Application of a generic two-age model to a benchmark scenario for radiation dose effects to populations – preliminary results

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Study objectives

- Develop a two-age, logistic population model with radiation effects.
- Test the model with the EMRAS benchmark scenario "Population response to chronic irradiation".
  - Stable generic populations of mice, hare/rabbit, wolf/wild dog and deer.
  - Carrying capacity = 1000 individuals.
- Predict population effects for chronic low-LET radiation
  - Dose rates of 0 to 50 mGy/day in increments of 10 mGy/day.
  - 5 years, with an additional 2 years to test for recovery of the population.
- Benchmark endpoints:
  - Survival fraxction at T = 1, 2, 3, 4 and 5 y
  - Recovery time after end of exposure.

Basis of the population model

- Logistic function with a built-in self-recovery capacity:

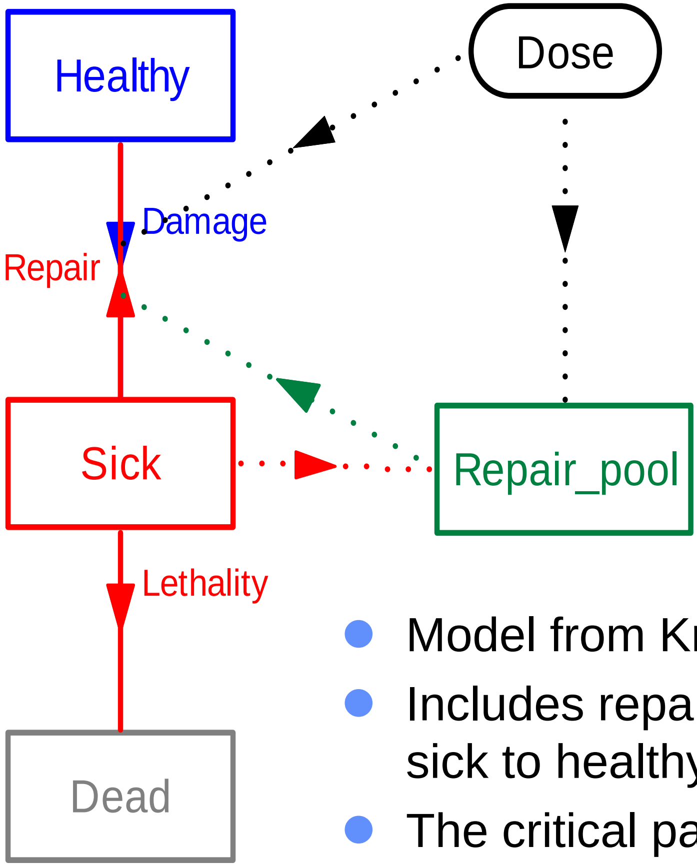
$$\frac{dN_0}{dt} = rF\left(1 - \frac{N_0 + N_1}{K}\right)\left(1 - \frac{W}{N_1}\right) - (s + d_0)N_0$$

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

$$\frac{dF}{dt} = -rF\left(1 - \frac{N_0 + N_1}{K}\right)\left(1 - \frac{W}{N_1}\right) + fF\left(1 - \frac{F}{L}\right)$$

- *Where:*
  - N_0, N_1: Population numbers for young and adult
  - *F*: Fecundity
  - K = *L*: Carrying capacity and fecundity recovery constant
  - *r* = *f*: Reproduction and fecundity rates
  - *s*, d_0, d_1: growth and death rates

Effects and repair model



$$\frac{dH}{dt} = -\alpha d_r H + \kappa SR$$

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

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

- Model from Kryshev et al. (2008)
- Includes repair pool mediating recovery from sick to healthy.
- The critical parameter is the LD50.

The full model

- Complete set of equations:

$$\frac{dN_0}{dt} = -\alpha_0 d_r N_0 + \kappa_0 Y_0 R_0 + rF\left(1-\frac{N_0+N_1+Y_0+Y_1}{K}\right)\left(1-\frac{W}{N_1}\right) - (s+d_0)N_0$$

$$\frac{dY_0}{dt} = \alpha_0 d_r N_0 - \kappa_0 Y_0 R_0 - \varepsilon_0 Y_0 - (s+d_0)Y_0$$

$$\frac{dR_0}{dt} = r_0 R_0\left(1-\frac{R_0}{M_0}\right) - k_R^0 Y_0 R_0 - \alpha_R^0 d_r R_0$$

