Modelling radiation dose effects to wildlife populations

Jordi Vives i Batlle
SCK.CEN, Belgium
Jordi.vives.i.batlle@sckcen.be

13th International Congress of the International Radiation Protection Association
Glasgow, 13-18 May 2012 Session TS11a: Environmental Protection (16/05/2012)

Objectives of the study

- The need to protect animals and plants from the effects of ionizing radiation is internationally recognized (ICRP, IAEA, UNSCEAR, EC, National regulatory bodies).
- Assessing the degree of environmental protection from ionizing radiation requires the evaluation of exposure in relation to effects.
- Some considerable work has focused on compiling relevant dose effects information for individual organisms but very little on the effects on population dynamics.
- In order to realize the goal of assessing the level of protection for the population rather than the individual of the species, it is necessary to develop population models integrating the effects of radiation.

Methodology used

- We developed a two-age, logistic population dynamics model applicable to a range of biota populations.
- We a radiation repair mechanism and an independent fecundity function to assess the effects of chronic radiation (mortality, morbidity and reproduction).
- We obtained life history parameters for several species of fish (carp, Loach, Tilapia, roach, Goldfish and Pike) and mammals (mice, vole) – AnAge, Arkive, Fishbase.
- We converted the information into a stylised set of rate constants for the model, addressing mathematically any data gaps.
- We compared model predictions with radiation effects data on fish and mammals (EPIC and ERICA projects).
- We made predictions of population response to chronic irradiation in mice, hare/rabbit, wolf/wild dog and deer).

Population model approach

- Logistic growth model with 'allee' term and built-in self-recovery capacity:

$$\frac{dN_0}{dt} = rF\left(1 - \frac{N_0}{K_0}\right)\left(1 - \frac{W}{N_1}\right) - (s + d_0)N_0$$

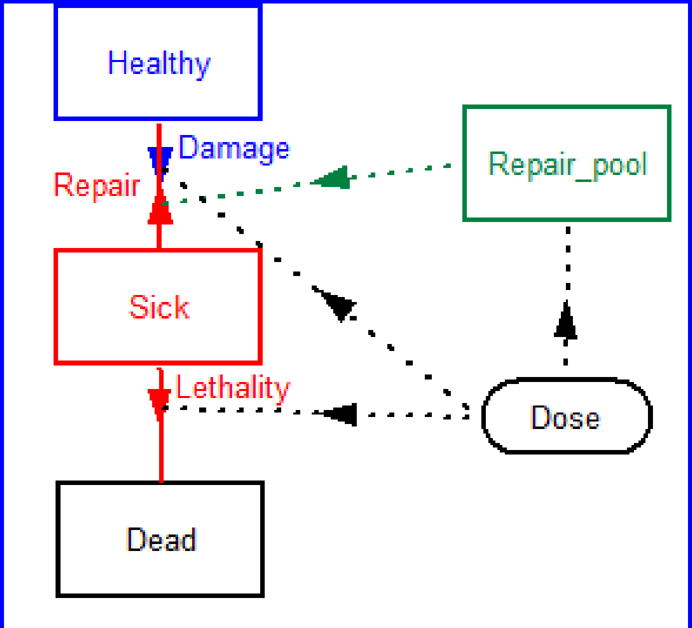
$$\frac{dN_1}{dt} = sN_0 - d_1 N_1$$

$$\frac{dF}{dt} = -rF\left(1 - \frac{N_1}{K_1}\right) + fF\left(1 - \frac{F}{L}\right)$$

Pierre François Verhulst

- N_0, N_1 are the population numbers for young and adult; F is the fecundity
- Key parameters of the model:
  - $K = L$: Saturation constants (related to carrying capacity)
  - $r = f$: Reproduction and fecundity rates
  - s, d_0, d_1: growth rate; young and adult death rates
- Mathematical relationship between saturation constants: $K_0 = K_1 d_1 / s$

Effects and repair model



$$\frac{dH}{dt} = -\alpha d_r H + \kappa SR \qquad \frac{dS}{dt} = \alpha d_r H - \varepsilon S - \kappa SR$$

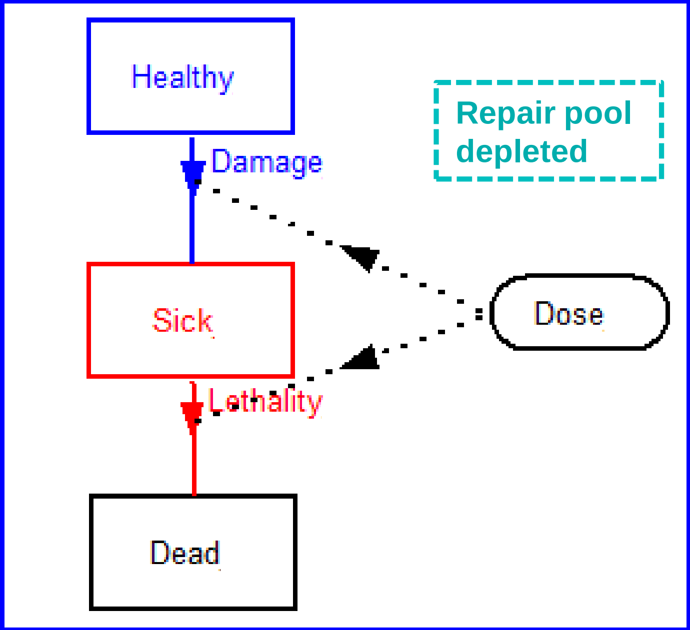
$$\frac{dR}{dt} = r_r R\left(1 - \frac{R}{K}\right) - k_R SR - \alpha_R d_r R$$

At high doses tends to…

$$\frac{dH}{dt} \sim -\alpha d_r H$$

$$\frac{dS}{dt} \sim \alpha d_r H - \varepsilon S$$

$$R \sim 0$$



Continuity hypothesis :

Key parameter driving model

$$\alpha d_r = \varepsilon \text{ when } d_r = \frac{LD_{50}}{30\,d}. \text{Consequently} : \alpha = \frac{\ln 2}{LD_{50}} \text{ and } \varepsilon = \frac{\ln(2)}{30\,d}$$

Population model parameters

Value	Description	Generic fish	Tilapia	Carp	Pike	Mouse	Rabbit	Dog	Deer
d_0	Death rate juvenile (d^{-1})	1.23E+00	1.23E+00	1.84E+00	1.44E+00	2.74E-05	1.34E-05	9.68E-06	5.80E-06
m_0	Mass juvenile (kg)	1.78E-06	1.78E-06	1.30E-06	1.01E-05	1.90E-03	8.25E-02	4.50E-01	6.71E+00
d_1	Death rate adult (d^{-1})	8.85E-04	1.49E-03	7.57E-04	6.64E-04	1.42E-03	6.40E-04	3.15E-04	2.93E-04
m_1	Mass adult (kg)	4.94E+00	6.22E-01	9.26E+00	1.56E+01	2.32E-02	3.00E+00	3.33E+01	1.49E+02
s	Growth rate (d^{-1})	1.14E-04	4.54E-04	8.20E-05	1.05E-04	4.12E-02	2.10E-02	2.11E-02	4.87E-03
f	Fecundity rate (d^{-1})	7.53E+02	7.53E+02	1.37E+03	6.85E+02	2.98E-02	1.99E-02	7.39E-03	1.60E-03
r	Reproduction rate (d^{-1})	7.53E+02	7.53E+02	1.37E+03	6.85E+02	2.98E-02	1.99E-02	7.39E-03	1.60E-03
w_1	Sparsity parameter	2.00E+00	2.00E+00	2.00E+00	2.00E+00	2.00E+00	2.00E+00	2.00E+00	2.00E+00

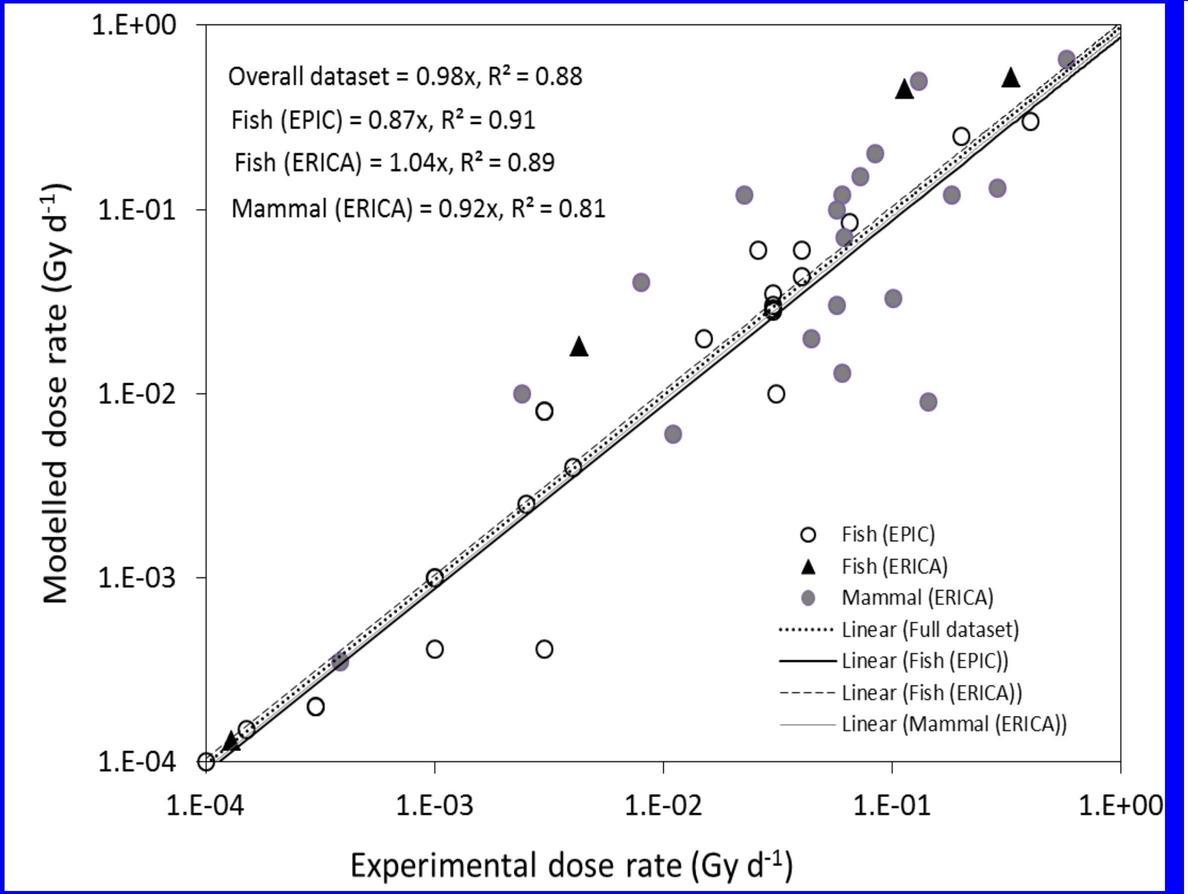
- Reproduction rate from = clutch size / 2 (50% male and 50% female).
- Exponential growth model to calculate mean age at maturity
- Fish mortality rate - Peterson & Wroblewski model: $d(d^{-1}) = 5.26 \times 10^{-3} \times m(g)^{-0.25}$
- Simple allometric approach to calculate mass ot the young: $m = k \times L^3$
- Relationship between survivorship, growth & death rates at equilibrium

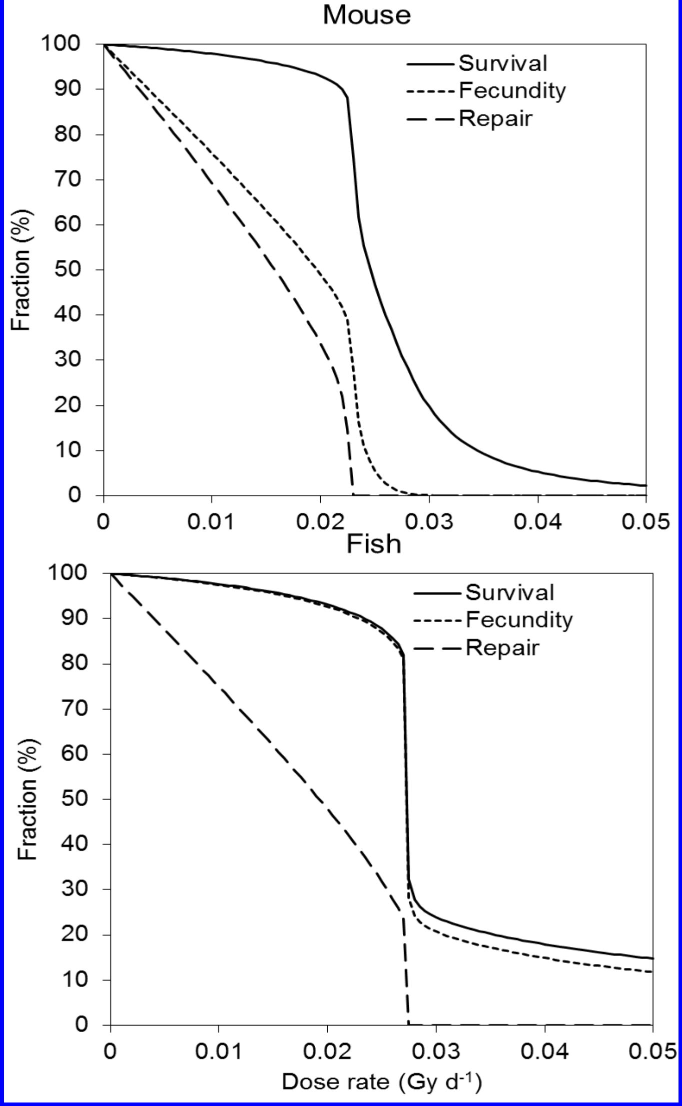
SCK•CEN STUDIECENTRUM VOOR KERNENERGIE CENTRE D'ETUDE DE L'ENERGIE NUCLEAIRE

Dose effects predictions for fish

Mean dose rate (Gy d^{-1})	Exposure Time (d)	Species	Predicted loss of survival/repairing pool/fecundity: Kryshev single age model	Predicted loss of survival/repairing pool/fecundity: Present study	Mod d_r for same effect (Gy d^{-1})	Observed effect
Increase in mortality (model prediction) vs. survival of eggs (experimental data)						
< 3.0E-02	14	Various species	No effect	< 0.4 %	< 3.0E-02	No effect
6.5E-02	14	Tench, loach	2–4%	0.4 – 3%	8.5E-02	2–3%
4.0E-01	14	Pike	66–82%	54.8%	3.0E-01	53%
9.4E-01	14	Pike	< 4%	20%	N/A	100%
< 1.0E-04	150, 100	Salmon, trout	No effect	No effect	<1.0E-04	No effect
1.5E-04	150	Salmon	No effect	No effect	1.5E-04	No effect
3.0E-03	150	Salmon	0.3–1.8%	0.1 – 0.5%	8.0E-03	Early onset
3.0E-02	150	Salmon	~ 43%	43%	3.5E-02	50%
2.0E-01	150 100	Salmon trout	100% for salmon eggs 80–90% for trout eggs	85-95% for salmon eggs 65-85% for trout eggs	2.5E-01	100% for salmon; 80–100% for trout
Decrease of repairing pool (model predictions) vs. morbidity of fish eggs (experimental data)						
3.0E-04	14	Various species	No effect	0.7-2.1%	2.0E-04	No effect
3.0E-04	150	Salmon	0.4–1.5%	0.5-2.4%	2.0E-04	Minor blood changes
3.0E-03	150	Salmon	4–21%	4.8-24%	8.0E-03	30–50%
3.1E-02	14	Pike	50%	78%	1.1E-02	30–35%
Loss of fecundity (model prediction) vs. depletion of reproduction of adult fish (experimental data)						
< 1.0E-03	213	Tilapia	No effect	< 0.06%	< 1.0E-03	No effect
2.5E-03	365, 1825	Tilapia, pike, perch	< 5%	0.2 – 0.8%	2.5E-03	No effect
2.6E-02	N/A	Roach	100%	21%	6.0E-02	91–98%
4.0E-02	213, 550	Tilapia	98–100%	51-80%	6.0E-02	100%
Increase in mortality (model prediction) vs. survival of adult fish (experimental data)						
< 1.0E-03	180,800	Tilapia	No effect	0.05 – 0.16%	<1.0E-03	No effect
4.0E-03	180	Tilapia, goldfish	No effect	0.2%	4.0E-03	No effect
3.0E-02	800	Tilapia	60%	73%	2.8E-02	62%
4.0E-02	180	Tilapia	17%	31%	4.3E-02	35 %
Decrease of repairing pool (model predictions) vs. morbidity of fish (experimental data for carp)						
< 1.0E-03	30, 90, 180, 270	Carp	No effect	< 2.5%	< 4.1E-04	No effect
3.0E-03	15, 30, 114	Carp	0.1 -7%	2.2 – 12%	< 4.1E-04	No effect
1.5E-02	21, 73	Carp	40-60%	31- 38%	2.0E-02	51–68%
3.0E-02	N/A	Carp	100%	85% after 100 days	2.9E-02	80–85%

Combined analysis of all data





- Slope close to 1 indicates near 1:1 relationship and R^2 close to 1 indicates good correlation
- Some data scatter mainly due to species variability

Adaptation to beta dosimetry

Endpoint	Species	Dose rate	Time	Effect	Survival/fecund. loss		Dose for
		(Gy d^{-1})	(d)		Observed	Predicted	same effect
Mortality	Mice	3.6E-03	7.2E+02	No effect on lifespan	0%	2.9%	1.3E-03
Fecundity	Rats	4.8E-03	4.1E+01	Moderate effect in female reproductive organs (oocytes)	30%	11%	1.4E-02
Fecundity	Mice	1.7E-02	3.0E+01	Severe effect in female reproductive organs (oocytes)	93%	20%	N/A
Fecundity	Rats	3.0E-02	4.3E+01	Reduction in sperm content. No effects in females	77%	56%	5.0E-02
Fecundity	Rats	3.0E-02	2.3E+01	Major decrease of fecundity	60%	40%	5.0E-02

- Calibration for <10 keV β-radiation (~25% repairable damages) the model returns a R_{WF} of 4.5, resembling 3 for ^{3}H.
- Only a few data points in ERICA database – limited validation!
- Somewhat lower estimates of loss of survival and fecundity (mean diff. 26%)
- Reproduces moderate effects on fecundity at $< 5 \times 10^{-3}$ Gy d^{-1} and significant effects at ~ 2×10^{-2} Gy d^{-1} (3 × below γ-doses inducing significant effect).

SCK•CEN
STUDIECENTRUM VOOR KERNENERGIE
CENTRE D'ETUDE DE L'ENERGIE NUCLEAIRE

Summary of main findings

- Reasonable results for fish population, e.g. 5% survivorship, adult/egg ratio of 4.64×10^{-5} (pike = 3.12×10^{-5}).
- Reasonable predictions of mortality, morbidity and reproductive changes for fish and mice at various γ-doses (< ± 20%).
- Experimental doses at which effects are observed and those for model-predicted same effect are well correlated ($R^2 = 0.88$).
- Limited data for <10 keV β-exposures in mammals suggests same model may be applicable by recalibrating 1 parameter.
- Simulations for mammals (mouse/rabbit/dog/deer) predict better survival of short-lived populations than for long-lived animals after 5-y exposure.
  - 10^{-2} Gy d^{-1}: Significant reduction of wolf/dog and deer populations; 80-100% survival for mice and rabbit populations.
  - 2×10^{-2} Gy d^{-1}: Considerable reduction of all populations except mice (70% survival). Higher doses cause progressive extinction of all populations.

Conclusions

- From the present study, a potential relationship between higher reproduction rates and lower radiation effects at population level can be hypothesized.
  - Fish: significant mortality at 0.017 Gy d^{-1} (adult) and 0.007 Gy d^{-1} (eggs).
  - Mammals: < 0.01 Gy d^{-1} not fatal to small mammals but fatal for large mammals.
- Results make sense of the ERICA benchmark of 10 μGy h^{-1} and the USDoE value of 40 μGy h^{-1} for terrestrial animals.
- Preliminary comparison with other models suggests the model is giving logical answers.
- Full model validation not possible because data for chronic irradiation in natural conditions are not yet available.
- Need to move from effects on species to full ecosystems:
  - Incorporate radiation-induced predator-prey unbalances
  - Model the interaction of radiation with other contaminants