

SOURCES AND EFFECTS OF IONIZING RADIATION

United Nations Scientific Committee on the
Effects of Atomic Radiation

UNSCEAR 2008
Report to the General Assembly
with Scientific Annexes

VOLUME II
Scientific Annexes C, D and E



UNITED NATIONS
New York, 2011

NOTE

The report of the Committee without its annexes appears as *Official Records of the General Assembly*, Sixty-third Session, Supplement No. 46.

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UNITED NATIONS PUBLICATION

Sales No. E.11.IX.3

ISBN-13: 978-92-1-142280-1

e-ISBN-13: 978-92-1-054482-5

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Publishing production: English, Publishing and Library Section, United Nations Office at Vienna.

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INTRODUCTION

A. Background

1. The estimation of human exposure to ionizing radiation from radionuclides of natural and artificial origin is an important and ongoing function of the Committee. The Committee has used simplified generic models of the dispersion and transfer of radionuclides through the environment to estimate the internal and external exposure of humans and the resulting doses. Owing to the complexity and interactions of the underlying processes, special attention has been given to radionuclide transfer via human food chains and the assessment of ingestion doses. The underlying model assumptions and parameters are kept under review and revised as necessary. The last revision was documented by the Committee in annex A, “Dose assessment methodologies” of the UNSCEAR 2000 Report [U3].

2. In the past decades, scientific and regulatory activities related to radiation protection focused on the radiation exposure of humans. The prevailing view has been 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 questioned on occasion and therefore consideration has been given to the potential effects of exposure to ionizing radiation of non-human biota. This has occurred, in part, as a result of the increased worldwide concern over the sustainability of the environment, including the need to maintain biodiversity and protect habitats and endangered species [U22, U23]; in part, because it has increasingly been recognized that the exposure scenarios and pathways for assessing human exposure may not apply to non-human biota; and, in part, as a result of various efforts to assess the effects of exposure to ionizing radiation on plants and animals [C1, D1, F5, I1, I2, I3, I4, I9, N6, P13, R9, T1, W16].

3. The Committee initially addressed the effects of radiation exposure on plant and animal communities in a scientific annex, “Effects of radiation on the environment”, of the UNSCEAR 1996 Report [U4]. Prior to this, the Committee had considered living organisms primarily as part of the environment in which radionuclides of natural or artificial origin may be present and contribute to the internal exposure of humans via the food chain. Like man, however, organisms are themselves exposed internally to radiation from radionuclides that have been taken up from the environment and externally to radiation in their habitat. In general terms, the Committee, in its 1996 report, considered that population-level effects were of primary interest and, of those, that reproductive effects were the most sensitive indicator of

harm. Furthermore, it also concluded that it was unlikely that radiation exposures causing only minor effects on the most exposed individual member of a population would have significant effects at the population level; that chronic exposures to low-LET radiation at dose rates of less than 100 mGy/h to the most highly exposed individuals would be unlikely to have significant effects on most terrestrial animal populations; and that maximum dose rates of 400 mGy/h to a small proportion of the individuals in aquatic populations of organisms would not have any detrimental effects at the population level.

4. The International Commission on Radiological Protection (ICRP), the International Atomic Energy Agency (IAEA) and other international organizations have encouraged the exchange of information on the effects of radiation exposure on non-human biota [I19, N6]. The IAEA’s action plan on the protection of the environment was discussed at the 2003 Stockholm Conference [I1], which concluded that “While accepting that there remain significant gaps in knowledge and that there needs to be continuing research ... there was an adequate knowledge base to proceed and (the Conference) strongly supported the development of a framework for environmental radiation protection”. It also found that “the time is ripe for launching a number of international initiatives to consolidate the present approach to controlling radioactive discharges to the environment by taking explicit account of the protection of species other than humans”.

5. In 2000, the ICRP, recognizing that environmental protection is a global matter, set up a Task Group to examine the issues. It considered that an approach to environmental protection from ionizing radiation “should relate as closely as possible to the current system for human radiological protection, and that these joint objectives could therefore best be met by the development of a limited number of Reference Animals and Plants” [I9]. Subsequently, the ICRP decided to establish a new Committee (ICRP Committee 5) on the Protection of the Environment. The ICRP further noted that “as radiation effects at the population level—or higher—are mediated via effects on individuals of that population, it seems appropriate to focus on radiation effects on the individual for the purpose of developing a framework of radiological assessment that can be generally applied to environmental issues” [I10].

6. Since the preparation of the UNSCEAR 1996 Report [U4], the approaches to evaluating radiation doses to non-human biota have been reviewed and improvements made [C1, E1, F1, F5, U26]. Information on the levels of radiation

exposure below which biological effects are not expected or, alternatively, above which such effects might be expected, has been developed. This has been obtained, in part, for the projects on the Framework for Assessment of Environmental Impact (FASSET) [F1] and the Environmental Risk from Ionising Contaminants: Assessment and Management (ERICA) [E1], in particular, as part of the development of the FASSET Radiation Effects Database (FRED) [F3]. This information was subsequently integrated with the database on the effects of radiation exposure from the project on Environmental Protection from Ionising Contaminants in the Arctic (EPIC) [B26] resulting in the so-called FREDERICA database [F20].

B. Scope of annex

7. The scientific information given in the FRED [F20] combined with that obtained in the subsequent ERICA programme [G11, J6] and that from more recent studies, especially those undertaken around the site of the Chernobyl accident, provided the basis for the Committee's review of the effects of exposure to ionizing radiation on non-human biota given in this annex. In particular, the Committee used the information from its review to re-evaluate its recommendations on dose rates below which exposure to ionizing radiation is unlikely to result in detrimental effects on populations of non-human biota, given in the UNSCEAR 1996 Report [U4].

8. This annex only provides the Committee's overview of the current data and methods to assess doses to non-human biota and a brief discussion of the nature of effects of radiation exposure on individual organisms and populations. Detailed discussion of these topics is beyond the scope of this annex.

C. Effects of exposure to ionizing radiation

9. Since the preparation of the UNSCEAR 1996 Report [U4], a number of radiobiological phenomena have been described, including genomic instability (genomic damage expressed post irradiation after many cell cycles) and the bystander effect (whereby non-irradiated cells in proximity to irradiated cells exhibit effects similar to those seen in the irradiated cells). These phenomena were discussed in annex C, "Non-targeted and delayed effects of exposure to ionizing radiation", of the UNSCEAR 2006 Report [U1]. While such phenomena are relevant to understanding mechanisms for the development of effects on non-human biota after exposure to ionizing radiation, a discussion of such phenomena is beyond the scope of this annex.

10. The immediate effects of ionizing radiation exposure may be seen at various levels of organization from the sub-cellular through individual organisms to populations and ecosystems [G16]. Responses of various biological functions to radiation exposure (e.g. reproductive success,

metabolic impairment and changes in genetic diversity) can be traced to events at the cellular or subcellular level in specific tissues or organs.

1. Individual level effects

11. Even though mutational events in somatic cells are primarily responsible for cellular transformation and tumour formation, the occurrence of cancer in individual organisms is normally of low relevance to the ecosystem as a whole, except in the case of endangered or protected species [A13]. However, mutational effects in germ cells may lead to reproductive impairment [A14]. Genotoxic stressors, including ionizing radiation, may alter reproductive success by decreasing fertility via clastogenic and mutagenic effects in germ cells resulting in a decrease of the number of gametes. Such stressors may also increase the frequency of developmental abnormalities, e.g. when mutations are induced in germ cells and the progeny of exposed parents develop abnormally.

12. There are a number of weaknesses in the data on which to base estimates of the dose rates below which effects on non-human biota are not considered likely. In addition, there are also issues in extrapolating from the effects observed at cellular and subcellular levels to effects that might be observed in individual organisms, populations and ecosystems. Moreover, it is only under controlled conditions in the laboratory that organisms can be exposed to a single stressor. This presents a further source of uncertainty in extrapolating the results to real ecosystems where multiple stressors exist. Although beyond the scope of this annex, the Committee acknowledges that improved understanding of the mechanisms of radiation damage, of how to extrapolate information from lower to higher trophic levels, and of the possible consequences of multiple stressors is of great interest and worthy of further study.

13. The scientific literature provides many examples of adaptive responses to and hormetic effects of exposure to ionizing radiation. Annex B of the UNSCEAR 1994 Report [U5] provided a comprehensive discussion of adaptive responses. In that report, the Committee concluded that there was evidence of an adaptive response in selected cellular processes following exposure to low doses of low-LET radiation but went on to suggest that it was premature to conclude that adaptive cellular responses had beneficial effects that outweighed the harmful effects of exposure. Subsequent to the UNSCEAR 1994 Report [U5], there have been numerous papers and considerable discussion concerning the possibility of hormetic responses to low doses of gamma radiation. For example, Boonstra et al. [B39] reported possible hormetic effects of gamma radiation exposure on populations of meadow voles. These authors suggested that increases in glucocorticoid levels associated with chronic gamma irradiation at a rate of about 1 mGy/d may be an important factor in the increased longevity of exposed meadow voles compared to non-exposed ones. Mitchel et al.

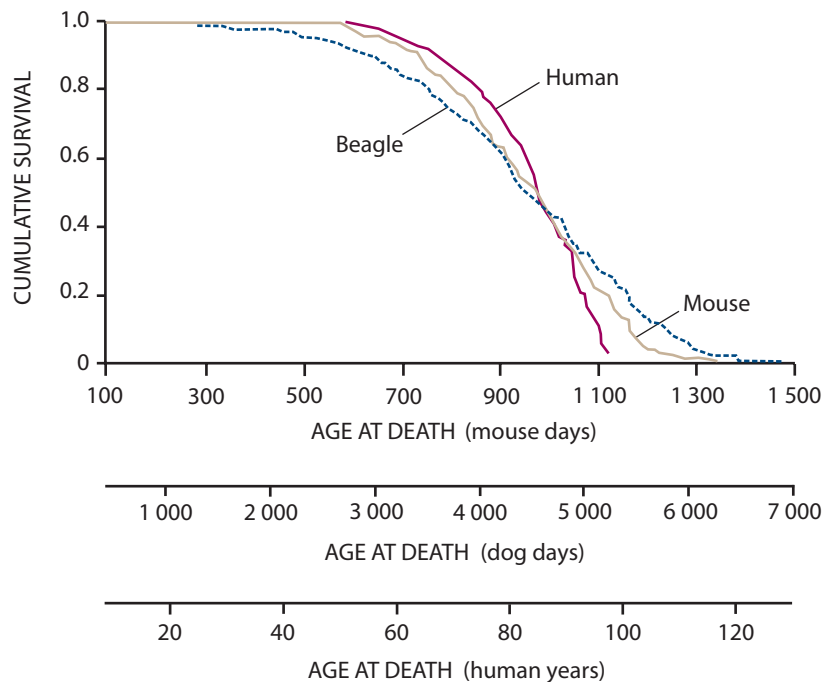
[M9] found that a single dose of 10 mGy to radiation-sensitive mice (Trp53 heterozygous) reduced the risk of both lymphoma and spinal osteosarcoma by greatly delaying the onset of malignancy. Further discussion of adaptive responses and potential hormetic effects of low dose and low dose-rate gamma radiation exposure is beyond the scope of this annex.

14. The various life stages of organisms differ in their sensitivity to exposure to ionizing radiation. It is often assumed that a population will be protected if the most sensitive stage of the life cycle is protected. For a large number of stressors, this assumption seems to be widely true [F9]. However, the most sensitive life stage is often difficult to identify a priori. Consequently, if data on effects only exist for one or two life stages, it may not be possible to know for certain if these data represent information for the most sensitive life stage, even though most of the available information indicates that gametogenesis and embryonic development are among the most radiosensitive stages of the life cycle [I4]. For example, Anderson and Harrison [A15] showed that the synchronous spawning in polychaete

worms rendered the organisms susceptible to low-level cumulative impact of ionizing radiation exposure. Because they spawned synchronously and died, oocytes were formed all at once, and damaged gametes could not be replaced.

15. The propagation of effects on individuals to the population as a whole depends greatly on the characteristics of the specific life history. The relative importance of each stage in the life history also varies between species, depending on the specific reproductive characteristics (short generation time versus long generation time, iteroparous versus semelparous, sexual versus asexual reproduction, etc.). Changes in the value of an individual parameter such as age of reproduction (i.e. generation time) often have much stronger consequences for species with fast population growth rates (i.e. with short generation time and high fecundity rate) than for those with slow population growth rates [G3]. On the other hand, the National Council of Radiation Protection and Measurements (NCRP) [N8] noted that when natural causes of deaths are considered collectively on a biologically comparable time scale, natural mortality occurs at a biologically comparable age, as illustrated in figure I.

Figure I. Cumulative survival curves of the mouse, beagle and human for natural causes of death



2. Population and ecosystem level effects

16. Whatever the stressor considered, population-level effects are valuable indicators of ecological hazard (e.g. [F9]). However, because of experimental constraints, most available data describe the effects on the individual traits of irradiated organisms. Many studies have documented the effects of radiation exposure at the cellular, tissue and individual levels. The consequences have been found to be

increases in morbidity and mortality, decreases in fertility and fecundity, and increases in mutation rate [W10]. These types of effect, observed at the individual level, may have consequences for a population of a species.

17. Matson et al. [M12] and Baker et al. [B29] investigated the possible genetic and population effects resulting from the chronic radiation exposure of bank voles, *Clethrionomys glareolus*, inhabiting contaminated sites near Chernobyl.

Both groups reported that genetic diversity was elevated in the contaminated sites when compared to relatively uncontaminated sites but were unable to attribute any significant detrimental effects among the bank vole populations to radiation exposure.

18. Ionizing radiation does not appear to have any direct effects at the population or higher ecological levels (i.e. community or structure and function of ecosystems). At present, it appears that all such effects are mediated by effects at the individual or lower levels. In addition, indirect effects through food-web mediated processes may occur [G16]. One approach to extrapolating from the effects on individuals to effects at the population level is to integrate the effects on survival and reproduction in terms of population growth rate. Population growth rate is one of the most important characteristics of a population and is defined as the population increase per unit time divided by the number of individuals in the population. Population models are used to extrapolate from the toxic effects on individuals, expressed as modifications to values of life-cycle parameters, to effects at the population level. This method has been used, for example, by Woodhead [W10] in a theoretical way and was implemented through experiments within the ERICA project for the chronic exposure of two invertebrates exhibiting contrasting life cycles: the earthworm and the daphnid [A26, G3].

19. An ecosystem has complex interactions between biotic and abiotic components and among biotic components. The latter are called interspecific interactions and include competition, predation and association. These interactions contribute to the flow or cycle of energy, materials and information in the ecosystem, and thus provide the ecosystem with its fundamental property of self-organization. It is possible that if one species is directly damaged by a toxic agent, another species more resistant to that agent is also indirectly affected by the depletion of interactions with the directly damaged species. As a result, the entire ecosystem can be affected in extreme cases. These indirect effects have been observed in ecosystems exposed to ultraviolet radiation [B37] and some chemicals [C23, H24, M24, T24, W20]. Similarly, some indirect effects through inter-species interactions have been observed in irradiated ecosystems, as reviewed in the UNSCEAR 1996 Report [U4]. Given this backdrop, the importance of indirect effects has been considered in reviews of the effects of exposure to ionizing radiation on ecosystems [B38, C21, I2, I3, I4, N1, U4]. Since these indirect effects cannot necessarily be deduced from effects on individuals and populations, ecosystem-level effects are evaluated using mathematical modelling, model ecosystem experiments and field irradiation experiments.

3. Multiple stressors

20. In general terms, the modifying effects of multiple stressors can be considered in one of two broad categories, namely (a) the modification by the other stressors of the

organism's uptake of radioactive material and the distribution of radioactive material within the organism, and (b) the influence of the other stressors on the radiosensitivity of the species [A18, B28, F5, G18, L8, P9, R19, S17, S18].

21. Metabolic manifestations of exposure to ionizing radiation include impairment in enzyme function, altered protein turnover, impairment in general metabolism and inhibition of growth. Sugg et al. [S17] showed that the body condition of largemouth bass exposed to mercury and ^{137}Cs in different lakes near the Savannah River site could be related to DNA damage. Changes in lipid metabolism in fish liver and a stimulation of the ventilation rate of a lamellibranch species have also been shown to occur at low doses in this mixed exposure scenario [P22, P23].

22. Experiments involving multiple exposures to metals (cadmium and zinc), organic pollutants, such as polychlorinated biphenyl (PCB), polycyclic aromatic hydrocarbon (PAH), endocrine disruptors, and radionuclides (radioactive isotopes of cobalt, caesium, and silver) have been conducted both under controlled conditions and in the field [G17]. Experiments using a freshwater bivalve (*Dreissena polymorpha*) and a carnivorous fish (*Oncorhynchus mykiss*) exposed under chronic conditions to water containing concentrations of 1–4 $\mu\text{g/L}$ of cadmium and/or 170–250 $\mu\text{g/L}$ of zinc showed a 60% decrease in the bioaccumulation of the isotopes of silver and caesium in the bivalve and a 30% decrease in the fish. However, no effect was observed for other radionuclide/organism pairs (such as cobalt for the fish). On the other hand, prior exposure to organic micro-pollutants enhanced both the uptake and retention of ^{57}Co and ^{134}Cs in the fish. Several possible explanations, linked to a modification of the health status of the animal by the presence of stable pollutants, were advanced by the authors and supported by biomarker measurements: an increase in respiratory activity by alteration of the global metabolism; a decrease in the Na^+/K^+ -ATPase in gills and therefore modification of the ionic flux; or an alteration of the epithelium permeability [A16, A17, F15].

23. Genotoxic/cytotoxic damages are not specific to ionizing radiation and may also be initiated by other toxins [S18]. Indeed, most biochemical techniques for detecting DNA damage at the molecular or cellular level lack specificity for radiation-induced DNA damage [T9]. However, Tsytsugina [T8] and Tsytsugina and Polikarpov [T6] analysed the distribution of chromosome aberrations in cells and the frequency of the different types of aberrations in order to discriminate between the contributions of radiation and chemical factors to the total damage to natural populations in aquatic organisms. These studies showed that the chromosome damage observed in aquatic worm populations exposed to dose rates of 10 $\mu\text{Gy/h}$ or more in lakes located in the vicinity of the site of the Chernobyl accident was mainly caused by radioactive contamination. Hinton and Bréchnignac [H20], however, cautioned that, while there is a great potential value in using biomarkers for assessing risks to non-human biota, there remain many challenges in linking changes in biomarkers at

the molecular or cellular levels to effects on individual organisms and populations of organisms.

24. The antioxidant status modified by exposure to various stressors may influence the radiosensitivity of organisms. The cellular damage due to radiation exposure is mainly associated with oxidation. This oxidative stress may also be caused by other stressors, such as chemical pollutants, and cellular defence mechanisms against reactive oxidative species (ROS) that may be solicited are not stressor specific [S27]. Therefore, the interaction of heavy metals and radionuclides, and the resulting modification of radiosensitivity, may depend on the capability of the antioxidant defence systems of the organism [C13, C14, C15, S27, V1].

25. The potential effects of exposure to uranium in the environment may arise from the chemical toxicity of the metal and its radiotoxicity (arising from the uranium alpha particles) and thus, such situations can be regarded as being due to a mixture of stressors coming from a single element [B30, C19, P24]. Thus, while an evaluation of the chemical toxicity of uranium to non-human biota is beyond the scope of this annex, it is important to recognize that the chemical toxicity and the radiological effects of uranium occur concurrently, and that both may need to be considered in a practical assessment of risks to non-human biota.

4. Commentary

26. Most of the data on the effects of exposure to ionizing radiation on non-human biota are from observations made on individual organisms. Radiation effects on populations occur as a result of the exposure of individual organisms. The propagation of effects from individual organisms to populations is complex and depends on a number of factors. However, as suggested in the UNSCEAR 1996 Report [U4], the most important effects appear to be those on reproduction

and reproductive success. Many questions remain with respect to the following: the mechanisms whereby radiation exposure can cause harm; inter-species extrapolation; propagation of harm from nuclear DNA to the population; and the effects of multiple stressors. Moreover the possibility of hormetic effects at low doses and dose rates of gamma radiation, the relation between changes in biomarkers at the molecular and cellular level and the effects on individual organisms or populations of organisms, and the effects of multiple stressors continue to be of considerable interest.

D. Observations from case studies

27. Ecological risk assessments (ERAs) have been conducted for a wide variety of situations where non-human biota are exposed to enhanced levels of radiation or radioactive material. ERA studies are available for a wide variety of nuclear fuel cycle activities from uranium mining to waste management, as well as for sites with enhanced levels of naturally occurring radioactive materials, and for sites contaminated as a result of accidents. Table 1 outlines the key elements of an ERA framework for assessing the effects of exposure to ionizing radiation on non-human biota. Various approaches for performing ERAs have been outlined including those of the IAEA [I2, I3, I4], NCRP [N1], the United States Department of Energy (DOE) [U26], Jones et al. [J1], Environment Canada and Health Canada [E2], FASSET [F1, L4] and ERICA [B17]. All of the approaches necessarily involve simplifications of the knowledge about the actual environment. A common approach to the assessment of the effects of radiation exposure on non-human biota involves the use of a screening index (*SI*), where *SI* is simply a dimensionless ratio of the estimated dose rate (to an individual organism) to the reference radiation dose rate, viz.:

$$SI = \frac{\text{estimated dose rate}}{\text{reference dose rate}} \quad (1)$$

Table 1. Key elements of a framework for the assessment of the effects of radiation exposure on non-human biota

<i>Element</i>	<i>Considerations</i>
Exposure of biota	<ul style="list-style-type: none"> • Spatial and temporal patterns of radionuclide concentrations in environmental material • Uptake by organism • Non-uniform distribution within organism
Reference biota	<ul style="list-style-type: none"> • Not possible to evaluate all biota • Need to select reference biota or indicator species appropriate for area of interest and desirable basis for selection • Possible need to consider individual biota per se when species are endangered
Dosimetry model for (reference) biota	<ul style="list-style-type: none"> • Absorbed dose (to whole body or to tissue/organ) • Geometry corrections • Relative biological effectiveness (RBE): the effects of different qualities of radiation on biota
Endpoints in radiological assessment	<ul style="list-style-type: none"> • Selection of appropriate population-level (deterministic) "umbrella" effects such as mortality or reproductive capacity and corresponding reference doses
Effects on biota	<ul style="list-style-type: none"> • Connection between radiation effects on "umbrella" endpoint in individual, and consequent "possible" effects on population • Role of background radiation levels • Natural population variability

28. The reference dose rate refers to the chronic dose rate (commonly expressed in milligray per day) below which potential effects on populations of organisms are not expected. The ratio, *SI*, assumes that the estimated dose rate and the reference dose rate relate to the same endpoint (e.g. mortality, reproductive capacity). The estimation of dose rate to an individual organism is discussed in section I of this annex. As there are many complex factors involved, caution is needed in extrapolating from the effects of radiation exposure on an individual organism to those on a population of organisms [B17].

29. The reference radiation dose rates for particular endpoints developed by the Committee in the UNSCEAR 1996 Report [U4] have been the most commonly used for the denominator of the *SI* calculation. However, other guidance has also been developed [C1, E1, E2, F5, I4, N1] and, more recently, the concept of species sensitivity distributions (SSDs) has been introduced [B17, G3]. These developments may necessitate a re-evaluation of the reference dose rates obtained in the ERA case studies.

30. Because of the sparsity of peer-reviewed literature, all of the various sources of information on reference dose rates (e.g. various reports and supporting environmental assessments in Canada, technical reports of government agencies in various countries and conference proceedings) have been considered in this annex.

31. Of the numerous reports [A24, A25, B17, C1, C2, C20, C22, E2, E3, E5, E22, E23, F2, G2, G3, G27, J2, S10, S11, S32, S33, U26, W19], only a few provide studies of the radiation exposure of non-human biota arising from radioactive waste management activities or accidents involving dose rates close to or exceeding the reference dose rates [A25, E8, E22]. For example, one study [S39] which involved investigation of the risks to biota from exposure to ionizing radiation from nuclear fuel cycle activities in Canada concluded that the largest risk is associated with past uranium mining activities; that discharges of radioactive material from power reactors under normal operating conditions are not expected to cause environmental harm; that organisms within one of the waste management areas examined may be harmed by exposure to ionizing radiation; and that current radioactive discharges from uranium refineries and conversion plants are not expected to cause environmental harm. Similar results can be derived from a consideration of the case studies reported in ERICA [B17] of a wide variety of nuclear fuel cycle and other activities.

32. One study in which the estimated dose rates to biota exceeded the reference dose rates, at least over a limited area, was of the radioactive waste management site at the Chalk River Laboratories (CRL) located on the shore of the Ottawa River, 160 km north-west of Ottawa, Ontario, Canada [E23]. The CRL site was established in the mid-1940s and has a history of various nuclear operations and facilities, primarily related to research. An ERA was conducted to assess the doses to biota arising from elevated levels of tritium, ^{14}C ,

^{41}Ar , ^{90}Sr , ^{131}I , ^{137}Cs and ^{239}Pu and from radionuclides that are naturally present in the environment, for example, the uranium series radionuclides, using standard methods for evaluating the uptake of these radionuclides by biota from the affected aquatic and terrestrial environments [B12]. A reference dose rate of 1 mGy/d was used for all organisms [B36]. Dose rates to some aquatic organisms such as frogs, small fish, snails and aquatic plants within the on-site waste management areas were estimated to be above the reference dose rate of 1 mGy/d; however, outside of the actual waste management areas, dose rates were estimated to be below the reference dose rate. The main contributor to the estimated dose rates to invertebrates and terrestrial plants was ^{90}Sr in surface soil, while that to the woodchuck (estimated at 51 mGy/d) was inhalation in the burrow of ^{222}Rn decay products from background levels of ^{226}Ra in the soil. A few individual invertebrates and terrestrial plants actually within the confines of small on-site waste management facilities were also estimated to have been subjected to dose rates above 1 mGy/d. Based on the limited spatial extent of the estimated dose rates that exceeded the reference dose rate and environmental observations, the authors considered that significant effects at the population level were unlikely.

33. Much of the new information on the effects of exposure to ionizing radiation on organisms has arisen from studies in the area surrounding the site of the Chernobyl accident, where dose rates to organisms were above the reference dose rate suggested in the UNSCEAR 1996 Report [U4]. A summary of the results of these studies up to 1996 is provided in this annex. Section III of this annex provides a comprehensive review of the more recent data from studies of non-human biota in the area surrounding the site of the Chernobyl accident.

E. Structure of this annex

34. The prime purpose of this annex is to build on the information reported in the UNSCEAR 1996 Report [U4]; to compile data that has since become available on the effects of exposure to ionizing radiation on non-human biota; and to determine if the reference dose rates need to be updated. However, it is necessary first to provide some general information on the relationships between the levels of radiation in the environment in which the biota live and the consequent dose (or dose rate) to biota as a whole or selected tissues and organs. Table 1 provides a summary of five key elements that form the basis for assessing the effects of exposure to ionizing radiation on non-human biota.

35. The relationships between the levels of radiation exposure and the activity concentration of radioactive material in the environment and the dose to an organism living in that environment is the subject of section I.

36. Section II provides a summary of the information considered in the UNSCEAR 1996 Report [U4] and the key observations from that report.

37. Section III provides an overview of the findings of the studies of non-human biota in the area surrounding the site of the Chernobyl accident. It includes the work of the Chernobyl Forum [E8].

38. Section IV provides a summary of the effects of exposure to ionizing radiation on non-human biota derived from the material given in earlier sections and reviews carried out by other scientific organizations and groups, namely, the IAEA [I4], Bird et al. [B1], the DOE [J1, U26], Environment Canada and Health Canada [E2],

Canada's former Advisory Committee on Radiological Protection (ACRP) [A1], the UK Environment Agency [C1], the FASSET group [F1, F5, L1, L4], and the ERICA group [E1, G11, G15]. The published literature was also reviewed.