$$\frac{dN_1}{dt} = -\alpha_1 d_r N_1 + \kappa_1 Y_1 R_1 + sN_0 - d_1 N_1$$

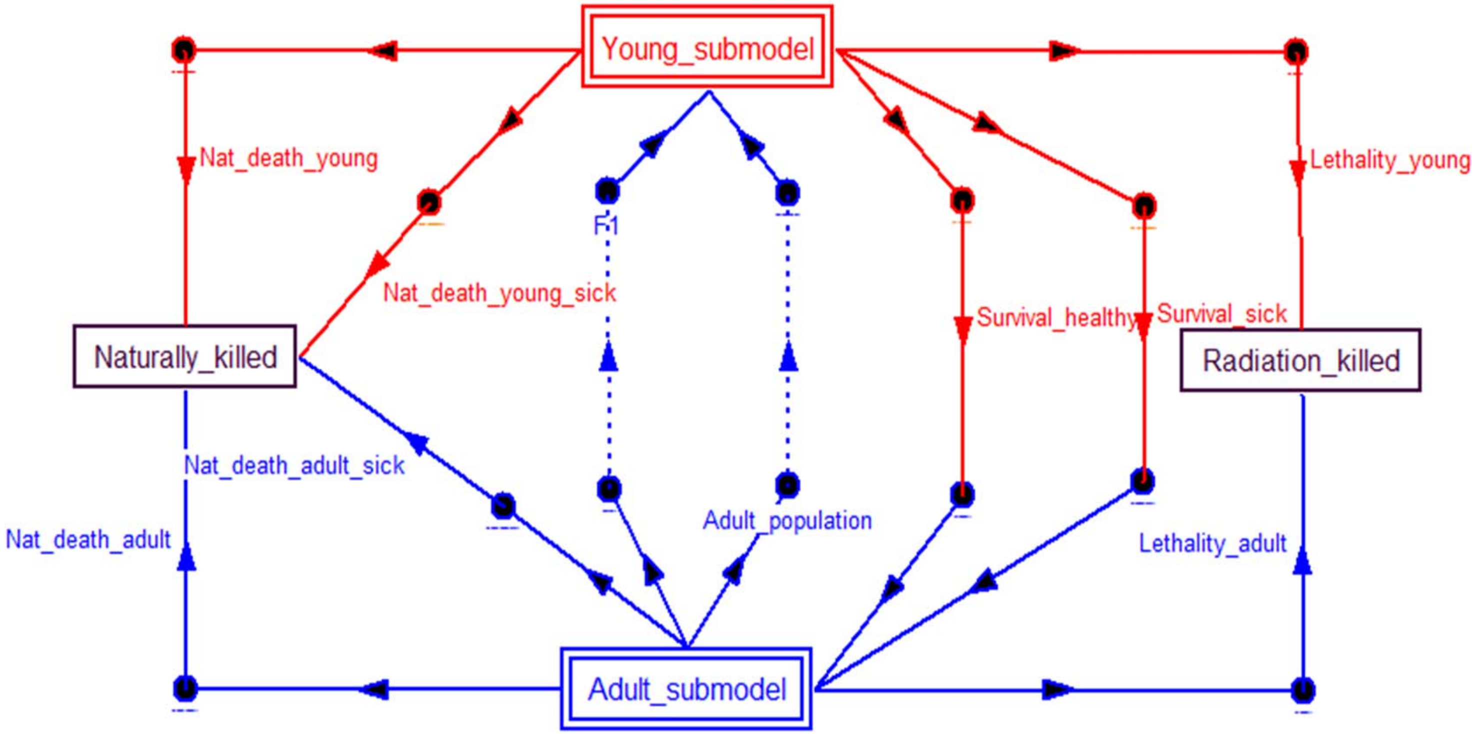
$$\frac{dY_1}{dt} = \alpha_1 d_r N_1 - \kappa_1 Y_1 R_1 - \varepsilon_1 Y_1 + sN_0 - d_1 N_1$$

$$\frac{dR_1}{dt} = r_1 R_1\left(1-\frac{R_1}{M_1}\right) - k_R^1 Y_1 R_1 - \alpha_R^1 d_r R_1$$

$$\frac{dF}{dt} = -\alpha_f^1 d_r F - rF\left(1-\frac{N_0+N_1+Y_0+Y_1}{K}\right)\left(1-\frac{W}{N_1}\right) + fF\left(1-\frac{F}{L}\right)$$

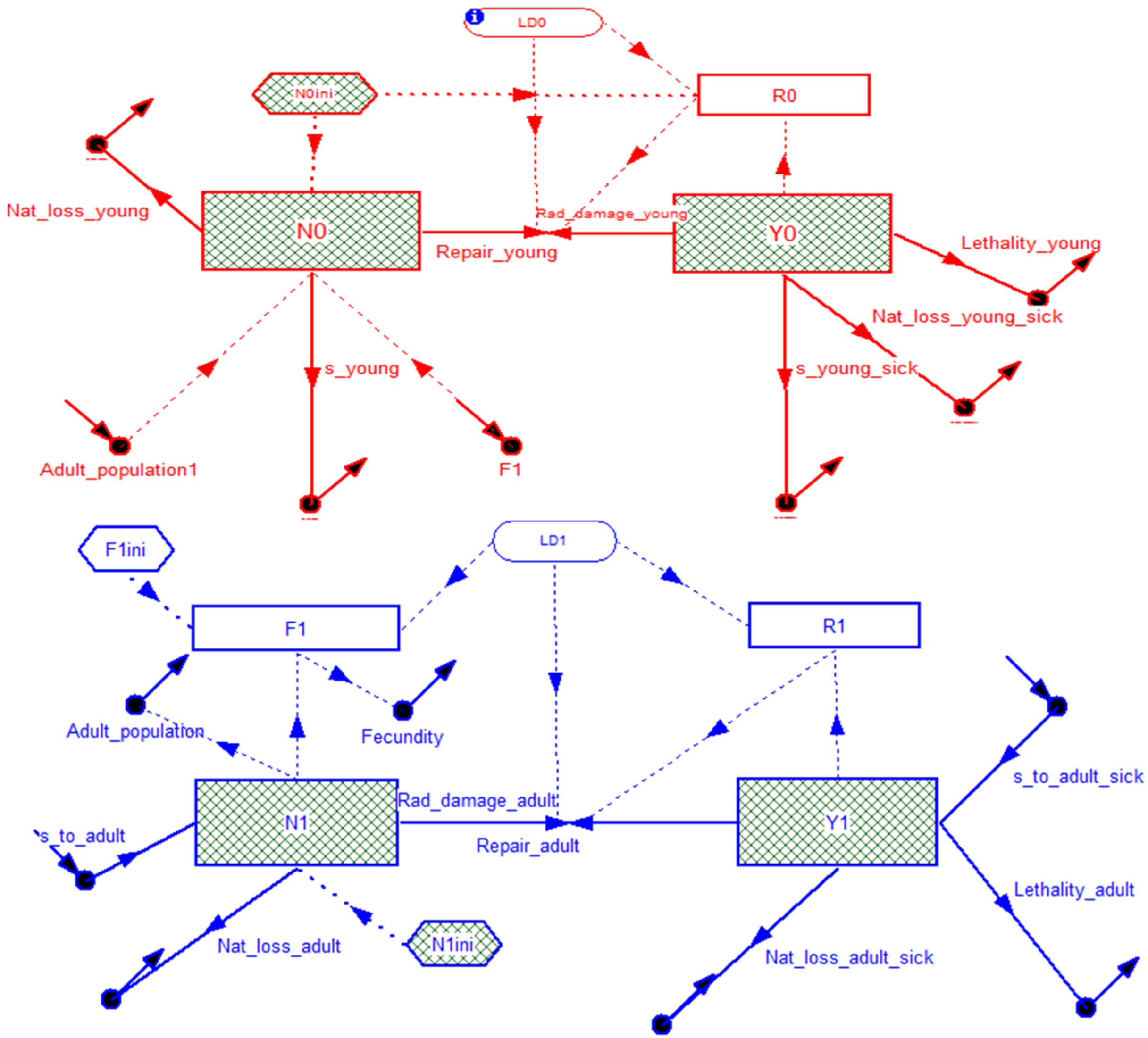
- $\alpha_i, \alpha_R^i, \alpha_f^i, \varepsilon_i, \kappa_i, k_R^i, r_i, f_3$: parameters for the radiation model

ModelMaker main model



- Gear numerical integration method
  - 2500 output points,
  - Relative error per step of 0.001
  - Random seed = 1.

ModelMaker submodels

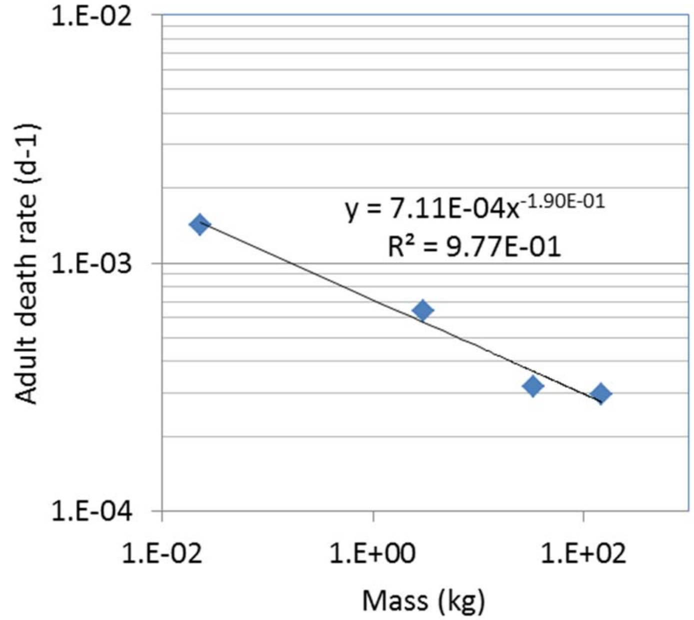


Raw genomics data

Common name	Latin name	Longevity (field)	Longevity (captivity)	Mean age of maturity	Adult mass (kg)	Newborn mass (kg)	Basal metabolic rate (Watts/g)	Growth rate (d^{-1})	IMR	Reprod rate (d^{-1})
Field vole	Microtus agrestis	7.31E+02	1.75E+03	3.90E+01	2.80E-02	2.30E-03	1.47E-02	1.30E-02		
Field mouse	Apodemus sylvaticus	5.48E+02	1.46E+03	6.80E+01	2.34E-02	1.50E-03	1.11E-02			5.41E-02
Red-backed mouse	Clethrionomys glareolus	5.48E+02	1.79E+03	5.95E+01	2.08E-02		1.45E-02	8.09E-02		
House mouse	Mus musculus		1.46E+03	4.20E+01	2.05E-02		1.51E-02	2.98E-02	2.74E-05	1.03E-01
Common shellduck	Tadorna tadorna	3.65E+03	5.48E+03	7.30E+02	1.15E+00			7.40E-02		
Western roe deer	Capreolus capreolus		5.48E+03	5.34E+02	2.17E+01	1.00E+00	2.16E-03			4.38E-03
Spotted deer	Axis axis		7.60E+03	8.40E+02	3.60E+01	3.14E+00				
Reindeer	Rangifer tarandus		7.93E+03	6.71E+02	1.01E+02	6.50E+00	1.41E-03	4.70E-03		
Red deer	Cervus elaphus		1.15E+04	7.91E+02	2.00E+02	1.01E+01	1.68E-03	6.00E-03		2.46E-03
Moose	Alces alces		6.72E+03	6.82E+02	3.86E+02	1.28E+01	8.83E-04	3.90E-03		3.56E-03
Horse	Equus caballus	8.22E+03	1.83E+04	9.44E+02	2.50E+02	7.90E+01			5.48E-07	2.74E-03
Gray wolf	Canis lupus	4.02E+03	5.84E+03	6.70E+02	2.66E+01	4.50E-01		1.77E-02		1.31E-02
Dog (big)	Canis domesticus	4.02E+03	8.77E+03	5.10E+02	4.00E+01			2.44E-02		1.64E-02
Elephant	Loxodonta africana	1.28E+04	2.56E+04	7.31E+03	4.80E+03	1.05E+02		3.00E-04	5.48E-06	5.48E-04
Rabbit	Oryctolagus cuniculus		3.29E+03	7.31E+02	1.80E+00	4.50E-02	3.41E-03	2.28E-02		5.89E-02
European hare	Lepus europaeus		3.91E+03	2.36E+02	4.20E+00	1.20E-01		1.91E-02		2.08E-02

Plugging the IMR data gap

- Adult mortality rate in the laboratory = ln(10) / longevity, Tmax = maximum age (age of 10% longest survivors).
- Allometric relationship between death rate and mass for adult: $d_1 = 7.11E\text{-}04 \times m_1^{-0.19}$; $R^2 = 0.98$.
- We adapt this law to fit the IMR of the young mouse with the same exponent: $2.74 \times 10^{-5} = \alpha \times 0.0019^{-0.19}$ so $\alpha = 8.32E\text{-}06$ and $d_0 = 8.32 \times 10^{-6} \times m_0^{-0.19}$.
- Allometric calculation of LD_{50} for adult: $LD_{50} = 7.21 \times M^{-0.13}$



- For the young we assume conservatively the same LD50 as the Bytwerk study is for adults of the species.

Model parameters

Sub-model	Parameter	Description	Mouse	Hare/rabbit	Wolf/wild dog	Deer
Young	d_0	Death rate for young (d^{-1})	2.74E-05	1.34E-05	9.68E-06	5.80E-06
	m_0	Mass for young (kg)	1.90E-03	8.25E-02	4.50E-01	6.71E+00
Adult	d_1	Death rate for adult (d^{-1})	1.42E-03	6.40E-04	3.15E-04	2.93E-04
	m_1	Mass for adult (kg)	2.32E-02	3.00E+00	3.33E+01	1.49E+02
General	Allom_int_LD50	Intercept for LD_{50} (Gy $kg^{0.1297}$)	7.21E+00	7.21E+00	7.21E+00	7.21E+00
	Allom_slo_LD50	Slope for LD_{50} (dimensionless)	-1.30E-01	-1.30E-01	-1.30E-01	-1.30E-01
	s	Growth rate (d^{-1})	4.12E-02	2.10E-02	2.11E-02	4.87E-03
	f	Recovery rate for fecundity (d^{-1})	7.88E-02	3.98E-02	1.48E-02	2.68E+02
	r	Reproduction rate (d^{-1})	7.88E-02	3.98E-02	1.48E-02	3.47E-03
	K_f	Carrying capacity of fecundity (individuals)	1.00E+03	1.00E+03	1.00E+03	1.00E+03
	K_c	Carrying capacity of ecosystem (individuals)	1.00E+03	1.00E+03	1.00E+03	1.00E+03
	w_1	Allee parameter (individuals)	2.00E+00	2.00E+00	2.00E+00	2.00E+00
	e	Lethality rate (d^{-1})	2.30E-02	2.30E-02	2.30E-02	2.30E-02
	d_r	Dose rate (Gy)	0.01 - 0.05	0.01 - 0.05	0.01 - 0.05	0.01 - 0.05
	T_c	Cut-off time for exposure (d)	2.00E+03	2.00E+03	2.00E+03	2.00E+03

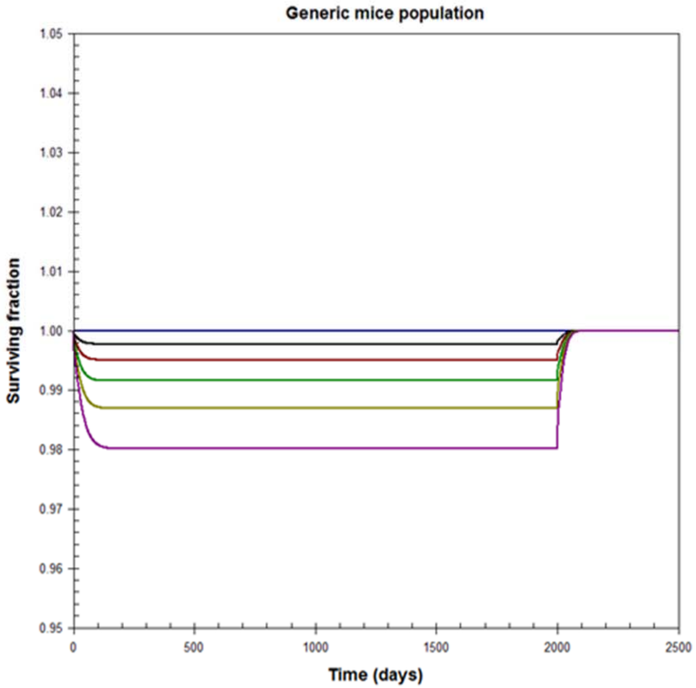
Results – % survival versus dose rate (Gy d^{-1})

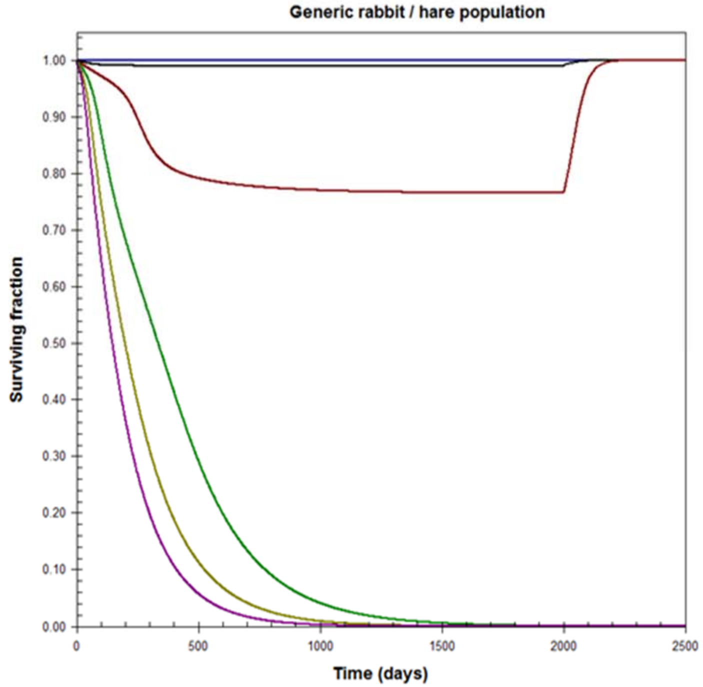
Organism	Time (y)	d_r = 0.00	d_r = 0.01	d_r = 0.02	d_r = 0.03	d_r = 0.04	d_r = 0.05
Rat	1	100.0%	99.8%	99.5%	99.1%	98.7%	98.0%
	2	100.0%	99.8%	99.5%	99.1%	98.7%	98.0%
	3	100.0%	99.8%	99.5%	99.1%	98.7%	98.0%
	4	100.0%	99.8%	99.5%	99.1%	98.7%	98.0%
	5	100.0%	99.8%	99.5%	99.1%	98.7%	98.0%
	End sim	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
Rabbit/Hare	1	100.0%	99.1%	81.7%	46.1%	22.6%	13.3%
	2	100.0%	99.1%	77.7%	11.9%	3.5%	1.4%
	3	100.0%	99.1%	76.9%	2.8%	0.6%	0.1%
	4	100.0%	99.1%	76.7%	0.7%	0.1%	0.0%
	5	100.0%	99.1%	76.6%	0.2%	0.0%	0.0%
	End sim	100.00%	100.00%	100.00%	0.06%	0.00%	0.00%
Wolf/dog	1	100.0%	70.2%	35.2%	19.4%	11.0%	6.2%
	2	100.0%	40.8%	10.4%	3.3%	1.1%	0.3%
	3	100.0%	21.3%	3.1%	0.6%	0.1%	0.0%
	4	100.0%	10.9%	0.9%	0.1%	0.0%	0.0%
	5	100.0%	5.6%	0.3%	0.0%	0.0%	0.0%
	End sim	100.00%	3.49%	0.13%	0.01%	0.00%	0.00%
Deer	1	100.0%	53.1%	26.4%	13.3%	6.7%	3.4%
	2	100.0%	24.4%	6.2%	1.6%	0.4%	0.1%
	3	100.0%	11.2%	1.4%	0.2%	0.0%	0.0%
	4	100.0%	5.1%	0.3%	0.0%	0.0%	0.0%
	5	100.0%	2.4%	0.1%	0.0%	0.0%	0.0%
	End sim	100.00%	1.41%	0.03%	0.00%	0.00%	0.00%

Results – % survival versus dose rate (Gy d^{-1})

Organism	Time (y)	d_r = 0.00	d_r = 0.01	d_r = 0.02	d_r = 0.03	d_r = 0.04	d_r = 0.05
Rat	1	100.0%	99.8%	99.5%	99.1%	98.7%	98.0%
	2	100.0%	99.8%	99.5%	99.1%	98.7%	98.0%
	3	100.0%	99.8%	99.5%	99.1%	98.7%	98.0%
	4	100.0%	99.8%	99.5%	99.1%	98.7%	98.0%
	5	100.0%	99.8%	99.5%	99.1%	98.7%	98.0%
	End sim	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
Rabbit/Hare	1	100.0%	99.1%	81.7%	46.1%	22.6%	13.3%
	2	100.0%	99.1%	77.7%	11.9%	3.5%	1.4%
	3	100.0%	99.1%	76.9%	2.8%	0.6%	0.1%
	4	100.0%	99.1%	76.7%	0.7%	0.1%	0.0%
	5	100.0%	99.1%	76.6%	0.2%	0.0%	0.0%
	End sim	100.00%	100.00%	100.00%	0.06%	0.00%	0.00%
Wolf/dog	1	100.0%	70.2%	35.2%	19.4%	11.0%	6.2%
	2	100.0%	40.8%	10.4%	3.3%	1.1%	0.3%
	3	100.0%	21.3%	3.1%	0.6%	0.1%	0.0%
	4	100.0%	10.9%	0.9%	0.1%	0.0%	0.0%
	5	100.0%	5.6%	0.3%	0.0%	0.0%	0.0%
	End sim	100.00%	3.49%	0.13%	0.01%	0.00%	0.00%
Deer	1	100.0%	53.1%	26.4%	13.3%	6.7%	3.4%
	2	100.0%	24.4%	6.2%	1.6%	0.4%	0.1%
	3	100.0%	11.2%	1.4%	0.2%	0.0%	0.0%
	4	100.0%	5.1%	0.3%	0.0%	0.0%	0.0%
	5	100.0%	2.4%	0.1%	0.0%	0.0%	0.0%
	End sim	100.00%	1.41%	0.03%	0.00%	0.00%	0.00%

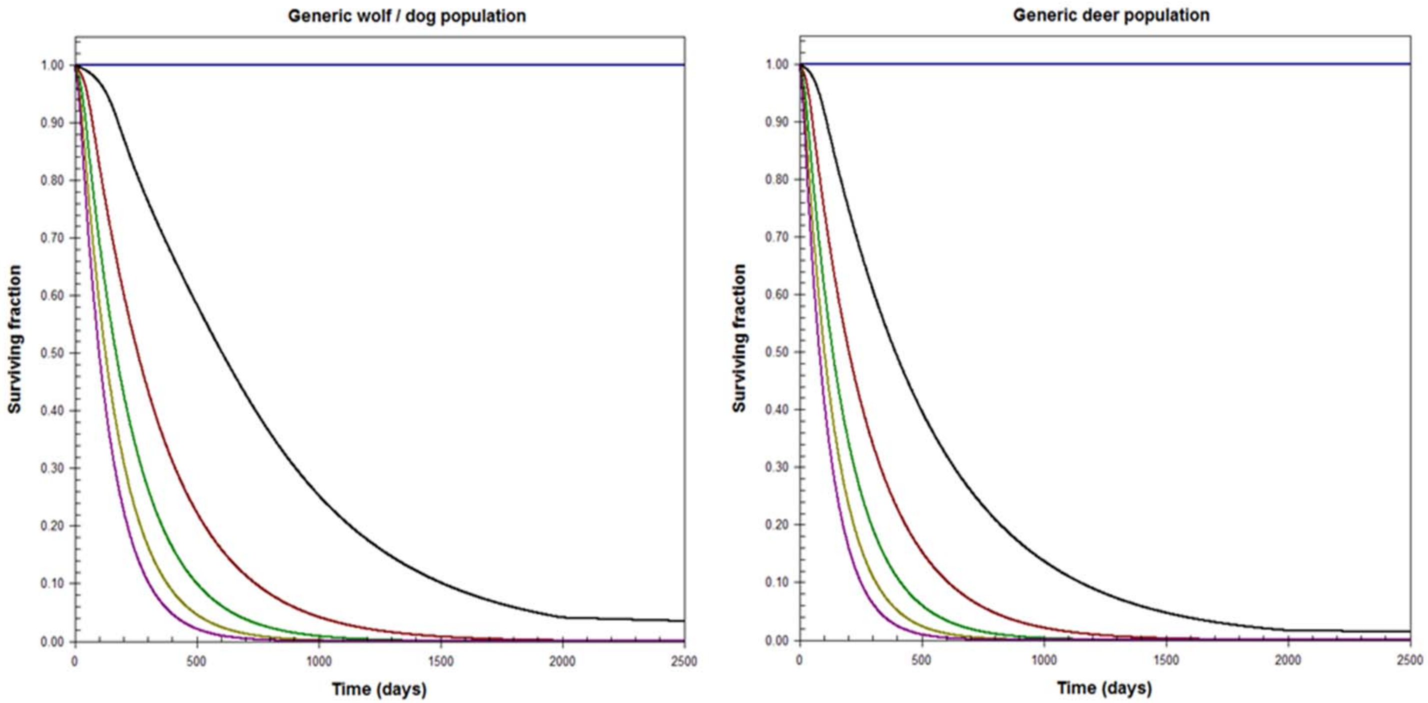
Results – mice & rabbit/hare





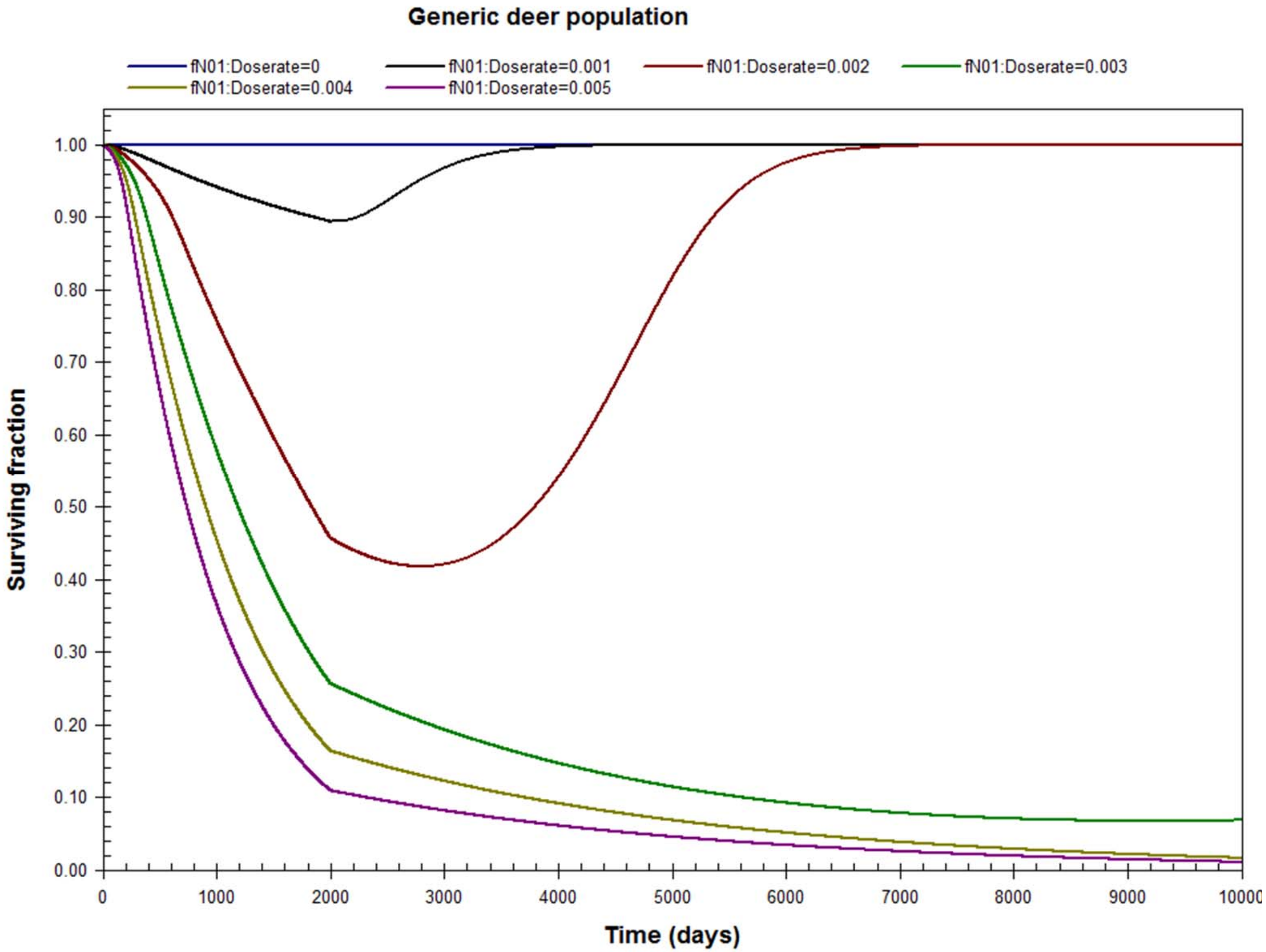
- Mice: population reaches a new stable level in 150 days with loss of less than 2%. Recovery in about 100 days.
- Rabbit / hare: At 0.01 Gy d^{-1} stable level with loss of less than 1%. At 0.01 Gy d^{-1} loss of 25% in 2000 days recovering in ~ 250 days. Population crashes at higher dose rates.

Results – wolf / dog & deer



- Dog / wolf: Reduction to less than 6% for 0.01 Gy d^{-1} and to extinction for higher doses.
- Deer: Similar results - surviving population at year 5 for 0.01 Gy d^{-1} is 2.5%.

Results at lower doses



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Conclusions

- For small mammals, dose rates less than 0.01 Gy d^{-1} or about 400 μGy h^{-1} are not fatal to the population
- For large mammals chronic exposure at this level is predicted to be fatal.
- Adose rate of 0.001 Gy d^{-1} (40 μGy h^{-1}) is the highest that will not drive the deer population to extinction, causing a population loss of < 10% and allowing for recovery after about 5 years post- exposure.
- At an even lower exposure of 0.00025 Gy d^{-1} (10 μGy h^{-1}) effects are negligible (< 2%).
- The results from this model are preliminary and yet to be validated.
- Nevertheless results make sense of the ERICA benchmark value of 10 μGy h^{-1} and the USDoE benchmark of 40 μGy h^{-1} for terrestrial animals.