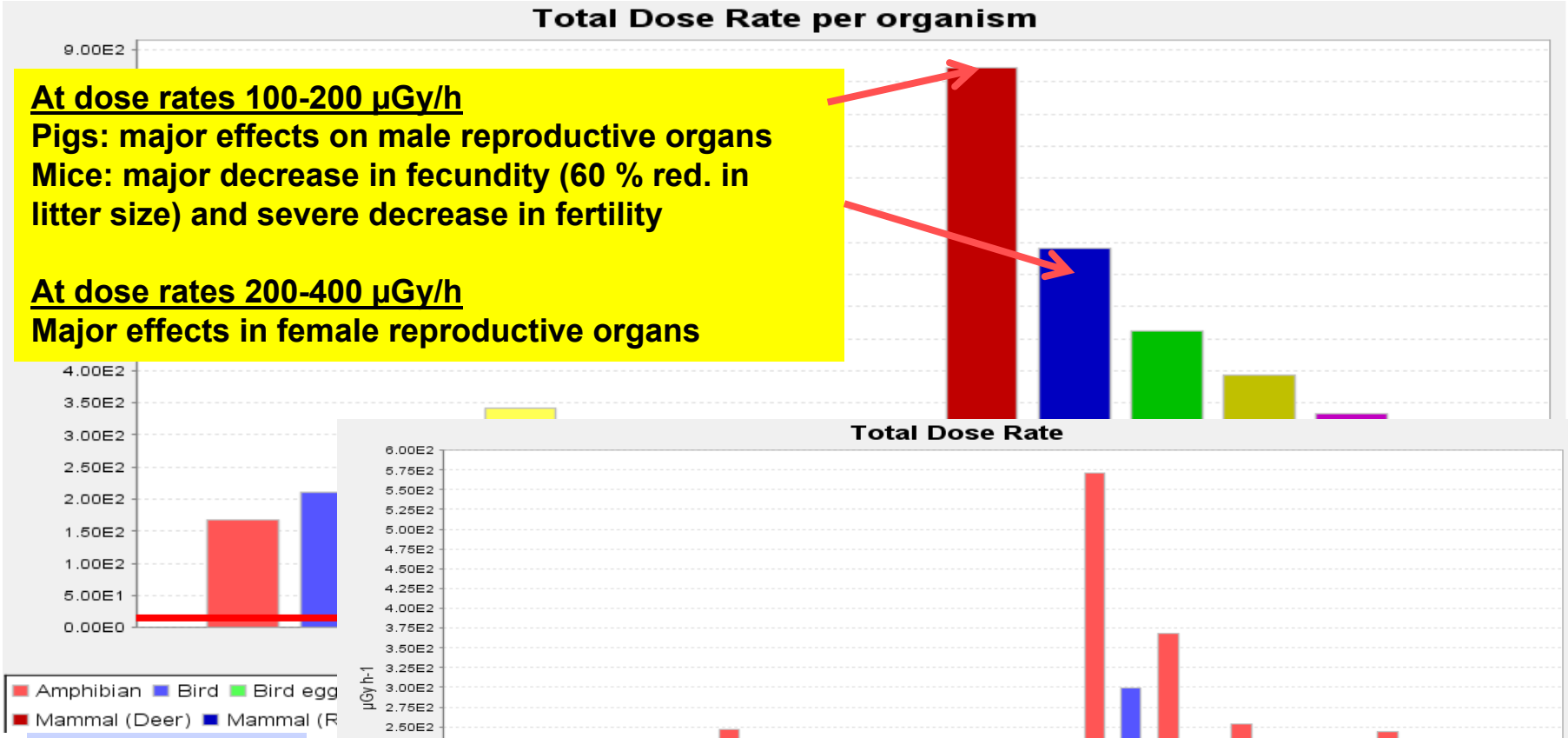
Dose rates in the terrestrial environment
Medium-long-term
For highest soil conc recorded 290000 Bq/kg Cs-137



Dose rates in the terrestrial environment
Medium-long-term
For highest soil conc recorded 290000 Bq/kg Cs-137/134

At dose rates 100-200 µGy/h
Pigs: major effects on male reproductive organs
Mice: major decrease in fecundity (60 % red. in litter size) and severe decrease in fertility

At dose rates 200-400 µGy/h
Major effects in female reproductive organs



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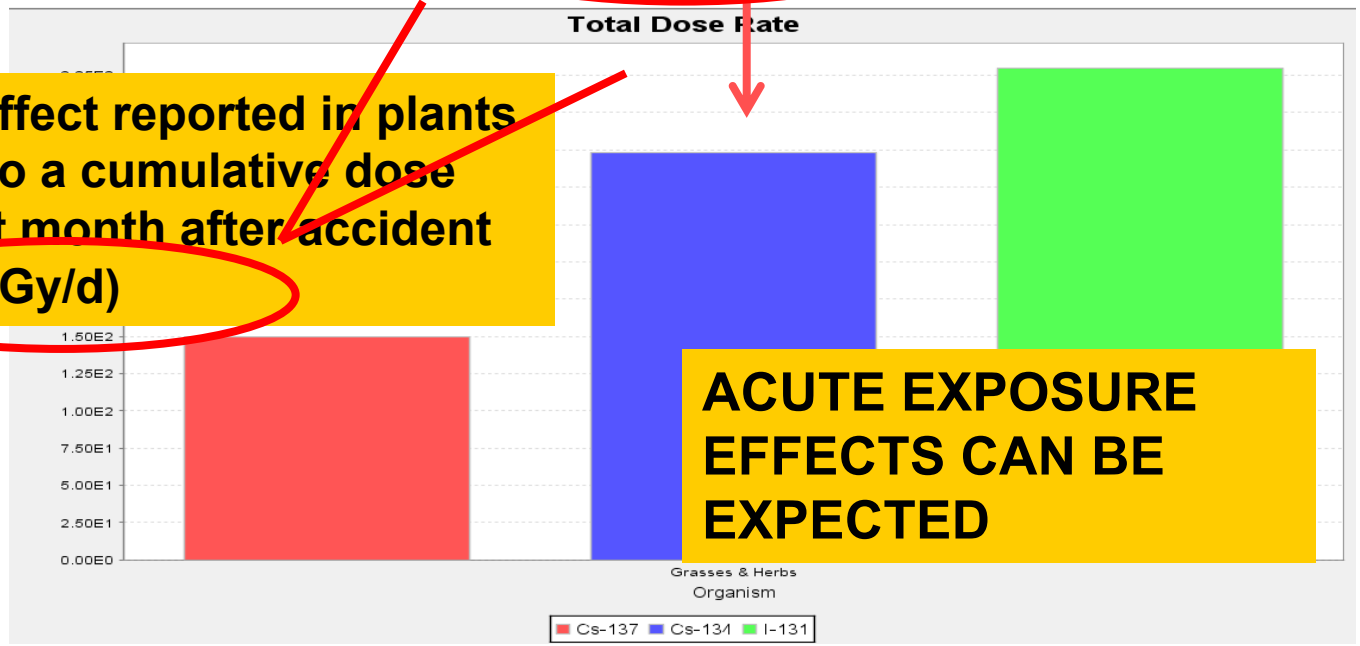
Acute exposure

	Cs-137 Bq/kg	Cs-134 Bq/kg	I-131 Bq/kg	Total dose rate µGy/h	Total dose (if 10 days days) Gy
Maximum	2650000	2650000	2500000	3750	0.9
More likely	500000	500000	500000	753	0.18



No adverse radiation effect reported in plants and animals exposed to a cumulative dose <0.3 Gy during the first month after accident (i.e. <10 mGy/d = 400 µGy/d)

ACUTE EXPOSURE EFFECTS CAN BE EXPECTED