39. Section V provides an overall summary of the data reviewed and, based on these data, the Committee's evaluation of the dose rates below which effects on non-human biota are not considered likely. A few important areas for potential future study are also noted.

I. ESTIMATING DOSES TO NON-HUMAN BIOTA

40. Data on the effects of radiation exposure on non-human biota have been obtained from experimental studies carried out in the laboratory and in the field. Additional data have been obtained from the results of studies on environments with elevated levels of radiation or of radioactive material resulting from normal operations of nuclear facilities, waste management activities, or accidents. The interpretation of the results of these studies requires an understanding of the relationship between the levels of radiation and the activity concentrations of radionuclides in the various environmental media in which the organism resides, the consequent dose rate to an organism (or a tissue or organ of the organism) that lives in the environment, and the biological effect of interest. For example, radionuclides in the ambient environment may lead to external irradiation and internal irradiation as a result of radionuclides being taken into the organism via inhalation, ingestion, or uptake through its skin or membrane. Empirically determined concentration factors and transfer factors are commonly used to estimate contaminant concentrations in the organism (e.g. expressed for wet or dry weight in units of Bq/kg) from concentrations in the ambient environment (e.g. expressed in units of Bq/kg for sediment or soil, or Bq/L for water). Dosimetric models can then be used to derive, for selected organisms, dose conversion coefficients (DCCs) that relate ambient concentrations to internal or external exposure, as appropriate, and hence to dose.

A. Assessing exposures of biota

1. Choice of reference organisms

41. In view of the enormous variety of living organisms, it would be impossible to consider all species of flora and fauna as part of an environmental impact assessment even for a limited area. Instead, a concept has been developed involving the selection of reference organisms that are representative of large components of common ecosystems and for which models are adopted for the purpose of deriving doses and dose rates to organisms, tissues, or organs from radionuclides in the environment. The results of such dose assessments for these predefined reference organisms will

allow a basic assessment to be made concerning the possible biological effects. This approach provides a strategy that allows the modelling effort to be reduced to a manageable level. It further provides information on the exposures of different organisms under varying exposure conditions, which allows the estimation of the impacts on those components of the environment for which data may be sparse or absent.

42. The reference organism approach of the ICRP had its genesis in some earlier publications [P6, P13]. In the framework of the FASSET project [F20, L4], reference organisms were defined as "a series of entities that provide a basis for the estimation of radiation dose rate". The idea was that these organisms would provide a basis for assessing the doses to organisms and consequential effects in general due to radionuclides in the environment. The main criterion for the selection of reference organisms within the FASSET project was that the habitats and feeding habits should be such that the external and internal exposures are maximized.

43. The ICRP is assembling databases that relate to a limited number of "reference animals and plants". These are defined as "hypothetical entities with the assumed basic characteristics of a specific type of animal or plant, as described to the generality of the taxonomic level of family, with defined anatomical, physiological, and life-history properties that can be used for the purposes of relating exposure to dose, and dose to effects, for that type of living organism" [I12].

44. Both the FASSET and the ICRP approaches were intended to simplify the process of estimation and evaluation of exposures to ionizing radiation of non-human biota. Whereas reference organisms in FASSET were specifically selected for different ecosystems (e.g. agricultural, semi-natural, freshwater, and marine), ICRP [I10] described the reference animals and plants in groups (family or taxonomic level). The reference organisms selected cover a range of ecosystems and taxonomic families (table 2). The generic (reference) organisms that are explicitly considered in this annex are summarized in table 2. Organisms similar to those adopted by the ICRP were selected for consistency. The features of the selected organisms are described in reference [I10].

Table 2. Comparison of reference organisms defined by different international bodies

<i>Defined by</i>	<i>Reference organisms</i>
FASSET Terrestrial ecosystems [L1]	Soil microorganisms Soil invertebrates Plants and fungi Bryophytes Grasses, herbs and crops Shrubs Above ground invertebrate Burrowing mammal Herbivorous mammals Carnivorous mammals Reptile Vertebrate eggs Amphibians Birds Trees
FASSET Aquatic ecosystems [L1]	Benthic bacteria Benthic invertebrates Molluscs Crustaceans Vascular plants Amphibians Fish Fish eggs Wading birds Sea mammals Phytoplankton Zooplankton Macroalgae
ICRP Proposal on Reference Animals and Plants [I10]	Deer Rat Duck Frog Trout Flatfish Bee Crab Earthworm Pine tree Wild grass Brown seaweed
This annex	Earthworm/soil invertebrate Rat/burrowing mammal Bee/above ground invertebrate Wild grass/grasses, herbs and crops Pine tree/tree Deer/herbivorous mammal Duck/bird Frog/amphibian Brown seaweed/macroalgae Trout/pelagic fish Flatfish/benthic fish Crab/crustaceans

2. Radioecological models

45. Three classes of radioecological model can be distinguished and are presented here in terms of increasing complexity—equilibrium models, dynamic models and research models.

46. Equilibrium models are primarily intended for the assessment of exposures due to routine discharges of radioactive material into air or water. They are based on two fundamental assumptions: (a) the emission rates of the radionuclides are constant in time; and (b) the duration of the discharges is long compared to the time needed for radionuclide transfer

along the environmental pathways considered. With these assumptions, the radionuclide concentrations reach equilibrium within each of the compartments into which the environment is subdivided for modelling purposes, and the transfers between compartments are easily characterized by time-invariant ratios of concentrations between the acceptor and donor compartments.

47. Since equilibrium radionuclide concentrations in the environment are typically attained after considerably long operational times of a nuclear facility, the equilibrium models are likely to give conservative exposure estimates. This type of radioecological model has been used to determine compliance of routine discharges from nuclear facilities with authorized limits [H4, I11, N3, U3].

48. Ciffroy et al. [C22] tested the influence of the time-dependence assumption frequently used in radioecological models in a case study conducted on the Loire River in France. For routine discharges of radionuclides from nuclear power plants, their main conclusions were that: (a) attention must be paid to the temporal variations in the discharges, and gaps between actual instantaneous discharges and maximum discharges on a yearly time scale must be analysed; (b) the equilibrium assumption at the water-suspended matter interface must be justified and eventually corrected when equilibrium conditions are not expected; and (c) for organisms showing slow uptake/elimination rates, a kinetic approach to the bioaccumulation process can avoid some overestimation of radionuclide concentrations. The assumption of equilibrium led to overestimations of one to two orders of magnitude in predicting ^{60}Co concentrations in invertebrates.

49. A number of inherent advantages have contributed to the proliferation of equilibrium models. The model structure can be kept simple, but there is flexibility to allow more detailed structure, if necessary. Under equilibrium conditions, dispersion of trace amounts of radionuclides in the atmosphere or rivers is adequately represented by analytical solutions of more general physical models; transfer via food chains is represented by simple multiplicative chains of concentration ratios.

50. A major conceptual limitation of radioecological models is that many of the parameters involved (e.g. concentration ratios) have to be established empirically. Experience gained during recent decades has amply demonstrated that numerical values of many of these parameters may vary by several orders of magnitude; this has been well documented, for example, for plant-soil relationships of radiocaesium and radiostrontium concentrations [F7, F8, N4]. While for the purposes of screening or environmental protection as may be established by the ICRP or required by a national regulator, representative parameter values can be selected that ensure that the model assessments are conservative, obvious difficulties exist if a realistic assessment of exposures in specific ecosystems is needed.

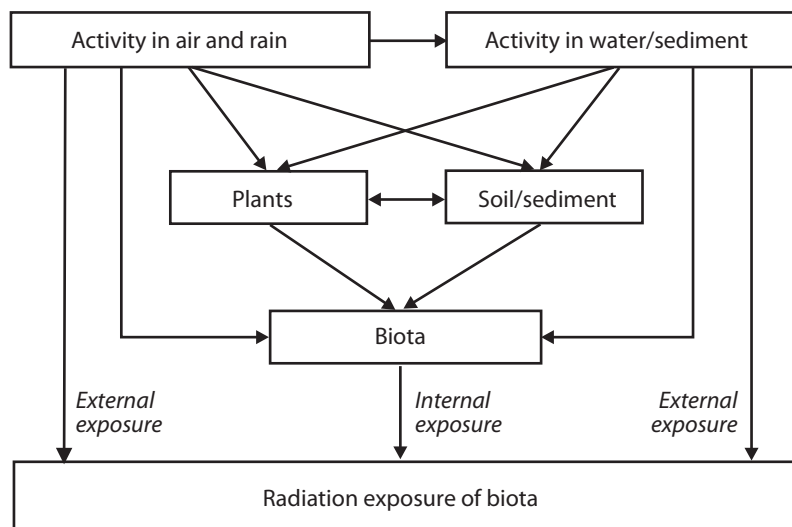
51. Dynamic radioecological models [M4, S13, W3] are applied if the time dependence of exposures that result from varying or instantaneous releases has to be taken into account. Examples of their use include the assessment of the time-dependent radionuclide concentrations in the environment, such as those resulting from accidental radionuclide releases varying over time, and the simulation of seasonal effects, which are of major importance in terrestrial environments during the first year following deposition of radionuclides after an accidental release [M7].

52. Research models are characterized by a high degree of complexity and longer computation times, and presently are limited to simulating a few of the important processes in analyses of environmental pathways for radionuclides [C7, P9]. Currently, therefore, they do not offer an alternative to equilibrium and dynamic radioecological models for environmental assessments, although they do constitute an important tool for improving understanding of the sources of variability observed empirically.

53. The scope of this annex is limited to providing a broad overview of the approach to estimating radiation exposure and subsequent doses to non-human biota. The reader interested in these topics is referred to the extensive literature. Exposure assessments are generally based on equilibrium models. However, for case studies at specific locations contaminated by accidental releases of radionuclides, information on the levels of exposure of local biota taken from the literature is sometimes based on simulations using dynamic radioecological models.

3. Transfer of radionuclides in the environment and resulting exposures

54. The major pathways of radiation exposure of biota in the environment are summarized in figure II. In this schematic representation, the physical components of the terrestrial environment are air, soil and sediment; the biological components include plants, invertebrates, and vertebrates (mammals, birds, reptiles, and land-based amphibians). The physical components of the freshwater aquatic environment include streams, rivers, lakes and sediments; the biological components are phytoplankton, zooplankton, macroinvertebrates, sessile aquatic plants and vertebrates (fish, water-based amphibians and some aquatic mammals). In a marine environment, the physical components include tidal zones, coastal waters and marine sediments; and the biological components include phytoplankton, zooplankton, macroinvertebrates, sessile aquatic plants, and vertebrates (fish and marine mammals), molluscs, crustaceans and marine birds. The terrestrial and aquatic environments are not totally separate. Some birds and terrestrial mammals eat fish and shellfish; moose and waterfowl feed on aquatic plants; and terrestrial animals ingest drinking water from the aquatic environment.

Figure II. Major environmental transfer routes for evaluating radiation exposure of biota

55. The total radiation dose received by an organism (or some organ or tissue of the organism) is the sum of the contributions from both external and internal exposure. External exposure results from complex non-linear interactions of various factors, such as the levels of the radionuclides in the habitat, the geometrical relationships between the radiation source and the target, the shielding properties of the materials in the environment, the size of the organism and the radionuclide-specific decay properties (characterized by the type and energy of the radiations emitted and their emission probabilities).

56. Internal exposure is determined by the activity concentrations of the radionuclides in the organism, the size of the organism, the radionuclide distributions within the organism and the specific decay properties of the radionuclides. In addition, the relative biological effectivenesses (RBE) of alpha, beta and gamma radiation need to be taken into account in assessing the consequences of the exposure.

B. Transfer of radionuclides in the terrestrial environment

57. Radioactive material released into the atmosphere is dispersed and transported by the wind. Exposures of biota are calculated from the activity concentrations of radionuclides in the environmental media, such as air, soils and vegetation, and in the organisms under consideration. The principal processes involved in the transport

of radionuclides in the terrestrial environment include dry deposition, wet deposition, interception by vegetation, loss of radionuclides from plants due to weathering, resuspension, the systemic transport of radionuclides within plants, uptake from soil, run-off to water bodies and the transfer to animals. This section discusses the factors that affect the behaviour of radionuclides in a terrestrial environment and the uptake of radionuclides from the environment to plants and animals.

1. Dry deposition

58. Dry deposition per unit time is proportional to the near-surface concentration of the material in air. Usually, the dry deposition of a radionuclide from the atmosphere to soil and vegetation is expressed in terms of the deposition velocity, v_g (m/s), which is defined as the ratio of the activity deposition rate per unit area and the local activity concentration in air of the radionuclide at a reference height. This empirical quantity depends on a variety of factors such as the size of any associated particles, the characteristics of the surface-air interface, the meteorological conditions and the chemical form of the radionuclide.

59. Typical estimates of deposition velocities for grass and forests are summarized in table 3. These values are used for the calculation of the exposures of biota resulting from the atmospheric release of radionuclides.

Table 3. Typical estimates of deposition velocities for grass and forest [P14, R11]

Chemical/physical form	Deposition velocity (m/s)			
	Grass	Forest ^a		
		Crown	Trunk	Soil
Particles, 0.1–1 μm	0.001	0.005	0.000 5	0.000 8–0.003
Elemental iodine	0.01	0.05	0.005	0.006–0.02
Methyl iodide	0.000 1	0.000 5	0.000 05	0.000 08–0.000 3

^a Coniferous trees and deciduous trees with fully developed foliage.

2. Interception of radionuclides deposited from the air

60. Interception defines the fraction of radioactivity deposited by wet and dry deposition processes that is initially retained by the plant. There are several possible ways to quantify the interception of deposited radionuclides. The simplest is the interception fraction, f , which is defined as the ratio of the activity initially retained by the standing vegetation, A_i , immediately subsequent to the deposition event to the total activity deposited. A full description of the interception process is beyond the scope of this annex and the reader interested in this topic is referred to the extensive literature (e.g. see reference [H26]).

61. Radioactive material in air can be washed out by rain and snow. A fraction of the radionuclides deposited with precipitation is retained by the vegetation, and the rest falls through the canopy to the ground. Although the radioactive material retained eventually transfers to soil through weathering and is retained only temporarily by vegetation, the fraction initially intercepted is important owing to the fact that the concentration of radioactive material will be at its highest at this time. Interception of wet deposits is the result of a complex interaction of the amount of rainfall, the chemical and physical form of the deposit and the actual stage of development of the plant [M4] and thus, interception fractions for a single event may vary from 0 to 1.

62. To account for its dependence on biomass in some models, the interception of wet deposited activity is modelled as a function of the biomass density, according to the approach of Chamberlain [C8]. The chemical form is a key factor; since the plant surface is negatively charged, the absorption of anions is less effective than that of cations [H6, H7, K4, M4, P11]. Differences between plants seem to be of minor importance compared to those between radionuclides, e.g. the interception of polyvalent cations is higher than that for anions by as much as a factor of 8 [H5]. However, in general, for the estimation of interception following the routine discharge of radioactive material, very simple approaches are used in the models [P10]. Anspaugh [A22] suggested a default value for the interception fraction of the order of 0.3 for all elements, plants and precipitation events for routine discharges of radionuclides.

3. Weathering

63. Following deposition on vegetation, radionuclides are removed by wind and rain. In addition, the increase of biomass during growth leads to a reduction in the activity concentration. Since growth is subject to seasonal variations, the post-deposition reduction of the activity concentration of radionuclides in plants depends on the season. These processes of reduction in the activity concentration of radionuclides in plants occur simultaneously after deposition. As it is difficult to quantify the exact contribution of each process, the net reduction in the activity concentration with time is usually called “weathering” and expressed by the empirical weathering half-time, T_w .

64. The chemical form of the contaminant seems to be of minor importance in weathering. After the Chernobyl accident, the median weathering half-times observed for iodine and caesium on grass were approximately 8 and 10 days, respectively [K5]. Shorter half-times were observed primarily in regions with fast growing vegetation, while longer half-times were found in Scandinavia, where the growth rates were lower because of the later spring in the area [K5]. In general, longer weathering half-times are observed for slowly growing or dormant vegetation [M8].

65. In forests, weathering is more complex because of the canopy structure, which comprises several vegetation layers, such as crown, trunk and understorey vegetation. Radionuclides lost from the crown may be retained by the understorey vegetation, thus reducing the overall loss rate of radionuclides from vegetation to soil.

4. Distribution of radionuclides within plants

66. The currently available dosimetric models for the assessment of the exposure of biota do not take into account heterogeneous radionuclide distributions within plants. Hence, any information on these distributions cannot currently be used in the assessment.

5. Uptake of radionuclides from soil

67. Soil is the main reservoir for long-lived radionuclides deposited on terrestrial ecosystems. The behaviour of radionuclides in

soils controls their migration in soil, the possible transport to groundwater, and the long-term radionuclide concentration in vegetation and thus the exposure of soil organisms. As for all minerals, the uptake of radionuclides by plants mainly takes place via dissolution from soil. The concentration of radionuclides in soil solutions is the result of complex physical-chemical interactions with the soil matrix, with ion exchange being the dominant mechanism. Ion exchange by its very nature is a competitive mechanism. The concentrations and composition of the major competing elements present in soil thus are of primary importance in determining the distribution of radionuclides between soil, soil solution and plant roots (which are able to influence the microspace in their vicinity in order to provide and maintain conditions that favour the uptake of nutrients) [E6].

68. The physical chemistry of sorption and desorption of radionuclides in the soil–soil solution system and their possible uptake by plants are the result of complex interactions between soil type, pH, redox potential, sorption capacity, clay content, content of organic matter and soil management practice. Although these factors are qualitatively known, they are difficult either to quantify or to integrate into a universal model applicable to a wide range of soil conditions. Consequently, the approaches used include classifying the transfer according to soil types (e.g. peat, sand, loam and clay) and other physical and chemical parameters. In addition, various biological factors should be considered, especially whether or not the radionuclide is an essential element.

69. For the quantification of the root uptake of radionuclides, empirically derived (aggregated and greatly simplified) parameters—soil–plant transfer factors or concentration

ratios—are usually applied despite their inherent limitations [E6]. In this case, these parameters are the ratios of the activity concentrations in the plant to those in the soil within the uppermost layer of a standardized thickness. Transfer factors were originally defined for agricultural ecosystems within which radionuclides are distributed homogeneously within the rooting depth of agricultural plants because of ploughing.

70. The aggregated transfer factor is defined as the activity concentration of a radionuclide in a material (Bq/kg) divided by the total deposition—activity per unit area (Bq/m²)—at equilibrium. The concept of aggregated transfer factors was developed as a simplification of detailed physical and chemical processes to a single value, *inter alia*, to avoid difficulties with determining radionuclide concentrations in soils with a multi-layered structure, such as in forests.

71. Alternatively, concentration ratios that relate to the activity concentrations of radionuclides in specific soil horizons exploited by the mycelium or the root system were proposed in the late 1980s and proved to be useful, especially in connection with the prediction of the transfer of ¹³⁷Cs to fungi [G4, R8, Y1, Y4, Y5].

72. Illustrative ranges of soil–plant transfer factors for a number of elements are summarized in table 4 [T11]. This table shows that the uptake of caesium from soil usually does not result in a simple proportional accumulation in plants. Radiocaesium is effectively sorbed by micaceous clay minerals that are present in almost all soils in varying amounts. A detailed compilation of soil–plant transfer factors including data for specific plant groups, plant organs and soil types can be found elsewhere [I14].

Table 4. Typical ranges of soil–plant transfer factors [T11]

<i>Element</i>	<i>Concentration ratio Bq/kg plant (d.m.) per Bq/kg soil (d.m.)</i>	<i>Aggregated transfer factor^a Bq/kg plant (d.m.) per Bq/m² soil</i>
Sr	0.01–1	4×10^5 – 4×10^3
Cs	0.001–0.1	4×10^6 – 4×10^4
Cs ^b	0.1–10	4×10^4 – 4×10^2
I	0.001–1	4×10^6 – 4×10^3
Tc	0.1–10	4×10^4 – 4×10^2
Pb	0.001–0.01	4×10^6 – 4×10^5
Ra	0.001–0.1	4×10^6 – 4×10^4
U	0.001–0.1	4×10^6 – 4×10^4
Np	0.001–0.1	4×10^6 – 4×10^4
Pu	10^5 – 10^3	4×10^8 – 4×10^6
Am	10^5 – 10^3	4×10^8 – 4×10^6
Cm	10^5 – 10^3	4×10^8 – 4×10^6

^a Calculated from the concentration ratio assuming a mass density for dry matter (d.m.) in the soil rooting zone of 280 kg/m² taking account of the mass of the soil within the rooting zone.

^b Observed range in natural and semi-natural ecosystems on acid sandy soils poor in potassium.

73. Caesium uptake is particularly high from organic soils with a low pH and pronounced potassium deficits [F11]. Such soils are frequently found in the Russian Federation, Belarus and Ukraine, as well as in Scandinavia, the upland areas of the UK and the alpine areas of Europe. For organic matter, the cation exchange capacity decreases with increasing acidity owing to the saturation of carboxyl groups with hydrogen ions. Furthermore, the availability of caesium for uptake is enhanced in soils that are poor in potassium. Additionally, the clay content of organic soils is low and this prevents strong sorption and leads to persistently high caesium levels in plants [A7, F12, F13, K6]. Another important aspect is that the bioavailability of radionuclides and their uptake after deposition may change with time. This was observed in areas close to the site of the Chernobyl accident and was caused by the degradation of fuel particles, the fixation of caesium within the soil and changes in the sorption strength of the soil for caesium [N5, S14, S15].

74. In recent years, a number of experiments have been performed to determine soil–plant transfer factors for tropical and subtropical environments [C9, F11, R6, T12, T13,

U24, U25, W12, W13]. The anaerobic soil conditions in flooded paddy fields change the solubility of some elements, such as I and Tc, and thus possibly their soil–plant transfer factors [M25, T26, Y3]. In general, however, the results do not indicate any systematic impact of climatic conditions on the transfer of radionuclides from soil to plants, although the numbers of data are still small. Further data on the tropical and subtropical environments are therefore needed [M25].

75. In forest ecosystems, the transfer of radionuclides from soil to plants and fungal fruit bodies depends on the depth profile of the radionuclides and the vertical distribution of fine roots and fungal mycelia in soil. At least in the case of fungi, the use of transfer factors referring explicitly to the soil layer exploited by fungal mycelia seems to be the best approach for quantifying the uptake to radionuclides, balancing overall simplicity with mechanistic considerations of the dynamic processes [S37]. However, the concentrations of radionuclides in understorey vegetation, trees and fungal fruit bodies can be estimated roughly in a simplified manner using aggregated transfer factors. The ranges of aggregated transfer factors given in table 5 summarize the available observations.

Table 5. Typical ranges of aggregated transfer factors for ^{137}Cs from soil to vegetation and fungal fruit bodies in forest ecosystems [A8, B27, G7, I16, I17, K15, L7, Z1]

Data are given on a dry weight basis unless otherwise noted

<i>Species or genus</i>	<i>TF_{agg} (Bq/kg organism (d.m.) per Bq/m² soil)</i>
Fungal fruit bodies	
Agaricus	0.002–0.007
Amanita	0.008–5
Armillaria	0.001–0.2
Boletus	0.001–10
Cantharellus	0.01–2
Clitocybe	0.01–2
Collybia	0.03–0.3
Coprinus	0.004 ^a
Cortinarius	0.02–10
Hydnum	3 ^a
Hygrophorus	0.2–7
Laccaria	0.4–10
Lactarius	0.006–5
Leccinum	0.005–0.9
Lepista	0.002 ^a
Lycoperdon	0.009–0.5
Macrolepiota	0.000 7–0.1
Paxillus	0.01–5
Ramaria	0.05–0.6
Rozites	0.08–10
Russula	0.04–5
Sarcodon	0.3–0.4
Suillus	0.02–2
Tuber	0.000 3–0.008 ^b
Xerocomus	0.002–7

Species or genus	TF_{agg} (Bq/kg organism (d.m.) per Bq/m ² soil)
Understorey vegetation	
<i>Rubus chamaemorus</i> (cloudberry), fruit	0.002–0.2
<i>Vaccinium vitis-idaea</i> (lingonberry), fruit	0.03–0.07
<i>Vaccinium myrtillus</i> (bilberry), fruit	0.02–0.1
<i>Rubus idaeus</i> (raspberry), fruit	0.001–0.004
<i>Fragaria vesca</i> (strawberry), fruit	0.004–0.01
<i>Rubus fruticosus</i> (blackberry), fruit	0.006–0.05
Green parts of understorey vegetation, including the stems of berry plants	0.001–1
Trees	
<i>Fagus sp.</i> (beech) Bole wood	0.001–0.002
Leaves	0.002–0.003
<i>Picea sp.</i> (spruce) Bole wood	0.000 3–0.002
Needles	0.000 6–0.02
<i>Pinus sp.</i> (pine) Bole wood	0.000 2–0.003
Needles	0.001–0.04
<i>Quercus sp.</i> (oak) Bole wood	0.002–0.004
Leaves	0.008–0.01
<i>Betula sp.</i> (birch) Bole wood	0.000 03–0.001
Leaves	0.000 3–0.04
<i>Populus sp.</i> (aspen) Bole wood	0.000 5–0.002
Leaves	0.008 ^a
<i>Alnus sp.</i> (alder) Bole wood	0.001 ^a
Leaves	0.008 ^a

^a Only a single value available.

^b Data are given on a fresh weight basis and refer to the top 10 cm of soil.

76. Fungi are able to accumulate radiocaesium in their fruit bodies [G14, H8]. Some species exhibit activity levels that exceed those of green plants by more than one order of magnitude. On average, the radiocaesium levels in symbiotic fungi are higher than those in saprophytic species [R7, Y4, Y5].

77. Radionuclides in growing wood originate from two sources: the initial atmospheric deposits that enter the plant by foliar absorption, and root uptake from the soil. Their relative contributions depend on the type of tree (coniferous versus deciduous) and the age [B20, E7, G5, H9], the season at the time of deposition and the time elapsed after deposition, with root uptake being the dominant pathway for growing wood in the long term. Transfer factors or concentration ratios that are calculated on the basis of the total content of radionuclides in wood inevitably include both uptake processes and therefore are likely to overestimate root uptake (table 5) [G5].

6. Migration in soil

78. Vertical migration of radionuclides in the soil column is driven by various transport mechanisms, such as convection, dispersion, diffusion and bioturbation. The long-term consequences of downward migration differ considerably, however, depending on the dominant mechanism. For convective-driven migration, for example, the radionuclide input due to the Chernobyl accident moves down the soil as a marked peak and shows broadening with time as a result of dispersive mixing. Convective transport of radionuclides usually dominates in soils showing high hydraulic conductivities, e.g. sandy soils. For further discussion of the importance of downward migration of radionuclides in soil and forest litters, see section III and the references cited.

79. For diffusive transport, the concentration is always at a maximum at the surface with a close to exponential decrease with depth. For this type of transport, which is typical in

soils of low hydraulic conductivity, the bulk of the radionuclides deposited from the atmosphere thus remains within the rooting zone of plants.

80. Agricultural practices have a major impact on radionuclide behaviour. Depending on the intensity and type of soil cultivation, mechanical redistribution of radionuclides may occur. This causes, in arable soils, a rather uniform distribution of radionuclides in the tilled horizon. Fertilization shifts the ratio of radionuclide to nutrient concentrations in soil and soil solution and thus may influence plant root uptake of the radionuclides [E6].

81. Some investigations indicate [B21, S16] that element-independent transport mechanisms, such as the transport of radionuclides attached to clay particles or soil colloids, may play a relevant role in determining the migration rate of radionuclides in soil. Furthermore, the activity of soil animals that cause a turnover of soil, e.g. earthworms, cannot be neglected. The authors of references [B21, S16] suggest that a value of 100 years for the default residence half-time for the upper 25 cm layer is adequate for all elements with low mobility, such as radium, lead, uranium, plutonium and americium. Iodine under aerobic conditions is strongly bound to organic matter and therefore a residence half-time of 100 years can also be assumed [K7]. On the other hand, iodine can be released from soil to soil solution under anaerobic conditions, such as in a flooded paddy field [M25].

82. The situation with forest soil is more complex owing to the more pronounced soil horizons. Radionuclides deposited directly onto forest soil or washed from the canopy and understorey vegetation initially infiltrate the soil rather rapidly. They are therefore initially assigned to a labile pool. In the long term, they will become immobilized through fungal or microbial activity or by mineral constituents of the soil. The radionuclides in the non-labile pool may be available for root uptake, e.g. via symbiotic fungi, but are assumed not to be leached to deeper soil layers. The rate of downward migration is correspondingly reduced considerably over time, and, in the organic horizons, is determined mainly by the rates of decomposition of the organic material, and litter accumulation. Subsequently, downward migration of radionuclides is rather slow and partially offset by upward translocation by fungal mycelia and roots [R4]. Fungal and microbiological activity is likely to contribute substantially to the long-term retention of radionuclides, notably radiocaesium, in organic layers of forest soil. In this phase, radiocaesium is well mixed and almost equilibrated with stable caesium within the biologically connected compartments [Y6]. When radionuclides reach the mineral horizons of forest soil, essentially the same processes may occur as in arable soils, e.g. radiocaesium can be fixed by micaceous clay minerals.

7. Resuspension

83. Resuspension refers to the removal of deposited material from the ground to atmosphere as a result of wind, traffic,

soil cultivation and other activities. Potentially, resuspension is a persistent source of radionuclides in air subsequent to their deposition on the ground. Furthermore, it may lead to redistribution of radionuclides and their deposition onto clean surfaces. Resuspension is influenced by a variety of factors, such as the time since deposition, meteorological conditions, surface characteristics and human activities. For biota, resuspension is of low importance. For animals living in the soil, it is not relevant. The contribution of resuspension to the activity concentration of radionuclides in plants in humid ecosystems usually is negligible compared to that of dry deposition and interception [G6, H10].

8. Transfer to animals

84. The transfer of radionuclides to animals is usually estimated using element-dependent concentration ratios or transfer factors. The transfer factor is defined either as the ratio of the activity concentration in an organism or tissue and the intake rate under equilibrium conditions, or as the ratio of the activity concentration in an organism or tissue and the deposition density (activity per unit area). It is only applicable to an intake of a radionuclide by adult animals that is constant over long periods. To account for time-dependent (dynamic) intakes, one or more biological half-lives are considered [M4].

85. In recent decades, many data have been accumulated on the transfer factors for domestic animals. They depend on animal mass, performance level, feeding regimes and feed components. However, these data are not generally applicable to estimating activity concentrations in biota, since they were determined in order to estimate activity concentrations in animal products for human food (such as meat, milk and eggs) while this annex is concerned with the estimation of activity concentrations in whole animals. Furthermore, the application of transfer factors presumes knowledge of the feed intake as well as the activity concentrations of the feed components. It has been demonstrated that highly contaminated feed components may determine the activity levels of game, even if consumed in low quantities. The seasonal peak activity concentration of ^{137}Cs in roe deer, for example, has been attributed to the ingestion of mushrooms [Z1]. Fungal fruit bodies can show radiocaesium levels exceeding those of green plants by one order of magnitude or more. Wild boar ingest deer truffle (*Elaphomyces granulatus*), a preferred “delicacy”, which dominates the radiocaesium uptake, despite being only a few per cent of the boar’s total diet [F14, P12]. However, the relevant data are not available for wild animals in general.

86. In most cases, the activity concentrations of radionuclides in game are calculated in a simplified manner using aggregated transfer factors. This transfer factor neither takes into account the time-dependent intake rates nor can reproduce the time-dependent activity concentrations in game. Values for aggregated transfer factors for different species are compiled in table 6.

Table 6. Aggregated transfer factors (soil-to-game) for ¹³⁷Cs [A9, I16, J3, K8, S19, Z1]

Data are given on a fresh mass basis unless otherwise noted

Species	TF_{agg} (Bq/kg organism (dry mass) per Bq/m ² soil (dry mass))	
	Default value	Range of literature data
<i>Alces alces</i> (moose)	0.02	0.006–0.03
<i>Capreolus capreolus</i> (roe deer)	0.05	0.001–0.2
<i>Cervus elaphus</i> (red deer)	0.03	0.02–0.04
<i>Lepus arcticus</i> (arctic hare)	0.03	0.009–0.1
<i>Lepus capensis</i> (brown hare)	0.004	0.002–0.05
<i>Lynx lynx</i> (lynx)	0.3	0.01–10 ^a
Game except roe deer	0.02	

^a Data are given on a dry weight basis.

87. Table 7 summarizes the equilibrium concentration ratios for the reference organisms considered. The values are “order-of-magnitude” estimates based on the compilation in reference [F4]. Some of the original values were given as aggregated transfer factors and have been converted to concentration ratios. At least in temperate environments, concentration ratios are higher in forest and semi-natural ecosystems than in agricultural systems, because of their often lower nutrient supply and pH values. Furthermore, the high content of organic matter in forests is accompanied by high concentrations of fulvic and humic acids, which act as

complexing agents and increase the mobility of cationic radionuclides in soil.

88. The nominal values of transfer factors provided in table 7 have been suggested for use [E10, F4], in the absence of site-specific information, to estimate the exposure rates for biota after the release of radionuclides to atmosphere and their subsequent transfer to soil. As such, these transfer factors were intended to be applied for screening purposes to obtain an order of magnitude estimate, but they may not be appropriate for application to specific sites.

Table 7. Nominal values of transfer factors for reference organisms (adapted from [E10, F4])

Element	Transfer factors (Bq/kg (fresh weight) per Bq/kg soil)							
	Earthworm	Rat	Deer	Duck	Frog	Bee	Grass	Pine tree
H	150	150	150	150	150	150	150	150
Cl	0.2	7	7	7	7	0.3	20	1
Sr	0.01	2	2	0.6	1	0.06	0.2	0.5
Tc	0.4	0.4	0.4	0.4	0.4	0.4	20	0.3
I	0.2	0.4	0.4	0.4	0.4	0.3	0.1	0.1
Cs	0.09	3	3	0.8	0.6	0.06	0.7	0.2
Np	0.1	0.04	0.04	0.04	0.04	0.1	0.02	0.3
Pu	0.03	0.02	0.02	0.02	0.02	0.06	0.01	0.03
Am	0.1	0.04	0.04	0.04	0.04	0.1	0.005	0.000 1
Pb	0.03	0.04	0.04	0.06	0.1	0.06	0.07	0.08
Ra	0.09	0.03	0.03	0.04	0.04	0.04	0.04	0.000 7
Th	0.009	0.000 1	0.000 1	0.000 4	0.000 4	0.009	0.04	0.001
U	0.009	0.000 1	0.000 1	0.000 5	0.000 5	0.009	0.02	0.007

C. Transfer to freshwater organisms

89. Radionuclides can enter water bodies as a result of discharges to the aquatic environment (e.g. directly from a nuclear facility), by deposition of airborne radioactive material onto the water surface and by run-off of material

deposited onto soil. For a point source of emission into a swiftly flowing stream, the flow rate of the stream can be divided by the flow rate of the effluent discharge to obtain the dilution factor. A certain mixing distance must be assumed, which could vary from a few tens of metres for a small stream to a few kilometres for a large river. Beyond the

mixing distance, a uniform concentration of the radionuclide in water can be assumed. Suspended material may be deposited as sediment. The deposited material may become locked in the sediments and, over time, migrate to deeper sediments or be redissolved by physical and biological processes and re-enter the water column. Dissolved or finely suspended material may be transported over large distances, being progressively diluted by water from other streams and rivers, eventually reaching the oceans.

90. The movement of radionuclides in rivers is often modelled using the diffusion–transport equation and the behaviour of radionuclides in the “water column–river bed sediment” system is often assessed using compartment models [M23]. At present, although the structures of the models have not been subjected to significant revisions, the scope of the transfers modelled (physical, chemical and biological) and of the associated radionuclide specific parameters has been considerably enlarged. For instance, the previous state-of-the-art publication of the IAEA, “Handbook of parameter values for the prediction of radionuclide transfer in temperate environments” [I16], listed solely values of water–sediment partition coefficients and concentration factors for edible portions of fish. The most recent version also incorporated equations and parameters for representing transfer by wash-off from watersheds of deposited radionuclides, interaction between liquid and solid phases, migration to and from sediments, and transfers to freshwater biota [I14].

91. The mixing of radionuclides discharged into a lake or pond is much slower than is the case for rivers. As a first

approximation, a uniform radionuclide concentration throughout the pond could be assumed, with a dilution factor equal to the pond outflow rate divided by the effluent input rate. In a large lake or coastal environment, a uniform concentration would never be reached. Plume models have been developed for lake-shore environments analogous to atmospheric transport models. The lake-shore environment is often complicated by thermal layering within the water column, which impedes vertical mixing. Moreover, removal of material from the water column via sedimentation is an important long-term process which results in an approximately exponential decline with time of the radionuclide concentrations present in the water column.

92. Sedimentation and attachment to suspended particulates are the main processes influencing the residence times of radionuclides in freshwater. Fractions of dissolved and of particle-bound radionuclides are usually determined by the distribution coefficient, K_d , which is defined as the ratio of the radionuclide concentration in water and the concentration of the radionuclide attached to particulate matter, under equilibrium conditions. Values of K_d are element-dependent. Low K_d values and concentrations of suspended matter indicate high dissolved fractions, whereas high K_d values and suspended load values indicate a considerable sorption of radionuclides by particles and favour sedimentation. Once deposited, radionuclides may migrate down within the sediment or may become involved in resuspension processes. These processes may create additional sources or sinks with potential impact on the long-term behaviour. The distribution coefficients for various elements in freshwater are given in table 8.

Table 8. Distribution coefficients K_d in freshwater ecosystems [I14]

Element	K_d (m^3/kg)	
	Geometric mean	Geometric standard deviation
Be	42	3.6
Mn	130	12
Co	43	9.5
Sr	0.18	4.6
Ru	32	1.9
Ag	85	2.3
Sb	5	3.8
I	4.4	14
Cs	8.5	6.7
Ba	2	3.6
Ce	220	2.8
Th	180	21
Ra	7.4	3.1
Pu	240	6.6
Am	850	3.7

93. Aquatic organisms may be directly irradiated by radionuclides present in their habitats (e.g. water, sediment). They may also take up radionuclides from water and/or the food chain and incorporate them into their tissues. External irradiation of most aquatic organisms, with the exception of burrowing invertebrates and benthic organisms, is limited by the shielding provided by the surrounding water or sediment.

94. Considerable attention has been focused on fish because they are at a higher trophic level in aquatic food chains and serve as food for humans and predators. Polikarpov [P2] has given concentration ratios, CR, (CR here is the ratio of the activity concentration in fish expressed in units of Bq/kg and

that in water expressed in units of Bq/L, under equilibrium conditions) for ^{137}Cs ranging from 500 to 9,500 L/kg for freshwater fish, compared to values of 3 to 25 L/kg for marine fish. The lower values for marine fish were thought to be as a result of the competition for uptake from potassium and other cations. Freshwater amphibians can also show high values of CR (1,000 to 8,000 L/kg) in the aqueous environment.

95. Table 9 gives values of CR for ^{137}Cs in fish in Canadian lakes in the Northwest Territories [L5] and for the upper Great Lakes [T15]. High trophic level fish such as trout, pike and cisco show an especially high accumulation of radiocaesium.

Table 9. Concentration ratios for ^{137}Cs in freshwater fish

Species	Concentration ratio (L/kg)	
	NWT Lakes [L5]	Great Lakes [T15]
Burbot	800	
Lake whitefish	400–1 000	
Round whitefish	1 000–1 800	
Sucker	700	1 500–2 500
Chub		1 900
Alewife		1 800–2 300
Bullhead		2 300
Cisco	1 600–5 000	
Pike		2 500–5 500
Lake trout	3 000–6 000	6 100

96. Swanson [S20] has summarized concentration ratios for water to fish tissues for the naturally occurring radionuclides of uranium, ^{226}Ra , ^{210}Pb , and ^{228}Th (table 10).

Table 10. Concentration ratios for natural radionuclides in freshwater fish [S20]

Element/ radionuclide	Concentration ratio (L/kg)					
	Bone	Flesh	Liver	Kidney	Gonad	Gut
U	20–800	0.1–25	<0.04–0.5	0.1–0.5	0.01–0.35	0.05–0.5
^{226}Ra	35–1 800	1–60	1–45	3–30	5–115	7–45
^{210}Pb	100–2 500	4–100	3–420	6–780	10–150	11–206
^{228}Th	15–160	4–32	4–36	5–46	13–50	23–50

D. Transfer of radionuclides to marine organisms

97. The main processes that modify the activity concentrations of radionuclides in marine water are (a) dilution due to convective and dispersive mixing during transport, driven by local, regional and global currents, (b) sedimentation after attachment to suspended particles and (c) radioactive decay.

98. For a given continuous discharge rate into a specific section of the marine system, the steady-state concentration of a dissolved radionuclide in water, C_w (Bq/m³), can be calculated according to:

$$C_w = \frac{A}{V \cdot (\tau^{-1} + \lambda_r)} \cdot \frac{1}{1 + K_d \cdot S} \quad (2)$$

where A is the activity of the radionuclide discharged per unit time to a specific part of the sea (Bq/a), V is the volume of this part (m³), τ is the mean residence time (a), λ_r is the radioactive decay constant (a⁻¹), K_d is the distribution coefficient (m³/kg), and S is the concentration of suspended particles (kg/m). The steady-state activity concentration of the radionuclide in suspended particles, C_s (Bq/kg), is then:

$$C_s = \frac{A}{V \cdot (\tau^{-1} + \lambda_r)} \cdot \frac{K_d}{1 + K_d \cdot S} \quad (3)$$

The distribution coefficients for a number of elements in marine waters are summarized in table 11.

Table 11. Distribution coefficients K_d for open ocean and ocean margins [I20]

Element	K_d (m ³ /kg)	
	Open ocean	Ocean margins
H	0.001	0.001
Cl	0.001	0.000 3
Sr	0.2	0.008
Tc	0.1	0.1
I	0.2	0.07
Cs	2	4
Pb	1×10^4	1×10^2
Ra	4	2
Th	5×10^3	3×10^3
U	0.2	1
Np	1×10^2	1
Pu	2×10^3	1×10^2
Am	2×10^3	2×10^3

99. A value of 3 years was given in reference [U3] for the mean residence time, t , in a specified part of the marine system, for all radionuclides in coastal waters with the exception of ²³⁹Pu, for which a value of 3.5 years was assumed. These values took account of radionuclide losses from water to sediment.

From simulations of the transport of radionuclides discharged from the reprocessing plants at Sellafield and La Hague through the North Atlantic and its marginal seas, the mean residence times given in table 12 were estimated using the North Atlantic–Arctic Ocean Sea Ice Model (NAOSIM) [I21].

Table 12. Residence times in different parts of the North Atlantic according to the NAOSIM model

Part of ocean	Volume (km ³)	Mean residence time (a)
North Sea	41 000	2.5 ± 0.36
Norwegian Sea	59 000	0.37 ± 0.11
Barents Sea	220 000	2.4 ± 0.24
Kara Sea	38 000	4.5 ± 1.2
Central Nordic Seas	44 000	0.52 ± 0.18

100. As for freshwater aquatic biota, activity concentrations of radionuclides in marine biota can be estimated using a concentration ratio approach. Concentration ratios for various elements in marine biota are compiled in table 13. For

most elements, these data are based on concentrations in muscle (fish) and soft tissue (crustaceans). For the bone seeking elements such as strontium, however, the entries in table 13 are based on whole body concentrations.

Table 13. Concentration ratios for marine biota [I20]

Element	Concentration factors (L/kg fresh weight)		
	Fish	Macroalgae	Crustaceans
H	1	1	1
Cl	0.06	0.05	0.06
Sr	3	10	10
Tc	80	30 000	1 000
I	9	10 000	100
Cs	100	50	30
Np	1	50	100
Pu	100	4 000	200
Am	100	8 000	400
Pb	200	1 000	9 000
Ra	100	100	100
Th	600	200	1 000
U	1	100	10

E. Evaluating doses to biota

1. Fraction of radiation absorbed by organism

101. Radionuclides distributed in the environment lead to external exposure of an organism living in or close to a medium that contains radionuclides. The external exposure of biota is the result of complex and non-linear interactions of various factors:

- The geometrical relation between the source of the radiation and the target;
- The activity levels of the radionuclides in the environment;
- The materials in the environment and their shielding properties;
- The radionuclide-specific decay properties characterized by the radiation type, the energies emitted and their emission probabilities; and
- The habitat and size of the organism.

102. The geometric relationship between the radiation source and the exposed organism is an important factor in relation to the absorbed dose rate incurred. The intensity of the radiation field around a source decreases with distance and is influenced by the material between the radiation source and the target. The number of possible source target configurations is infinite; therefore, a number of limited and representative situations need to be selected for detailed consideration.

103. The exposure due to radionuclides incorporated into the organism is determined by the activity concentrations in the organism, the size of the organism, and the type and the energy of the emitted radiation. A key quantity for estimating internal doses is the absorbed fraction of energy, $\phi(E)$, which is defined as the fraction of energy emitted by a radiation source that is absorbed within the target tissue, organ or organism. In the simplest case, the organism is assumed to be in an infinite homogeneous medium and to have a uniform activity concentration throughout its body. The densities of the medium and the organism's body are assumed to be identical. Under these conditions, both internal (D_{int}) and external (D_{ext}) dose conversion coefficients (DCCs; the DCC is defined as either the absorbed dose or the absorbed dose rate, according to the circumstances, per unit activity concentration of the relevant radionuclide in the organism or medium) for monoenergetic radiation can be expressed as a function of the absorbed fraction [N1, V2]:

$$D_{int} = E \cdot \phi(E) \quad \text{and} \quad D_{ext} = E \cdot (1 - \phi(E)) \quad (4)$$

104. Absorbed fractions for photon and electron sources uniformly distributed in soft-tissue spherical bodies immersed in an infinite water medium have been systematically calculated by Monte Carlo simulation [U17]. The calculations covered a particle energy range of 10 keV to 5 MeV, a range for the mass of the body from 10^{-6} to 10^3 kg, and shapes from spheres to ellipsoids with varying degrees of non-sphericity. Figures III and IV show, respectively, the results for electrons and photons.

Figure III. Absorbed fraction, $\phi(E)$, for electrons of different energy uniformly distributed in spheres of different mass in a water medium

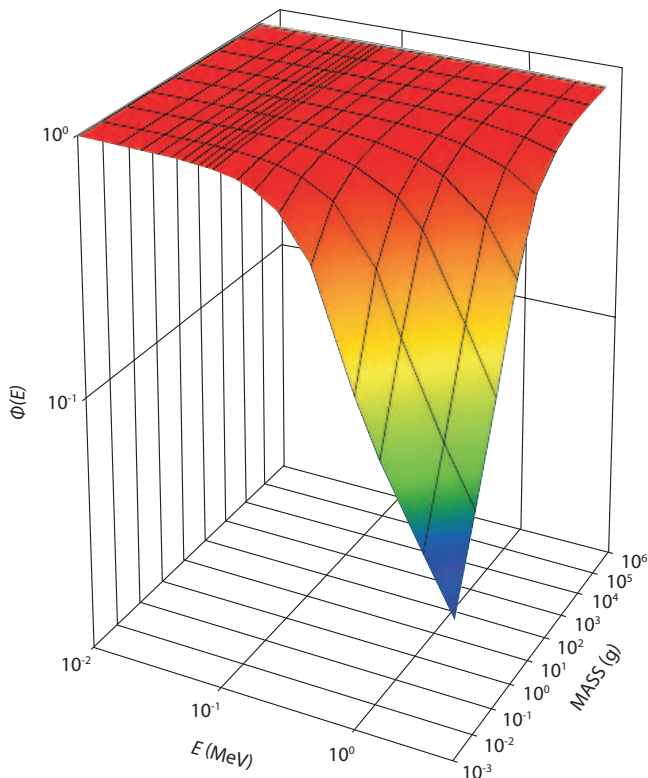
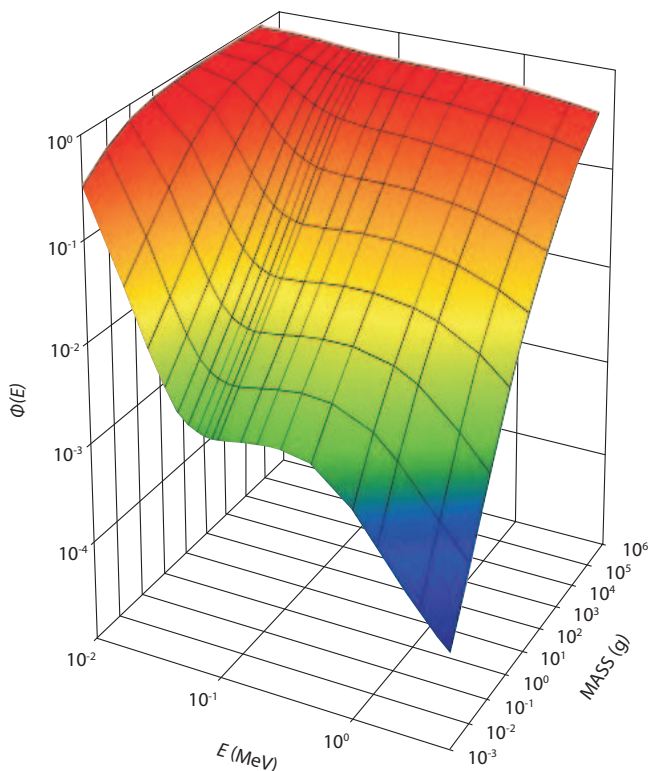


Figure IV. Absorbed fraction, $\phi(E)$, for photons of different energy uniformly distributed in spheres of different mass in a water medium



105. For electron energies below 100 keV, the absorbed fraction is close to unity, even for very small organisms. The mean free path of electrons in living tissue increases from 160 μm for 100 keV electrons to 5 mm for 1 MeV electrons. Thus, even above 100 keV, the absorbed fraction is close to unity if the diameter of the target is much greater than the range of the electron. Only for very small targets and high energies does the absorbed fraction become considerably smaller than 0.5.

106. The mean free path of photons is considerably longer than that of electrons. The absorbed fractions cover a range from nearly unity for low photon energies and large organisms to less than 0.0001 for small organisms and high photon energies. Absorption is a non-linear function of target size and energy. The main processes causing absorption of photon energy are the Compton effect, the photoelectric effect and pair production; their contributions to absorption depend on the energy of the emitted photons. As a result, the absorbed fraction of photons in the energy range from 20 to 100 keV decreases by a factor of 10–15 for small organisms, but is relatively constant for photons with energies between 100 keV and 1 MeV. Beyond energies of 1 MeV, the absorbed fraction decreases steeply with energy.

107. The range of alpha particles in living tissue is very short, increasing from 16–130 μm within the energy range of 3–10 MeV. Therefore, with the exception of bacteria, it is assumed for all organisms that all the energy emitted is absorbed. Since the dimensions of bacteria are well below the range of alpha particles, the absorbed fraction is assumed to be zero.

108. Re-scaling factors have been derived from the computed absorbed fractions for spheres to determine the dose coefficients for ellipsoidal shaped organisms, using the mass and proportions of the organism. The relationship between the re-scaling factors and the non-sphericity parameter of the organism's body are described analytically in reference [U17]. Owing to the short range of alpha particles, the internal exposure due to incorporated alpha emitters is independent of the shape of the organism.

109. The approach was also applied to the calculation of the absorbed fractions for non-aquatic animals and their internal exposures. With the use of the absorbed fractions for spheres and the suggested re-scaling and interpolation techniques, a set of internal DCCs has been calculated for all reference animals and plants [U17].

110. The estimation of external exposures of terrestrial reference animals and plants is more complex than that of biota in the aquatic environment. The intrinsically different density and composition of soil, air and organic matter cannot, in general, be adequately taken into account by the application of analytical solutions. Dosimetric models for estimating external doses to biota in the terrestrial environment were developed within the FASSET project [F4, T10]. A key factor for determining external exposure is the geometric

relationship between the radiation source and the exposed organism. A number of limited and representative exposure situations were selected for detailed consideration.

111. Simple three-dimensional phantoms, i.e. ellipsoids and cylinders, were defined as model geometric equivalents of reference organisms based on their average mass and size characteristics. The dimensions ranged from a millimetre to a metre and the respective masses range from 0.2 g to 550 kg. The ellipsoids represented organisms such as woodlouse, earthworm, mouse, mole, snake, fox, deer and cattle. Details of the assumed exposure conditions are given in reference [T10]. The fur and the outer layers of skin consist of non-active tissue, and therefore shield the living organism.

112. Herbaceous vegetation, shrubs and trees were considered as reference plants. Exposure of the meristem and buds was calculated because these organs are characterized by very intensive cell division, which may make them highly radiosensitive.

113. In order to take account of the distribution of radionuclides in the canopy, a distinction was made between alpha, beta and gamma radiation because of their different ranges. For gamma radiation, the whole canopy was considered to have a homogeneous activity concentration. For high-energy beta radiation, the irradiation of the target was also assumed to result from a canopy with a homogeneous activity concentration. However, owing to the much shorter range of alpha and low-energy beta radiation, the irradiation resulting from external deposits on, or internal activity of, the target organ had to be considered explicitly. Because of the very short range of alpha particles in air, only the exposure due to the external deposits on, or internal exposure of, the target needed to be taken into account [T10].

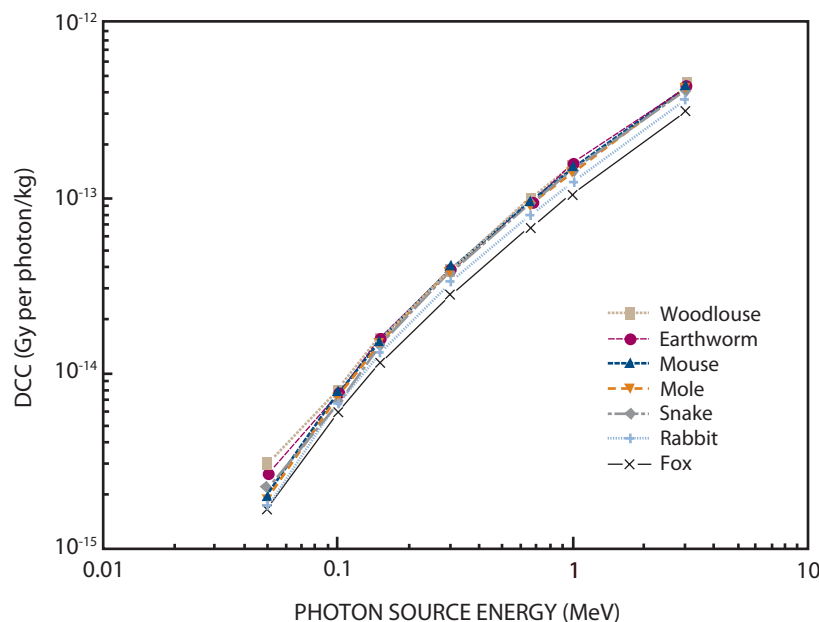
114. The elemental composition and density of the materials involved have an important impact on the radiation transport calculation. All organisms were assumed to be composed of skeletal muscle alone with the characteristics/parameters given in reference [I15]. The DCCs were derived using Monte-Carlo techniques; all relevant processes of radiation transport and interaction with matter were included. For electrons, a thick-target bremsstrahlung model was used instead of an electron-transport simulation. For the calculation of DCCs for a species in the soil, a volume source with uniform activity concentration was assumed. For the calculation of DCCs for a species on the ground, a planar radiation source on top of the soil with a surface roughness of 3 mm and a volume source with a depth of 10 cm were assumed. Calculations were made for monoenergetic gamma energies of 50 keV, 300 keV, 662 keV, 1 MeV and 3 MeV. Data for other energies were obtained by interpolation.

2. Principal relationships for internal and external exposure

(a) External exposure

115. Although the simulations cover only a limited number of possible exposure conditions, they allow the relationships between organism size, radiation energy and habitat to be deduced. The DCC (Gy per photon per kg) increases in proportion to the photon energy as illustrated in figure V for a volumetric source with a thickness of 0.5 m and target organisms that live at a depth of 0.25 m. Whereas the DCCs vary by a factor of 200 between photon energies of 50 keV to 3 MeV, the variation between the organisms does not exceed a factor of 2, even for low-energy photons (for high-energy photons, the difference is a factor of only 1.5).

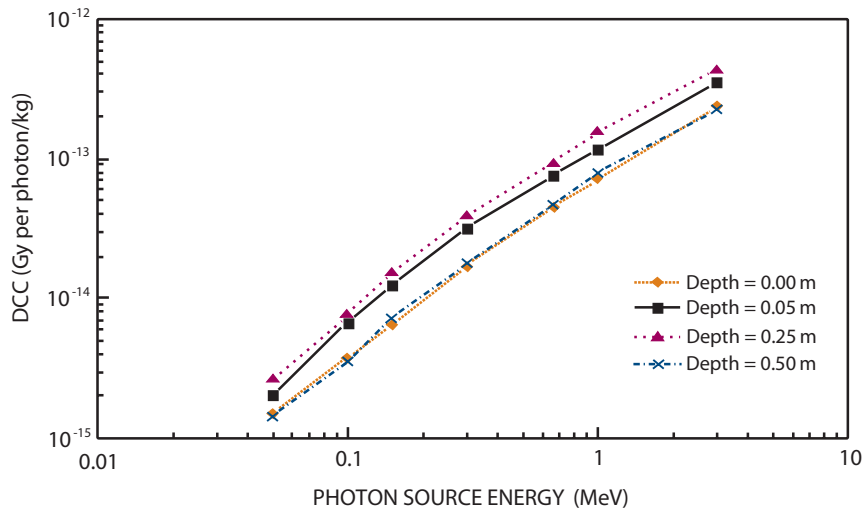
Figure V. Dose conversion coefficients for various soil organisms at a soil depth of 25 cm, for monoenergetic photons from a uniformly distributed source in the upper 50 cm of soil (soil density: 1,600 kg/m³) [F4]



116. The DCC (Gy per photon per kg) for an earthworm as a function of soil depth for monoenergetic photons is shown in figure VI. The upper 50 cm of the soil was assumed to have a homogeneous activity concentration. The maximum

DCC was found to be at a depth of 25 cm and the lowest, at depths of 0 cm and 50 cm. The maximum DCC is a factor of 2 higher than the lowest.

Figure VI. Dose conversion coefficients for an earthworm at various depths in soil, for monoenergetic photons from a uniformly distributed source in the upper 50 cm of the soil (soil density: 1,600 kg/m³) [F4]

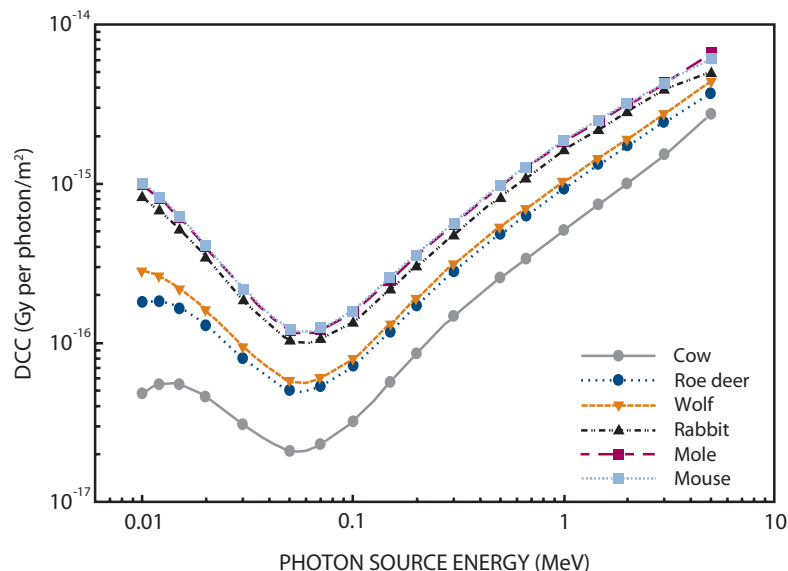


117. The DCC at a depth of 5 cm is only about 20% lower than the maximum. This is because of the relatively short mean free path of photons in soil, which is about 0.2, 2 and 10 cm for photon energies of 20 keV, 100 keV and 3 MeV, respectively. Thus, an organism in soil would be irradiated by photons originating within a surrounding shell of, at most, 10 cm radius.

118. The DCCs (Gy per photon per m²) for different reference organisms for a planar source on the soil surface are

given in figure VII. The DCCs decrease as the photon energy increases from 10 to 100 keV by a factor of about 5 for small animals and 2 for large animals. Above 100 keV, the DCCs gradually increase by approximately two orders of magnitude; the DCCs for small animals are greater than those for large animals owing to the more effective self-shielding in large organisms. Such differences are more pronounced at low energies; for example, the difference between the mouse and the cow is a factor of about 6 for 50 keV photons, whereas it is a factor of 3 for 3 MeV photons.

Figure VII. Dose conversion coefficients as a function of the source energy for various reference organisms for a planar source on top of the soil [F4]

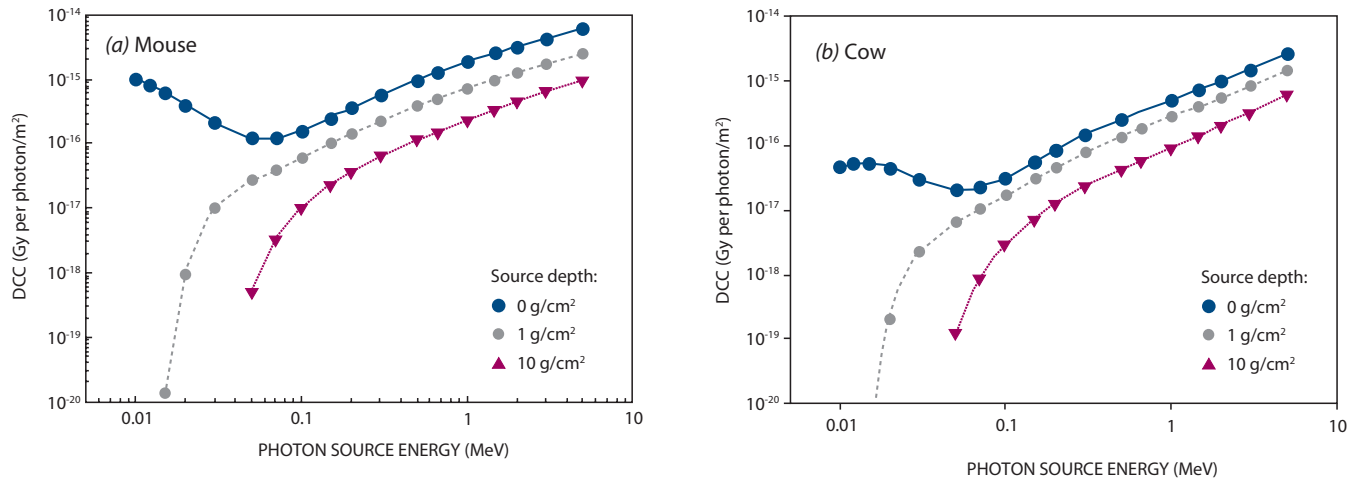


119. The DCCs for different animals as a function of the depth of a planar source in the soil are summarized in figure VIII. The results show that the DCCs for low-energy

photons for animals living on soil are low. Relatively shallow depths of soil over the planar source suffice to attenuate the photons completely.

Figure VIII. Dose conversion coefficients as a function of the source energy and depth of a planar source in the soil for (a) the mouse and (b) the cow living on the soil

The source depth quantifies the amount of soil by which the photon source is covered (e.g. the source depth of 10 g/cm² for soil densities of 1.0 and 1.6 g/cm³ are equivalent to a depth of the source in the soil of 10 and 6.25 cm, respectively) [F4]



120. The data indicate that the relationship between the DCCs, the size and habitat of the organism and the energy and type of the radiation is complex. Nevertheless, these data provide an appropriate basis for deriving data, either by interpolation or by extrapolation, for other exposure conditions that were not explicitly considered. They were used to derive radionuclide-specific DCCs ($\mu\text{Gy/h}$ per Bq/kg) for internal and external exposure of a number of reference organisms, taking into account the type of radiation as well as the energy and intensity of the emission, as specified by the ICRP [I13]. Table 14 summarizes the DCCs ($\mu\text{Gy/h}$ per Bq/kg) for external exposure. The data are provided according to the habitat of organisms considered. Animals living in soil were assumed to be at a depth of 25 cm in a soil layer that is homogeneously contaminated by radionuclides to a depth of 50 cm. Above ground organisms were assumed to be irradiated by a source homogeneously distributed in the soil layer to a depth of 10 cm. For the terrestrial organisms, only the contribution of photons was included, whereas for aquatic organisms, exposure due to electrons (including bremsstrahlung) was also implicitly taken into account. This has the effect of causing the DCCs for ^3H , ^{90}Sr and

^{135}Cs to appear to be inconsistent: the DCCs for ^3H and ^{135}Cs for terrestrial organisms are zero, whereas the values for aquatic organisms are very small. Aquatic organisms are in direct contact with the contaminated medium, whereas electrons emitted from soil are attenuated by the surface roughness of the soil, the air and the fur of terrestrial organisms. So, this apparent inconsistency is of no significant practical consequence.

(b) Internal exposure

121. The DCCs ($\mu\text{Gy/h}$ per Bq/kg) for internal exposure are provided in table 15 [U17]. The values are given in terms of weighted absorbed dose rate per unit activity concentration in the organism, assuming homogeneous distribution of the radionuclides. The DCCs have been weighted to take account of the different RBEs of the different qualities of radiation; a factor of 10 to reflect the RBE has been used for alpha radiation and a factor 1 to reflect that for gamma and beta radiation including that from tritium (see the next subsection).

Table 14. Dose conversion coefficients for external exposure of reference organisms [E10, T10, U17]

Radionuclide	Absorbed dose rates per activity concentration ($\mu\text{Gy}/\text{h}$ per Bq/kg)															
	In soil ^a				On soil ^b								In water ^c			
	Earthworm	Rat	Deer	Duck	Frog	Bee	Grass	Pine tree	Pelagic fish	Benthic fish	Brown seaweed	Crab				
³ H	0	0	0	0	0	0	0	0	7.9×10^{12}	7.8×10^{12}	8.2×10^{11}	1.0×10^{11}				
⁹⁰ Sr	1.5×10^{-10}	1.2×10^{-10}	4.6×10^{-12}	1.5×10^{-11}	1.6×10^{-11}	1.6×10^{-11}	1.6×10^{-11}	1.6×10^{-11}	2.2×10^5	4.9×10^5	2.0×10^4	2.2×10^5				
⁹⁹ Tc	0	0	0	0	0	0	0	0	1.2×10^7	1.2×10^7	1.5×10^6	1.4×10^7				
¹²⁹ I	3.5×10^6	3.0×10^6	4.0×10^7	1.1×10^6	1.1×10^6	1.1×10^6	1.1×10^6	1.1×10^6	7.7×10^6	9.2×10^6	1.3×10^5	7.9×10^6				
¹³¹ I	1.9×10^4	1.8×10^4	3.7×10^5	7.1×10^5	7.7×10^5	7.8×10^5	7.8×10^5	7.8×10^5	1.9×10^4	2.0×10^4	2.3×10^4	1.9×10^4				
¹³⁴ Cs	8.3×10^4	7.8×10^4	1.6×10^4	2.9×10^4	3.2×10^4	3.2×10^4	3.2×10^4	3.2×10^4	7.6×10^4	8.0×10^4	8.9×10^4	7.6×10^4				
¹³⁵ Cs	0	0	0	0	0	0	0	0	4.5×10^8	4.5×10^8	4.3×10^7	5.2×10^8				
¹³⁷ Cs	3.0×10^4	2.8×10^4	5.6×10^5	1.1×10^4	1.1×10^4	1.2×10^4	1.1×10^4	1.1×10^4	2.7×10^4	2.9×10^4	3.4×10^4	2.8×10^4				
²¹⁰ Pb	6.0×10^7	5.2×10^7	7.7×10^8	2.6×10^7	2.8×10^7	2.9×10^7	2.9×10^7	2.9×10^7	2.7×10^6	4.7×10^6	4.7×10^5	3.0×10^6				
²²⁶ Ra	9.0×10^4	8.5×10^4	1.8×10^4	3.2×10^4	3.4×10^4	3.5×10^4	3.4×10^4	3.4×10^4	9.1×10^4	9.6×10^4	1.1×10^3	9.1×10^4				
²³² Th	1.4×10^7	1.2×10^7	1.3×10^8	3.9×10^8	4.3×10^8	4.4×10^8	4.3×10^8	4.3×10^8	1.5×10^7	1.8×10^7	5.0×10^7	1.6×10^7				
²³⁸ U	1.2×10^7	1.0×10^7	1.0×10^8	4.3×10^8	4.8×10^8	5.0×10^8	4.9×10^8	4.9×10^8	1.0×10^7	1.3×10^7	5.1×10^7	1.1×10^7				
²³⁷ Np	7.6×10^6	7.0×10^6	1.4×10^6	3.3×10^6	3.6×10^6	3.6×10^6	3.6×10^6	3.6×10^6	1.2×10^5	1.3×10^5	1.8×10^5	1.3×10^5				
²³⁹ Pu	8.5×10^8	7.2×10^8	9.5×10^9	3.0×10^8	3.3×10^8	3.3×10^8	3.3×10^8	3.3×10^8	8.2×10^8	1.0×10^7	3.0×10^7	8.7×10^8				
²⁴⁰ Pu	1.6×10^7	1.3×10^7	1.4×10^8	5.4×10^8	6.0×10^8	6.2×10^8	6.1×10^8	6.1×10^8	1.4×10^7	1.9×10^7	6.8×10^7	1.6×10^7				
²⁴¹ Am	6.1×10^6	5.5×10^6	9.2×10^7	2.4×10^6	2.6×10^6	2.6×10^6	2.6×10^6	2.6×10^6	1.1×10^5	1.2×10^5	1.7×10^5	1.1×10^5				

^a Organisms are assumed to live at 25 cm depth of a soil with radionuclides distributed homogeneously to a depth of 50 cm.

^b Organisms are assumed to live on a soil layer with radionuclides distributed homogeneously to a depth of 10 cm.

^c Organisms are assumed to be immersed in water.

Table 15. Weighted dose conversion coefficients for internal exposure of reference organisms [T10, U20]

Radionuclide	Weighted absorbed dose rates per activity concentration ($\mu\text{Gy/h per Bq/kg}$) ^{a,b}											
	Earthworm	Rat	Deer	Duck	Frog	Bee	Grass	Pine tree	Pelagic fish	Benthic fish	Brown seaweed	Crab
³ H	3.3×10^{-6}											
³⁶ Cl	1.5×10^{-4}	1.6×10^{-4}	1.6×10^{-4}	1.6×10^{-4}	1.6×10^{-4}	1.5×10^{-4}	1.5×10^{-4}	1.6×10^{-4}	1.6×10^{-4}	1.6×10^{-4}	1.4×10^{-4}	1.6×10^{-4}
⁹⁰ Sr	5.3×10^{-4}	6.2×10^{-4}	6.5×10^{-4}	6.3×10^{-4}	5.9×10^{-4}	4.4×10^{-4}	5.1×10^{-4}	6.5×10^{-4}	6.3×10^{-4}	6.0×10^{-4}	4.5×10^{-4}	6.3×10^{-4}
⁹⁹ Tc	5.8×10^{-5}	5.8×10^{-5}	5.8×10^{-5}	5.8×10^{-5}	5.8×10^{-5}	5.7×10^{-5}	5.8×10^{-5}	5.8×10^{-5}	5.8×10^{-5}	5.8×10^{-5}	5.7×10^{-5}	5.8×10^{-5}
¹²⁹ I	3.8×10^{-5}	4.2×10^{-4}	5.0×10^{-5}	4.4×10^{-5}	3.9×10^{-5}	3.7×10^{-5}	3.8×10^{-5}	5.0×10^{-5}	4.3×10^{-5}	4.2×10^{-5}	3.8×10^{-5}	4.3×10^{-5}
¹³¹ I	1.1×10^{-4}	1.4×10^{-4}	2.6×10^{-4}	1.5×10^{-4}	1.2×10^{-4}	1.1×10^{-4}	1.1×10^{-4}	2.5×10^{-4}	1.4×10^{-4}	1.3×10^{-4}	1.0×10^{-4}	1.4×10^{-4}
¹³⁴ Cs	1.1×10^{-4}	1.9×10^{-4}	7.1×10^{-4}	2.5×10^{-4}	1.4×10^{-4}	9.9×10^{-5}	1.1×10^{-4}	6.5×10^{-4}	2.3×10^{-4}	1.9×10^{-4}	9.7×10^{-5}	2.3×10^{-4}
¹³⁵ Cs	3.9×10^{-5}	3.9×10^{-5}	3.9×10^{-5}	3.9×10^{-5}	3.9×10^{-5}	3.8×10^{-5}	3.9×10^{-5}	3.9×10^{-5}	3.9×10^{-5}	3.9×10^{-5}	3.8×10^{-5}	3.9×10^{-5}
¹³⁷ Cs	1.5×10^{-4}	1.8×10^{-4}	3.7×10^{-4}	2.0×10^{-4}	1.6×10^{-4}	1.4×10^{-4}	1.4×10^{-4}	3.5×10^{-4}	1.9×10^{-4}	1.8×10^{-4}	1.3×10^{-4}	1.9×10^{-4}
²¹⁰ Pb	2.3×10^{-4}	2.4×10^{-4}	2.5×10^{-4}	2.5×10^{-4}	2.4×10^{-4}	2.2×10^{-4}	2.3×10^{-4}	2.5×10^{-4}	2.5×10^{-4}	2.4×10^{-4}	2.0×10^{-4}	2.5×10^{-4}
²²⁶ Ra	1.3×10^{-1}	1.3×10^{-1}	1.4×10^{-1}	1.4×10^{-1}	1.3×10^{-1}	1.4×10^{-1}	1.3×10^{-1}	1.4×10^{-1}	1.4×10^{-1}	1.3×10^{-1}	1.4×10^{-1}	1.4×10^{-1}
²³² Th	2.3×10^{-2}											
²³⁸ U	2.4×10^{-2}											
²³⁷ Np	2.7×10^{-2}											
²³⁸ Pu	3.0×10^{-2}											
²⁴⁰ Pu	3.0×10^{-2}											
²⁴¹ Am	3.2×10^{-2}											

^a Assumes a homogeneous activity distribution in the organism.

^b Assumes an RBE of 10 for alpha and 1 for beta.

(c) Relative biological effectiveness

122. The effects of radiation exposure on biota depend not only on the absorbed dose, but also on the type or quality of the radiation. For example, alpha particles and neutrons can produce observable damage at much lower absorbed doses than beta or gamma radiation. Thus, the absorbed dose (in gray) is often multiplied by a factor in order to account for the RBE of the quality of the radiation.

123. A number of authors have evaluated the data on the RBE of different types of radiation [A1, C1, E2, F4, T7, U4, U26]. Nominal values for the factor to reflect the RBE of alpha particles derived from these reviews are

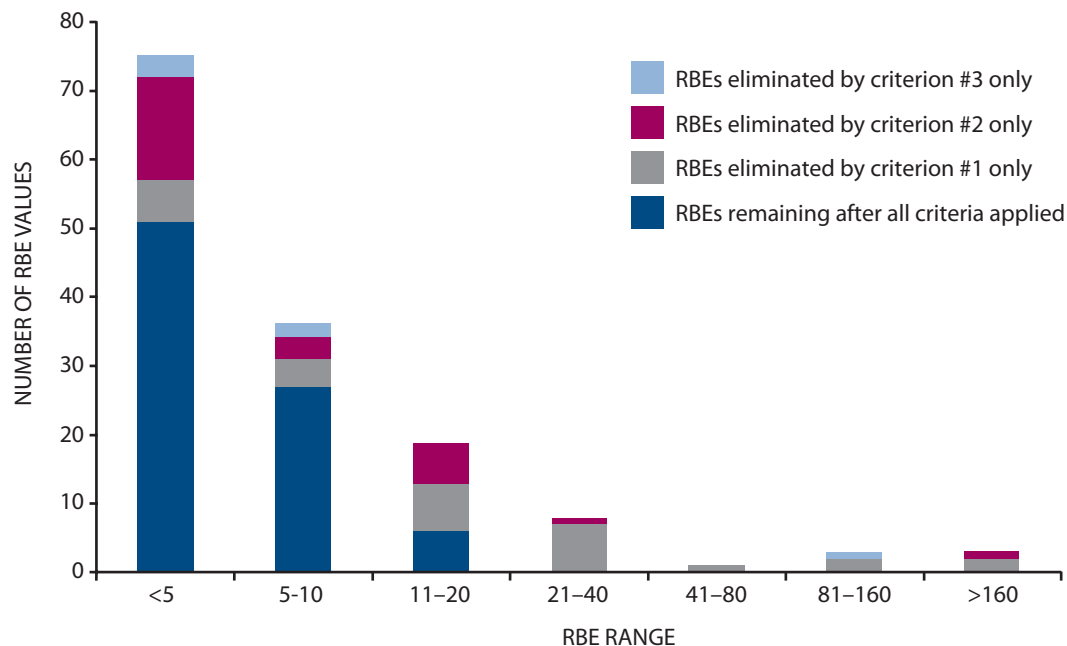
summarized in table 16. The experimental values of RBE are specific to the endpoint studied, the biological, environmental and exposure conditions (e.g. reference radiation, dose rate, and dose) amongst other factors. Thus, as noted in a FASSET report [F4], it is difficult to develop a generally valid factor to reflect the RBE for different radiation qualities for use in an environmental risk assessment. The ACRP [A1] and FASSET [F4] have therefore proposed ranges of values for general application. Both selected a factor of 10 to reflect the RBE for alpha particles, the ACRP, citing references [K2, T7, U4], referring to it as a notional central value, and FASSET as a value “to illustrate” the impact of the RBE for an internally deposited alpha emitter.

Table 16. Modifying factors to reflect the RBE of alpha radiation for deterministic effects on non-human biota (relative to low-LET radiation)

Source	Nominal value	Comment
[N1]	1	Built-in conservatism in dose model
[I4]	20	Numerically the same as the radiation weighting factor used in the protection of humans
[B22]	2–10	Non-stochastic effect of neutrons and heavy ions
[U4]	5	Average for deterministic effects
[T7]	10	Deterministic population-relevant endpoints
[C1]	20	Likely to be conservative for deterministic effects
[E3]	40	Includes studies with high RBE values
[E12]	<35	Based on concentrations in the whole body
[A1]	5–20 (10)	5–10 deterministic effects (cell-killing, reproductive) 10–20 cancer, chromosome abnormalities 10 nominal central value
[F4]	5–50 (10)	10 to illustrate the effect of the alpha RBE
[K19]	<7 to <35	Upper bound of estimate of RBE

124. Chambers et al. [C5] reported a review of the literature on experimentally determined RBEs for internally deposited alpha-emitting radionuclides. The relevance of each experimental result in selecting a factor to reflect the RBE for alpha particles was judged on the basis of pre-established criteria. They recommended a nominal factor of 5 to reflect the RBE for alpha particles for population-relevant deterministic and stochastic endpoints but, to reflect the limitations in the experimental data, they also suggested uncertainty ranges of 1–10 and 1–20 for population-relevant deterministic and stochastic endpoints, respectively. The

data developed by Chambers et al. [C5] after application of their evaluation criteria are summarized in figure IX. Three evaluation criteria were used in reference [C5]. Criterion 1 required the dosimetric conditions to be sufficiently well defined and not peculiar to the source of radiation. Criterion 2 required the dose–effect relationships to be sufficiently well known so that the results from the dose rates used experimentally can be applied to effects that may occur with environmental dose rates. Criterion 3 required the experimental uncertainties to be discussed by the authors of the original studies.

Figure IX. Application of the criteria to the distribution of RBEs (all endpoints) [C5]

125. Knowles [K19] reported on experimental studies on groups of zebra fish that were exposed from an early age to different dose rates of gamma and alpha radiation (the latter was from ^{210}Po). Among the gamma-irradiated fish, only those in the highest dose-rate group (7,400 mGy/h) showed radiation-related damage. No groups of alpha-irradiated fish showed evidence of radiation-induced reduction in egg production even though autoradiographs showed concentrations of ^{210}Po in the testes and ovaries. Since the highest alpha dose rate (214 mGy/h) showed no effect, comparison with the gamma dose rate of 7,400 mGy/h, which caused egg production to cease, resulted in only upper limits to the RBE. These were calculated to be in the range of <7 to <20 based on ovary concentrations and <35 based on whole body concentrations. The authors suggested that the RBEs derived from their work provide the best available (upper bound) estimates for a population-relevant effect for fish.

126. The ACRP [A1] considered tritium beta radiation because the low velocity of the beta particles (maximum energy = 18.6 keV) results in a relatively high LET over a short path length. It has an LET very similar to that of 70 keV photons, which are representative of the X-rays used in radiobiological research and in diagnostic medicine [M6]. In their review of the effects of tritiated water (HTO) in mammals and fish, Environment Canada in their Priority Substances List (PSL2) [E3] listed tritium RBE values ranging from 1.7 to 3.8, with gamma rays from ^{60}Co or ^{137}Cs being used as the reference radiation. Based on this, they recommended a factor of 3 to reflect the RBE of beta radiation from tritium. Research conducted at Atomic Energy of Canada Ltd. on breast cancers in female rats [G1] and on myeloid leukaemia in male mice indicated an RBE value of 1.2 for tritium, with X-rays being used as the reference

radiation. The difference between these values is largely the result of the choice of reference radiation. Sinclair [S8] has shown that, at low doses, X-rays are about twice as effective as gamma rays in producing damage. Hence, the radiation from tritium has an effectiveness for biological damage in the higher part of the range expected for the gamma and X-ray photon energies likely to be experienced in the environment. Citing Straume and Carsten [S9] amongst others, the ACRP concluded that for the dosimetry of non-human species, where the endpoints are usually deterministic in nature, a reasonable average factor to reflect the RBE of beta particles may be 2 with a range of 1–3, depending on the endpoint being assessed [A1].

127. A number of studies suggested that beta radiation with energies below 10 keV has a higher RBE than electrons with energies above 10 keV [M10, S9]. Straume and Carsten [S9] reviewed 33 studies of the RBE of tritium beta particles and found arithmetic means of 1.8 based on X-rays as the reference radiation, and 2.3 with ^{137}Cs or ^{60}Co gamma rays as the reference radiation. Most of these studies related to deterministic effects. Moiseenko et al. [M10] considered an appropriate factor to reflect the RBE of beta particles from tritium (mean beta energy <10 keV) to be between 2 and 3. The UK Health Protection Agency (HPA) [H21] reviewed the RBE studies on tritium beta particles along with a wide variety of experimental studies using X-rays and gamma rays as reference radiations and noted that the RBEs generally ranged from 1 to 2 when compared to orthovoltage X-rays and from 2 to 3 when compared to gamma rays [H21]. Little and Lambert [L9] also reviewed the experimental studies of cancer induction, chromosomal aberration, cell death and various other endpoints and arrived at similar conclusions for the RBE of tritium in water.

128. In order to illustrate the effect of the radiation quality of emissions from internally deposited radionuclides, the FASSET programme recommended the use of a factor of 10 to reflect the RBE of alpha radiation, 3 for low-energy beta radiation ($E < 10$ keV), and 1 for both beta radiation with energies greater than 10 keV and for gamma radiation [F4, L4].

129. The Committee, in its UNSCEAR 1996 Report [U4], recommended a nominal factor of 5 to reflect the RBE for internally deposited alpha emitters. The Committee now recommends a nominal (generic) factor of 10 to reflect the RBE for internally deposited alpha radiation. For beta and gamma radiation, the Committee recommends a nominal (generic) factor of 1 to reflect the RBE. However, it should be understood that the most appropriate factor to reflect the RBE for low-energy (<10 keV) beta radiation remains an open question and ought to be the subject of future research. These recommended values to reflect the RBE are intended to apply on a generic basis across all organisms and endpoints. Where appropriate scientific information specific to a particular organism and endpoint exists, such information is preferred.

(d) *Dose rates for internal exposure*

130. The dose from unit exposure of the selected reference organisms is estimated from the weighted absorbed dose rate due to external exposure arising from deposits in the ground and that due to internal exposure. Weighted absorbed dose rates to the reference organisms normalized for continuous exposure to 1 Bq/m³ in air for each radionuclide are given in table 17. These weighted absorbed dose rates were calculated assuming the factors to reflect the RBE recommended by the Committee. Table 18 summarizes the ratios of weighted to non-weighted normalized total doses. The

results are particularly sensitive to the choice of factor, especially for radiation from the actinides and tritium. The contributions of weighted internal doses to the total normalized doses are close to or above 90%, which indicates that internal exposure is the dominant pathway.

131. These annual doses took account of external exposure as well as internal exposure via inhalation and ingestion. They are compared with the weighted absorbed doses to biota in table 19. The ranges given in the table for biota reflect the variations between the different reference organisms considered. This comparison has however some inherent limitations. The values for humans are expressed in terms of annual effective dose, whereas the values for biota are in terms of weighted absorbed dose and were estimated assuming a homogeneous distribution of the radionuclide in the organism. Furthermore, the annual effective doses per unit deposition to humans were based on a radiation weighting factor of 20 for alpha particles, whereas the weighted absorbed doses to biota were based on a factor of 10 to reflect the RBE for alpha particles. Further still, the values for humans reflect largely the transfer of radionuclides through agricultural ecosystems, whereas the values for biota are more typical of the transfer in forests and semi-natural ecosystems.

132. Despite these differences, the estimated normalized effective doses to humans and the weighted absorbed doses to biota are about the same order of magnitude, except in the cases of ¹²⁹I and ¹³¹I. These exceptions are probably due to the special importance of radiation exposure of the human thyroid in evaluating effective dose, which has no counterpart in the dosimetry for biota. Thus, apart from these exceptions, the comparison indicates that for similar levels of radionuclides in the environment, the effective doses to humans and the weighted absorbed doses to biota are comparable.

Table 17. Normalized weighted absorbed dose rates per unit activity concentration to various biota from internal exposure

Radionuclide	Weighted dose rate per unit activity concentration ($\mu\text{Gy/h per Bq/m}^3$)							
	Earthworm	Rat	Deer	Duck	Frog	Bee	Grass	Pine tree
³ H	1.7×10^{-19}	1.7×10^{-19}	1.7×10^{-19}	1.7×10^{-19}	1.7×10^{-19}	1.7×10^{-19}	1.7×10^{-19}	1.7×10^{-19}
³⁶ Cl	5.6×10^{-15}	3.3×10^{-13}	3.3×10^{-13}	3.3×10^{-13}	3.3×10^{-13}	9.3×10^{-15}	5.4×10^{-13}	5.5×10^{-14}
⁹⁰ Sr	6.1×10^{-15}	1.2×10^{-12}	1.3×10^{-12}	7.3×10^{-13}	7.5×10^{-13}	5.1×10^{-14}	1.8×10^{-13}	4.3×10^{-13}
⁹⁹ Tc	4.4×10^{-15}	4.4×10^{-15}	4.4×10^{-15}	4.4×10^{-15}	4.4×10^{-15}	4.4×10^{-15}	2.4×10^{-13}	4.8×10^{-15}
¹²⁹ I	2.3×10^{-14}	4.8×10^{-14}	4.9×10^{-14}	4.5×10^{-14}	4.0×10^{-14}	2.9×10^{-14}	1.7×10^{-14}	2.1×10^{-14}
¹³¹ I	4.6×10^{-16}	1.3×10^{-15}	1.8×10^{-15}	4.2×10^{-16}	3.4×10^{-16}	1.9×10^{-16}	1.6×10^{-15}	2.8×10^{-15}
¹³⁴ Cs	1.7×10^{-13}	2.7×10^{-13}	4.5×10^{-13}	9.7×10^{-14}	8.1×10^{-14}	6.6×10^{-14}	8.7×10^{-14}	1.2×10^{-13}
¹³⁵ Cs	8.3×10^{-15}	2.7×10^{-13}	2.7×10^{-13}	7.1×10^{-14}	5.4×10^{-14}	5.0×10^{-15}	6.7×10^{-14}	1.7×10^{-14}
¹³⁷ Cs	4.7×10^{-13}	4.4×10^{-13}	1.1×10^{-13}	1.9×10^{-13}	2.0×10^{-13}	2.0×10^{-13}	1.9×10^{-13}	2.3×10^{-13}
²¹⁰ Pb	2.9×10^{-14}	9.4×10^{-15}	9.2×10^{-15}	1.2×10^{-14}	1.2×10^{-14}	1.1×10^{-14}	1.3×10^{-14}	8.7×10^{-16}
²²⁶ Ra	5.0×10^{-12}	2.1×10^{-12}	4.7×10^{-13}	8.9×10^{-13}	9.3×10^{-13}	3.7×10^{-12}	1.5×10^{-11}	1.3×10^{-12}
²³² Th	4.9×10^{-13}	6.4×10^{-15}	5.6×10^{-15}	2.8×10^{-14}	2.8×10^{-14}	4.9×10^{-13}	8.4×10^{-13}	4.0×10^{-13}
²³⁸ U	5.8×10^{-12}	2.4×10^{-12}	2.4×10^{-12}	2.4×10^{-12}	2.4×10^{-12}	7.5×10^{-12}	9.9×10^{-13}	1.8×10^{-11}
²³⁷ Np	1.9×10^{-12}	1.5×10^{-12}	1.5×10^{-12}	1.5×10^{-12}	1.5×10^{-12}	4.0×10^{-12}	4.1×10^{-12}	4.9×10^{-12}
²³⁹ Pu	2.1×10^{-12}	1.7×10^{-12}	1.7×10^{-12}	1.7×10^{-12}	1.7×10^{-12}	4.4×10^{-12}	4.5×10^{-12}	5.4×10^{-12}
²⁴⁰ Pu	7.2×10^{-12}	2.9×10^{-12}	2.9×10^{-12}	2.9×10^{-12}	2.9×10^{-12}	9.3×10^{-12}	3.9×10^{-12}	3.1×10^{-12}
²⁴¹ Am	8.8×10^{-14}	8.6×10^{-14}	7.6×10^{-14}	7.9×10^{-14}	8.0×10^{-14}	8.0×10^{-14}	3.7×10^{-12}	3.3×10^{-12}

Table 18. Ratio of weighted and unweighted doses

Radionuclide	Ratio of weighted dose/unweighted dose ^a							
	Earthworm	Rat	Deer	Duck	Frog	Bee	Grass	Pine tree
³ H	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
³⁶ Cl	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
⁹⁰ Sr	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
⁹⁹ Tc	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
¹²⁹ I	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
¹³¹ I	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
¹³⁴ Cs	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
¹³⁵ Cs	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
¹³⁷ Cs	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
²¹⁰ Pb	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
²²⁶ Ra	2.0	1.0	1.1	1.2	1.1	3.3	7	2
²³² Th	9.9	7.1	9.5	9.7	9.7	10	10	10
²³⁸ U	10	10	10	10	10	10	10	10
²³⁷ Np	9.1	8.9	9.6	9.4	9.3	9.6	9.6	9.7
²³⁹ Pu	10	10	10	10	10	10	10	10
²⁴⁰ Pu	10	10	10	10	10	10	10	10
²⁴¹ Am	4.1	4.3	7.9	6.1	5.9	5.9	10	10

^a Factors to reflect the RBE: alpha radiation, 10; beta and gamma radiation, 1.

Table 19. Comparison of doses to biota and humans, normalized for unit deposition to terrestrial ecosystems

Radionuclide	Biota (range) ^a Normalized weighted absorbed dose rate (Gy a ⁻¹ per Bq m ⁻² a ⁻¹)		Humans ^b Normalized effective dose rate (Sv a ⁻¹ per Bq m ⁻² a ⁻¹)
	Minimum	Maximum	
⁹⁰ Sr	6.2 × 10 ⁻⁹	1.3 × 10 ⁻⁶	4.7 × 10 ⁻⁷
⁹⁹ Tc	4.4 × 10 ⁻⁹	2.5 × 10 ⁻⁷	1.8 × 10 ⁻⁸
¹²⁹ I	1.7 × 10 ⁻⁸	5.0 × 10 ⁻⁸	6.3 × 10 ⁻⁷
¹³¹ I	2.0 × 10 ⁻¹⁰	2.8 × 10 ⁻⁹	1.0 × 10 ⁻⁷
¹³⁴ Cs	6.7 × 10 ⁻⁸	4.6 × 10 ⁻⁷	1.3 × 10 ⁻⁷
¹³⁵ Cs	5.1 × 10 ⁻⁹	2.8 × 10 ⁻⁷	1.2 × 10 ⁻⁸
¹³⁷ Cs	1.1 × 10 ⁻⁷	4.8 × 10 ⁻⁷	1.3 × 10 ⁻⁷
²¹⁰ Pb	8.9 × 10 ⁻¹⁰	2.9 × 10 ⁻⁸	2.5 × 10 ⁻⁶
²²⁶ Ra	4.8 × 10 ⁻⁷	1.5 × 10 ⁻⁵	1.6 × 10 ⁻⁶
²³² Th	5.6 × 10 ⁻⁹	8.5 × 10 ⁻⁷	1.2 × 10 ⁻⁶
²³⁸ U	1.0 × 10 ⁻⁶	1.8 × 10 ⁻⁵	6.0 × 10 ⁻⁷
²³⁷ Np	1.5 × 10 ⁻⁶	5.0 × 10 ⁻⁶	4.9 × 10 ⁻⁷
²³⁹ Pu	1.7 × 10 ⁻⁶	5.5 × 10 ⁻⁶	6.8 × 10 ⁻⁷
²⁴⁰ Pu	3.0 × 10 ⁻⁶	9.5 × 10 ⁻⁶	6.8 × 10 ⁻⁷
²⁴¹ Am	7.7 × 10 ⁻⁸	3.8 × 10 ⁻⁶	5.8 × 10 ⁻⁷

^a Range represents the minimum and maximum among the organisms considered.

^b Calculated according to [111].

3. Doses to non-human biota

(a) Calculation of doses to biota

133. In terrestrial environments, the most important source of radiation exposure as a consequence of discharges of radionuclides to the environment is due to deposition on soil. Radionuclides present in soil are generally a persistent radiation source for all terrestrial biota. Aquatic organisms are irradiated externally by the activity in water and, in the cases of bottom dwellers and benthic organisms, the activity in sediments, and internally by incorporated radionuclides. The dose rate, D , can be calculated according to:

$$D = \sum_r [DCC_{ext,r} \cdot C_{soil,water,r} + DCC_{int,r} \cdot C_{biota,r}] \quad (5)$$

where $DCC_{ext,r}$ is the DCC for external exposure to radionuclide r ($\mu\text{Gy/h per Bq/kg}$); $C_{soil,water,r}$ is the activity concentration of radionuclide r in soil or water (Bq/kg); $DCC_{int,r}$ is the DCC for internal exposure to radionuclide r ($\mu\text{Gy/h per Bq/kg}$); and $C_{biota,r}$ is the internal activity concentration of radionuclide r in biota (flora or fauna) (Bq/kg).

(b) Activities in environmental media

134. In the absence of measurements, in order to evaluate equation (5), the activity concentrations, $C_{soil,water,r}$, and $C_{biota,r}$, have to be estimated. Assuming a constant discharge of radionuclides over a period of 50 years, the activity in soil for the last year of that period is calculated as indicated in reference [I11]:

$$C_{s,r} = \frac{D_{tot,r}}{(\lambda_r + \lambda_m) \cdot m_s} \cdot [1 - \exp(-(\lambda_r + \lambda_m) \cdot t_e)] \quad (6)$$

where $C_{s,r}$ is the activity concentration in soil (Bq/kg); $D_{tot,r}$ is the total (wet plus dry) deposition rate to soil ($\text{Bq m}^{-2} \text{a}^{-1}$); m_s is the mass of the upper soil layer (kg/m^2); λ_r is the radioactive decay constant (a^{-1}); λ_m is the loss rate from the upper soil layer (a^{-1}); and t_e is the discharge period (50 a).

135. The total deposition is calculated as the sum of dry ($D_{dry,r}$) and wet deposition ($D_{wet,r}$). The activity concentration in flora, $C_{flora,r}$, is estimated by taking into account direct deposition on the foliage and uptake from soil according to reference [I11]:

$$C_{flora,r} = \frac{D_{dry,r} + f_w \cdot D_{wet,r}}{(\lambda_{w,r} + \lambda_r) \cdot b} \cdot [1 - \exp(-(\lambda_{w,r} + \lambda_r) \cdot t_w)] + C_{s,r} \cdot TF_{flora,r} \quad (7)$$

where f_w is the interception fraction (dimensionless); b is the standing biomass (kg/m^2); $\lambda_{w,r}$ is the activity loss rate from plants due to weathering (a^{-1}); t_w is the exposure time (a); and

$TF_{flora,r}$ is the transfer factor from soil to flora ($\text{Bq/kg flora per Bq/kg soil}$).

136. The activity concentration in reference fauna is estimated from the soil concentration and the soil–fauna transfer factor as follows:

$$C_{fauna,r} = C_{s,r} \cdot TF_{fauna,r} \quad (8)$$

where $TF_{fauna,r}$ is the soil–fauna transfer factor ($\text{Bq/kg fauna per Bq/kg soil}$).

137. The habitats of the reference fauna are differentiated according to whether the organisms live in or above soil. DCCs for species living in soil are expressed in units of $\mu\text{Gy/h per Bq/kg}$ and are based on the assumption that the organism lives in the centre of a slab containing radionuclides uniformly distributed to a depth of 50 cm. For organisms living on soil, it is assumed that radionuclides are homogeneously distributed to a depth of 10 cm; the DCCs in this case have units of $\mu\text{Gy/h per Bq/m}^2$.

138. The estimation of the activity concentration of a radionuclide in aquatic biota ($C_{aqua biota}$) is usually obtained from the activity concentration in water (C_{water}) and the concentration factor ($CF_{water-biota}$) according to:

$$C_{aqua biota} = C_{water,r} \cdot CF_{water-biota,r} \quad (9)$$

139. As outlined above, the exposure due to incorporated radionuclides is determined by the size and geometry of the organism, the radionuclide distribution, and the type and energy of the emitted radiation. Currently, DCCs are not available for specific target organs in the reference organisms; the DCCs for internal exposure are therefore based on the assumption that the radionuclides are homogeneously distributed throughout the organism [T10].

(c) Doses to marine organisms and to humans due to consumption of marine food

140. As an example of the calculations of exposures of aquatic organisms, the exposures to marine organisms are calculated assuming a radionuclide concentration in water of 1 Bq/m^3 and applying the appropriate concentration factor for water–biota in table 13 and the appropriate DCCs given in tables 14 and 15. The weighted absorbed dose rates to flatfish, crab and brown seaweed are summarized in table 20. For all radionuclides considered, the dose rates to biota are almost completely a result of internal exposure. For comparison, the effective dose rates to an adult human are given assuming an annual fish intake of 20 kg. In general, the effective dose rates to humans are much less than the weighted absorbed dose rates to biota for a unit activity concentration of a radionuclide in marine water.

Table 20. Comparison of doses to non-human biota and humans, normalized to an activity concentration in marine water of 1 Bq/m³

Radionuclide	Non-human biota			Humans ^a
	Weighted absorbed dose rate ($\mu\text{Gy/h per Bq/m}^3$)			Normalized effective dose rate ($\mu\text{Sv/h per Bq/m}^3$)
	Flatfish	Crab	Macroalgae	
³ H	3.3×10^{-9}	3.3×10^{-9}	3.3×10^{-9}	4.1×10^{-11}
³⁶ Cl	9.6×10^{-9}	9.6×10^{-9}	7.0×10^{-9}	1.3×10^{-10}
⁹⁰ Sr	1.8×10^{-6}	6.3×10^{-6}	4.5×10^{-6}	1.9×10^{-7}
⁹⁹ Tc	4.6×10^{-6}	5.8×10^{-5}	1.7×10^{-4}	1.2×10^{-7}
¹²⁹ I	3.8×10^{-7}	4.3×10^{-6}	3.8×10^{-4}	2.3×10^{-6}
¹³¹ I	1.2×10^{-6}	1.4×10^{-5}	1.0×10^{-3}	4.5×10^{-7}
¹³⁴ Cs	1.9×10^{-5}	6.9×10^{-6}	4.9×10^{-6}	4.3×10^{-6}
¹³⁵ Cs	3.9×10^{-6}	1.2×10^{-6}	1.9×10^{-6}	4.6×10^{-7}
¹³⁷ Cs	1.8×10^{-5}	5.7×10^{-6}	6.5×10^{-6}	3.0×10^{-6}
²¹⁰ Pb	4.8×10^{-5}	2.3×10^{-3}	8.0×10^{-4}	3.2×10^{-4}
²²⁶ Ra	1.3×10^{-2}	1.4×10^{-2}	1.4×10^{-2}	6.4×10^{-5}
²³² Th	1.4×10^{-2}	2.3×10^{-2}	4.6×10^{-3}	3.2×10^{-4}
²³⁸ U	2.4×10^{-5}	2.4×10^{-4}	2.4×10^{-3}	1.0×10^{-7}
²³⁷ Np	2.7×10^{-3}	2.7×10^{-3}	1.4×10^{-3}	2.5×10^{-5}
²³⁹ Pu	3.0×10^{-3}	6.0×10^{-3}	1.2×10^{-1}	5.7×10^{-5}
²⁴⁰ Pu	3.0×10^{-3}	6.0×10^{-3}	1.2×10^{-1}	5.7×10^{-5}
²⁴¹ Am	3.2×10^{-3}	1.3×10^{-2}	2.5×10^{-1}	4.6×10^{-5}

^a For an intake of marine fish of 20 kg/a.

4. Conclusions

141. In this section, approaches have been described for the assessment of exposures of flora and fauna to radiation from natural background levels of radionuclides or regulated discharges of radionuclides to the environment. The models cover two major fields. One is concerned with the transport processes of radionuclides from the source to plants and animals, to which approaches may be applied that are similar to those used to assess the exposures of humans. In the terrestrial environment, these are mainly atmospheric dispersion, deposition, interception, weathering and uptake from soil. For discharges to aquatic systems, models can be used that describe dispersion, dilution, sedimentation and uptake by freshwater or marine organisms.

142. There are major differences in the dosimetry involved in the assessment of the exposures of humans and non-human biota. The current approaches for biota rely on the mean activity concentrations in the whole organism rather than on those in distinct organs or tissues. Thus, the calculated absorbed doses are to the whole organism. There is an ongoing discussion about the appropriate factors to be applied in order to account for the different RBEs of the different kinds of radiation involved. Example calculations in this annex show that the estimated weighted absorbed doses from exposure to alpha radiation are sensitive to the value of the factor used. This is relevant to the assessment of doses to biota both as a result of radioactive discharges from

a nuclear site and as a result of exposure to radiation from radionuclides that are naturally present in the environment.

143. The estimated doses to biota are compared in this annex with those to humans in accordance with the approach given in reference [U3]. The comparison shows that the weighted absorbed doses to terrestrial non-human biota and the effective doses to humans are generally of a similar order of magnitude, for a given level of environmental contamination by radionuclides. The weighted absorbed doses to marine biota are, in general, considerably higher than the effective doses to humans (for whom an annual consumption of marine fish of 20 kg is assumed for illustrative purposes).

144. The results of the dosimetric calculations presented in this annex are based on stylized models of ecosystems using average values for most of the model parameters. Thus, they do not accurately reflect the variability of ecosystems and the processes present in nature that control the environmental mobility of radionuclides. In addition, the exposures due to the various sources of natural background radiation and their variabilities would have to be included if the results presented in this annex were to be used in a site-specific assessment. As indicated earlier, there are substantial uncertainties associated with the estimation of dose rates to non-human biota, including those associated with the environmental pathways (such as in the values of the transfer factors) and those related to dosimetric issues.

II. SUMMARY OF DOSE-EFFECTS DATA FROM THE UNSCEAR 1996 REPORT

145. In the absence of reports of obvious deleterious effects on other organisms from exposure to environmental radiation, whether of natural origin or due to the controlled discharges of radionuclides to the environment, it had generally been accepted that priority should be given to evaluating the potential consequences for humans (which are among the most radiosensitive mammalian species) and to providing a sound basis for protecting human health. By 1996, this position had, however, been questioned [D1, T1], and at least one situation (namely deep-sea sediments, an environment very remote from man) had been identified where the above accepted priority could be incorrect [I3]. In response to such concerns, the Committee noted that the impact of radiation exposure of non-human biota had been studied in a number of situations [I2, I3, I4, M1, N1, W1, W2] and considered that it was appropriate to conduct an independent review of the matter and to summarize the state of knowledge existing at that time. The UNSCEAR 1996 Report [U4] took account of the earlier reviews and studies and the Committee's summaries of the radiobiological work carried out over the previous 50 years.

146. In its 1996 report, the Committee noted that there was a fundamental difference in the approaches to the protection of humans and non-human biota from the effects of exposure to ionizing radiation. For humans, ethical considerations had made the individual the principal object of protection. This meant, in practice, that any incremental risk to the individual arising from increased radiation exposure was to be constrained below some level that society judged to be acceptable; this level of risk, although small, was not zero [I5]. For non-human biota, the populations of the biota were considered to be important and protection from a significantly increased risk to each population arising from radiation exposure might be the appropriate objective. Exceptions might be populations of small size (rare species) or those reproducing slowly (i.e. with long generation times and/or low fecundity) for which protective measures might be more appropriately targeted at the level of the individual organism. The Committee noted that there could not be any effect at the population level (or at the higher levels of community and ecosystem) if there were no effects on the individual organisms constituting the different populations. It went on to suggest that radiation-induced effects on some members of a population would not necessarily have any significant consequences for the population as a whole.

147. The Committee noted that natural populations of organisms existed in a state of dynamic equilibrium within their communities and environments and that exposure to ionizing radiation was but one of the stresses that may affect this equilibrium. The incremental radiation exposure from human activities could not, therefore, be considered in isolation from other sources of stress, whether natural (e.g. climate, altitude, or volcanic activity) or of human origin (e.g. synthetic chemical toxins, oil discharges, exploitation for

food or sport, or habitat destruction). When (as is not uncommon) ionizing radiation and chemicals, both resulting from human activities, acted together on a population, the difficult problem arose of correctly attributing any observed response to a specific cause.

148. The objective of the UNSCEAR 1996 Report on the "Effects of radiation on the environment" [U4] was to summarize and review information on:

- The exposures (actual or potential) of organisms in their natural habitats to the natural background radiation, to radionuclides discharged into the environment in a controlled manner from industrial activities, and to radionuclides released as a consequence of accidents; and
- The responses of plants and animals, both as individuals and as populations, to acute and chronic irradiation.

149. The Committee hoped that its review would assist national and international bodies to select appropriate criteria for the radiological protection of natural populations, communities and ecosystems. The following paragraphs recapitulate the information available to the Committee in 1996.

A. Dosimetry for environmental exposures

150. As discussed in the annex to the UNSCEAR 1996 Report [U4], reliable determination of the dose rate to organisms is essential for assessing the potential or actual impacts of contaminant radionuclides in the environment. The Committee noted that "this simple statement conceals a multitude of difficulties that prevent the easy achievement of that estimation". In practice, it is necessary to make simplifying assumptions, with the degree of simplification depending on the purpose of the assessment. For example, for the purpose of screening, the concept of a single generic biota that represented all plants and animals had been used [A2]. More sophisticated models attempted to account for the dose distributions within reference organisms of assumed shapes and sizes and the fraction of radiation being absorbed within the organism [W2]. The Committee's views on dosimetry for estimating the exposure of biota based on what was known in the UNSCEAR 1996 Report [U4] are summarized below.

151. A dosimetric model is essentially a mathematical construction that allows the energy deposition in a defined target to be estimated from a given radionuclide (source) distribution. The model was often derived using theoretical or empirical functions that described the distribution of dose about a point source [B2, B3, L1, W2]. The dose at a point in the target was then obtained by integrating the point source dose distribution function over the defined radionuclide source, either internal or external to the organism. This

procedure was frequently simplified by using ideal geometries (spheres, ellipsoids, etc.) of appropriate size to represent the target and by assuming that the radionuclide distribution was uniform (over a surface or through a volume) or varied in a way that could be described by a simple mathematical expression (e.g. an exponential decline in radionuclide concentration with depth in soil or sediment). Alternatively, Monte-Carlo calculations had been used to determine the absorbed fractions of energy for a variety of source and target geometries [B4, E2]. These data could be used, either directly or with interpolation (or, to a lesser extent, with extrapolation) for geometries that could represent targets of environmental concern. In principle, these procedures could be adapted for use in estimating doses to terrestrial and aquatic organisms, from both the plant and animal kingdoms, for both internal and external sources of radiation.

152. Dosimetric models had been developed to take account of the radiation type; the specific geometry of the target (e.g. the whole body, the gonads, the developing embryo or the plant meristem); and the source of exposure (e.g. radionuclides accumulated in body tissues, adsorbed onto the body surface or distributed in the underlying soil). Clearly, it was not possible to consider all organisms, and there were limitations in the basic data that were available as input to the models (e.g. the spatial and temporal distributions of radionuclides both within the organism and in the external environment). Additional sources of complexity arose from the behaviour of mobile organisms, particularly some aquatic organisms and many insects, which inhabit different environmental niches at different stages of their life cycles. Thus, the models had to be simplified and generalized without undue loss of the realism that is essential for a valid estimation of dose.

153. The presence of an alpha particle component in the total absorbed dose rate to a tissue in a plant or animal raised the question of how to take account of the probably greater effectiveness of this type (quality) of radiation in producing biological damage. The RBEs of different qualities of radiation had been very critically examined for the purposes of human radiation protection. Each component of the absorbed dose to a tissue or organ was weighted by a factor which took account of the RBE of the radiation involved [15]. It seemed reasonable to apply a similar approach to the radiation dosimetry for organisms other than man. In practice, however, there were circumstances that altered the detailed application of this approach. In the human case, the major concern had been with the induction of stochastic effects (principally cancer) at low doses and dose rates. For alpha radiation, experimental determinations of the RBE had led to a recommended radiation weighting factor of 20 for the purpose of human radiation protection. In the case of wild animals, however, the Committee assumed that it was likely that deterministic effects were of greater significance. For alpha radiation, the experimental data for animals indicated that a lower factor to reflect the RBE would be more appropriate; the factor to reflect the RBE of beta and gamma radiations

would however be numerically the same as the radiation weighting factor used in human radiation protection. On the assumption that mammals are the most sensitive species, these values could be applied to other taxonomic groups.

154. In its 1996 UNSCEAR Report [U4], the Committee assumed that these factors would also apply to effects on plants, although there were no definitive experimental data to support this. In the absence of protection quantities (equivalent and effective dose) for non-human organisms, the absorbed doses from low-LET radiation (beta particles, X-rays and gamma rays) and from high-LET radiation (alpha particles) were assessed and specified separately in the UNSCEAR 1996 Report [U4]. The absorbed doses retained the unit, joule per kilogram (J/kg), with the special name gray (Gy).

155. An IAEA technical report [I4] provided estimates of the dose rates to terrestrial plants due to radionuclides deposited following discharges to the atmosphere. The model, PATHWAY [W3], developed to estimate doses to humans, had been used to derive the equilibrium concentrations of radionuclides in plants and animals for the limiting case in which humans, while living on the land, breathing the air over it and eating the food produced from it, would receive an annual effective dose of 1 mSv. To estimate the dose to plants from internal sources, it was assumed that the energy of alpha and beta particles would be totally absorbed (except for emissions from ^{32}P , which would be 50% absorbed) and that 10% of the gamma-ray energy would be absorbed. An additional degree of conservatism was provided by using estimates of the radionuclide concentrations in plant tissue on a dry weight basis (which are 5–10 times higher than on a wet weight basis) to calculate the absorbed dose rates to living (i.e. “wet”) plant tissue. The results are given in table 21. As these estimates had been made using a radioecological model and a scenario designed for calculating exposures to humans, the calculated exposures of non-human species should be interpreted cautiously.

156. The annex of the UNSCEAR 1996 Report [U4] noted that there have been fewer estimates of the potential exposures of fully terrestrial animals than of animals occupying semi or fully aquatic niches. This was thought to be a reflection of the greater use that had been made of aquatic systems for the discharge of radioactive waste.

157. The annex of the UNSCEAR 1996 Report [U4] suggested that naturally occurring alpha-emitting radionuclides appeared to be the most significant sources of background radiation exposure for the majority of wild organisms.

158. In its 1996 report, the Committee considered that the data on the radiation exposures of non-human biota due to both natural background radiation and contaminant radionuclides were incomplete, more in some areas than in others. The Committee also noted that the aquatic environment was probably the most thoroughly studied environment up to that time [I2, I3, I7, N1, N2, W1], even with the substantial

generalizations that had had to be made, particularly with respect to the range of organisms that could reasonably be considered [I3]. As had been emphasized elsewhere [I3, I6], the limiting factor was not the development of an appropriate dosimetric model for a particular organism but rather the acquisition of essential input data on the temporal and spatial distributions of the radionuclides both external to and within the organism. Although dynamic models had been employed to describe the dispersion and dilution of radionuclides in a water body, related phenomena (e.g. transfers to sediments and biological tissues) were almost always

modelled as equilibrium processes, i.e. using simple distribution coefficients and (whole-body) concentration factors. This simplification largely neglected the temporal variations in dose rate due, for example, to short-term fluctuations in discharge rate, differing stages in the life cycle, and behavioural and short-term environmental processes (e.g. seasonality). As a consequence, while the estimated absorbed dose rate might be a reasonable indication of the general magnitude of the actual environmental value, the Committee considered that it did not provide a very secure basis for evaluating total doses over time.

Table 21. Estimated dose rates to organisms from controlled discharges of radionuclides that would each result in an annual dose of 1 mSv to humans residing in the same environment

Table 6 of UNSCEAR 1996 Report [U4]; based on [I4, N1]

Radionuclide	Dose rate ($\mu\text{Gy/h}$)		
	Plants ^a	Animals ^{a,b}	Fish ^c
³ H	5.8	5.8	0.59
¹⁴ C	18	11	
³² P	32	28	4.8
⁶⁰ Co			0.53
⁹⁰ Sr	2.0	0.042	67
⁹⁵ Zr	38	2.0	
⁹⁹ Tc			3.8
¹³¹ I	1.2	0.058	
¹³⁷ Cs	5.4	3.1	0.72
²²⁶ Ra ^d			3.6
²³⁵ U ^d			2.6
²³⁸ U ^d			4.7
²³⁹ Pu ^d	0.023	0.000 55	0.49
²⁴¹ Am ^d			0.71

^a Discharges to atmosphere.

^b Domestic sheep.

^c Discharges to water (lakes).

^d High-LET radiation.

159. The Committee also noted that accident situations were by nature quite different from routine situations, particularly in their potential to produce high dose rates and doses to the environment. It concluded that generalization is difficult because the actual exposure regime depends on the types and quantities of radionuclides released, their initial dispersal and deposition patterns, and their redistribution over time in the environment. Following the accident at the Chernobyl nuclear power plant, large quantities of short-lived radionuclides were released, leading to high dose rates in the local area. Total doses up to 100 Gy were delivered to trees (and, by inference, to most other organisms in the locality) over a period of a few days [K1]. This radiation regime might have been characterized as “acute” in that the doses were delivered in periods that were shorter than or comparable to the time taken for severe damage to become apparent. During this initial (acute) phase, the dose rates declined rapidly as the very short-lived radionuclides decayed. The release following the accident in 1957 in the south-eastern Urals was dominated by ¹⁴⁴Ce–¹⁴⁴Pr (approximately 66%;

$t_{1/2} = 285$ d) and ⁹⁵Zr–⁹⁵Nb (approximately 25%; $t_{1/2} = 65$ d). In that case, the dose rates locally were also relatively high during the initial phase (more than 4 mGy/h) but declined more slowly, such that high total doses (causing severe effects, including mortality) could still be accumulated from essentially chronic exposure. Close to the release point, total doses up to 2,000 Gy were experienced [T4]. In the longer term, the exposure regime for the Chernobyl release was dominated by ¹³⁷Cs ($t_{1/2} = 30$ a) and ⁹⁰Sr ($t_{1/2} = 28.6$ a), and that for the south-eastern Urals accident area by ⁹⁰Sr. In both cases, the exposures were chronic and moderately high, with responses other than mortality becoming significant.

160. Radioactive waste discharges to atmosphere, landfills or aquatic systems from man-made practices entail increased radiation exposure of wild organisms. The incremental radiation exposures are chronic (i.e. continuing) at absorbed dose rates of generally no more than 100 $\mu\text{Gy/h}$, but, very exceptionally, they may reach several thousand microgray per hour. The Committee [U4] noted that these additional

radiation exposures may be greater than the normal range of natural background exposures but generally are within the extreme range of background exposures, if the exceptional cases of areas of uranium and thorium mineralization are included. Given that radioactive waste discharged to the environment will normally be dispersed and diluted, dose rates higher than those due to normal natural background exposure are likely to apply to only a small proportion of the individual organisms in any population and the average dose rate to the population would probably be much lower [W8, W9].

B. Effects of radiation exposure on plants and animals

161. Studies of the effects of ionizing radiation exposure on plants and animals were started immediately following the discovery of X-rays and radioactivity (see, for example, reference [A4]). Since 1945, when the first nuclear detonations were conducted, there was widespread concern about the impact of environmental radiation exposures and interest in the environmental behaviour of radioactive materials. As a result, studies using a wide variety of plant and animal species were performed [A4, B5, C3, P1].

162. The Committee, in its 1996 report [U4], noted that the responses of organisms to radiation exposure were varied and may become manifest at all levels of organization, from individual biomolecules to ecosystems. The significance of a given response depended 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.

163. The Committee also noted that a population might be defined as all members of a population species [U4]. Alternatively, a population might be considered as an aggregate of inter-breeding individuals of a species occupying a specific location in space and time [S5]. The latter definition is perhaps more useful given the Committee's observation that radiation fields, such as those arising from radioactive waste discharges, generally show large spatial variability, not least because of the often discrete nature of the source, and therefore many members of a population might not receive any significant exposure from a particular source. The natural distributions of most species are inhomogeneous because of the variations in physical, chemical and biological conditions under which the individuals of the species are able to survive, i.e. species are geographically restricted. Thus, it is probable that a more limited, and relevant, definition of a population could be developed for the purposes of environmental impact assessment.

164. The following definition (developed for use in population ecology) has been suggested as a useful basis for discussion and progress [I4]: "A population is a biological unit for study, with a number of varying statistics (e.g. number, density, birth rate, death rate, sex ratio, age distribution), and which derives a biological meaning from the fact that some

direct or indirect interactions among its members are more important than those between its members and members of other populations" [B6]. Notwithstanding this definition, it has to be understood that a population of a particular species is always linked to its environment. Such a population would (or could) be a self-sustaining unit, independent of other, geographically separate populations of the same species. However, protection of this population would require that increased radiation exposure did not significantly affect the attributes mentioned in the definition on which the population depended for its maintenance within the normal dynamic range of variation dictated by the interactions of natural physical, chemical and biological factors.

165. These attributes, which could be defined only for populations of organisms and might be taken to be indicators of their health, are nevertheless amalgamations of properties that relate to individuals (in no sense was this meant to imply simple addition). The Committee concluded, in effect, that for a response to radiation exposure at the population level (or, indeed, at any higher level of organization) some clearly detectable effect in individual organisms (i.e. at lower levels of organization) would be expected. This clearly implied that the protection of the population (as the ultimate objective) might be achieved by restricting the exposure of individual organisms to the extent that there are no significant radiation effects on those processes necessary for the maintenance of the population. It is therefore necessary to consider the available information on the effects of radiation exposure (mainly at chronic low dose rates) on the relevant processes in individual organisms, to consider how these responses might translate to an impact on the population, and to examine the results of studies of population responses to deliberate experimental irradiation or to exposure in the environment due to controlled or accidental releases of radionuclides.

166. Examination of the population attributes indicated 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 (birth rate), fecundity (birth rate, age distribution, number and density) and the induction of mutations (birth rate and death rate). These individual responses can be traced to events at the cellular level in specific tissues or organs. An extended summary discussing the processes involved was provided in annex J, "Non-stochastic effects of irradiation", of the UNSCEAR 1982 Report [U9]. 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 is 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 occurs. It was also well known that radiosensitivity varies within the cell cycle, with the greatest sensitivities being apparent at mitosis and the commencement

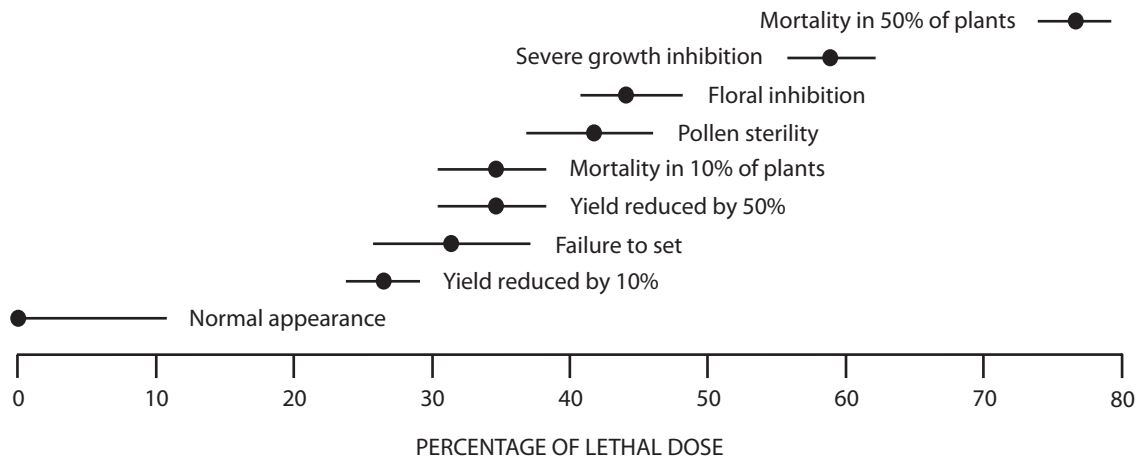
of DNA synthesis [U9]. It followed that the greatest radiosensitivity is likely to be found in cell systems undergoing rapid cell division for either renewal (e.g. spermatogonia) or growth (e.g. plant meristems and the developing embryo); these examples clearly underlie the processes in individual organisms that are important for the maintenance of the population.

167. Fractionation or protraction of exposure to low-LET radiation increases the total dose required to produce a given degree of damage since at low dose rates, the factors responsible for mitigating the response come into play. These include the repair of sublethal damage, the repair of potentially lethal damage, the replacement of killed cells through proliferation of survivors, and other slow repair processes not related to cell repopulation [U9]. Although it was clear to the Committee that repair, in the general sense, is possible, the existence and extent of residual injury was less clear. While such an outcome might be demonstrated for moderate, acute doses, it was not possible to extrapolate these results in order to predict the likely response to low-level exposures extending over a significant fraction of the lifetime of an organism. However, given that genetic mutations might be passed from generation to generation, it was reasonable to suppose that somatic mutations individually consistent with cell survival could occur and accumulate over time until the combined impact might reduce cell viability.

1. Terrestrial plants

168. Radiation injury in plants expresses itself as abnormal shape or appearance, reduced growth or yield, loss of reproductive capacity, wilting and (at high exposures) death [S1]. Acute lethal doses to higher plants ranged from 10 to about 1,000 Gy (approximate mean absorbed doses averaged over the whole plant). The Committee concluded that plants such as mosses, lichens and unicellular species are at one extreme of radiosensitivity being highly resistant to radiation exposure; woody species are at the other extreme being the most sensitive. In 12 species of woody plants assessed 10–14 months after exposure, the lethal doses were found to be in the range of 8–96 Gy [S2]. The pine tree was the most sensitive, experiencing mortality following short-term absorbed doses of about 10 Gy [W5]; growth was severely inhibited at 50–60% of the lethal dose. Floral inhibition was observed at 40–50% of the lethal dose, and failure to set seed at 25–35%. Thus, the capacity of the plant population to maintain itself could be damaged at acute doses lower than those required to cause mortality. Below 10% of the lethal dose, effects were not so apparent and the plants maintained a normal appearance. These general observations for several herbaceous plant species are illustrated in figure X [S3]. Another general relationship was that the dose that reduced survival by 10% (LD_{10}) was roughly equivalent to the dose that reduced the yield by 50% (YD_{50}) [S1].

Figure X. General ranges of response to radiation exposure by herbaceous plants as a percentage of the lethal dose (LD_{100}) [S3]



169. The Committee, in the UNSCEAR 1996 Report [U4], noted that protraction of radiation exposures increased the total doses required to kill plants [S4].

170. A range of sensitivities to radiation exposure was exhibited by the components of plants, ranging from dry seed (least sensitive) to apical meristems (most sensitive). Various crop plants showed different reductions in yield following radiation exposures, with further modifications being caused by external factors (e.g. temperature and humidity).

171. Plant species also varied in their tolerance to chronic radiation exposures. For the more sensitive pine species, dose rates of more than 3 mGy/h over 3–4 years reduced needle growth; in one-year-old saplings, needle length was substantially reduced when subjected to a dose rate of 7 mGy/h over a single growing season. Trunk growth was reduced in mature pine trees by dose rates in the range 0.4–2 mGy/h over a 9-year period. Delayed bud burst and an extended period of leafing out was demonstrated in white oaks chronically exposed to gamma radiation. At dose rates greater than 4 mGy/h, the trees were more susceptible to aphid infestation.

172. In view of the effects on the most sensitive plants evident with chronic exposure at dose rates of 1–3 mGy/h and of some specific changes noted at dose rates of 0.4–2 mGy/h, the Committee [U4] suggested that chronic dose rates at or below 400 μ Gy/h (10 mGy/d) should have only slight effects on sensitive plants but would be unlikely to produce any significant deleterious effects on the wider range of plants present in natural plant communities.

2. Terrestrial animals

173. The effects of radiation exposure on mammals had been extensively studied in radiobiological experiments using laboratory animals (mice, rats, dogs and monkeys) and domestic livestock (pigs, sheep, goats, burros and cattle) [B7, B8]. Except in the case of exposure involving unusually high doses, radiation damage or lethality in mammals results from disturbances in the haematopoietic system and the gastrointestinal mucosa. These cell self-renewal systems contain stem cells, differentiating cells and functional end cells, with the stem cells being the most radiosensitive and thus having the predominant influence on the radiation response. Symptoms become apparent when end cells are not replaced.

174. Protraction of a given total exposure generally reduces the extent of injury, as it allowed two distinct processes to intervene. First, sublethal damage is repairable at the cellular level, which is particularly important for exposures to low-LET radiation. Secondly, cell proliferation could replace lethally damaged cells and maintain the cell population at a new level, which is determined by the dynamic interaction between the dose rate and the rate of cell death, and by the total reserve proliferative capacity.

175. The Committee noted that at reduced dose rates (protraction of a given total dose) of low-LET radiation, all species showed a gradual increase in LD_{50} , i.e. higher total doses were tolerated. This changing response was attributed to the increasingly effective influence of cellular repair of sublethal damage at the lower dose rates. As the dose rate was further reduced, a sharply increasing trend in the values for the median lethal dose was apparent for mice, pigs, dogs, goats and sheep; the approximate threshold dose rates for this change in response corresponded to the accumulation of an LD_{50} dose within periods ranging from 0.2 days (mouse) to 9 days (goat). This rapid change in LD_{50} with dose rate was interpreted as being the consequence of a shifting balance in the dynamic interaction between the dose-rate-dependent cell loss and the cell proliferation and maturation kinetics in the haematopoietic system; the latter processes are under homeostatic control, i.e. their rate constants can alter in response to radiation-induced cell loss. The data for the burro (donkey) and primates did not show any sharp increase in the median lethal dose at dose rates down to 8.3 mGy/h (LD_{50} in 18 days) and 5.4 mGy/h (LD_{50} in 60 days), respectively. There did not appear to be any data for LD_{50} values at dose rates of less than 4 mGy/h or for exposure periods exceeding 60 days, although studies had been made outside these levels for other purposes.

176. While acknowledging that the numbers of mammalian species that had been (or indeed were likely to be) studied were extremely limited and probably atypical, the Committee noted [U4] that, even taking account of substantial interspecific variability, the available data provided very little evidence that chronic dose rates below 400 μ Gy/h (approximately 10 mGy/d) to the most exposed members of the population would seriously affect their mortality (and, thus, the death rate in populations of these species) from either deterministic or stochastic responses.

177. The effects of radiation exposure on reproduction had also been much studied, with most of the results suggesting that natality is a more radiosensitive parameter than mortality in species other than man and therefore of more relevance in an environmental context. The Committee considered that the minimum dose required to depress reproduction rates might be less than 10% of the dose required to produce direct mortality [W6].

178. The Committee suggested that damage to the developing mammalian embryo appeared to be a potentially significant criterion for assessing the impact of contaminant radionuclides in the natural environment. Dose rates of 420 μ Gy/h throughout gestation produced readily detectable reductions in the populations of germ cells in the developing gonads of a number of mammalian species, and the lowest dose rate at which damage had been seen was 10 μ Gy/h from tritium (as HTO in drinking water) incorporated in female mouse embryos. In addition, dose rates of the order of 420 μ Gy/h induced reductions in neonatal brain weight, although the significance of this deficit was unknown in functional or behavioural terms. The wider significance of these responses at the population level had not been investigated. Even recognizing that only very limited data were available, the Committee concluded that maximum dose rates of 100 μ Gy/h (2.4 mGy/d) to pregnant members of a mammalian population were unlikely to have any consequences for the population as a whole from the induction of damage in the developing embryos.

179. The Committee noted that the data on the 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. When a total dose of magnitude similar to the $LD_{50/30}$ was delivered over a lifetime—for example, 7 Gy to the mouse (420 μ Gy/h, or 10 mGy/d)—the average loss of lifespan had been estimated to be about 5% and resulted from the induction of neoplastic disease [U9]. There was substantial inter-species variability, but, in general, little indication that dose rates below about 400 μ Gy/h to the most exposed individual would seriously affect mortality in the population.

180. The Committee noted that reproductive capacity was more sensitive to the effects of radiation exposure than life expectancy (mortality) and felt that the reproductive rates of mammals might be depressed at doses that were 10% of

those leading to mortality. It also felt that some loss of oocytes might occur at 1% of the lethal dose, but because of excess oocyte production, fecundity should be affected to a lesser extent. Mice, exposed from conception to a dose rate of 800 $\mu\text{Gy/h}$, could be made sterile at 25 weeks. In the most sensitive mammal studied, the beagle dog, a dose rate of 180 $\mu\text{Gy/h}$ caused progressive cell depletion and sterility within a few months, but a dose rate of 36 $\mu\text{Gy/h}$ over the whole life produced no damaging response. The Committee concluded that a radiation dose rate of less than 40 $\mu\text{Gy/h}$ to the most exposed individual in a population (and most probably, therefore a lower mean dose rate to individuals in the population as a whole) would be unlikely to have an impact on the overall reproductive capacity of a mammalian population as a consequence of the effects of radiation exposure on fertility, fecundity or the production of viable offspring.

181. The effects of radiation exposure on birds had been shown to be similar to those on small mammals. Reptiles and invertebrates were less radiosensitive, although physiological differences began to make direct comparisons with other species less appropriate. The chronic exposure of one short-lived species of lizard in enclosures had shown no evident effects when exposed over 5 years at a dose rate of 830 $\mu\text{Gy/h}$. In two longer-lived species of lizard, some individuals had been made sterile after 3.5 years at a dose rate of 630 $\mu\text{Gy/h}$ in one species and after 5.5 years at a dose rate of 210 $\mu\text{Gy/h}$ in another species. Adult invertebrates were seemingly quite insensitive to the effects of radiation exposure in terms of induced mortality, but the process of gametogenesis, developing eggs and juvenile stages were more sensitive.

3. Aquatic organisms

182. A number of reviews of the studies of the effects of exposure to ionizing radiation on aquatic organisms were available to the Committee [A3, B9, C3, E2, I2, I3, N1, N2, P2, T5, W9] during the preparation of the annex of the UNSCEAR 1996 Report [U4]. Some of these had been prepared specifically to provide a basis for assessing the potential effects of discharges of liquid radioactive effluents on aquatic organisms in their natural environment [I2, I3, N1, N2, W1].

183. Among aquatic organisms, fish were the most sensitive to the effects of radiation exposure; the developing fish embryos were particularly sensitive. The LD_{50} for acute irradiation of marine fish was in the range 10–25 Gy for assessment periods of up to 60 days following exposure. The upper end of the range of LD_{50} for marine invertebrates had been found to be several hundred grays. Embryos, on the other hand, were affected at much lower doses, for example, the $\text{LD}_{50/90}$ for salmon embryos was 0.16 Gy [B10].

184. Chronic exposures at dose rates of 10–30 mGy/h had no effect on the mortality of snails, marine scallops, clams and blue crabs. Dose rates somewhat above this range had

some effects on food-limited populations of *Daphnia pulex*. Short-term (40 days) exposure of mosquito fish at dose rates in the range 14–54 mGy/h showed no radiation-induced mortality, but, for the closely related guppy, there was some indication that long-term exposure (>470 days) at dose rates above 1.7 mGy/h reduced the normal lifespan, particularly for males.

185. Reproductive effects are a more sensitive indicator of radiation response for aquatic organisms. Chronic dose rates in the range 3.2–17 mGy/h reduced the reproductive capacity in the freshwater snail, *Physa heterostropha*, and in the marine polychaete worms, *Ophriotrocha diadema* and *Neanthes arenaceodentata*. Exposure at a dose rate of 7.3 mGy/h rendered male freshwater fish (*Ameioba splendens*) effectively sterile after 50 days, and exposure at a dose rate of 1.7 mGy/h over the lifespan of pairs of guppies (the freshwater fish, *Poecilia reticulata*) significantly reduced the lifetime production of offspring [W7]. It had been concluded that significant effects on fish gonads from chronic radiation exposure would be unlikely at dose rates less than 1 mGy/h [I3, W1]. Overall consideration of the data available led to the conclusion that chronic irradiation at dose rates up to 400 $\mu\text{Gy/h}$ to a small proportion of the individuals in an aquatic population (and, therefore, with correspondingly lower average dose rates to the whole population) would not have any detrimental effects at the population level [I4, N1].

C. Effects of radiation exposure on populations of plants and animals

186. The Committee noted in the annex of the UNSCEAR 1996 Report [U4] that one of the difficulties in evaluating the effects of radiation exposure on populations and ecosystems was the determination of the parameters to measure. Typically measured attributes at the population level included numbers of individuals, mortality rate, reproduction rate and mean growth rate. The Committee also noted that measurable changes in populations and communities required rather severe effects to be induced at the cellular and individual organism levels [e.g. W8]. The Committee also noted that genetic or somatic mutations that could be produced by relatively low levels of exposure might have little or no impact on population or community performance because of natural selection [B10, C4, M2, P3, T5] and the convergence of genetic information among adjacent populations [R1, T5].

187. The Committee also noted that the effects of radiation exposure at the population and community levels were manifest as a combination of direct changes due to radiation damage and indirect responses to the direct changes. This seriously complicated the interpretation of the effects of radiation exposure on organisms in the natural environment. The wide range of radiosensitivities of the organisms that make up most natural communities creates a situation where, if doses are such that the sensitive species, but not the more resistant ones, are affected, the latter might gain a significant competitive advantage and increase in abundance or vigour.

This could erroneously be interpreted as a hormetic response; such a response might not however be produced if the resistant species alone were irradiated. This is but one of many examples of indirect response to the direct effects of radiation exposure.

188. Because of the compensation and adjustment possible in animal species, the Committee considered that it is unlikely that radiation exposures causing only minor effects on the most exposed individual would have significant effects on the population. 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, chronic dose rates of less than 100 $\mu\text{Gy/h}$ to the most highly exposed individuals would be unlikely to have significant effects on most terrestrial animal communities. The Committee also concluded that maximum dose rates of 400 $\mu\text{Gy/h}$ to a small proportion of the individuals in aquatic populations of organisms would not have any detrimental effect at the population level. These conclusions referred to the effects of low-LET radiation exposure. Where a significant part of the incremental radiation exposure comes from high-LET radiation (alpha particles), the Committee considered that it is necessary to take account of the different RBEs.

D. Effects of major accidents

189. The UNSCEAR 1996 Report [U4] discusses the effects of two accidents in the former Soviet Union (at Chernobyl and at Mayak in the south-eastern Urals) leading to major releases of radioactive material into the environment [A28, G19, I23, I24, K1, K22, K23, N9, S29, S34, S40, T4, T27]. These accidents provided opportunities to observe radiation-related changes in plant and animal communities. The Committee noted however that any major accident is likely to be unique in terms of the quantity and composition of the radioactive material released, the time course of the release, the dispersal and deposition patterns, which are governed by local and regional meteorological or hydrological conditions, and the biochemical and geochemical character of the areas subject to contamination. Where long-lived radionuclides are released, biochemical and geochemical processes would determine the long-term behaviour and redistribution of the radionuclides in the environment. Given this multiplicity of factors, any major nuclear accident would be expected to yield new radioecological information. However, the primary concern following an accidental release of radionuclides is to ensure that the radiation risks to human populations are controlled and minimized. Consequently, the only environmental information likely to be collected is that which is immediately necessary to meet this objective. Such information is unlikely to be sufficient for the purposes of developing a complete radioecological description of the situation. The larger the incident and the greater its potential human impact, the more limited would be the resources available to collect radioecological information, particularly in the early phase following the accident.

190. In particular, the data required to develop estimates of the radiation exposure of wild organisms (i.e. the space and time-dependent variations of the radionuclide concentrations, especially of the short-lived radionuclides both within the organisms and in their external environment immediately following an accident) would not be known. These variations would result in substantial intra-species and inter-species inhomogeneities in exposure and would pose considerable difficulties for establishing a clear and reliable relationship between cause (the accumulated radiation dose) and any observed effect. In practice, it is likely that estimates of the dose rates in the early period following the release would be calculated subsequently from the observed distribution of deposition densities of the longer-lived radionuclides, from a knowledge of the relative quantities of the radionuclides released, and using models of radionuclide behaviour in the environment. Such dose-rate estimates are inevitably imprecise and could be subject to significant systematic error.

191. The highly variable habits and target geometries of the wild organisms are additional complicating factors. These range, for example, from soil bacteria to single-celled algae and protozoa, and include a wide variety of terrestrial and aquatic invertebrates, mammals (ranging from shrews to deer) and large deciduous or evergreen trees. Plants provide a very high surface area to mass ratio (compared with animals) for deposition/adsorption of a radioactive aerosol. Because the leaves, flowers and terminal buds of plants are responsible for energy absorption, growth and reproduction, a coincidence arises between radionuclide accumulation (and hence radiation dose) and potential radiosensitivity. Other examples of coincidence are the surface litter layer and its populations of invertebrate decomposers in terrestrial environments, and surface sediments and benthic organisms in aquatic systems.

192. Depending on the quantities of specific radionuclides released following an accident, the radiation exposures might range from low (a few multiples of the natural background) to high (absorbed doses greater than 1 Gy). Different phases of biological response to the higher total doses might be distinguished. Initially, and, in particular if short-lived radionuclides made up a significant proportion of the release, there might be an acute phase in which total doses sufficient to produce immediate or relatively early detectable biological responses are accumulated. In the intermediate phase, dose rates would decrease owing to the decay of the short-lived radionuclides and possibly, but not necessarily, owing to the redistribution of the longer-lived radionuclides by natural processes. Even in this phase, the slower accumulation of radiation dose might still result in total integrated doses sufficient to prevent recovery of organisms damaged in the initial phase or lead to the appearance of medium-term damage. In the long-term phase, post-irradiation recovery (and adaptation) becomes apparent, provided that the initial and medium-term damage had not been large enough to radically alter the population or community structure.

III. SUMMARY OF DOSE-EFFECTS DATA FROM THE CHERNOBYL ACCIDENT

193. A great deal of scientific information concerning the effects of exposure to ionizing radiation has been developed from studies of non-human biota in the area surrounding the site of the Chernobyl accident. The follow-up studies provided the main source of new information on the effects of radiation exposure on non-human biota since the UNSCEAR 1996 Report [U4]. This area has a temperate climate and flourishing flora and fauna. Much of the new information, originally reported in Russian, has been summarized in a report prepared for the Committee [A5] and by the work of the Chernobyl Forum [E8]. The following discussion of radiation levels and effects on biota observed in the region around the Chernobyl nuclear power plant is based on information presented in reference [E8] and in other recent reviews [G26].

A. Radiation exposure

194. The Chernobyl Forum Expert Group on Environment (EGE) [E8] noted that the effects of the Chernobyl accident should be studied within specific time periods. Three distinct phases of radiation exposure have been identified in the area local to the accident [U4]. In the first 20 days, radiation exposures were essentially acute because of the large quantities of short-lived radionuclides present in the passing cloud (^{99}Mo , $^{132}\text{Te/I}$, ^{133}Xe , ^{131}I and $^{140}\text{Ba/La}$). Most of these short-lived, highly radioactive nuclides deposited onto plant and ground surfaces, resulting in gamma radiation dose rates of up to about 20 Gy/d. However, for surface tissues and small biological targets (e.g. mature needles and the growing buds of pine trees) there was a considerable additional dose rate due to the beta radiation from the deposited radionuclides. High doses to the thyroids of vertebrate animals also occurred during the first days/weeks following the accident owing to the inhalation and ingestion of radioactive isotopes of iodine and their radioactive precursors.

195. The second phase of radiation exposure extended through the summer and autumn of 1986, during which time the short-lived radionuclides decayed and the longer-lived radionuclides were transported to different components of the environment by physical, chemical and biological processes. Dominant transportation processes included rain-induced transfer of radionuclides from plant surfaces onto soil, and bioaccumulation through plant tissues. Dose rates at the soil surface declined to much less than 10% of the initial values owing to radioactive decay of the short-lived radionuclides, but damaging total doses were still accumulated. Approximately 80% of the total radiation dose accumulated by plants and animals was received within 3 months of the accident, and over 95% of this was due to beta radiation exposure [E8]. Measurements made with thermoluminescent dosimeters on the soil surface at sites within the 30-km exclusion zone indicated that the ratio of beta to gamma dose was about 26:1, (i.e. 96% of the total dose was due to beta radiation exposure) [P18].

196. The EGE [E8] also defined a third (and continuing) phase of radiation exposure with chronic dose rates less than 1% of the initial values and derived mainly from ^{137}Cs . With time, the decay of the short-lived radionuclides and the migration of much of the remaining ^{137}Cs into the soil meant that the contributions to the total radiation exposure from the beta and gamma radiations tended to become more comparable. Reference [E8] noted that the balance depended on the degree of bioaccumulation of ^{137}Cs in organisms and the behaviour of the organism in relation to the main source of external exposure resulting from the ^{137}Cs in the soil.

B. Effects of radiation exposure on plants

197. The report of the EGE was a great advance on previous publications describing the follow-up work on the effects of the Chernobyl accident. In particular, the report gave considerable attention to evaluating the dosimetry of, and consolidating the information on the effects on non-human biota. Thus, given both the greatly improved quality of the data and the comprehensive nature of the evaluation provided by the EGE, much of the following discussion is adapted from reference [E8].

198. Doses received by plants arising from the deposited radionuclides resulting from the Chernobyl accident were influenced by the physical properties of the various radionuclides (i.e. their half-lives, radiation emissions, etc.), the physiological stage of the plant species at the time of the accident, and the different species-dependent propensities to take up radionuclides into critical plant tissues [E8]. The occurrence of the accident in late April 1986 was thought to have enhanced the damaging effects of the deposition because it coincided with the period of accelerated growth and reproduction of plants.

199. The deposition of beta-emitting radionuclides onto critical plant tissues resulted in their having received a significantly larger dose than animals living in the same environment [P18, P19]. According to reference [G9], large apparent inconsistencies in the dose-response observations occurred when the beta-irradiation component was not appropriately taken into account.

200. Within the 30-km zone around the Chernobyl plant, the doses to plants associated with the deposition of total beta activity (0.7–3.9 GBq/m²) were sufficient to cause short-term sterility and reduction in productivity of some species [P19]. By August 1986, crops that had been sown prior to the accident began to emerge. Growth and development problems were observed in plants in fields with deposition densities of 0.1–2.6 GBq/m² of total beta activity, and with estimated dose rates initially received by the plants having reached 300 mGy/d. Spot necroses on leaves, withered tips of leaves, inhibition of photosynthesis, transpiration and metabolite

synthesis were detected, as well as an increased incidence of chromosome aberrations in meristem cells [S22]. The frequency of various anomalies in winter wheat exceeded 40% in 1986–1987, with some abnormalities apparent for several years afterwards [G12].

201. Coniferous trees were already known to be among the more radiosensitive plants, and the pine forests, 1.5–2 km west of the Chernobyl nuclear power plant, received sufficient doses, more than 80 Gy, at dose rates that exceeded 20 Gy/d, to cause mortality [T18]. The first signs of radiation injury were yellowing and needle death in pine trees in close proximity to the nuclear power plant and appeared during the summer of 1986. The colour of the dead pine stands resulted in the forest being referred to as the “red forest”.

202. Tikhomirov and Shcheglov [T18] and Arkhipov et al. [A11] found that mortality rate, reproduction anomalies, stand viability, and re-establishment of pine-tree canopies were dependent on absorbed dose. Acute irradiation of *Pinus silvestris* at doses of 0.5 Gy caused detectable cytogenetic damage; at doses of more than 1 Gy, growth rates were reduced and

morphological damage occurred; and, at more than 2 Gy, the reproductive abilities of trees were altered. Doses of less than 0.1 Gy did not cause any visible damage to the trees. Table 23 shows the variation in activity concentration and dose among pine trees within the 30-km zone. The radiosensitivity of spruce trees was observed to be greater than that of pines. At absorbed doses as low as 0.7–1 Gy, spruce trees had malformed needles, buds and shoot growth [K1].

203. About 90% of the absorbed dose to critical parts of the trees was due to beta irradiation from the deposited radionuclides with the remaining 10% from gamma irradiation. Table 22 summarizes the external gamma dose rates and the internal radionuclide concentrations in the conifers around the Chernobyl plant. By 1987, recovery processes were evident in the surviving tree canopies and the forests were re-establishing themselves where the trees had perished [A11]. In the decimated pine stands, a sudden invasion of pests occurred that later spread to adjoining areas. Grassland, with a slow invasion of self-seeding deciduous trees, has now replaced the deceased pine stands. Four distinct zones of radiation-induced damage to conifers were discernable (table 23).

Table 22. Activity concentration in needles of coniferous trees and estimated external gamma dose rates in October 1987 as a function of distance from the Chernobyl nuclear power plant

For azimuth 205 to 260 degrees (adapted from reference [K12])

Distance from NPP (km)	External exposure rate ($\mu\text{Gy/h}$) ^a	Accumulated external dose (mGy) ^a	Activity concentration in needles (kBq/kg)					
			¹⁴⁴ Ce	¹⁰⁶ Ru	⁹⁵ Zr	⁹⁵ Nb	¹³⁴ Cs	¹³⁷ Cs
2	2 500	126 000	13 400	4 100	800	1 500	1 500	4 100
4	120	5 000	150	60	8	15	17	72
16	0.4	14	1.5	0.6	0.1	0.17	0.18	0.55

^a Based on gamma radiation levels at 1 m height above the soil surface. The values given in the original reference were in mR/h and have been converted assuming 1 mR/h is equivalent to 10 $\mu\text{Gy/h}$.

Table 23. Zones and corresponding damage to coniferous forest in the area around the Chernobyl nuclear power plant (from reference [K1])

Zone and classification	External gamma dose (Gy)	Exposure rate ($\mu\text{Gy/h}$) ^a	Internal dose to needles (Gy)
Conifer death (4 km ²) Complete death of pines Partial damage to deciduous trees	over 80–100	over 5 000	over 100
Sublethal (38 km ²) Death of most growth points Partial death of coniferous trees Morphological changes to deciduous trees	10–20	2 000–5 000	50–100
Medium damage (120 km ²) Suppressed reproductive ability Dried needles, morphological changes	4–5	500–2 000	20–50
Minor damage Disturbances in growth, reproduction and morphology of coniferous trees	0.5–1.2	<200	<10

^a The values given in the original reference were in mR/h and have been converted assuming 1 mR/h is equivalent to 10 $\mu\text{Gy/h}$.

C. Effects of radiation exposure on soil invertebrates

204. Between 60% and 90% of the initial fallout of radionuclides was captured by the forest canopy and other plants [E8]; however, within weeks to a few months, the processes of wash-off by rain and leaf fall removed most of the initial deposition to the litter and soil layers, where soil and litter invertebrates were exposed to high radiation levels for protracted time periods. The timing of the accident coincided with the most radiosensitive life stages of the soil invertebrates: reproduction and moulting following their winter dormancy [T18]. Within two months after the accident, the numbers of invertebrates in the litter layer of forests 3–7 km from the nuclear power plant were reduced by a factor of 30 [K11], and reproduction was strongly impacted (larvae and nymphs were absent). These effects corresponded to doses of approximately 30 Gy (estimated from TLDS placed in the soil) resulting in mortality of eggs and early-life stages, as well as reproductive failure in adults. However, within a year of the accident, reproduction of invertebrates in the forest litter resumed, due, in part, to the migration of invertebrates from less contaminated sites. After 2–3 years, the ratio of young to adult invertebrates in the litter layer, as well as the total mass of invertebrates per unit area, were no different from those in control sites; however, species diversity remained markedly lower [K11]. As noted in the report of the EGE [E8], this is important since the diversity of invertebrate species within the soil facilitates an analysis of the community-level effects of radiation exposure (i.e. changes in species composition and abundance). For example, only five species of invertebrates were found in 10 soil cores taken from pine stands in July 1986, 3 km from the Chernobyl nuclear power plant, compared to 23 species at a control site 70 km away. The mean density of litter fauna was reduced from 104 individuals per 225 cm² core at the control location to 2.2 at the 3-km site. Six species were found in all 10 cores taken from the control site, whereas no one species was found in all 10 cores from the 3-km location [K13]. The number of invertebrate species found in the heavily contaminated sites was only half that of controls in 1993, and complete species diversity did not recover until 1995, almost 10 years after the accident [K11].

205. A fourfold reduction in earthworm numbers was found in arable soils, but no catastrophic mortality in any group of soil invertebrates was observed. The dose to invertebrates in forest litter was 3–10 fold higher than that to those residing in unploughed surface soil since the radionuclides deposited on the surface had not migrated downwards. The result was no reduction in the numbers of soil invertebrates below a depth of 5 cm in the soil as they were shielded by the overlying soil [K11].

206. Although, the researchers were unclear if sterility of invertebrates occurred in the heavily contaminated sites around the Chernobyl nuclear power plant [K11], the 30 Gy cumulative dose reported in the field studies was within the range of experimental doses used to control pest insects by external irradiation. A recent review indicated that most insect, mite and tick families require a sterilization dose of less than 200 Gy [B40], although the sterilization dose for some insects and related arthropods is much lower than this and varies widely. As was found for plants [S2], the radiosensitivity of insects is related to the average interphase nuclear volume [B40].

D. Effects of radiation exposure on farm animals

207. Ruminants, both domestic (cattle, goats and sheep) and wild (elk and deer), generally receive relatively high doses in radioactively contaminated environments, because they consume large amounts of vegetation, and many radionuclides accumulate in their bodies. For example, a single cow consumes about 75 kg of fresh grass each day.

208. In the period shortly after the accident, domestic livestock within the 30-km zone were exposed to high levels of radioactive iodine (¹³¹I and ¹³³I with half-lives of 8 days and 21 hours, respectively). This resulted in significant internal and external doses due to beta and gamma radiation exposure (table 24). A dose of about 76 Gy is sufficient to cause harm to the thyroid gland [B23]. Soils of Ukraine and Belarus are naturally low in stable iodine, cobalt and manganese. In conditions of endemic deficiency of stable iodine, the transfer of radioactive iodine from blood to the thyroid gland may be 2–3 times greater than normal [P19]. These conditions accentuated the consequences of the accident.

Table 24. Doses to cattle that stayed in the 30-km zone around the Chernobyl plant from 26 April to 3 May 1986 [K12]

Distance from nuclear power plant (km)	Surface activity (10 ⁸ Bq/m ²)	Absorbed dose (Gy)		
		Thyroid	GI tract	Whole body internal
3	8.4	300	2.5	1.4
10	6.1	230	1.8	1.0
14	3.5	260	1.0	0.6
12	2.4	180	0.7	0.4
35	1.2	90	0.4	0.2

209. Depressed thyroid function in cattle was related to the dose received (69% and 82% reductions in function with thyroid doses of 50 Gy and 280 Gy, respectively). The concentration of thyroid hormones in the blood of animals was lower than the physiological norm during the whole lactation period. Radiation damage to the thyroid gland was confirmed by histological studies (i.e. hyperplasia of connective tissue and sometimes adipose tissue, vascular hyperaemia and necrosis of epithelium). Animals with practically no thyroid tissue were observed in Ukraine. Disruptions of the hormonal status in calves born to cows with irradiated thyroid glands were especially pronounced [A12]. Similar effects were observed in cattle evacuated from the Belarusian portion of the 30-km zone [I18].

210. Although most livestock were evacuated from the area after the accident, several hundred cattle were maintained in the more contaminated areas for a 2–4 month period. By autumn 1986, some of these animals had died; others showed impaired immune responses, lowered body temperatures and cardiovascular disorders. Hypothyroidism lasted until 1989, and may have been responsible for reproductive failures in animals that received thyroid doses of more than 180 Gy [I18]. Offspring of highly exposed cows had reduced weight, reduced daily weight gains, and signs of dwarfism. Reproduction returned to normal in the spring of 1989. Haematological parameters were normal for animals kept in areas with ^{137}Cs deposition densities of 0.2–1.4 MBq/m² (5–40 Ci/km²) [A12].

211. No increase in the rates of birth defects were detected above background levels at annual doses below about 0.05 Gy [P17].

E. Effects of radiation exposure on other terrestrial animals

212. Surveys and autopsies of wildlife and of abandoned domestic animals that remained within 10 km of the Chernobyl nuclear power plant were conducted four months after the accident. [K11]. Fifty species of birds were identified, including some rare ones; all appeared normal in appearance and behaviour. No dead birds were found. Swallows and house sparrows were found to be producing progeny that also appeared normal. Forty-five species of mammals from six orders were observed and no unusual appearances or behaviours were noted.

213. In a review of thirty-three studies of the biological consequences of the Chernobyl accident, Møller and Mousseau [M19] commented on various increases in mutations and cytogenetic abnormalities attributed to elevated radiation levels. They noted that the fitness consequences of such increases were largely unknown and cited a study

of differences in phenotypes in barn swallows from near Chernobyl and those from relatively uncontaminated control areas [M18]. The authors suggested that mutations with slightly negative fitness effects could have been exported from the contaminated zones and potentially affected unexposed populations. In an exchange of views, Møller et al. [M17, M20] challenged the hypothesis of Smith [S26] that the impacts on barn swallows arose from factors other than radiation exposure, namely the change in habitat and wildlife community arising from changes in agricultural practices resulting from efforts to reduce the spread of radioactively contaminated food. Smith however noted that the most contaminated sites were located within abandoned lands, which had large differences in both land use and ecology from the control sites.

214. Some wildlife and domestic animals were shot and autopsied in August and September 1986. Dogs and chickens showed signs of chronic radiation syndrome (reduced body mass; reduced fat reserves; increased mass of lymph nodes, liver and spleen; haematomas present in liver and spleen; and thickening of the lining of the lower intestine). No eggs were found in the nests of chickens, nor in their ovaries.

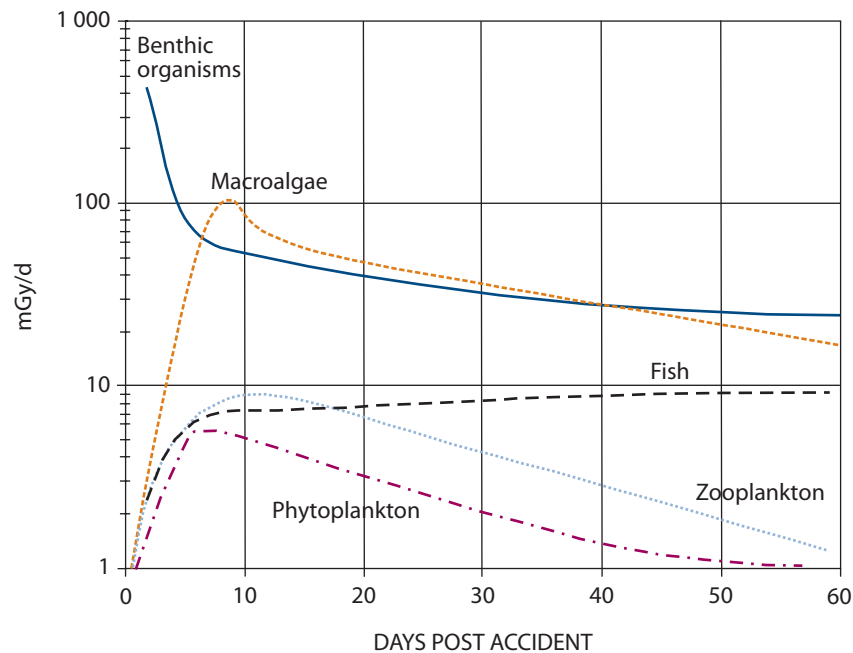
215. During the autumn of 1986, the number of small rodents on highly contaminated research plots decreased by a factor of 2–10. Estimates of absorbed doses during the first five months after the accident ranged from 12–110 Gy for gamma and 580–4,500 Gy for beta irradiation. By the spring of 1987, the numbers of animals were recovering, mainly due to immigration from less affected areas. In 1986 and 1987, the percentage of pre-implantation deaths in rodents in the highly contaminated areas was 2–3 fold greater than that in the controls. Resorption of embryos also increased markedly in rodents from the impacted areas; however, the number of progeny per female did not differ from that of the controls [T16].

F. Effects of radiation exposure on aquatic organisms

216. Cooling water for the Chernobyl nuclear power plant was obtained from a 21.7 km² man-made reservoir located to the south-east of the plant site. The cooling reservoir became heavily contaminated following the accident with a total activity of over 6.5 ± 2.7 PBq of a mixture of radionuclides (alpha and beta emitters) in the water and sediments [K14]. Aquatic organisms were exposed to external radiation from the radionuclides in the water, contaminated bottom sediments, and aquatic plants. Internal irradiation occurred as organisms took up radionuclides in their food and water or inadvertently consumed contaminated sediments. The resultant doses to aquatic biota over the first 60 days following the accident are depicted in figure XI.

Figure XI. The dynamics of absorbed dose rate to organisms within the Chernobyl nuclear power plant cooling pond during the first 60 days following the accident

Data are model results based on concentrations of radionuclides in the water column and lake sediments (adapted from reference [K12])



217. The maximum dose rates to aquatic organisms (excluding fish) were reported in the first two weeks after the accident, when short-lived radionuclides (primarily ^{131}I) contributed 60–80% of the dose. During the second week, the contribution of short-lived radionuclides to the doses of aquatic organisms decreased by a factor of two. Maximum dose rates to fish were delayed (see figure XI) owing to the time required for their food webs to become contaminated with longer-lived radionuclides (largely $^{134,137}\text{Cs}$, $^{144}\text{Ce/Pr}$, $^{106}\text{Ru/Rh}$ and $^{90}\text{Sr/Y}$). The dose rates to fish depended on their trophic positions. Non-predatory fish (carp, goldfish and bleak) incurred estimated peak dose rates of 3 mGy/d due to internal exposure in 1986, followed by significant reductions in 1987. Dose rates to predatory fish (perch), however, increased in 1987 and did not start to decline until 1988 [K12]. Accumulated doses were greatest for the first generation of fish born in 1986 and 1987. Bottom-dwelling fish (goldfish, silver bream, bream and carp) that were significantly irradiated by the bottom sediments accumulated total doses of approximately 10 Gy.

218. The reproductive capacity of young silver carp was analysed in 1990 [R10]. The fish were in live boxes within the cooling pond at the time of the accident. By 1988, the fish had reached sexual maturity. Over the entire post-accident period, they received a dose of 7–8 Gy. Biochemical analyses of muscles, liver and gonads indicated no difference from the controls. The amount of fertilized spawn was 94%; 11% of the developing spawn was abnormal. Female fertility was 40% higher than that of the controls, but 8% of the irradiated sires were sterile. The level of fluctuating asymmetry in offspring did not differ from that of the controls, although the level of cytogenetic damage (22.7%) significantly exceeded that of controls (5–7%). In contrast, Pechkurenkov [P20] reported that the number of cells with chromosome aberrations in 1986–1987 in carp, bream flat and silver carp was within the norm. It is worth noting that the cooling pond was subjected not only to radioactive contamination, but also to chemical pollution. Table 25 provides a summary of the recent reviews of the chronic effects of ionizing radiation exposure on the reproduction in fish. The Chernobyl accident data are included.

Table 25. Chronic effects of exposure to ionizing radiation on reproduction in fish

Derived from the FASSET database [C11]

Dose rate ($\mu\text{Gy/h}$)	Dose rate (mGy/d)	Reproductive effects
0–99	0–2.4	Background dose group, normal cell types, normal damage and normal mortality observed
100–199	2.4–4.8	No data available

Dose rate ($\mu\text{Gy/h}$)	Dose rate (mGy/d)	Reproductive effects
200–499	4.8–12	Reduced spermatogonia and sperm in tissues
500–999	12–24	Delayed spawning, reduction in testis mass
1 000–1 999	24–48	Mean lifetime fecundity decreased, early onset of infertility
2 000–4 999	48–120	Reduced number of viable offspring Increased number of embryos with abnormalities Increased number of smolts in which sex was undifferentiated Increased brood size reported Increased mortality of embryos
5 000–9 999	120–240	Reduction in number of young fish surviving to 1 month of age Increased vertebral abnormalities
> 10 000	> 240	Inter-brood time tends to decrease with increasing dose rate Significant reduction in neonatal survival Sterility in adult fish Destruction of germ cells within 50 days in medaka fish High mortality of fry, germ cells not evident Significant decrease in number of male salmon returning to spawn; after 4 years, female salmon had significantly reduced fecundity

G. Genetic effects in animals and plants

219. High quality data on the incidence of radiogenic mutations in plants and animals as a result of the accident are relatively sparse. An increased mutation level was apparent in 1987 in the form of various morphological abnormalities in Canada fleabane, common yarrow and mouse millet. Examples of abnormalities included: unusual branching of stems; doubling the number of racemes; abnormal colour and size of leaves and flowers; and development of “witch’s broom” in pine trees. Similar effects within 5 km of the nuclear power plant also appeared in deciduous trees (leaf gigantism, and changes in leaf shapes). Morphological changes were observed at an initial gamma dose rate of 4.2–6.3 mGy/d. At a dose rate of 15.8–31.5 mGy/d, enhancement of vegetative reproduction (in heather) and gigantism of some plant species were observed [A11, K10, T17, T18].

220. Cytogenetic analysis of cells from the root meristem of winter rye and wheat germ of the 1986 harvest demonstrated a dose dependency in the number of aberrant cells. A significant excess over the control level of aberrations was observed at an absorbed dose of 3.1 Gy. Inhibition of mitotic activity occurred at a dose of 1.3 Gy, and germination was reduced at a dose of 12 Gy [G10]. The analysis of three successive generations of winter rye and wheat on the most contaminated plots revealed that the rates of aberrant cells in the intercalary meristem in the second and third generations were higher than in the first.

221. From 1986–1992, mutation dynamics were studied in populations of *Arabidopsis thaliana* Heynh. (L.) within the

30-km zone [A10]. On all study plots during the first 2–3 years after the accident, *Arabidopsis* populations exhibited an increased mutation burden. In later years, the level of lethal mutations declined; nevertheless the mutation rate in 1992 was still 4–8 times higher than the spontaneous level. The dose dependence of the mutation rate was best approximated by a power function with an exponent value of less than one.

222. Zainullin et al. [Z2] observed elevated levels of sex-linked recessive lethal mutations in natural *Drosophila melanogaster* populations living under conditions of increased chronic exposure to radiation resulting from the Chernobyl accident. The mutation levels were increased during 1986–1987 in flies inhabiting the more contaminated areas with initial exposure rates of 2 mGy/h (expressed as 200 mR/h in the original text) and more. During the subsequent two years, mutation frequencies gradually returned to normal.

223. Shevchenko et al. [S21] and Pomerantseva et al. [P16] reported studies of adverse genetic effects in wild mice. These involved mice caught during 1986–1991 within a 30-km radius of the Chernobyl nuclear power plant with different levels of gamma radiation exposure and, during 1992–1993, on a site in the Bryansk Oblast, Russia. The estimated total doses of gamma and beta radiation varied widely; the dose rates reached 3–4 Gy per month in 1986–1987. One endpoint was dominant lethality, measured by embryo mortality in the offspring of wild male mice mated with unexposed female laboratory mice. The dominant lethality rate was elevated for a period of a few weeks following capture in mice sampled at the most contaminated site. At dose rates

of about 2 mGy/h, 2 of 122 captured males produced no offspring and were assumed to be sterile. The remainder showed a period of temporary infertility and reduced testis mass. Fertility and testis mass, however, recovered with time after capture.

224. The frequencies of reciprocal translocations in mouse spermatocytes were consistent with previous studies. A dose-rate-dependent incidence of increased reciprocal translocations (scored in spermatocytes at meiotic metaphase I) was observed in all collected mice. The frequency of mice harbouring recessive lethal mutations decreased with time after the accident [P16]. Radiation-related gene mutation is unlikely to have any adverse effect on populations, at the dose rates that prevail now.

225. Increasing sophistication in the technologies for the detection of molecular and chromosomal damage have allowed researchers on the genetic consequences of the Chernobyl accident to examine endpoints not previously considered [E8]. Most prominent, and controversial, is the technique involving the measurement of mutation frequencies in repeat DNA sequences termed “minisatellite loci” or “expanded simple tandem repeats” (ESTR). These are repeat DNA sequences that are distributed throughout the germline and have a high background (spontaneous) mutation rate. Presently, ESTRs are considered to have no function, although this is a matter of much interest and discussion [B33, C10, I9]. Minisatellite mutations have only rarely been associated with recognizable genetic disease.

226. Although laboratory examination of mutations in mouse ESTR loci show clear evidence of a mutational dose response [D4, F16], the EGE was not aware of any convincing data on elevated levels of minisatellite mutations in plants or animals residing in the contaminated areas having been published in peer-reviewed scientific literature [E8]. In general, quantitative interpretation of the ESTR data is difficult because of conflicting findings, their weak association with genetic disease, dosimetric uncertainties and methodological problems [C10]. This is an area of science that requires additional research.

H. Overall observations on the effects of the Chernobyl accident

227. According to the EGE [E8], prior to the accident, much of the area around the Chernobyl nuclear power plant was covered by 30–40 year old pine stands that, from a successional standpoint, represented mature, stable ecosystems. The high dose rates due to ionizing radiation exposure during the first few weeks following the accident altered the balance in the community and opened niches for immigration of new individuals.

228. The ecological conditions within the 30-km Chernobyl exclusion zone arose from the complex interaction of a number of factors. The highest level of contamination

occurred within this zone. As a result of the elevated radiation doses associated with the contamination, human activities such as agriculture, forestry, hunting and fishing within the exclusion zone were stopped [E8]. After the accident, the fields continued to yield agricultural produce for a number of years and, in the absence of active management in the areas that had been evacuated, many animal species, especially rodents and wild boars, consumed the abandoned cereal crops, potatoes and grasses as an additional source of forage [E8]. This was advantageous to these animal species and, along with the special reserve regulations established in the exclusion zone (e.g. a ban on hunting), tended to compensate for the adverse biological effects of radiation exposure and promoted an increase in the populations of wild animals, including game mammals (wild boars, roe deer, red deer, elk, wolves, foxes, hares, beaver, etc.) and bird species (black grouse, ducks, etc.) [G8, S23]. In addition, the Chernobyl exclusion zone has become a breeding area of white-tailed eagles, spotted eagles, eagle owls, cranes and black storks [G9].

229. The high dose rates from ionizing radiation during the first few weeks following the Chernobyl accident affected the balanced community by killing sensitive individuals, altering reproduction rates, destroying some resources (e.g. pine stands), making other resources more available (e.g. soil water), and opening niches for immigration of new and sometimes negative organisms (e.g. negative entofauna). These components and more, were interwoven in a complex web of action and reaction that altered populations and communities of organisms [E8].

230. Overall, the EGE [E8, H25] arrived at a number of general observations from their evaluation of the Chernobyl data, namely that:

- 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). Beyond the exclusion zone, no acute radiation-induced effects on biota have been reported;
- 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 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])

<i>Non-human species</i>	<i>CDV_b (mGy/d) cited in [F17]</i>	<i>Literature data</i>
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]

<i>Species effect</i>	<i>Estimated minimum doses (or dose rates) at which effect was observed</i>	<i>Estimated maximum doses (or dose rates) at which effect was not observed</i>
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 lethalties	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

<i>Species effect</i>	<i>Estimated minimum doses (or dose rates) at which effect was observed</i>	<i>Estimated maximum doses (or dose rates) at which effect was not observed</i>
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 μ Gy/d [R17]	5 μ Gy/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 ¹³¹I 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

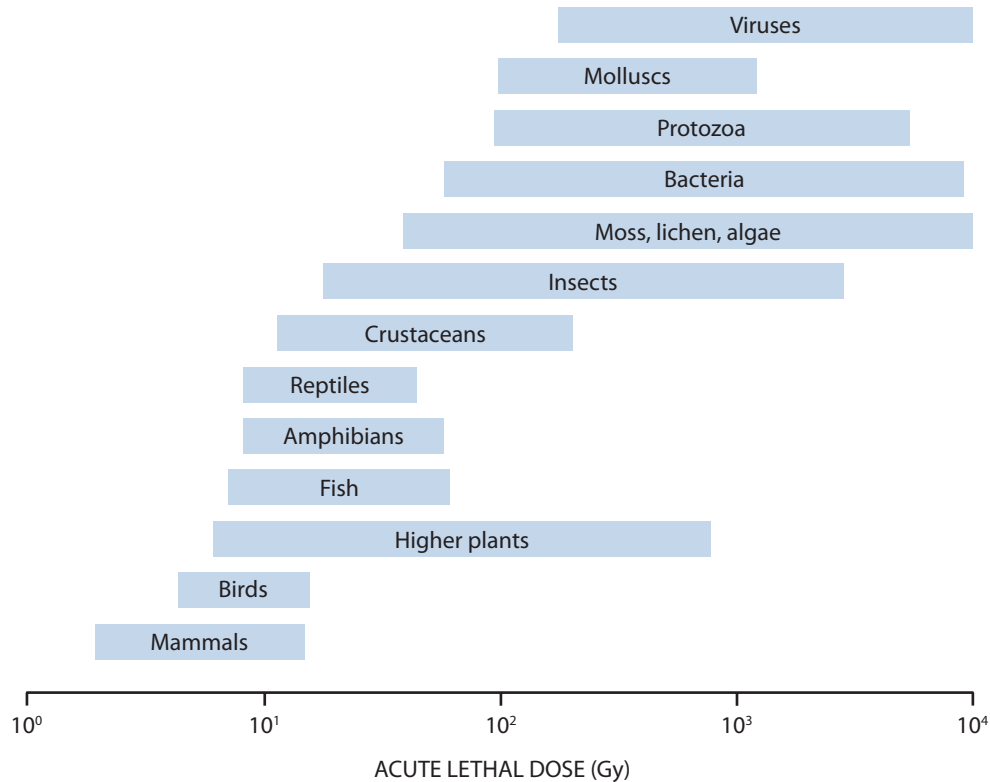
235. The main observations from the Committee's 1996 evaluation [U4] are described in chapter III of this annex.

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 μ Gy/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 μ Gy/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 μ Gy/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 μ Gy/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]

<i>Taxa</i>	<i>ENEV (Gy/a)^a</i>
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]

<i>Biota</i>	<i>IAEA [I4]</i>	<i>NCRP [N1]</i>	<i>UNSCEAR 1996 Report [U4]</i>
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 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 ¹³⁷Cs or ⁶⁰Co); 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 ($\mu\text{Gy/h}$)	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]
$>2 \times 10^4$	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 ($\mu\text{Gy/h}$)	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]

<i>Dose rate</i> ($\mu\text{Gy/h}$)	<i>Species</i>	<i>Radiation</i>	<i>Effects described</i>	<i>Endpoint</i>	<i>Reference</i>
$<10^2$	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 Field study. Increased % of sterile pairs; reduced mean offspring sired and weaned	Reproduction Reproduction	[M14, M15] [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 2 nd 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]

<i>Wildlife group</i>	<i>Morbidity</i>	<i>Mortality</i>	<i>Reproductive capacity</i>	<i>Mutation</i>
Plant	Plant growth begins to be affected at more than 100 $\mu\text{Gy/h}$. Continued exposure at 21 $\mu\text{Gy/h}$ for 8 years increases the sensitivity in pines	50% mortality at 8 years at $\sim 1\,000\ \mu\text{Gy/h}$ in pines	A field study indicated a decrease in seed weight of a herb at 5.5 $\mu\text{Gy/h}$	The mutation rate in microsatellite DNA increased at $\sim 40\ \mu\text{Gy/h}$
Fish	One experiment, but not another, indicates effects on the immune system at 8.3 $\mu\text{Gy/h}$	Too few data to draw conclusions	One study showing effects on gametogenesis at 230 $\mu\text{Gy/h}$. Otherwise effects at more than 1 000 $\mu\text{Gy/h}$	Radiation exposure increases the mutation rate
Mammals	Rat growth not affected at 16 $\mu\text{Gy/h}$ but affected at more than 3 000 $\mu\text{Gy/h}$. Some blood parameters affected at 180–850 $\mu\text{Gy/h}$. No effect on thyroid function at 8 000 $\mu\text{Gy/h}$	No effect on mouse lifespan at 460 $\mu\text{Gy/h}$, but significant reductions above $\sim 1\,000\ \mu\text{Gy/h}$ in the mouse, goat and dog	Threshold for effects at $\sim 100\ \mu\text{Gy/h}$, with clear effects at more than 1 000 $\mu\text{Gy/h}$	Too few data to draw conclusions. One of nine references gives an LOEDR of 420 $\mu\text{Gy/h}$ 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 $4 \times 10^3\ \mu\text{Gy/h}$ 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 $4 \times 10^3\ \mu\text{Gy/h}$ 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 $10^3\ \mu\text{Gy/h}$ do not result in irreversible effects on mortality, morbidity and reproduction. A dose rate of 100 $\mu\text{Gy/h}$ (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 $\mu\text{Gy/h}$) 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 $\mu\text{Gy/h}$ ”. 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

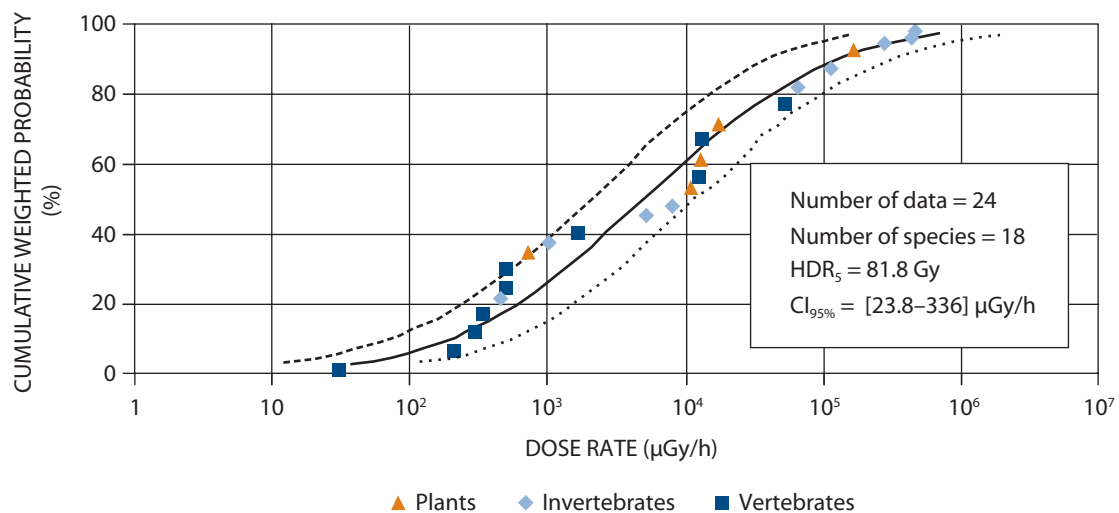
No-Effect Concentration (PNEC) for chemicals [E11]. A three-step methodology was used. First, a coherent data subset was extracted from each experiment, covering endpoints related to mortality, morbidity and reproduction. Next, a systematic mathematical treatment was applied to reconstruct dose-rate–effect relationships and to estimate critical toxicity endpoints. For chronic exposure, the critical toxicity endpoint was the estimated Effect Dose Rate (EDR_{10} , expressed in $\mu\text{Gy/h}$), 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 $82 \mu\text{Gy/h}$ (with 95th percentile confidence intervals of 23.8 and $336 \mu\text{Gy/h}$). 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 $10 \mu\text{Gy/h}$ 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]



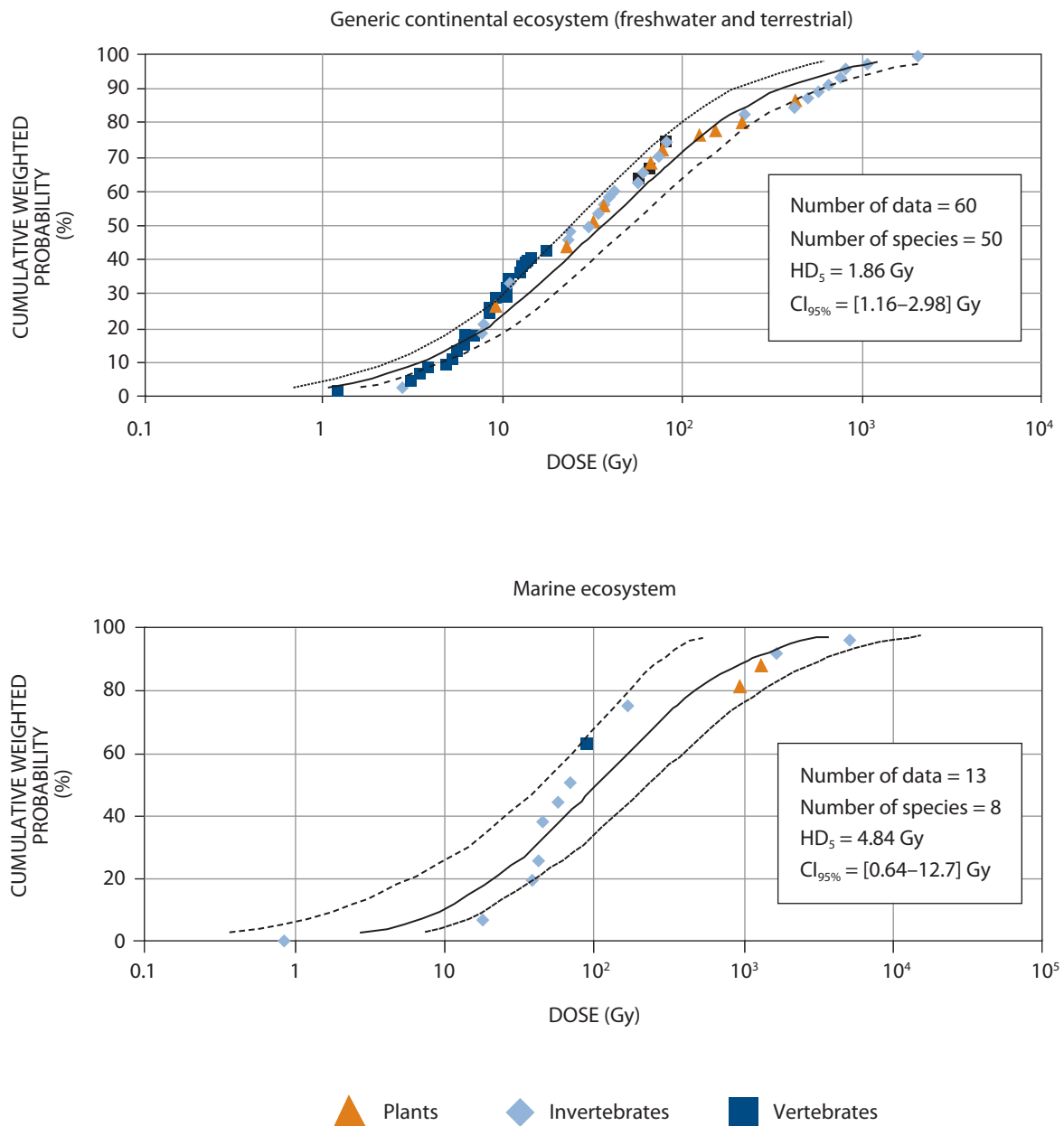
255. At the ecosystem level, the value of the ERICA integrated approach screening dose rate lies in the range giving rise to minor effects [F5, G3, G15, G27]. The authors suggested that such effects are not expected to be directly relevant at higher organizational levels, such as the structure and functioning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

<i>Targeted protected level as described in the source</i>	<i>Method/justification of the value</i>	<i>Dose rate ($\mu\text{Gy/h}$)</i>	<i>Source reference</i>
Terrestrial ecosystems			
Generic ecosystems	SSD-95% species protected plus <i>SF</i> of 5 SSD giving an <i>HDR</i> ₅ of 81.8 $\mu\text{Gy/h}$ divided by an <i>SF</i> of 5 and rounded down	10	[G3]
Generic ecosystems	SF method: <i>SF</i> of 10 applied to the lowest critical radiotoxicity value <i>EDR</i> ₁₀	0.6	[G3]
Plants	Background	0.02–0.7	[U4]
Plants	Review, <i>SF</i> 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, <i>SF</i> on the lowest critical radiotoxicity value	110	[B31, E5]
Invertebrates	Review, <i>SF</i> 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 <i>SF</i> of 5 SSD giving an <i>HDR</i> ₅ of 81.8 $\mu\text{Gy/h}$ divided by an <i>SF</i> of 5 and rounded down	10	This annex
Generic freshwater ecosystems	SF method: <i>SF</i> of 50 applied to the lowest critical radiotoxicity value <i>EDR</i> ₁₀	10	This annex
Generic marine ecosystems	SSD-95% species protected plus <i>SF</i> of 5 SSD giving an <i>HDR</i> ₅ of 81.8 $\mu\text{Gy/h}$ divided by an <i>SF</i> of 5 and rounded down	10	[G3]
Generic marine ecosystems	SF method: <i>SF</i> of 50 applied to the lowest critical radiotoxicity value <i>EDR</i> 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, <i>SF</i> 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, <i>SF</i> on the lowest critical radiotoxicity value	110	[B31, E5]
Benthic invertebrates	Review, <i>SF</i> on the lowest critical radiotoxicity value	220	[B31, E5]
Fish	Review, <i>SF</i> 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 (*Eisenia fetida*) and woodlice (*Porcellioscaber*) [H23]. Both species were continuously exposed to gamma radiation from a ¹³⁷Cs 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 (*Eisenia 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 $\sim 10^4$ 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 $\mu\text{Gy/h}$ [A19]. These authors reported that exposure to dose rates of 110 $\mu\text{Gy/h}$ 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 $\mu\text{Gy/h}$ 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 $\mu\text{Gy/h}$ 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 ($\mu\text{Gy/d}$)	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 <i>Hypophthalmichthys molitrix</i>	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 <i>Rutilus rutilus</i>	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 $\mu\text{Gy/h}$ 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 ($\mu\text{Gy/h}$) (LNOEDR or LOED))	Reference
Zebrafish (<i>D. rerio</i>), larvae (2 d)	Lab in vivo, external, ^{137}Cs	400, 1 200, 7 200 $\mu\text{Gy/h}$	1 hour, 24 hours	Alkaline comet (tail moment)	+ 1 200 $\mu\text{Gy/h}$	[J5]
Pond slider (<i>T. scripta</i>) Snapping turtle (<i>C. serpentina</i>), adults	In situ, (White Oak Lake) external + internal, ^{235}U , $^{238,240}\text{Pu}$, ^{137}Cs , ^{60}Co , ^{90}Sr , Hg, HAP, PCB	External dose rate: 50 $\mu\text{Gy/h}^b$	n.d.	Alkaline and neutral unwinding (hepatocytes)	+ 50 $\mu\text{Gy/h}$	[M5]
Mosquitofish (<i>G. affinis</i>), adults	In situ, (Oak Ridge) external + internal, ^{235}U , $^{238,240}\text{Pu}$, ^{137}Cs , ^{60}Co , ^{90}Sr , Hg, HAP, PCB	External dose rate: 50 $\mu\text{Gy/h}$	49 years	Agarose gel electrophoresis (hepatocytes, erythrocytes)	+ 50 $\mu\text{Gy/h}$	[T21]
Channel catfish (<i>I. punctatus</i>), adults	In situ, Chernobyl, cooling pond, ^{137}Cs	125 $\mu\text{Gy/h}^b$	n.d.	Alkaline unwinding (hepatocytes, gill cells, erythrocytes)	=	[S18]
Largemouth bass (<i>M. salmoides</i>), adults	In situ, Savannah River site, $^{134,137}\text{Cs}$ + $^{89,90}\text{Sr}$ + Hg	80 $\mu\text{Gy/h}^c$	n.d.	Alkaline unwinding (hepatocytes, gill cells, erythrocytes)	=	[S17]
Marine polychaete worm (<i>N. arenaceodentata</i>), larvae	Lab in vivo, external, ^{60}Co	400–25 000 Gy/h	12 hours 24 hours	SCE	+ 400 $\mu\text{Gy/h}$	[H15]
Midge (<i>C. tentans</i>), larvae	In situ, Savannah River site, $^{134,137}\text{Cs}$ + $^{89,90}\text{Sr}$ + Hg	260 $\mu\text{Gy/h}$	Lifetime	CA	+++ : inversion + : deletion 260 $\mu\text{Gy/h}$	[B34]
Marine polychaete worm (<i>N. arenaceodentata</i>), larvae	Lab in vivo, external, ^{60}Co	3 000 $\mu\text{Gy/h}$ (24 d) 6 000 $\mu\text{Gy/h}$ (48 d)	24 days 48 days	CA (metaphase)	+ 3 000 $\mu\text{Gy/h}$ + 6 000 $\mu\text{Gy/h}$	[P4]
Slider turtle (<i>T. scripta</i>), fibroblasts and lymphocytes	Lab, external, ^{137}Cs	1 000 $\mu\text{Gy/h}$ to > 100 Gy/h	n.d.	CA (symmetrical translocations)	230 000 $\mu\text{Gy/h}$ (LNOEDR)	[H14, U18]
18 different fish species	Various conditions (literature review)	Background 5×10^{-3} to 0.5 $\mu\text{Gy/h}^d$	n.d.	MN per 1 000 erythrocytes	+ Mean [min; max] : 3 [0; 13] 5×10^{-3} to 0.5 $\mu\text{Gy/h}$	[G23]
Plaice, (<i>P. platessa</i>), adult	Lab, in vivo, external, ^{137}Cs	240–1 000 $\mu\text{Gy/h}$	197 days	MN per 1 000 erythrocytes	=	[K16]
Pike (<i>E. lucius</i>), perch (<i>P. fluviatilis</i>), roach (<i>R. rutilus</i>) and bream (<i>A. brama</i>)	In situ, Swedish lake, Chernobyl fallout 1988, external + internal, ^{137}Cs	10 000 Bq/kg d.w. ^{137}Cs 10 $\mu\text{Gy/h}^d$	n.d.	MN per 1 000 erythrocytes	=	[A20]
Pike (<i>E. lucius</i>), perch (<i>P. fluviatilis</i>), roach (<i>R. rutilus</i>) and bream (<i>A. brama</i>)	In situ, Swedish lake, Chernobyl fallout 1988, external + internal, ^{137}Cs	18 000 Bq/kg d.w. ^{137}Cs Ext. dose rate : 10 $\mu\text{Gy/h}^d$	n.d.	MN per 1 000 erythrocytes	=	[A21]
Pike (<i>E. lucius</i>), adults	In situ, Siberian (Toms-7) nuclear site	57 000 $\mu\text{Gy/h}^d$ 1 200 Bq/kg w.w.	n.d.	MN per 1 000 erythrocytes	++ 57 000 $\mu\text{Gy/h}$	[I22]

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

Symbols and abbreviations: Dose rates are either those indicated in the article or those taken from other studies (β from reference [T21]; b 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 ($\mu\text{Gy/h}$) : Lowest Observed Effect Dose Rate; LNOEDR ($\mu\text{Gy/h}$) : 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 hybridization (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 radio-resistant 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 LD₅₀ 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 ¹³⁷Cs 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 ¹³⁷Cs 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.

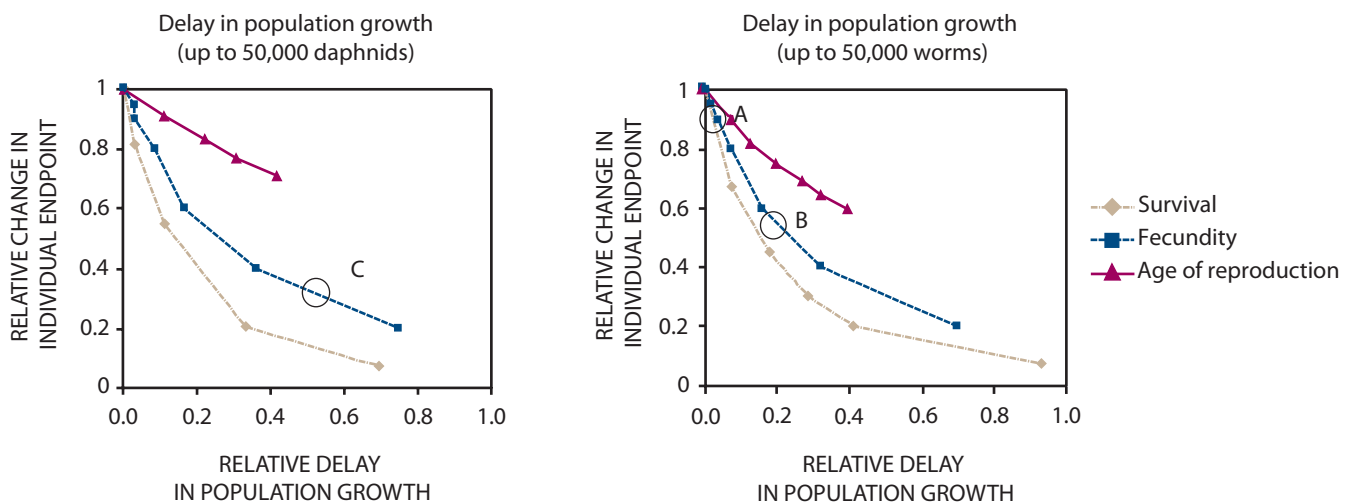
287. Two field-irradiation experiments were conducted at the Whiteshell Laboratories in Manitoba, Canada. One is the Field-Irradiated Gamma (FIG) experiment in which a boreal forest was chronically irradiated from 1973–1986 to study the effects on plant communities [G13]. The radiation source was 370 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 $\mu\text{Gy/h}$ 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 $\mu\text{Gy/h}$ 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 ($\text{LD}_{50/30}$) 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 μ Gy/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 μ Gy/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 $\mu\text{Gy/h}$ (with 95th percentile confidence intervals of 23.8 and 336 $\mu\text{Gy/h}$). 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, HDR₅ 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 ($\mu\text{Gy/h}$)	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]

<i>Category</i>	<i>Dose rate ($\mu\text{Gy/h}$)</i>	<i>Effects</i>	<i>Endpoint</i>	<i>Reference</i>
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_{95} , 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 $\mu\text{Gy/h}$ to the most highly exposed individuals would be unlikely to have significant effects on most terrestrial communities and that maximum dose rates of 400 $\mu\text{Gy/h}$ 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.

REFERENCES

- A1 Advisory Committee on Radiological Protection (ACRP22). Protection of Non-Human Biota from Ionizing Radiation. Canadian Nuclear Safety Commission (CNSC), INFO-0703, March 2002.
- A2 Amiro, B.D. Radiological dose conversion factors for generic non-human biota used for screening potential ecological impacts. *J. Environ. Radioact.* 35(1): 37-51 (1997).
- A3 Anderson, S.L. and F.L. Harrison. Effects of radiation on aquatic organisms and radiobiological methodologies for effects assessment. USEPA EPA-520/1-85-016 (1986).
- A4 Atkinson, G.F. Report upon some preliminary experiments with the Rontgen rays on plants. *Science* 7(158): 7-13 (1898).
- A5 Alexakhin, R.M. Effects of ionizing radiation on non-human biota relating to actual contaminated sites. Communication to the UNSCEAR Secretariat (2004).
- A6 Amiro, B.D. and S.C. Sheppard. Effects of ionizing radiation on the boreal forest: Canada's FIG experiment, with implications for radionuclides. *Sci. Total Environ.* 157(1-3): 371-382 (1994).
- A7 Alexakhin, R.M., S.V. Fesenko and N.I. Sanzharov. Serious radiation accidents and the radiological impact on agriculture. *Radiat. Prot. Dosim.* 64(1): 37-42 (1996).
- A8 Agenzia Nazionale per la Protezione dell'Ambiente, Italy. SEMINAT: Long-term dynamics of radionuclides in semi-natural environments: derivation of parameters and modelling. