– Following the natural reduction of exposure levels due to radionuclide decay and migration, populations have been recovering from acute radiation effects. By the next growing season following the accident, the population viability of plants and animals substantially recovered as a result of the combined effects of reproduction and immigration. A few years were needed for recovery from the major radiation-induced adverse effects on plants and animals.

231. Fesenko et al. have compared the relative radiological impact on people and non-human biota arising from the Chernobyl accident [F17]. They reviewed the data on reference dose rates for non-human biota (which they refer to as critical exposure doses or CDV_b below which an effect would not be expected). The authors adopted the commonly used endpoints of early mortality, morbidity, reduced reproductive success and deleterious genetic effects. Their values of CDV_b for non-human biota near Chernobyl are summarized in table 26. They noted that coniferous trees were known to be among the most radiosensitive components of the biosphere and indicated that the minimum dose rate at which morphological changes have been seen in the Chernobyl zone was about 1.2 mGy/d. The authors also indicated that this dose rate is about nine times lower than the reference dose rate provided in reference [U4] but suggested that such discrepancies can be explained by the use of generic reference dose rates for all terrestrial plants rather than for specific plants. For herbaceous plants, they suggested a reference dose rate of about 8.2 mGy/d [F17] which is comparable to the value suggested in reference [U4]. For cattle, they suggested a reference dose rate of about 1.6 mGy/d based on data given in references [C16, S36] but go on to indicate that radiation harm to farm animals in the Chernobyl zone was more related to damage to the thyroid from internally deposited radionuclides. Based on the assumption that impairment of reproduction usually occurs at doses about one order of magnitude below the LD_{50} of about 0.8 Gy and on observed reductions in the numbers of invertebrates, the authors [F17] suggested a reference dose rate of about 2.5 mGy/d. Finally, for aquatic systems, the authors [F17] suggested that fish are generally more radiosensitive than plankton and zoobenthos and proposed a reference dose rate of about 1.6 mGy/d.

Table 26. Review of CDV_b for non-human species inhabiting the study area
(adapted from reference [F17])

Non-human species	*CDV_b (mGy/d) cited in [F17]*	*Literature data*
Terrestrial ecosystems		
Coniferous trees (pine)	1.1	1.1 [S35], 2.4 [C16], 10 [U4]
Herbaceous plants (meadow grasses)	8.2	1.1 [S35, S36], 2.4 [C16], 10 [U4]
Herbaceous plants (cereals)	8.2	1.1 [S35, S36], 2.4 [C16], 10 [U4]
Cattle	1.6 (137[a])	1.1 [S36], 2.5 [C16]
Mouse-like rodents	1.1	0.1 [S35], 0.2 [S36], 1 [C16], 1 [U4], 2.7 [B31]
Soil invertebrates	2.5	1.1 [S35, S36], 2.4 [C16], 5.5 [B31]
Aquatic ecosystems		
Phytoplankton	8.2	2.4 [C16], 2.7 [B31]
Zooplankton	6.8	2.4 [C16], 2.7 [B31]
Zoobenthos	2.5	1.6 [C16], 5.5 [B31]
Fish	1.6	0.3 [S35], 0.5 [C16], 0.5 [B31], 10 [U26]

[a] Dose to the thyroid.

232. Another report provided a comprehensive evaluation of the effects of radiation exposure resulting from the Chernobyl accident on non-human biota along with corresponding dosimetry information [G26]. In total, 250 references were evaluated. Of these, some 79 papers were considered to have adequate information on environmental contamination and doses to biota. The review focussed on the assessment of the effects of radiation exposure on plants and animal populations inhabiting the contaminated areas around Chernobyl at the time of, and following, the accident [G26]. As described earlier, the radiation doses associated with the first phase following the Chernobyl accident was a period of short-term quite high radiation dose rates followed by a period with a gradual decline in dose rate. The most severe

environmental effects were associated with the high dose rates. Effects of radiation exposure were seen in both natural and agricultural systems. The authors noted that the effects depended on the radiosensitivity of the dominant species and observed that coniferous trees were one of the most sensitive plant species and mammals were the most radiosensitive animal species [G26]. To date, reference [G26] provides the most comprehensive evaluation of observations of the effects of the Chernobyl accident on non-human biota. The key observations from the review are summarized in table 27, which shows various effects on non-human biota around Chernobyl and the corresponding doses below which such effects were not observed.

233. The reliability of the estimated doses arising from the Chernobyl accident has been examined by the Chernobyl Forum [E8]. Table 27 provides a summary of the information on the effects and associated doses and dose rates from studies of non-human biota around the Chernobyl nuclear power plant. However, given the importance of this topic, a few additional comments are appropriate. The available information indicates that the forest close to the Chernobyl power plant captured much of the radioactive dust following the accident, reducing the spread of radioactive material outside the 10-km zone [A11]. The dose rate within the 10-km zone showed an exponential decay, with the majority of the total dose absorbed by the environment within the first month [A11, K20, S30]. Thus, the Committee has assumed, in table 27, that most (80% or so) of the dose would have been delivered in (about) the first month following the accident. Where appropriate for comparison purposes, a notional daily dose rate was derived by dividing the reported doses by 30.

Table 27. Effects on populations of non-human biota around the Chernobyl power plant [G26]

Species effect	*Estimated minimum doses (or dose rates) at which effect was observed*	*Estimated maximum doses (or dose rates) at which effect was not observed*
Scots pine		
Death of weakened trees	8–12 Gy [A11, K20]	5 Gy
Mass death of young cones and anthers	10–12 Gy [S29]	5 Gy
35–40 years old, mass yellowing of needles	8–12 Gy [K20]	5 Gy
Inhibition of reproductive capacity (reduced number of seeds per cone and increased fraction of hollow seeds)	1–5 Gy [F10]	0.5 Gy
Morphological disturbances one year after accident	0.1–1.0 Gy [A11]	0.05 Gy
Significant increase in cytogenetic effects in seedlings and needles	0.5 Gy [F10]	0.05 Gy
Frequency of mutations of enzyme loci in seed endosperm	0.07 Gy [F10]	0.01 Gy
Spruce		
10–15 years old. Death of trees	4–5 Gy [K20]	1 Gy
25 years old. Dying-off of young sprouts. Mortality of much of the trees within 2–3 years	8–10 Gy [K21]	5 Gy
40 years old. Noticeable reduction in sprout mass	2.5–3 Gy [K21]	1 Gy
Mass yellowing of needles	3.5–5 Gy [K21]	2 Gy
Herbaceous plants		
Reduced density of plants and species diversity in following year	17 mGy/d [S30]	10 mGy/d
Morphological changes	4.2–6.3 mGy/d [S30]	2 mGy/d
Enhanced vegetative reproduction and gigantism of some herbaceous species	16–30 mGy/d [S30]	10 mGy/d
Sterility of seeds	40 Gy – vetch; 10 Gy – dandelion and arabidopsis [S30]	5 Gy
Decrease in the number of peas in pods of wild vetch, increase in both fraction of sterile pods and fraction of embryonic lethalities	0.4 mGy/d [S31]	0.1 mGy/d
Soil fauna		
Drastic decrease in the population density and species composition of forest litter mesofauna	Dose absorbed on the soil surface 9 Gy [K13]	1 Gy

Species effect	*Estimated minimum doses (or dose rates) at which effect was observed*	*Estimated maximum doses (or dose rates) at which effect was not observed*
Amphibians (brown frogs)		
Increased yield of chromosome aberrations and damage severity in aberrant cells	Dose rate, mGy/d: 0.01 from ^{90}Sr to bone tissue, 0.038 from other sources to the whole body, 0.013 from external γ-radiation exposure [E18, E19]	0.01 mGy/d
Hydrobionts		
Silver carp. Higher occurrence of reproduction system alterations, reduced viability of progeny	9–11 Gy for 5 years [B19, M21]	1 Gy/a
Small mammals		
Inhibition of reproductive capacity (the significantly reduced testis mass as well as irreversible or temporary sterility in some males)	Absorbed gonad doses of 3 Gy per month [P16]	1 Gy/a
Pathological changes in haemopoietic system, liver, adrenals and thyroid	Absorbed dose from external γ-radiation exposure from the moment of accident till animal catching in autumn 1986 was 1 Gy. Contribution of β-radiation was 2–5 times higher than γ and incorporated radionuclides by 1–2 orders lower than from external [E20, M22]	0.5 Gy
A dose-dependent increase in the frequencies of chromosome aberrations in bone marrow cells and embryonic losses in bank voles, high frequency of polyploid cells and genome mutations	Whole-body absorbed dose rate in 1986: approximately 6–600 μGy/d [R17]	5 μGy/d
Cattle		
Destruction of thyroid, chronic radiation disease	Doses absorbed by thyroid >200 Gy, with dose to the whole body being no more than 0.2 Gy [A24, B16]	20 Gy to thyroid[a]

[a] Effect in the early days after the accident was mainly determined by ^{131}I action and depended greatly on content of stable iodine in animal ration.

IV. EFFECTS OF RADIATION EXPOSURE ON NON-HUMAN BIOTA

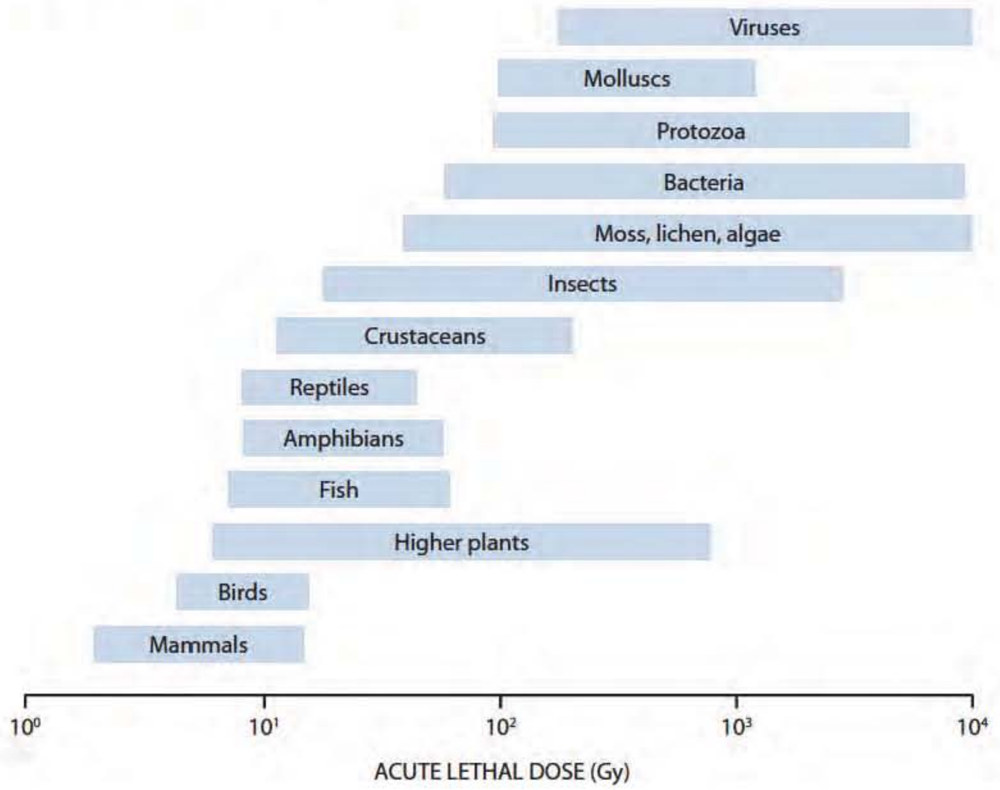
234. This chapter provides an overview of the independent evaluations of the published literature on the effects of radiation exposure on non-human biota, briefly considers the relevant observations from case studies where dose rates to non-human biota have been estimated and compared to reference dose rates (from, for example, reference [U4]), and extracts additional key observations from the post-1996 literature.

A. Overall conclusions of the UNSCEAR 1996 Report

235. The main observations from the Committee's 1996 evaluation [U4] are described in chapter III of this annex. The Committee, while emphasizing that only limited data were available for consideration, concluded that the production of viable offspring through gametogenesis and reproduction is a more radiosensitive population attribute than the induction of individual mortality.

236. The Committee also noted that there was a wide dose range over which organisms were sensitive to the lethal effects of radiation exposure. A schematic representation of the Committee's qualitative assessment of the overall sensitivities of various taxa to an acute dose of radiation is shown in figure XII [U4].

Figure XII. Approximate acute lethal dose ranges for various taxonomic groups [S12, W6]
Reproduction of figure VII of reference [U4]



237. Overall, the Committee judged that for the most sensitive plant species, the effects of chronic radiation exposure were noteworthy at dose rates of 1–3 mGy/h. It suggested that chronic dose rates of less than 400 μGy/h (10 mGy/d) would have effects, although slight, on sensitive plants but would be unlikely to have significant deleterious effects on the wider range of plants present in natural plant communities.

238. The Committee concluded that "for the most sensitive animal species, mammals, there is little indication that dose rates of 400 μGy/h to the most exposed individual would seriously affect mortality in the population. For dose rates of 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, the general conclusion was that 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. The radiation doses necessary to produce a significant deleterious effect are very difficult to estimate because of long-term recovery (including natural regeneration and the migration of individuals from surrounding less affected areas), compensatory behaviour and the many confounding factors present in natural plant and animal communities in both terrestrial and aquatic environments".

B. Evaluations since 1996

239. Since the UNSCEAR 1996 Report [U4], several national and international authorities have reviewed the available literature on the effects of ionizing radiation exposure on non-human biota [C1, E1, F5, W11, W17]. This section provides a short discussion of the recent work relevant to this annex.

1. United States Department of Energy

240. The United States DOE has conducted a considerable amount of work in developing a graded approach to radioecological risk assessments [H1, H2, J1, U26]. In developing their approach, the DOE considered a number of issues relevant to the re-evaluation, including assessment endpoints, effort levels and dosimetry. The DOE noted that radioecological risk assessments focused on population relevant endpoints, such as reproduction, and cited guidance from national and international organizations [I4, N1, U4]. The DOE went on to adopt screening dose rates corresponding to expected safe levels of exposure of populations of biota based on reviews of the data on the acute and chronic radiation effects of exposure to a dose rate of

10 mGy/d to populations of aquatic animals, 10 mGy/d to populations of terrestrial plants and 1 mGy/d to populations of terrestrial animals [I4, N1, R2, U4]. The DOE indicated that, if the dose rate to the most exposed individual in the population does not exceed the expected safe dose rate, the population should also be protected [B18].

2. Canada

241. In response to requirements under the Canadian Environmental Protection Act (CEPA), 1999 [C6], Environment Canada and Health Canada carried out an assessment of the impact of the discharge of radionuclides from nuclear facilities on non-human biota for all aspects of the uranium fuel chain, from mining and milling to power generation and waste management [E5].

242. The approach used in reference [E5] for ecological risk assessment required identifying "chronic toxicity values" (CTVs) from which "estimated no-effects values" (ENEVs) were derived using appropriate application factors [E2]. The application factor was intended to address the uncertainties related to differences between observed effects on endpoints and the success of organisms in the field. An application factor (safety factor) of 1 was used to estimate ENEVs for radiation exposure. The CTVs for the various taxonomic groups reported in reference [E5] were based on measures of effect applicable to the survival of populations of sensitive species and on chronic exposures. In assessing radiological risks, Environment Canada and Health Canada [E5] used factors of 1 for gamma and beta radiation and 40 for alpha radiation to account for the differences in the RBEs of the different types of radiation. The ENEVs used by Environment Canada and Health Canada are summarized in table 28 and were based on detailed evaluations of the published literature [I4, R2, U4] as well as on evaluations specifically carried out in support of the assessment [E4, H3, M3].

Table 28. Summary of "estimated no-effects values" (ENEVs) used to assess the potential toxicity of exposure of non-human biota to radiation near Canadian nuclear facilities [E2]

Taxa	*ENEV (Gy/a)*[a]
Fish[b]	0.2
Benthic invertebrates	2
Algae	1
Macrophytes	1
Mammals	1
Terrestrial plants	1
Terrestrial invertebrates	2

[a] In all cases, the application factor used to convert the CTV to an ENEV was 1.

[b] The assessment given in reference [E2], citing the lack of data for Canadian fish, referred to effects on carp (species different from those found in Canada) in the Chernobyl cooling pond, and acknowledged that the ENEV for fish may be conservative.

243. The (former) Advisory Committee on Radiological Protection (ACRP) to the Canadian Nuclear Safety Commission also reviewed the available information relevant to the protection of non-human biota [A1]. The ACRP considered that the ultimate goal of "ecological protection" is to ensure that communities and populations of organisms can thrive and that all the component parts will be self-sustaining. Similar to the DOE [H1], the ACRP [A1] reported the generic dose-rate criteria summarized in table 29 for the effects of ionizing radiation exposure on biota, which were based on reviews by national and international authorities, including UNSCEAR [U4], the NCRP [N1] and the IAEA [I4]. The ACRP also suggested that overall, dose-rate criteria in the range of 1–10 mGy/d were generally protective of populations of non-human biota and, given current knowledge (and the associated uncertainties), that perhaps a single nominal dose-rate criterion of about 3 mGy/d might be suitable on a broad basis for assessing risks to non-human biota.

Table 29. Generic dose-rate criteria for biota [A1]

Biota	*IAEA [I4]*	*NCRP [N1]*	*UNSCEAR 1996 Report [U4]*
Terrestrial plants	10 mGy/d (4 Gy/a)	—	10 mGy/d (4 Gy/a)
Terrestrial animals	1 mGy/d (0.4 Gy/a)	—	—
mortality		—	10 mGy/d (4 Gy/a)
reproduction		—	1 mGy/d (0.4 Gy/a)
Aquatic organisms		10 mGy/d (4 Gy/a)	10 mGy/d (4 Gy/a)

244. The ACRP [A1] noted that radionuclides incorporated in biota are not uniformly distributed and that some radionuclides tend to concentrate in certain tissues or organs but that for dosimetric calculations, radionuclides were often assumed to be distributed uniformly throughout the organism. This assumption can result in underestimation of the doses to specific tissues for those radionuclides that concentrate in these tissues (for example, bone-seeking radionuclides in fish). The ACRP emphasized that, in practice, simplifying assumptions have to be made especially for demonstrating compliance with regulatory standards or criteria and that the degree of simplification will depend on the purpose of the application [A1]. For screening purposes, the concept of a single "generic" biota, which represents all plants and animals irrespective of size, shape and composition, has been used [A2] while somewhat more sophisticated models took account of the dose distributions within reference organisms of assumed shapes and sizes and the fractions of radiation energies absorbed in the organisms [W2]. The ACRP also recognized that it is impractical to address organisms individually and recommended the use of reference biota, typically developed in terms of simple physical shapes and dimensions for the purpose of dosimetry [B14, I2, N1, P7].

3. FASSET

245. The group working on the Framework for Assessment of Environmental Impact (FASSET) [F1, F4, F6, L4] reported on a wide range of issues relevant to the protection of non-human biota from ionizing radiation, including dosimetric information and data on the effects of radiation on non-human biota. The FASSET project developed a database (FASSET Radiation Effects Database—FRED) on the effects of radiation exposure on non-human biota under four broad effects categories, referred to by FASSET as "umbrella effects". These included:

- Morbidity (including growth rate, effects on the immune system, and the behavioural consequences of damage to the central nervous system from radiation exposure of the developing embryo);
- Mortality (including the stochastic effect of somatic mutation and its possible consequence for cancer induction, as well as deterministic effects in particular tissues or organs that would change the age-dependent death rate);
- Reduced reproductive success (including fertility and fecundity); and
- Mutation (induced in germ and somatic cells).

246. Table 30 gives an overview of the quality and quantity of the available data within the FRED, based on a simplified categorization (ecosystem type, exposure duration and irradiation pathway). The data on effects are strongly weighted in favour of terrestrial ecosystems (73% of all data) and, for each ecosystem, the available data appear to be biased roughly 2:1 in favour of data of acute effects and an external gamma radiation exposure situation. As a consequence, the data on chronic effects are limited and largely dominated by external gamma radiation exposure conditions experimentally obtained using gamma sources (frequently either ^{137}Cs or ^{60}Co); thus, mathematical modelling such as that described in section I is needed to estimate doses for comparison with reference dose rates [G3, G15].

247. Real et al. [R9] summarized the available information from the FRED on the effects of continuous low dose-rate irradiation of plants, fish and mammals. The effects observed on plants, fish and mammals are shown in tables 31, 32 and 33, respectively. Each of these tables provides a brief description of the effect, the corresponding endpoint and the dose rate resulting in the effect. Table 34 provides an overall summary of the data on chronic effects of radiation exposure as provided by reference [R9].

Table 30. Allocation of the data on effects within the FRED database to freshwater, terrestrial and marine ecosystems, and to the radiation exposure regimes (duration and irradiation pathways) [G3]

Ecosystem (number of references)	*Total number of data (%)*	*Number of data for each exposure duration*			*Number of data for each exposure irradiation pathway*		
		Type	*Total number*	*%*	*External*	*Internal*	*Other[a]*
Terrestrial (579)	19 983 (72.6)	Acute	12 273	61.4	11 564	288	421
		Chronic	6 795	34.0	3 449	344	3 002
		Transitory[b]	913	4.57	670	40	203
		Not stated	2	0.03	0	0	2
Freshwater (195)	6 067 (22.0)	Acute	4 526	74.6	4 058	97	371
		Chronic	1 484	24.5	970	20	494
		Transitory	54	0.89	12	2	40
		Not stated	3	0.01	0	0	3

Ecosystem (number of references)	Total number of data (%)	Number of data for each exposure duration			Number of data for each exposure irradiation pathway		
		Type	Total number	%	External	Internal	Other[a]
Marine (45)	1 470 (5.4)	Acute	1 116	75.9	995	58	63
		Chronic	353	24.1	286	0	67
		Transitory	0	0	0	0	0
		Not stated	1	0	0	0	1

[a] "Other" means that the experiment reported in the literature was devoted to the study of the effects involved by mixed irradiation pathways, and/or not well characterized to be used for the present analysis.
[b] "Transitory" means in between "acute" and "chronic" in terms of exposure duration.

Table 31. Effects of chronic irradiation on plants [R9]

Dose rate (µGy/h)	Species	Radiation	Effects described	Endpoint	Reference
100–1 000	Pine	Gamma	Reduced trunk growth of mature trees	Morbidity	[W4]
			Death of some conifers; little changes in populations	Morbidity	[A6]
$(1–5) \times 10^3$	Pine	Gamma	Reduced canopy cover of individual conifers; whole canopy remains constant	Morbidity	[A6]
			Decreased stem growth of saplings	Morbidity	[A23]
			Reduced photosynthetic capacity of pines and thus growth	Morbidity	[B11]
$(5–10) \times 10^3$	Pine	Gamma	Death of all conifers within 2–3 years	Mortality	[A6]
$(1–2) \times 10^4$	Pine	Gamma	Reduced seed production and germination	Reproduction	[W11]
			Morphological changes in leaves of some plants	Morbidity	[W11]
			Withered crowns	Morbidity	[W11]
	Birch	Gamma	Underdeveloped leaves	Morbidity	[W11]
$>2 \times 10^4$	Herbaceous	Gamma	Reduced reproductive potential	Reproduction	[U4]
	Birch	Gamma	Death of trees	Mortality	[A6, W11]
	Grasses	Gamma	Death of grasses and forbs	Mortality	[W11]
$>1 \times 10^5$	Plants	Gamma	Death of all higher plants	Mortality	[A6, W11]
$>1 \times 10^6$	Lichen	Gamma	Reduced diversity of lichen communities after one year exposure	Mortality	[B13, W18]

Table 32. Effects of chronic irradiation on fish [R9]

Dose rate (µGy/h)	Species	Radiation	Effects described	Endpoint	Reference
$(1–10) \times 10^2$	Plaice, Medaka, Roach	Gamma	Reduction in testis mass and sperm production. Lower fecundity. Delayed spawning	Reproduction	[H11, K16, N1]
$(1–5) \times 10^3$	Plaice, Eelpout, Medaka, Guppy, Rainbow trout	Gamma or beta	Reduction in testis mass and sperm content. Severe depletion of spermatogonia. Reduced fertility or complete infertility. Reduced fecundity. Reduced male courtship activity. Reduced immune response	Reproduction Morbidity	[E10, G20, H11, H16, K16, K17, P5, W7]
$(5–10) \times 10^3$	Medaka	Gamma	Depletion of spermatogonia	Reproduction	[H11]
$(1–5) \times 10^4$	Medaka, Guppy	Gamma	Sterility. Reduction in larval survival. Increase in vertebral anomalies	Reproduction	[H17, W7]
$>5 \times 10^4$	Guppy	Gamma	No impact on offspring survival following parental irradiation	Mortality	[W7]

Table 33. Effects of chronic irradiation on mammals [R9]

Dose rate (μGy/h)	*Species*	*Radiation*	*Effects described*	*Endpoint*	*Reference*
$<10^2$	Mouse Rat	Gamma	No detrimental effects have been described	Morbidity Mortality Reproduction	[C17, P8] [C17, U21] [L2, Y2]
$(1–10) \times 10^2$	Dog	Gamma	Life shortening	Mortality	[C18]
	Mouse	Gamma	Life shortening	Mortality	[M13]
	Mouse	Neutrons	Life shortening	Mortality	[M13]
	Pig	Gamma	Prenatal irradiation decreased the number of primitive stem germ cells and the ovary and testis weight	Reproduction	[E14, E15]
	Rat	Gamma	Reduction in number of A1 spermatogonia	Reproduction	[E16]
	Mouse	Beta	Irradiation from conception to 14 days of age decreased the number of primary oocytes	Reproduction	[D2]
	Mouse	Gamma	Reduction of mean number of litters per female; higher mortality between birth and weaning; reduction in number of primary oocytes	Reproduction	[S6]
			Irradiation during three consecutive generations increased the % of sterile mice and the % of early deaths and decreased the mean litter size	Reproduction	[M14, M15]
			Field study. Increased % of sterile pairs; reduced mean offspring sired and weaned	Reproduction	[L3]
	Reindeer	Gamma	Natural forest. Increased number of chromosomal aberrations	Mutation	[R3]
$(1–5) \times 10^3$	Goat	Gamma	Life shortening	Mortality	[H18]
	Mouse	Gamma	Increased mortality ratio (the effect was dependent on the mice strain used); decreased mean after survival	Mortality	[G25, T2]
	Mouse	Neutrons	Life shortening	Mortality	[U21]
	Goat	Gamma	Reduced number of liveborn per female in the third generation and reduced total sperm production	Reproduction	[H19]
	Mouse	Gamma	Irradiation during the 2nd week after birth reduced the fertility and the litter size	Reproduction	[R5]
			Irradiation during 4–90 days reduced the fertility span, the germ cells per ovary and the testis weight	Reproduction	[M16, R12, R13]
	Rat	Beta	Prenatal irradiation reduced the litter size and increased the % of resorptions	Reproduction	[L2, L6]
	Rat	Gamma	Reduced number of spermatogonia and testis weight	Reproduction	[P15, P21]
			Prenatal irradiation reduced the number of germ cells in females and males	Reproduction	[E14]
	Mouse	Gamma	Increased mutation frequency at seven specific loci in mouse spermatogonia	Mutation	[R14]
$(5–10) \times 10^3$	Sheep	Beta	Reduction in the number of leukocytes in peripheral blood	Morbidity	[B15]
	Rat	Gamma	Reduced brain weight and cingulum volume	Morbidity	[R15]
	Mouse	Gamma	Life shortening after exposures of 68 days or longer	Mortality	[S7, S24]
			Increased paternal expanded simple tandem repeat (ESTR) mutation rate and paternal mutation per offspring band at loci MMS10 plus Ms6-hm plus Hm-2	Mutation	[D3, D5]
$>10^4$	Dog	Beta	Reduced survival	Mortality	[R16]
	Mouse	Gamma	Increased mortality ratio (dependent on the strain used)	Mortality	[G25]
	Rat	Gamma	Prenatal irradiation reduced the length and weight of embryos and increased the % mortality	Reproduction	[C19]
			Reduction in ovary and testis weight	Reproduction	[E17]

Table 34. Overall summary of data on the effects of chronic irradiation for plants, fish and mammals, based on the FASSET Radiation Effects Database (FRED) [R9]

Wildlife group	*Morbidity*	*Mortality*	*Reproductive capacity*	*Mutation*
Plant	Plant growth begins to be affected at more than 100 μGy/h. Continued exposure at 21 μGy/h for 8 years increases the sensitivity in pines	50% mortality at 8 years at ~1 000 μGy/h in pines	A field study indicated a decrease in seed weight of a herb at 5.5 μGy/h	The mutation rate in microsatellite DNA increased at ~40 μGy/h
Fish	One experiment, but not another, indicates effects on the immune system at 8.3 μGy/h	Too few data to draw conclusions	One study showing effects on gametogenesis at 230 μGy/h. Otherwise effects at more than 1 000 μGy/h	Radiation exposure increases the mutation rate
Mammals	Rat growth not affected at 16 μGy/h but affected at more than 3 000 μGy/h. Some blood parameters affected at 180–850 μGy/h. No effect on thyroid function at 8 000 μGy/h	No effect on mouse lifespan at 460 μGy/h, but significant reductions above ~1 000 μGy/h in the mouse, goat and dog	Threshold for effects at ~100 μGy/h, with clear effects at more than 1 000 μGy/h	Too few data to draw conclusions. One of nine references gives an LOEDR of 420 μGy/h for mice

248. Real et al. [R9] noted that plant morphology (size, shape and density of plant stands) can alter the exposure and the resulting radiation dose. They also noted that plants with exposed meristems or buds can receive higher doses to the critical tissues than those plants that grow and reproduce underground or are protected by thick scales.

249. Real et al. [R9] concluded that chronic exposures up to 4×10^3 μGy/h to developing fish embryos will not result in significant effects on growth. Furthermore, they considered that the available data suggest that dose rates of less than 4×10^3 μGy/h at any life stage would not be expected to affect survival. However, they felt that the limited amount of data further suggests that genetic damage caused by chronic irradiation is likely to occur at all dose rates and that the radiosensitivity for this damage is similar to that of other vertebrates.

250. There are a large number of data on mammals available within the FRED; therefore, Real et al. [R9] had to be selective in summarizing the information. Altogether, the authors considered 183 references for mammals, which provided more than 3,000 data points on effects. The authors concluded that chronic radiation dose rates lower than 10^3 μGy/h do not result in irreversible effects on mortality, morbidity and reproduction. A dose rate of 100 μGy/h (i.e. 2.4 mGy/d) had been described for reproductive capacity impairment; however, the detrimental effects observed were reversible [R9]. The authors indicated that the majority of the work had been conducted using mice and rats and that it would be beneficial to have additional information on the effects of chronic radiation exposure on other species.

251. An overall summary of the effects due to chronic exposure of plants, fish and mammals identified by FASSET was reported in reference [R9] for the different endpoint classifications (morbidity, mortality, reproductive capacity and mutation) provided in table 34. The authors concluded that the amount of available information on the effects of low dose rates (less than about 100 μGy/h) for continuous radiation exposure is reasonable for both plants and animals and that for chronic exposure conditions "the reviewed effects data give few indications for readily observable effects at chronic dose rates below 100 μGy/h". However, they advised that "using this information for establishing environmentally 'safe levels' of radiation should be done with caution, considering that the database contains large information gaps for environmentally relevant dose rates and ecologically important wildlife groups" [F5, R9].

4. ERICA

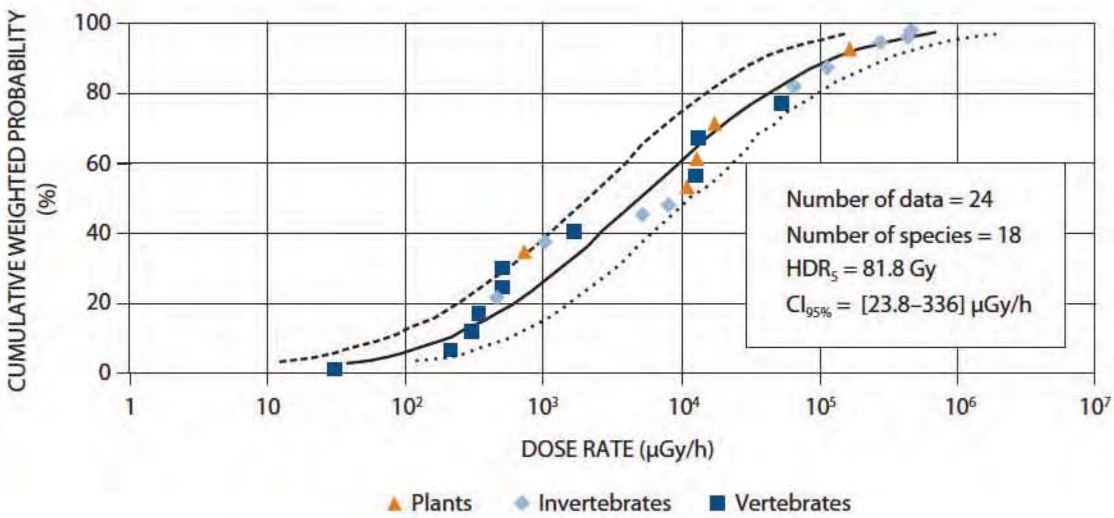
252. The project on Environmental Risks from Ionizing Contaminants: Assessment and Management (ERICA) carried out under the European Commission's 6th Framework Programme was the successor of the FASSET project. Extensive quality assurance of the data was carried out and this led to the development of an expanded effects database (referred to as FREDERICA). A database on the effects of chronic radiation exposure of fish, which was developed in the project on Environmental Protection from Ionising Contaminants in the Arctic (EPIC) [S25] was subsequently incorporated into the FREDERICA effects database [C12].

253. The ERICA integrated approach adopted an Ecological Risk Assessment tiered methodology that required values of the risk assessment screening dose rates for risk characterization within Tiers 1 and 2. The screening values used within Tiers 1 and 2 were derived on the basis of data taken from the FRED and compared from some key data from the EPIC project (making thus the best use of the FREDERICA database) [C12]. The method applied follows recommendations of the European Commission for the estimation of Predicted

No-Effect Concentration (PNEC) for chemicals [E11]. A three-step methodology was used. First, a coherent data subset was extracted from each experiment, covering endpoints related to mortality, morbidity and reproduction. Next, a systematic mathematical treatment was applied to reconstruct dose-rate–effect relationships and to estimate critical toxicity endpoints. For chronic exposure, the critical toxicity endpoint was the estimated Effect Dose Rate (EDR_{10}, expressed in µGy/h), the dose rate that gives rise to a 10% change in observed effect. The final step of the method consisted in using these estimated critical toxicity data to derive a Predicted No-Effect Dose Rate (PNEDR) by means of the species sensitivity distribution method (SSD) [E11, G15, G27].

254. The SSD method was used to estimate the Hazardous Dose Rate (HDR_5), the dose rate at which 95% of the species in the aquatic/terrestrial ecosystem are protected. After separate analyses of the data available for different ecosystems, the authors [G15] concluded there was no statistical justification for attempting to derive ecosystem-specific screening dose rates and all data were therefore analysed together as a generic ecosystem. The resultant HDR_5 was 82 µGy/h (with 95th percentile confidence intervals of 23.8 and 336 µGy/h). To derive the final dose rate for screening (i.e. PNEDR), a safety factor (*SF*) of 5 was used to allow for any remaining extrapolation and the resultant number rounded down to the nearest one significant figure. Based on this approach, the authors suggested a reference dose rate for incremental exposure of 10 µGy/h for "screening for potential radiological effects". The methodology and process used to derive this screening value are documented within references [G3, G11, G15] where the value is shown to be similar to that derived using alternative methods to SSD (figure XIII).

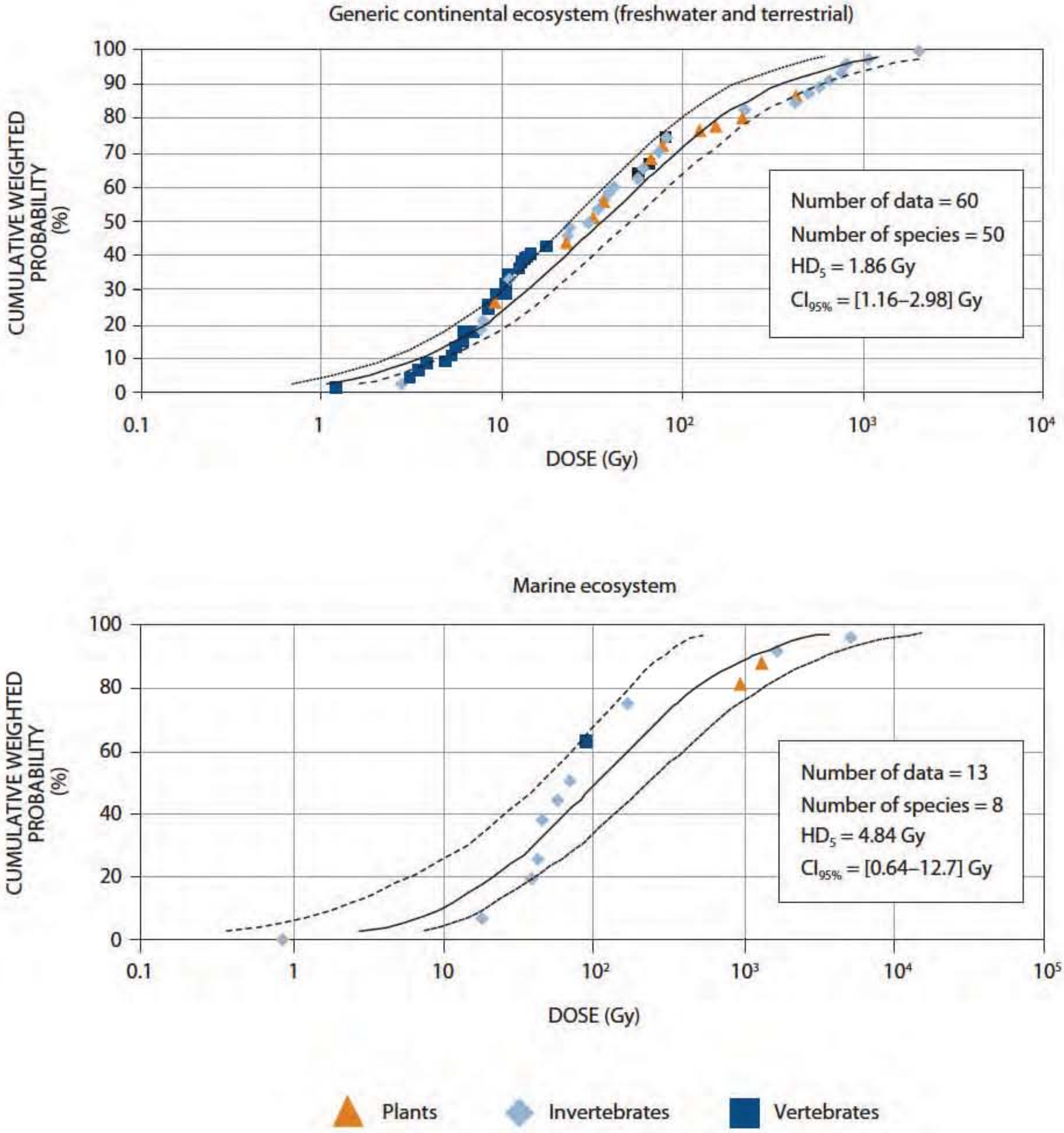
Figure XIII. Species sensitivity distributions for generic ecosystems and chronic external gamma irradiation conditions
The log-normal distribution with its associated 95% confidence interval is fitted to geometric means per effect category for each species calculated on critical ecotoxicity data (*EDR_{10}*) [G3]



255. At the ecosystem level, the value of the ERICA integrated approach screening dose rate lies in the range giving rise to minor effects [F5, G3, G15, G27]. The authors suggested that such effects are not expected to be directly relevant at higher organizational levels, such as the structure and functioning of ecosystems.

256. The same method was also applied to acute exposure conditions to guide interpretation of accidental situations; however, in this case, the authors [G11, G15] did find a difference between marine ecosystems compared to terrestrial and freshwater ecosystems. The values derived from an SSD analysis on the set of Effect Doses giving a 50% change in observed effect (ED_{50}) for limiting the potentially affected fraction to 5% of the species under acute external gamma irradiation conditions varied from about 1 to 5.5 Gy, according to the ecosystems type, with associated 95% confidence intervals covering less than one order of magnitude (see figure XIV). To derive screening values, an *SF* of 5 was applied and the results rounded down to the nearest one significant figure. This resulted in Predicted No-Effect Doses (PNED) of 900 mGy for marine ecosystems and 300 mGy for terrestrial and freshwater ecosystems [G3, G15, G27].

Figure XIV. Species sensitivity distributions for generic ecosystems and acute external gamma irradiation conditions
The log-normal distribution with its associated 95% confidence interval is fitted to geometric means per effect category for each species calculated on critical ecotoxicity data (ED_{50}) [G3]



257. Dose rates below which no significant effects are expected at various levels of organization (population, wildlife group or ecosystem) were compared by different organizations/authors [G3, G15], and are summarized in table 35. The selection was mainly based on observations of effects and expert judgement. The approach using SSD provides an alternative methodology for assessing radiation risks by deriving, for the first time for radioactive substances, protection thresholds using a rational and transparent process based on the approach adopted for chemicals in Europe [G15].

Table 35. Dose-rate values proposed by various organizations/programmes to support effect analysis for chronic exposure to radiation [G3, G11]

Targeted protected level as described in the source	*Method/justification of the value*	*Dose rate (µGy/h)*	*Source reference*
Terrestrial ecosystems			
Generic ecosystems	SSD-95% species protected plus *SF* of 5 SSD giving an HDR_5 of 81.8 µGy/h divided by an *SF* of 5 and rounded down	10	[G3]
Generic ecosystems	SF method: *SF* of 10 applied to the lowest critical radiotoxicity value EDR_{10}	0.6	[G3]
Plants	Background	0.02–0.7	[U4]
Plants	Review, *SF* on the lowest critical radiotoxicity value	110	[B31, E5]
Plants	Review based on NCRP 1991; IAEA 1992; UNSCEAR 1996	400	[O1, U26]
Plants	Critical review for screening purpose from IAEA 1992	400	[E12]
Organisms	Background – external irradiation and non-weighted	0.01–0.1	[G21]
Animals	Background	0.01–0.44	[U4]
Animals	Review based on NCRP 1991; IAEA 1992; UNSCEAR 1996	40	[O1, U26]
Animals	Critical review for screening purpose from IAEA 1992	40	[E13]
Small mammals	Review, *SF* on the lowest critical radiotoxicity value	110	[B31, E5]
Invertebrates	Review, *SF* on the lowest critical radiotoxicity value	220	[B31, E5]
Vertebrates and cytogenetic effects	Review contaminated environments	4–20	[S28]
Vertebrates and effects on morbidity	Review contaminated environments	20–80	[S28]
Vertebrates and effects on reproduction	Review contaminated environments	80–200	[S28]
Aquatic ecosystems			
Generic freshwater ecosystems	SSD-95% species protected plus *SF* of 5 SSD giving an HDR_5 of 81.8 µGy/h divided by an *SF* of 5 and rounded down	10	This annex
Generic freshwater ecosystems	SF method: *SF* of 50 applied to the lowest critical radiotoxicity value EDR_{10}	10	This annex
Generic marine ecosystems	SSD-95% species protected plus *SF* of 5 SSD giving an HDR_5 of 81.8 µGy/h divided by an *SF* of 5 and rounded down	10	[G3]
Generic marine ecosystems	SF method: *SF* of 50 applied to the lowest critical radiotoxicity value EDR_{10}	3.7	[G3]
Freshwater organisms	Background	0.022–0.18	[U4]
Freshwater organisms	Background–external irradiation and non-weighted	0.02–6	[B32]
Aquatic algae/macrophytes	Review, *SF* on the lowest critical radiotoxicity value	110	[B31, E5]
Aquatic animals	Review based on NCRP 1991; IAEA 1992; UNSCEAR 1996	400	[O1, U26]
Freshwater and coastal marine organisms	Critical review for screening purpose from IAEA 1992	400	[E12]
Amphibians/reptiles	Review, *SF* on the lowest critical radiotoxicity value	110	[B31, E5]
Benthic invertebrates	Review, *SF* on the lowest critical radiotoxicity value	220	[B31, E5]
Fish	Review, *SF* on the lowest critical radiotoxicity value	20	[B31, E5]
Marine organisms	Background–external irradiation and non-weighted	0.03–1	[B32]
Marine mammals	Critical review for screening purpose from IAEA 1992	40	[E13]
Deep ocean organisms	Critical review for screening purpose from IAEA 1992	1 000	[E13]
Aquatic and terrestrial flora and fauna	Review concluded that few indications of readily observable effects at chronic dose rates below	<100	[F5]

258. As indicated elsewhere in this annex, few new data on the effects of ionizing radiation exposure on non-human biota have been developed since 1996. In all the recent literature reviews [C1, F5, G16, R9, W11]), the specificities of the environmental situations of interest (chronic low-level exposure regimes) consistently emphasized the importance of all reproductive parameters to the population within a given ecosystem to the structure and functioning of that ecosystem. These reviews clearly argued for the need of a research programme to acquire specific data related to chronic low-level exposure and the effects on reproductive capacity in such a way as to be able to shift from observations on individual organisms to observations on populations. A brief summary of the data on effects from the FRED is given in table 36 along with assigned weight ratios based on the numbers of data sets available related to acute versus chronic exposure and, for chronic exposure data, to external versus internal exposure and reproductive endpoints. The extrapolation on the basis of the existing knowledge will become increasingly critical as the relative weights increase. In reviewing these data, Garnier-Laplace et al. [G16] concluded that operationally for any site-specific risk assessment, the present state-of-the-art on extrapolation issues allows the relative magnitudes of the various sources of uncertainty to be ordered as follows: one species to another > acute to chronic = external to internal = mixture of stressors > individual to population > ecosystem structure to function.

Table 36. Brief overview of the data on effects from FRED (adapted from reference [G16])

Wildlife group	*Number of data*	*Weight data ratio*		
		All data: acute/chronic	*Chronic data: (external)/(internal+mixed)*	
			All endpoints	*Reproduction*
Aquatic plants	616	2.7	4.1	0/0[a]
Aquatic invertebrates	542	1.2	4.1	8.3
Amphibians	749	1.3	0.02	0/0
Bacteria	171	0.5	2.4	0/0
Birds	1 732	3.4	3.4	5.5
Crustaceans	850	3.7	180	20/0
Fish	2 802	2.8	1.0	0.8
Fungi	120	0/120	120	0/0
Insects	1 237	5.2	5.4	0.8
Mammals	4 112	2.5	4.7	3.3
Molluscs	484	2.4	1.7	0.4
Moss/lichen	44	0/44	0.5	0/0
Plants	11 984	1.6	0.7	0.5
Reptiles	271	6.7	0/35	0/0
Soil fauna	398	1.6	0.15	0/0
Zooplankton	111	4.3	21/0	9/0

a (number of data devoted to reproduction endpoints and chronic external irradiation) / (number of data devoted to reproduction endpoints and chronic internal or mixed irradiation): for example, 0/0 means that no data exist.

5. Observations from recent literature

259. The European Commission (EC) has been supporting research on the effects of ionizing radiation exposure on non-human biota for the past several years. This included the development of the FRED. More recently, the ERICA project conducted a review of the quality of the data in the FRED and merged the FRED with the Russian EPIC database to form a new database, FREDERICA, with several hundred additional references [C12]. This database includes references to over 1,200 papers that focus on the effects of radiation exposure on non-human biota and is a valuable source of information. General information on the new data on effects or new interpretations of the data on effects is provided in the previous section. Additional observations from the literature identified in the ERICA database as well as the open literature are provided in the following section in an attempt to supplement the previous information in several areas of current interest.

(a) Terrestrial biota

260. Hingston et al. have described the effects of low doses of ionizing radiation on terrestrial invertebrates and reported experiments on earthworms (*Eisena fetida)* and woodlice *(Porcellioscaber)* [H23]. Both species were continuously exposed to gamma radiation from a ^{137}Cs source over a range of dose rates with total exposures for each experimental group

of 0.5–20 Gy delivered over a total of 14 and 16 weeks, respectively. The investigators considered a number of endpoints relevant to reproduction, growth and mortality. They reported on the results for woodlice [H23]. They found no deleterious effects for the endpoints studied up to a maximum dose rate of approximately 8 mGy/h (192 mGy/d); the woodlice were unaffected by the doses given. However, they noted that the results may, in part, have reflected the laboratory conditions, i.e. an environment protected from predation. Hertel-Aas et al. reported the results from a study of the reproductive capacity (numbers of cocoons, hatchability, etc.) of earthworms exposed chronically to gamma radiation [H22]. In this study, earthworms (*Eisena fetida*) were exposed over two generations to gamma radiation from a ^{60}Co source at five dose rates, from 0.18–43 mGy/h. The lowest dose rates at which an effect was observed was 4 mGy/h and 11 mGy/h in F_0 and F_1 worms, respectively. The experiments also suggested a possible acclimatization in F_1 worms.

261. Tanaka et al. [T3, T25] discussed the effects of chronic exposure of mice (SPF B6C3F1) to gamma rays at low dose rates. Mice of both sexes were divided into 4 groups, one of which was not irradiated and the other three which were irradiated. The exposed mice were irradiated at dose rates of 0.05, 1.1 and 21 mGy/d for about 400 days using a ^{137}Cs source. All mice were maintained until natural death, after which pathology was performed to identify the cause of death. Females exposed to 1.1 mGy/d and both sexes exposed to 21 mGy/d had significantly shortened lifespans compared to non-exposed mice. The mean survival times of mice of both sexes exposed to 0.05 and 1.1 mGy/d were shorter than for non-exposed mice but not significantly so.

(b) Aquatic and marine biota

262. The great majority of the data on aquatic invertebrates in the FRED concern the effects of chronic irradiation on crustaceans. The data indicate that observable impacts at dose rates up to 10^3 mGy/h are unlikely and that a dose rate of ~10^4 mGy/h is probably the lower limit for the onset of significant effects. However, effects were apparent in the embryonic development of the goose barnacle (*Pollicipes polymerus*) following a 32-day exposure to tritiated water at dose rates of 0.7, 6.5 and 64 mGy/h [F5].

263. Concerning the effects of internal radiation exposure on crustaceans, recent data exist on daphnids which were chronically exposed internally to alpha radiation from ^{241}Am under experimental conditions at dose rates up to 990 µGy/h [A19]. These authors reported that exposure to dose rates of 110 µGy/h or higher resulted in a significant (15%) reduction in body mass. Daphnids also showed increased respiratory demand after 23 days at the highest dose rate, suggesting increased metabolic cost of maintenance resulting from the need to cope with the stress from alpha irradiation. Fecundity remained unchanged over the 23-day period, but individual masses of eggs and neonates were significantly smaller compared to the control. This suggested that increased metabolic expenditure in chronically alpha-irradiated daphnids came at the expense of their energy investment per offspring. As a consequence, neonates showed significantly reduced resistance to starvation at every dose rate compared to the control.

264. Gilbin et al. [G22] reported effects on *Daphnia magna* of external gamma radiation exposure at dose rates ranging from 0.4–31 mGy/h over a 23-day period (i.e. 5 broods). Gamma radiation exposure caused no significant change in somatic growth. The mass-specific respiration rate was significantly lower at dose rates of 31 mGy/h than for the control. Broods were deposited earlier and fecundity was 20% lower at the highest dose rate than for the control. The combination of decreased fecundity and unchanged individual offspring mass resulted in a smaller total mass of eggs produced per daphnid at dose rates of 4.2 and 31 mGy/h than for the control. A decreased resistance of neonates to starvation was observed at every dose rate.

265. Alonzo et al. [A27] tested the chronic effects of internal alpha irradiation on *Daphnia magna* respiration, somatic growth and reproduction over three successive generations. They showed that the toxicological effects of internal alpha irradiation on life-history traits of *Daphnia magna* increased across generations. A 70-day experiment was performed with *Daphnia magna* exposed to waterborne ^{241}Am corresponding to average dose rates of 0.3, 1.5 and 15 mGy/h. In the first generation (F_0), a reduction in body length (5%) and the dry mass of females (16%) and eggs (8%) was observed after 23 days of exposure, while mortality and fecundity remained unaffected. New cohorts were started with neonates of broods 1 and 5, to examine the potential consequences of the reduced mass of the offspring for subsequently exposed generations. At the highest dose rate, an early mortality of 38–90% affected juveniles while survivors showed delayed reproduction and reduced fecundity in F_1 and F_2. At dose rates of 0.3 and 1.5 mGy/h, the mortality of daphnids in generation F_1 ranged from 31–38%. Reproduction was affected through a reduction in the proportion of breeding females occurring in the first offspring generation at a dose rate of 1.5 mGy/h (to 62% of total daphnids) and in the second generation at 0.3 mGy/h (to 69% of total daphnids). Oxygen consumption remained significantly higher at dose rates ≥0.3 mGy/h than for the control in almost every generation. Body size and mass continued decreasing in relation to dose rate, with a significant reduction in mass ranging from 15% at a dose rate of 0.3 mGy/h to 27% at 15 mGy/h in the second offspring generation.

266. Dose rates above 0.1 mGy/h to developing mollusc embryos affected the incidence of developmental abnormalities but not the subsequent overall survival of the resulting larvae. Significant detrimental effects are to be expected at dose rates greater than 1 mGy/h [F5]. Recently, Jha et al. [J4] exposed mussels (*Mytilus edulis*) to a series of concentrations of HTO equivalent to a dose rate ranging from 12–485 µGy/h for 96 hours. The study revealed a dose-dependent increase in the response for both the micronuclei test and the comet assay. Dose rates below 500 µGy/h induced genetic damage in the haemocytes. For the same species but another life stage (i.e. one-hour-old embryos exposed during 12 to 24 hours to a range of HTO doses between 0.02 and 21.41 mGy), Hagger et al. [H13] found that the embryo–larvae showed dose or concentration-dependent effects for mortality, developmental

abnormalities and induction of sister chromatid exchanges. However, they reported that there was a lack of a clear dose response for chromosomal aberrations and proliferative-rate index.

267. For annelids, Knowles and Greenwood [K3] exposed *Ophryotrocha diadema* to beta radiation at a dose rate of 7.3 mGy/h and observed that the number of eggs surviving to the larval stage was reduced, but did not affect egg production. This is in contrast to previous studies related to gamma irradiation where egg production is reduced but not the number becoming larvae.

268. Kryshev and Sazykina [K18] reported an evaluation of the radioecological effects on aquatic organisms exposed to high levels of radioactive contamination in lakes affected by the Mayak reprocessing facility, in lakes affected by the Kyshtym accident, in the cooling pond of the Chernobyl nuclear power plant (NPP) and in the littoral area downstream of the Leningrad NPP. The authors reported doses based on the concentrations of radionuclides in water, sediments and fish and indicated that the highest dose rates, up to 300–800 mGy/d, were to organisms in the lakes affected by the Mayak complex. They also noted that the biota in the Mayak lakes were exposed to chemical contamination in addition to radiation but commented that the fish population had retained its viability for the period of observation of 30 years. The lowest dose rates were for the Leningrad NPP, where the authors noted that, typically, aquatic organisms were exposed to background levels of radiation. However, the dose rates to aquatic organisms in the liquid radioactive-waste canal of the Leningrad NPP were elevated. Here, the authors noted an increased asymmetry of the soft rays of the pectoral fins of roach and suggested that this was due to the combined effects of exposure to radiation and elevated temperature. The overall observations from this study are summarized in table 37.

Table 37. Radioecological effects in water bodies exposed to radioactive contamination
(adapted from reference [K18])

Water body (period of assessment) species under study	*Dose rate assessment (μGy/d)*	*Brief description of the effects*
Southern Urals [K24, K25, K26]		
Lake Karachai (1951–1952) Techa River (1951–1951)	300 000–800 000 30–2 000	Total death of lake ecosystem Mass death of fish in the upper reaches of the river
Cooling pond of the Chernobyl NPP [B19, K12, K28] (1986–1992): Silver carp *Hypophthalmichthys molitrix*	0.2–3	Increased anomalies of the reproductive system; disturbances in the state of sexual cells to 47–90%; sterility of gonads
Waste channel of the Leningrad NPP [K27, R18] (1980–1983) Roach *Rutilus rutilus*	0.007–2	Increase by a factor of 2.3 in the variance of fluctuating asymmetry of the number of soft rays of pectoral fins at different sides of the body of roach

269. Real et al. [R9] in their review of the information in the FRED observed that the developing embryos of fish that were subjected to chronic exposures at dose rates up to 4 mGy/h will not result in significant effects on subsequent growth. They also noted conflicting results for the effects of radiation exposure of the immune system: for rainbow trout irradiated as embryos, there was a threshold at dose rates between 8.3–83 μGy/h from exposure to beta radiation from tritium, while there was no effect at a dose rate of 9 mGy/h from exposure to radiation from ^{137}Cs. According to the authors [R9], the limited data available on mortality effects of chronic irradiation indicated that dose rates less than 4 mGy/h at any life stage were unlikely to affect survival and that there was little consistent, significant evidence for any effects on reproductive capacity at dose rates of less than 0.2 mGy/h. Finally, the authors [R9] suggested, based on a very limited amount of data, that chronic irradiation-induced genetic damage probably occurs at all dose rates and that radiosensitivity for this damage is similar to that of other vertebrates.

270. An interesting recent study has been performed with zebrafish larvae by Jarvis and Knowles [J5]. Gamma radiation was delivered externally from sealed sources (^{137}Cs) at a dose rate ranging from 0.3–7.4 mGy/h. The alkaline comet assay was used to assess DNA damage on larvae (5–6 days post laying, 2 days post hatching), exposed for 24 hours to dose rates of 0.4, 1.2 or 7.2 mGy/h and for 1 hour to 0.4 or 1.2 mGy/h. Entire larvae were macerated and their cells embedded in agarose gel. Larvae exposed at dose rates of 7.2 or 1.2 mGy/h for 24 hours (total dose of 173 and 29 mGy, respectively) showed a significant increase in the percentage of DNA in the comet tail. The same observation was made for larvae exposed at the same rates for 1 hour (total dose of 7.2 and 1.2 mGy, respectively). The increase in tail movement was not correlated to the exposure time, indicating that DNA damage was repaired with time. No information was available on DNA repair in long-term irradiated or contaminated fish. It must be noted that for a similar dose rate (1 mGy/h), no effect on reproduction in adults after exposure of more than 12 months could be observed [E12].

(c) Genotoxicity

271. Data on genotoxicity are summarized in table 38. Knowles [K16] irradiated plaice under laboratory-controlled conditions using sealed ^{137}Cs sources to investigate potential genotoxic effects. No effect on the coefficient of variation (CV) of the DNA content, aneuploidy or polyploidy, measured by flow cytometry (FC), was observed even for the maximum exposure period (197 days) and maximum dose rate (1 mGy/h).

Table 38. Genotoxicity in aquatic species exposed to radionuclides in the laboratory or in situ [A13]

Species (life stage)	*Type of exposure*	*Dose rate, dose or internal concentration*	*Exposure duration*	*Assay (parameter)*	*Effect LOEDR (µGy/h) (LNOEDR or LOED)*	*Reference*
Zebrafish (*D. rerio*), larvae (2 d)	Lab in vivo, external, ^{137}Cs	400, 1 200, 7 200 µGy/h	1 hour; 24 hours	Alkaline comet (tail moment)	+ 1 200 µGy/h	[J5]
Pond slider (*T. scripta*) Snapping turtle (*C. serpentina*), adults	In situ, (White Oak Lake) external + internal, ^{235}U, ^{239,240}Pu, ^{137}Cs, ^{60}Co, ^{90}Sr, Hg, HAP, PCB	External dose rate: 50 µGy/h[a]	n.d.	Alkaline and neutral unwinding (hepatocytes)	+ 50 µGy/h	[M5]
Mosquitofish (*G. affinis*), adults	In situ, (Oak Ridge) external + internal, ^{235}U, ^{239,240}Pu, ^{137}Cs, ^{60}Co, ^{90}Sr, Hg, HAP, PCB	External dose rate: 50 µGy/h	49 years	Agarose gel electrophoresis (hepatocytes, erythrocytes)	+ 50 µGy/h	[T21]
Channel catfish (*I. Punctatus*), adults	In situ, Chernobyl, cooling pond, ^{137}Cs	125 µGy/h[b]	n.d.	Alkaline unwinding (hepatocytes, gill cells, erythrocytes)	=	[S18]
Largemouth bass (*M. salmoides*), adults	In situ, Savannah River site, ^{134,137}Cs + ^{89,90}Sr + Hg	80 µGy/h[c]	n.d.	Alkaline unwinding (hepatocytes, gill cells, erythrocytes)	=	[S17]
Marine polychaete worm (*N. arenaceodentata*), larvae	Lab in vivo, external, ^{60}Co	400–25 000 Gy/h	12 hours 24 hours	SCE	+ 400 µGy/h	[H15]
Midge (*C. tentans*), larvae	In situ, Savannah River site, ^{134,137}Cs + ^{89,90}Sr + Hg	260 µGy/h	Lifetime	CA	+++ : inversion + : deletion 260 µGy/h	[B34]
Marine polychaete worm (*N. arenaceodentata*), larvae	Lab in vivo, external, ^{60}Co	3 000 µGy/h (24 d) 6 000 µGy/h (48 d)	24 days 48 days	CA (metaphase)	+ 3 000 µGy/h + 6 000 µGy/h	[P4]
Slider turtle (*T. scripta*), fibroblasts and lymphocytes	Lab, external, ^{137}Cs	1 000 µGy/h to >100 Gy/h	n.d.	CA (symmetrical translocations)	230 000 µGy/h (LNOEDR)	[H14, U18]
18 different fish species	Various conditions (literature review)	Background 5×10^{3} to 0.5 µGy/h[d]	n.d.	MN per 1 000 erythrocytes	+ Mean [min; max] : 3 [0; 13] 5×10^{3} to 0.5 µGy/h	[G23]
Plaice, (*P. platessa*), adult	Lab, in vivo, external, ^{137}Cs	240–1 000 µGy/h	197 days	MN per 1 000 erythrocytes	=	[K16]
Pike (*E. lucius*), perch (*P. fluviatis*), roach (*R. rutilus*) and bream (*A. brama*)	In situ, Swedish lake, Chernobyl fallout 1988, external + internal, ^{137}Cs	10 000 Bq/kg d.w. ^{137}Cs 10 µGy/h[d]	n.d.	MN per 1 000 erythrocytes	=	[A20]
Pike (*E. lucius*), perch (*P. fluviatis*), roach (*R. rutilus*) and bream (*A. brama*)	In situ, Swedish lake, Chernobyl fallout 1988, external + internal, ^{137}Cs	18 000 Bq/kg d.w. ^{137}Cs Ext. dose rate : 10 µGy/h[d]	n.d.	MN per 1 000 erythrocytes	=	[A21]
Pike (*E. lucius*), adults	In situ, Siberian (Tomsk-7) nuclear site	57 000 µGy/h[d] 1 200 Bq/kg w.w.	n.d.	MN per 1 000 erythrocytes	++ 57 000 µGy/h	[I22]

Species (life stage)	*Type of exposure*	*Dose rate, dose or internal concentration*	*Exposure duration*	*Assay (parameter)*	*Effect LOEDR (µGy/h) (LNOEDR or LOED)*	*Reference*
Channel catfish (*I. Punctatus*), adults	In situ, Chernobyl, cooling pond, ^{137}Cs	125 µGy/h^{b}	n.d.	MN per 1 000 erythrocytes	-	[S18]
Plaice, (*P. platessa*), adult	Lab, in vivo, external, ^{137}Cs	240–1 000 µGy/h	197 days	FC (DNA CV, aneuploidy, polyploidy)	=	[K16]
Largemouth bass (*M. salmoides*), adults	In situ, Savannah River site, ^{134,137}Cs + ^{89,90}Sr + Hg	80 µGy/h^{c}	n.d.	FC erythrocytes (DNA CV, aneuploidy and CV distribution)	= : aneuploidy + : CV + : CV distribution 80 µGy/h	[L8]
Crucian carp (*Carassius carassius*), adults	In situ, Chernobyl, cooling pond, ^{137}Cs	125 µGy/h^{b}	n.d.	FC (DNA CV, aneuploidy)	= : aneuploidy + : CV 125 µGy/h	[L10]
Crucian carp (*Carassius carassius*), carp (*Cyprinus carpio*), tench (*Tinca tinca*), channel catfish (*I. punctatus*), adults	In situ, Chernobyl, cooling pond, ^{137}Cs	125 µGy/h^{b}	n.d.	FC whole blood, erythrocytes, leukocytes (DNA CV, aneuploidy, cell proliferation)	= : aneuploidy + : CV blood & erythrocytes ++ : CV leukocytes + : cell proliferation 125 µGy/h	[D8]
Slider turtles (*P. scripta*), adults	In situ, Savannah River site, ^{134,137}Cs + ^{89,90}Sr + Hg	80 µGy/h^{c}	n.d.	FC erythrocytes (DNA CV and aneuploidy)	= : aneuploidy + : CV 80 µGy/h	[B35]
Slider turtles (*P. scripta*), adults	In situ, Savannah River site, ^{134,137}Cs + ^{89,90}Sr + Hg	80 µGy/h^{c}	n.d.	FC erythrocytes (DNA CV and aneuploidy)	= : aneuploidy + : CV 80 µGy/h	[L11]
Mallard (*A. platyrhynchos*), ducklings	In situ, Savannah River site, ^{134,137}Cs + ^{89,90}Sr + Hg	80 µGy/h^{c}	9 months	FC erythrocytes (DNA CV, aneuploidy and cell proliferation)	= : aneuploidy = : cell proliferation + : CV 80 µGy/h	[G24]

Symbols and abbreviations: Dose rates are either those indicated in the article or those taken from other studies (^{a} from reference [T21]; ^{b} from reference [K9]; ^{c} from reference [H14]; ^{d} from reference [T6]). SCE : sister chromatid exchange; CA : chromosomal aberration; MN : micronuclei; FC : flow cytometry. Effect description: + : increase; ++ : strong increase (>3 fold the value of the control group); +++ : very strong increase; = : no significant response; - : decrease; -- : strong decrease (>3 fold the value of the control group). LOEDR (µGy/h) : Lowest Observed Effect Dose Rate; LNOEDR (µGy/h) : Lowest No Observed Effect Dose Rate; LOED (µGy) : Lowest Observed Effect Dose. By default, the endpoint is LOEDR. If not available, LNOEDR or LOED are given.

272. To date, experiments have failed to demonstrate a clear correlation between micronucleus (MN) induction and the ^{137}Cs concentration in fish muscle. Al-Sabti [A20] collected blood samples from pike, perch, roach and bream in Swedish lakes contaminated by Chernobyl fallout. Even if the ^{137}Cs concentrations in the muscle were high, up to 18 kBq kg^{-1} (dry weight), and MN induction significant, they were not correlated and the highest MN frequency (42 per 1,000 erythrocytes) was observed in the control lake. A similar observation was made in another study on Swedish lakes [A21]. In another in-situ study conducted by Sugg et al. [S18] on catfish from the Chernobyl area, the highest MN frequency (6 per 1,000 erythrocytes) was found in fish from the control site, although alkaline unwinding assay showed an increase (non-significant) of single-strand breaks (SBs) in the cooling pond. The authors hypothesized that other pollutants might have been present in the control lake or that the fish might have displayed an adaptive behaviour and increased defence mechanisms against ionizing radiation exposure. On the other hand, Ilyinskikh et al. [I22] found a positive correlation between the ^{137}Cs concentration in pike muscle (up to 1.2 kBq/kg wet weight) and the frequency of micronucleated erythrocytes, for fish caught in Siberian nuclear facilities. A positive correlation was also found between micronuclei frequency and age.

273. Gustavino et al. [G23] exposed carp to acute doses of X-rays (250 kV, 6 mA, 0.75 Gy/min). They found a dose and time-dependent response of MN to irradiation, the peak being 21 days after treatment. The lowest dose tested, for which there was a significant MN induction, was 0.1 Gy. It is interesting to remark that the baseline of micronuclei induction ranges over 2–3 orders of magnitude between different fish species. In the medaka (*Oryzias latipes*), an X-ray dose of 4 Gy (0.5 Gy/min) increased the frequency of MN to approximately 7 per 1,000 gill cells. Knowles [K16] irradiated plaice using ^{137}Cs sealed sources. He did not observe any MN induction, even for the highest dose tested (1 mGy/h over 197 days, total dose of 4.6 Gy). The lack of sensitivity of this assay for fish could be linked to its application to non-dividing cell populations or to dividing cell populations in which the kinetics of cell division are not well understood or controlled.

274. Ulsh et al. [U18, U19] used the fluorescence in situ hydridization (FISH) technique in a study involving slider turtles. They showed for *Trachemys scripta* fibroblasts and lymphocytes, that the dose rate below which no reduction in effect per unit dose was observed with further dose protraction was about 230 mGy/h. Interestingly, they also showed that this species had a much lower spontaneous background of symmetrical translocations in lymphocytes than humans (30-fold less), which makes it a sensitive species for the study of low doses and dose rates.

275. Theodorakis and Shugart [T21, T22] found different allele frequencies for mosquitofish populations exposed to radionuclides within the Oak Ridge nuclear site compared to fish in reference lakes. They showed that heterozygotes for the allozyme locus nucleoside phosphorylase (NP), an enzyme involved in nucleoside synthesis, were more prevalent in fish in the radionuclide-contaminated sites and, moreover, that they had fewer DNA strand breaks than the homozygotes. Finally, they showed that NP heterozygotes had a greater fecundity than homozygotes.

276. Genetic adaptation, i.e. the genetic basis for resistance, can be evaluated in populations exposed to a contaminant. The individuals that are not resistant are naturally eliminated, while tolerant individuals can be bred. Subsequently, F_1 and F_2 generations can be tested for resistance. If tolerance persists or increases in F_1 and F_2 generations, then the response can be said to be genetic. Further analyses can be conducted using molecular techniques to investigate thoroughly the mechanisms involved. Such experiments have been scarcely performed, probably because they are costly and time consuming. In a series of papers, Theodorakis et al. used such an integrated approach, and demonstrated the effects of contaminants (mostly radionuclide) on genetic patterns [T20, T21, T22, T23]. The bacterium *Escherichia coli* population became radioresistant after daily X-irradiation over many generations [E21], and it was shown that the most radioresistant strain isolated from this population has the mutation(s) in genes involved in inducible DNA repair [E9].

(d) Effects of acute exposure

277. For primary producers, the information is still rather limited (only 10 papers in the FRED), mainly describing morphological changes and growth inhibition for green microalgae at high doses (approximately 100–1,000 Gy). Chromosome aberration at doses from 1–5 Gy was evident in the macroalgae *Nitella flagelliformis* (as discussed in reference [F5]).

278. From the information in the FRED, acute doses up to 1 Gy have no significant effects on species representative of annelid, mollusc and crustaceans. Acute doses as low as 0.5 Gy can significantly decrease the percentage of live embryos in broods of the particularly radiosensitive polychaete worm, *Neanthes arenaceodentata*. This radiosensitivity is confirmed by the finding of an increased incidence of radiation-induced sister chromosome exchanges in juvenile worms exposed at total doses greater than 0.17 Gy. The explanation was that the response was due to the induction of dominant lethal mutations in gametes of irradiated adult worms [F5].

279. For fish, the existing knowledge mainly relates to acute exposures greater than 5 Gy. Acute doses below 1 Gy are unlikely to have any significant influence on their general health (morbidity). Fish embryos are much more radiosensitive than free swimming larvae, juveniles and adults. Doses less than 2 Gy are likely to have little effect on mortality. The lowest dose reported in the FRED with significant effect, is as low as 0.16 Gy delivered in the early 1-cell stage of

development and the consequent mortality is scored over long periods—150 days post fertilization. The developing fish embryo is very sensitive to the effects of acute irradiation, particularly at the very early stages just prior to, or immediately after the actual fertilization and during the process of division of the single cell. Irradiation of silver salmon embryos at this stage gave an estimated LD_{50} of 0.16 Gy when assessed at 150 days post-irradiation. Apart from this critical period in embryonic development, FASSET [F5] concluded that it appears unlikely that significant effects will follow doses below 0.5 Gy. An acute dose of this magnitude at any later stage of development will be unlikely to have any significant influence on adult male and female fertility. Mutagenic damages (specific locus mutations, dominant and recessive lethal mutations, polygenic characters, and chromosome aberrations) have been observed at all radiation doses used in the relevant studies. Where comparisons of relative radiosensitivity have been made, it has been concluded that fish show a sensitivity similar to, and most often less than, that of the mouse. There is a single example of apparently greater sensitivity—for specific locus mutations induced in medaka sperm [R9]. Although there are no data relating to radiation-induced mutagenesis in marine fish, there is no reasonable basis for expecting them to respond differently from freshwater fish.

6. Effects on populations and ecosystems

280. Ecosystems consist of various organisms that have a wide range of radiosensitivities and interact with one another in a complex fashion. As a result, indirect responses to the direct effects of radiation exposure are observed in the natural environment. Since these indirect responses cannot necessarily be deduced from the effects on individuals and populations, effects at the community level are evaluated by mathematical modelling, model ecosystem experiments and field irradiation experiments.

281. In mathematical modelling, physical, chemical and biological components of natural ecosystems and interactions among them are mathematically defined, and ecosystems are simulated in computers. Effects on the entire ecosystems are evaluated by applying single-species effect data to the mathematically constructed ecosystems. For example, Bartell et al. developed a comprehensive aquatic-systems model (CASM) [D6]. The CASM model is a bioenergetic ecosystem model that simulates the daily production dynamics of populations (including predator–prey interactions) with time, in relation to daily changes in light intensity, water temperature, and nutrient availability. This model has been adopted for estimating the ecological risks of chemicals for aquatic ecosystems in Quebec [B24], central Florida [B25] and Japan [N7]. In time, this type of model will also be useful for the evaluation of the effects of radiation exposure.

282. Model ecosystem experiments provide biotic or abiotic simplicity, controllability and replicability, which cannot be expected in field experiments. At the same time, they simulate the inter-species interactions of natural ecosystems. It is therefore expected that model ecosystem experiments can investigate the indirect effects of radiation exposure, which cannot be evaluated by conventional single-species experiments. Model ecosystem experiments can therefore be regarded as a bridge between single-species experiments and field experiments. Some model ecosystem experiments have been performed to investigate the effects of radiation exposure. For example, Williams and Murdoch [W14] made studies using two different types of marine model ecosystems. However, no effects for 23 possible effect endpoints were observed at dose rates of up to 0.79 Gy/d.

283. Ferens and Beyers [F18] acutely irradiated aquatic model ecosystems derived from a sewage oxidation pond consisting of various kinds of microorganisms. Effects on biomass, chlorophyll content and gross-community metabolism were more severe at doses of 1,000 Gy than at 10,000 Gy. This unexpected phenomenon might arise from the disappearance of inhibitory inter-species interactions after elimination of certain species at doses of 10,000 Gy.

284. Fuma et al. [F19] studied effects of acute gamma irradiation on the aquatic model ecosystem consisting of the flagellate alga, *Euglena gracilis*, as a producer, the ciliate protozoan, *Tetrahymena thermophila*, as a consumer and the bacterium, *Escherichia coli*, as a decomposer. After a dose of 1,000 Gy, the cell density of *T. thermophila* was increased temporarily, and then decreased compared with controls. This complicated change in *T. thermophila* might be an indirect response to direct effects on the other species, i.e. extinction of *E. coli* and decrease in *Eu. gracilis*. Doi et al. [D7] mathematically simulated a dose–effect relationship for this experimental model ecosystem with a particle-based model, in which inter-species interactions were taken into consideration. This suggests that experimental model ecosystems are useful for validation of mathematical models.

285. Hinton et al. [H12] constructed a Low Dose-Rate Irradiation Facility (LoDIF) in the Savannah River Ecology Laboratory (Aiken, South Carolina, USA). This facility consists of outdoor open-air tanks and is designed to house a variety of aquatic organisms. Gamma irradiation is conducted with an irradiator placed over each tank. Each irradiator contains a 0.74, 7.4 or 74.0 MBq sealed ^{137}Cs source. The 7.4 MBq source delivers a mean dose rate of approximately 10 mGy/d. The LoDIF is now used only for studies of the effects of chronic irradiation on the reproduction of small fish (Japanese medaka; *Oryzias latipes*), but can be used as an experimental model ecosystem.

286. Some field irradiation experiments have been performed, though these have already been terminated. The Brookhaven Irradiated Forest Experiment is a typical example. This experiment was designed to study the effects of radiation exposure on plant and animal communities [W15]. In 1961, a 350 TBq ^{137}Cs source was placed in an oak–pine forest at the Brookhaven National Laboratory (Upton, New York, USA). The dose rate within a few metres from the

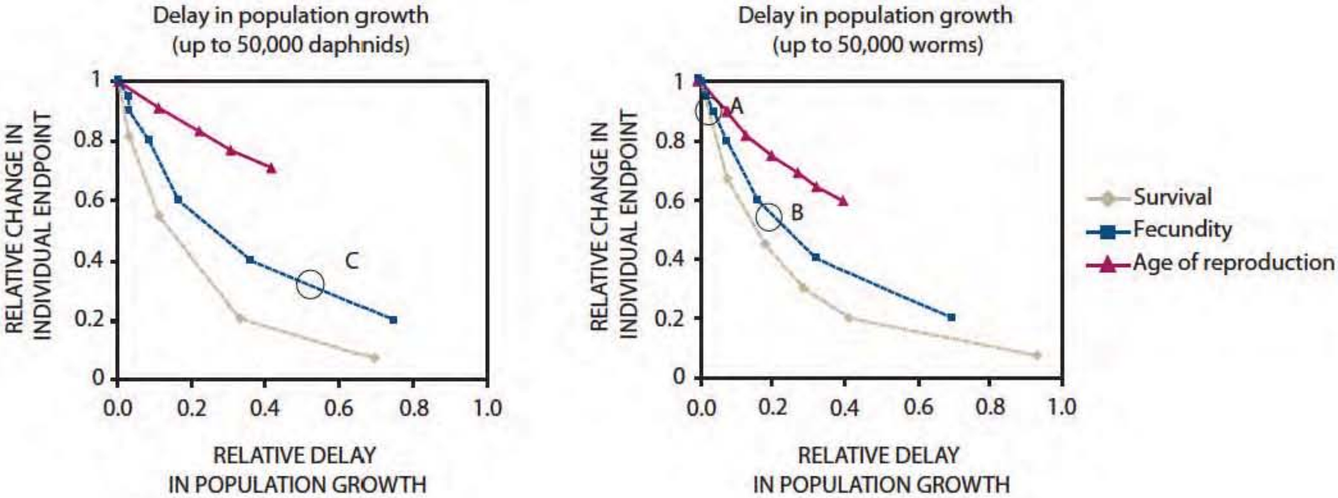
source was in the order of 10 Gy/d; it decreased to background levels beyond 300 m. After commencement of irradiation, biomass, species composition, densities and other ecological parameters were measured for plants, insects, fungi, lichens and soil algae. Many examples of the indirect effects described in the UNSCEAR 1996 Report [U4] were observed in a series of experiments conducted with this source.

287. Two field-irradiation experiments were conducted at the Whiteshell Laboratories in Manitoba, Canada. One is the Field-Irradiated Gamma (FIG) experiment in which a boreal forest was chronically irradiated from 1973–1986 to study the effects on plant communities [G13]. The radiation source was 370 TBq ^{137}Cs, and the dose rates ranged from 0.12–1,560 mGy/d. The effects of radiation exposure were investigated for tree canopy, naturally growing shrubs, ground cover species, germination of seeds, morphological change and tree-ring growth. One experimental observation was that the seed germination of Jack Pine showed deleterious effects at a dose rate of 1.1 mGy/h [S38]. In contrast, reference [S38] reported hormetic effects (increased germination) at dose rates up to 0.6 mGy/h. The other experiment was the Zoological Environment Under Stress (ZEUS) that was performed from 1981–1985 to study the effects on the individual or population characteristics of meadow voles [M11]. Vole populations were irradiated at nominal dose rates of 200, 9,000 and 40,000 times that from natural background radiation. No effects on individual or population-level characteristics were observed at a dose rate up to 81 mGy/d, the highest dose rate used. Mihok noted that experiments with radiation had not shown any individual or population effect from chronic exposure to low-LET external radiation in the range of 10–100 mGy/d and that the current guidelines in the range of 1–10 mGy/d appeared suitable as benchmarks for general environmental protection purposes [M11].

288. Simulation can be used to illustrate population-level effects arising from individual effects with different endpoints. By modelling the delay in population growth on the basis of the observed effects on individual traits (figure XV), simulation of the effects of chronic exposure to radionuclides at the population level appeared to be mediated through individual-effect endpoints as follows: *(a)* effects on the hatchability of cocoons and the number of hatchlings per hatched cocoon for earthworms; and *(b)* effects on larval resistance to starvation for daphnids. Ultimately, effects increase the early mortality of larvae in both species (offspring are produced but they never reach reproduction age) which are, with regard to population dynamics, equivalent to not producing those offspring. Observed effects can be assimilated to a reduction in fecundity in every case: 10% reduction in fecundity in earthworms at a dose rate of 4 mGy/h (point A on figure XV), 55% reduction in fecundity in earthworms at a dose rate of 11 mGy/h (point B on figure XV), 70% reduction in starved control daphnids and up to 100% reduction (i.e. extinction) in starved contaminated daphnids independent of the dose rate (point C on figure XV). The last result indicates that this species becomes more vulnerable to food depletion for the radionuclide-contaminated environment than for non-contaminated habitats [G3].

Figure XV. Relationship between effects at the individual level and their relative consequence at the population level (from reference [G3])

Earthworms chronically exposed to external gamma radiation: A: 10% reduction in fecundity at 3.3–3.6 mGy/h; B: 55% reduction in fecundity at the dose rate of 9–9.5 mGy/h. Daphnids chronically exposed to internal alpha radiation (^{241}Am); C: 70% reduction in starved control and up to 100% reduction (i.e. extinction) independent of the dose rate



289. The consequences of radiation exposure at the population level depend on the particular stage in the life history of the organism. Small effects on individual endpoints critical for population dynamics may impair population growth rate to a greater extent than large effects on neutral individual endpoints. The impact of chronic exposure to radionuclides at the population level depends on which stage in the life history is impaired. Individual endpoints do not show the same importance at the population level, population growth being by far more sensitive to changes in age of reproduction than changes in fecundity or survival [A26, G3] (figure XV).

290. Specific studies have provided evidence linking genotoxic syndrome to population-level changes [T20, T21, T22, T23]. Trabalka and Allen [T19] raised 2 generations of mosquitofish collected from a radionuclide-contaminated site. They showed that fish from the F_2 generation were less tolerant to thermal stress than fish from the control site.

291. Mutations occur at the molecular level, but heritable mutations in germ cells are capable of affecting the genetic diversity of populations, and can lead to increased or decreased genetic diversity, as well as to changes in phenotype that can affect Darwinian fitness. Increases in mutation rate can increase genetic diversity of the population by producing new alleles or genotypes, but they can also result in decreased genetic diversity, since the mutations could reduce the viability or fertility of the individuals [T14]. Consequently, increases in mutation rate can affect the genetic structure of the population, and thereby have ecologically relevant effects.

292. Exposure to contaminants can lead to alterations in the genetic makeup of populations, a process termed evolutionary toxicology. It is generally hypothesized that there is an alteration of genotype frequencies and a reduction in genetic variation in genotoxicant-contaminated environments. These changes may occur as a result of selection on specific alleles, selection for multi-locus genotypes, mortality in specific life stages, and changes in breeding period. They may induce reduction in population size, alterations in the degree of inbreeding, alteration of the level of gene flow and changes in age or class structure. Potentially, these shifts may alter population viability and fitness. Theodorakis and Shugart [T21] observed a higher percentage of polymorphism and heterozygosity in mosquitofish from the radionuclide-contaminated site, correlated with a higher fitness and lower level of DNA strand breaks. These findings suggest that there is a selective advantage in radionuclide-contaminated areas. More surprisingly, they found a higher genetic diversity in the radionuclide-contaminated populations, for which no definite explanation was given. The authors hypothesized that the higher diversity was linked to genomic rearrangements or different life-history processes.

293. Even though several factors complicate extrapolations of individual-level effects to populations, current knowledge supports the conclusion that measures intended to limit radiation damage to individuals to an acceptable degree will also provide a sufficient degree of protection for populations. However, in situations where the most sensitive life stage has not been positively identified, or where there is a lack of data on the most sensitive life stage, there may be a need to introduce a margin of safety when using the available dose–effect information on individual life stages to develop measures to protect field populations. Furthermore, population-level consequences of hereditary mutations might in some cases need to be allowed for in these extrapolations. If and how this might be done requires additional research and scientific review [G16].

294. Most studies of the effects of exposure to ionizing radiation have been performed under non-limiting growth conditions (i.e. sufficient food and space were available). In contrast, wild organisms are often regulated by various types of density-dependent factors such as competition for resources. Based on current knowledge, it is hard to draw general conclusions on how density-dependent factors may influence the propagation of effects on individuals to populations [G16].

295. In its 2008 report, the ICRP [I10] suggested that, in considering the potential effect of exposure to ionizing radiation, context should be provided by comparing the estimated dose rates to multiples of the dose rates experienced by the various biota in their natural environment. In this regard, the ICRP proposed the use of the concept of "Derived Consideration Levels" (DCLs) which were intended to serve as points of reference for assessing the potential effects of exposure to ionizing radiation on non-human biota. In doing this, the ICRP compiled available information for their various biota categories and summarized the data into bands of dose rate from less than 0.1 to more than 100 mGy/d. In commenting on the available data, the ICRP emphasized that the data are both incomplete and of varied quality and that their summary tables represent "an extreme oversimplification of existing data". The range of DCLs (dose rates) for various biota categories (e.g. mammals, birds, and trees) summarized by ICRP were:

- With regard to the mammals ("higher vertebrates"), deer and rat, the ICRP suggested that at dose rates in the region of 0.1–1 mGy/d, there was only a very low probability of certain effects occurring that could result in reduced reproductive success or morbidity. At dose rates in the band of 1–10 mGy/d, there was some potential for reduced reproductive success;
- For birds (the reference bird was the duck), the ICRP suggested that based on metabolism, longevity, and reproductive behaviour, it was reasonable to assume similar results to those for mammals;
- With regard to the "lower" poikilothermic vertebrates (frog, trout and flatfish), data are generally lacking below about 1 mGy/d. However, considering the general lack of physiological data on

amphibians, the ICRP suggested a lower DCL (dose-rate) band of 0.01–0.1 mGy/d for frogs compared to the two types of fish. For dose rates in the range of 1–10 mGy/d, the ICRP suggested that some reduction in reproductive capacity might occur in frogs and possibly also in fish species;

- The ICRP indicated that there are essentially no data for the invertebrates, bee, crab and earthworm, but suggested that invertebrates are less sensitive and recommended a DCL of 10–100 mGy/d; and
- The data for trees, plants and seaweeds are highly variable across species, the best data being for pine trees. The ICRP suggested DCLs of 1–10 mGy/d for grasses and seaweeds but a 10-times lower value for pine trees, which they attribute in part to their potential for very long periods of exposure.

V. SUMMARY AND CONCLUSIONS

296. All living organisms have existed and developed in environments where they are exposed to ionizing radiation from the natural background and, recently, to radiation resulting from global fallout of radioactive material following the atmospheric nuclear weapons tests. In addition, biota are exposed, generally in areas of limited spatial extent, to radiation from man's activities, such as the controlled discharge of radionuclides to the air, ground or aquatic systems, or from accidental releases of radionuclides.

297. Prior to the development of the annex, "Effects of radiation on the environment" of the UNSCEAR 1996 Report [U4], the Committee had not specifically addressed the effects of radiation exposure on plant and animal communities. Living organisms had been considered primarily as part of the environment in which radionuclides might be dispersed and as resources that, if they took up radionuclides, might contribute to human exposures via the human food chains. Like humans, however, organisms are themselves exposed internally from radionuclides that they may have taken up from the environment, and externally due to radiation from radionuclides in the environment.

298. In the past decades, scientific and regulatory activities related to radiation protection focused on the radiation exposure of humans arising from both artificial and natural sources. The prevailing view was that, if humans were adequately protected, then "other living things are also likely to be sufficiently protected" [I8] or "other species are not put at risk" [I5]. Over time, the general validity of this view has been challenged on occasion and more attention has therefore been given to the potential effects of exposure to ionizing radiation on non-human biota. In part, this has occurred as a result of the increased worldwide concern over sustainability of the environment, including the need to maintain biodiversity and protect habitats or endangered species (e.g. [U22, U23]), and, in part, as a result of various efforts to assess the effects of exposure to ionizing radiation on plants and animals [D1, I1, I2, I3, I4, I9, N6, T1].

299. Since the Committee issued its first report in 1996 [U4] on the doses and dose rates of ionizing radiation below which effects on populations of non-human biota are unlikely, the approaches to evaluating radiation doses have been reviewed and progress has been made (e.g. by the DOE [U26], the Environment Agency [C1], FASSET [F1], ERICA [E1]). In addition, the continuing follow-up of the consequences of the Chernobyl accident has provided a great deal of new information on the radiobiological effects of ionizing radiation exposure on non-human biota (e.g. [E8, G26]). Similarly, information not previously available to the Committee on the levels of radiation exposure below which radiobiological effects on non-human biota are unlikely has been further compiled and evaluated, in part, through the work carried out in support of the development of the FASSET effects database, FRED, and the subsequent FREDERICA effects database [B26, E1, F1]. The Committee undertook a review of the new scientific information that had become available since its previous report and assessed whether it needed to modify its previous recommendations concerning the dose rates below which effects on non-human biota are considered unlikely.

A. Estimating dose to non-human biota

300. The radiation dose received by an organism (or some organ or tissue of the organism) is the sum of both the external and internal exposure. Absorbed doses are calculated as the dosimetric endpoint; however, for radionuclides taken into the organism, an appropriate factor may be applied in order to account for the different RBEs of the different kinds of radiation.

301. External exposures of biota are the result of complex and non-linear interactions of various factors, such as the levels of radionuclides in the habitat, the geometrical relationship between the radiation source and the target, the shielding properties of materials in the environment, the size of the organism and the radionuclide-specific decay properties (characterized by the radiation type, the energies emitted and their emission probabilities).

302. Internal exposures of plants and animals are determined by the activity concentration in the organism, the size of the organism, the radionuclide distribution and the specific decay properties of the radionuclide.

303. In considering the potential effects of ionizing radiation exposure on non-human biota, the Committee assumed

that natural populations of non-human biota are in a state of dynamic equilibrium within their environment. Equilibrium models assume that radionuclide concentrations reach equilibrium within various environmental compartments and that transfer between compartments is reasonably characterized by time-invariant ratios of concentration between the compartments. One of the advantages of the equilibrium model is its simplicity. Such models are widely used by national regulators for assessment purposes. However, when it is necessary to assess a time-dependent response—for example, when considering an accidental release of radionuclides—dynamic radioecological models are needed. Within the context of this annex, equilibrium models have been assumed in the exposure assessments, unless otherwise indicated. Readers interested in dynamic radioecological models are referred to the published literature [M4, M7, S1, W3].

B. Summary of dose–effects data from the UNSCEAR 1996 Report

304. Notwithstanding the limitations of the data available in 1996, the Committee considered it unlikely that radiation exposures causing only minor effects on the most exposed individual would have significant effects on the population. It also suggested that the effects of radiation exposure at the population and community levels are manifest as some combination of direct changes due to radiation damage and indirect responses to the direct changes [U4].

305. The Committee considered that the individual responses to radiation exposure likely to be significant at the population level are mortality (affecting age distribution, death rate and density), fertility and fecundity (both affecting birth rate, age distribution, number and density) and the induction of mutations (birth rate and death rate). The response of these individual functions to radiation exposure could be traced to events at the cellular level in specific tissues or organs. An extended summary discussing the processes involved had been provided in annex J, "Non-stochastic effects of irradiation", of the UNSCEAR 1982 Report [U9]. The Committee also considered there was a substantial body of evidence indicating that the most radiosensitive sites are associated with the cell nucleus, specifically the chromosomes, and that, to a lesser extent, damage to intracellular membranes was additionally involved. The end result is that the cells lose their reproductive potential. For most cell types, at moderate doses, death occurs when the cell attempts to divide; death does not, however, always occur at the first post-exposure division: at doses of a few gray, several division cycles might be successfully completed before death eventually occurred. It was also well known that radiosensitivity varies within the cell cycle, with the greatest sensitivities being apparent at mitosis and the commencement of DNA synthesis [U9]. It followed that the greatest radiosensitivity is likely to be found in cell systems undergoing rapid cell division for either renewal (e.g. spermatogonia) or growth (e.g. plant meristems and the developing embryo); these examples clearly underlie the processes in individual organisms that are important for the maintenance of the population. Effects of radiation exposure on populations occur as the result of exposure of individual organisms. The propagation of effects from individual organisms to populations is complex and depends on a number of factors; however, the Committee considered that of the various effects on populations of non-human biota, the key effects are those that affected reproductive success.

306. The Committee noted that the responses of organisms to radiation exposure are varied and might become manifest at all levels of organization, from individual biomolecules to ecosystems. The significance of a given response depends on the criterion of damage adopted, and it was not to be concluded that a response at one level of organization would necessarily produce a consequential, detectable response at a higher level of organization.

307. In its 1996 assessment, the Committee considered that reproductive changes are a more sensitive indicator of the effects of radiation exposure than mortality, and mammals are the most sensitive animal organisms. On this basis, the Committee concluded that 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 animal populations. The Committee also concluded that maximum dose rates of 400 μGy/h to a small proportion of the individuals in aquatic populations of organisms would not have any detrimental effect at the population level. These conclusions refer to the effects of low-LET radiation. Where a significant part of the incremental radiation exposure comes from high-LET radiation (especially alpha particles) that is internal to the organism, it is necessary to apply an appropriate factor to adjust for the different RBEs of the different radiations.

308. Acute lethal radiation doses to plants had been noted to range from 10–1,000 Gy. In general, larger plants are more radiosensitive than smaller plants, with radiosensitivity decreasing in the order coniferous trees, deciduous trees, shrubs, herbaceous plants, lichens [U4]. The data on radiosensitivity of terrestrial animals were dominated by data on mammals, the most sensitive class of organisms. Acute lethal doses ($LD_{50/30}$) were 6–10 Gy for small mammals and 1.5–2.5 Gy for larger animals and domestic livestock [U4]. The Committee concluded [U4] that the effects of radiation exposure on birds are similar to those in small mammals. Separately, it [U4] found that reptiles and invertebrates are less radiosensitive than birds, with studies of acute radiation exposures of adult amphibians indicating LD_{50} values of between 2–22 Gy. With respect to aquatic organisms, fish are the most sensitive to the effects of radiation exposure; the developing fish embryos are particularly so. The LD_{50} for acute irradiation of marine fish is in the range of 10–25 Gy for assessment periods of up to 60 days following exposure [U4]. Overall, a notional range of dose of 1–10 Gy from acute radiation exposure is unlikely to result in effects on populations of non-human biota.

C. The current evaluation

309. Many of the new data subsequent to the Committee's 1996 report [U4] arose from follow-up studies of the consequences of the Chernobyl accident. Prior to the accident, much of the area around the Chernobyl nuclear power plant was covered in 30–40-year old pine stands that, from a successional standpoint, represented mature, stable ecosystems [E8]. The high dose rates during the first few weeks following the accident altered the balance in the community and opened niches for immigration of new individuals. All these components and many more, were interwoven in a complex web of action and reaction that altered populations and communities of organisms. In addition to the effects from the radiation exposure, activities such as agriculture, forestry, hunting and fishing within the 30-km zone were stopped [E8]. Moreover, after the accident, the agricultural fields remained productive for a number of years and, in the absence of active management of areas that had been evacuated, many animal species, especially rodents and wild boar, consumed the abandoned cereal crops, potatoes and grasses as an additional source of forage [E8]. This advantage, along with the special reserve regulations established in the exclusion zone (i.e. a ban on hunting) tended to mask potential adverse biological effects of radiation exposure and led to an increase in the populations of wild animals, including game mammals (wild boar, roe deer, red deer, elk, wolves, foxes, hares, beaver, etc.) and bird species (black grouse, ducks, etc.) [G8, S23]. The exclusion zone has become a breeding area of the white-tailed eagle, spotted eagle, eagle owl, crane and black stork [G9].

310. Overall, based on an evaluation of the available data arising from studies of plants and animals in the zone around the Chernobyl nuclear power plant, the Chernobyl Forum [E8] arrived at a number of general observations, including:

- Radiation from radionuclides released as a result of the Chernobyl accident caused numerous acute adverse effects on the biota located in the areas of highest exposure (i.e. up to a distance of a few tens of kilometres from the release point);
- The environmental response to the increased radiation exposure incurred as a result of the Chernobyl accident was a complex interaction among radiation dose, dose rate and its temporal and spatial variations, as well as the radiosensitivities of the different taxons. Both individual and population effects caused by radiation-induced cell death were observed in plants and animals and included increased mortality of coniferous plants, soil invertebrates and mammals; reproductive losses in plants and animals; and chronic radiation sickness in animals (mammals, birds, etc.);
- No adverse radiation-induced effects were reported in plants and animals exposed to a cumulative dose of less than 0.3 Gy during the first month after the accident (i.e. <10 mGy/d, on average); and
- Following the natural reduction of exposure levels due to radionuclide decay and migration, populations have been recovering from acute radiation effects. By the next growing season following the accident, the population viability of plants and animals substantially recovered as a result of the combined effects of reproduction and immigration. A few years were needed for recovery from major radiation-induced adverse effects in plants and animals.

311. Another, and even more recent comprehensive review of the effects of radiation exposure arising from the Chernobyl accident on non-human biota compiled and examined the data on effects along with the associated dosimetric information [G26]. The authors evaluated 250 references in total, of which, some 79 papers were considered to have adequate information on environmental contamination and doses to biota as well as information on the associated effects. The effects of radiation exposure were seen in both natural and agricultural systems. Consistent with the Committee's 1996 report [U4], the authors noted that the effects depended on the radiosensitivity of the dominant species and observed that coniferous trees are one of the most sensitive plant species and mammals are the most radiosensitive animal species. Table 27 summarizes the various effects seen in non-human biota around the Chernobyl nuclear power plant and the corresponding doses or dose rates below which such effects were not observed.

312. Alexakhin et al. [A29] reported on the environmental and agricultural impact of the Chernobyl accident. These authors described the effects of countermeasures on the doses to ecosystems and the public. High radiation doses within the 30-km exclusion zone led to numerous effects on biota ranging from subtle effects at the molecular and subcellular levels, to significant degradation of ecosystems, pine stands for example. On the other hand, evacuation of people from the 30-km zone reduced stresses arising from human use of the environment. Exclusion of people, along with the special reserve regulations established in the exclusion zone (i.e. a ban on hunting) overcame potential adverse biological effects of radiation exposure and led to an increase in the populations of wild animals and birds. Based on an evaluation of the FRED database, FASSET concluded that the information available on the effects of radiation exposure on non-human biota from low dose rates (less than about 100 μGy/h or 2.4 mGy/d) for continuous irradiation is reasonable for both plants and animals and that, for chronic exposure conditions, "the reviewed effects data give few indications for readily observable effects at chronic dose rates below 100 μGy/h". However, it advised that "using this information for establishing environmentally 'safe levels' of radiation should be done with caution, considering that the database contains large information gaps for environmentally relevant dose rates and ecologically important wildlife groups" [F5, R9].

313. For chronic exposures, the ERICA project used statistical methods to estimate the dose rates below which 95% of species in the aquatic/terrestrial ecosystems should be protected. Their analysis of the data on effects from external gamma irradiation of species of different ecosystems concluded that there was no statistical justification to attempt to derive ecosystem specific screening dose rates and hence all data were analysed together as a "generic" ecosystem. The resultant dose rate that would protect 95% of the species in the generic ecosystem was estimated at 82 μGy/h (with 95th percentile confidence intervals of 23.8 and 336 μGy/h). This is generally consistent with the Committee's 1996 assessment [E11, G27]. It should be noted that these authors implicitly adopted a further safety factor of 5 in an attempt to account for data limitations.

314. ERICA also applied the same statistical methods to the data on effects for acute exposure conditions but in this case, a statistically significant difference was seen between marine ecosystems compared to terrestrial and freshwater ecosystems. The values derived from a statistical analysis of the set of doses giving a 50% change in the observed effect for limiting the potentially affected fraction to 5% of the species under acute external gamma irradiation varied from about 1–5.5 Gy, according to the ecosystems type, with the associated 95% confidence intervals covering less than one order of magnitude. For screening purposes, ERICA applied a further *SF* of 5 and reported Predicted No-Effect Doses (PNED) of 900 mGy for marine ecosystems and 300 mGy for terrestrial and freshwater ecosystems [G3, G15, G27]. The application of such additional safety factors is of great interest in developing regulatory approaches for the protection of non-human biota; however, such judgements are beyond those of the Committee and properly lie in the domain of the ICRP and national authorities.

315. Information on the effects of acute doses of radiation has also been reviewed. For example, soil fauna are unlikely to be affected at doses below about 1 Gy [G3]. The same authors reported data that suggested that the reproductive capacity of Scots pine is inhibited at doses in the range of 0.5–5 Gy. The radiosensitivity of spruce is greater than that of pines with malformed needles, buds, and shoot growth at absorbed doses as low as 0.7–1 Gy [K1]. Information has been reported [G3] that shows a decrease in population density and species composition of forest litter mesofauna at doses in the range of 1–9 Gy. Based on a review of the FRED, FASSET concluded that acute doses of up to 1 Gy have no significant effect on annelids, molluscs and crustaceans, that acute doses below about 1 Gy are unlikely to have a significant effect on general health (morbidity), and that doses below about 0.5 Gy are unlikely to have any significant effect on adult male and female fertility [F5]. When the SSD method was applied to data on the effects of acute exposures, HDR_5 values in the range of about 1–5.5 Gy were estimated. Thus, on the basis of the available data, the Committee continues to recommend a nominal reference dose of about 1 Gy, within a factor of 2 or so, as a reference value below which population-level effects on non-human biota are unlikely in the event of an acute exposure.

D. Conclusions

316. As discussed in the UNSCEAR 1996 Report, the Committee considered it unlikely that radiation exposures causing only minor effects on the most exposed individual would have significant effects on the population. It also considered that reproductive changes are a more sensitive indicator of the effects of radiation exposure than mortality, and that mammals are the most sensitive animal organisms. Since 1996, new data on the effects of exposure to ionizing radiation have been developed from follow-up observations of non-human biota in the zone around the Chernobyl nuclear power plant (section III) and various organizations have carried out comprehensive reviews of the scientific literature on the data on effects and, in some cases, developed new approaches to the assessment of the potential risks to non-human biota (section IV). There is a considerable range of endpoints and corresponding effects levels (dose or dose rate) presented in the literature and also considerable variation in how different researchers have evaluated these data. Table 39 provides a summary of the data on the effects of radiation exposure for aggregated categories of biota. Details of endpoint effects are described in the corresponding references.

Table 39. Overall summary of data on chronic effects of radiation exposure for plants, fish and mammals

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]

Category	*Dose rate (µGy/h)*	*Effects*	*Endpoint*	*Reference*
Mammals	<100	No detrimental endpoints have been described	Morbidity, mortality, reproduction	[C17, L2, P8, R9, U21, Y2]
Generic ecosystems (terrestrial and aquatic)	about 80	A new statistical approach (species sensitivity distribution, SSD) was applied to the data on radiation effects to estimate HDR_5, the dose rate at which 95% of the species in the ecosystem are protected	Morbidity, mortality, reproduction	[G3, G11, G15]

317. Overall, the Committee concluded that 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 that maximum dose rates of 400 µGy/h to any individual in aquatic populations of organisms would be unlikely to have any detrimental effect at the population level. For acute exposures, significant effects on populations of non-human biota are unlikely at doses below (about) 1 Gy. These conclusions refer to the effects of exposure to low-LET radiation. Where a significant part of the incremental radiation exposure comes from high-LET radiation (alpha particles), the Committee concluded that it is necessary to take account of the different RBEs of the radiations.

318. In addition to new data on the levels at which the effects of radiation exposure have been observed, notably from follow-up studies of the consequences of the Chernobyl accident, various authors have investigated new analytical methods, notably that of species sensitivity distribution [G3, G11], which involves meta-analysis of the variations in radiosensitivity among species. However, at this time, insufficient data are available for the application of such methods. It is anticipated that as new information is developed in the future, the application of these new methods of analysis will facilitate future re-evaluations of the effects of ionizing radiation exposure on non-human biota.

319. A great deal of work has been done since 1996 to improve the data and methods for evaluating pathways through which biota are exposed to radiation from radioactive material in the host environment and many improvements in biota dosimetry have been made. However, many opportunities still remain to improve our understanding of the relation between the levels of radioactive material in the environment and the potential effects on biota residing in that environment.

320. Based on the new information described in this annex, and considering the overall limitations of the available data, the Committee considered that there is no need to change 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. Nonetheless, where data of suitable scientific quality are available for a specific species endpoint and/or other level of biological organization, the Committee would encourage their use in assessments of the potential effects of radiation exposure. However, there are very limited data for many taxa and therefore many assumptions are needed to extrapolate between species. There is a need to better understand the chronic effects at a multigenerational time scale, chronic effects for multiple stressors, and the propagation of effects at the molecular and cellular levels to higher levels of ecological organization. In this respect, the application of so-called "-omic" techniques (transcriptomic, proteomic and so on) will help in future assessments.

ACKNOWLEDGEMENTS

321. The Committee gratefully acknowledges the considerable help received by the principal consultants, D. Chambers and G. Kirchner, from M. Doi, J. Garnier-Laplace, J-J. Leguay, G. Pröhl, K. Sakai and D. Woodhead.

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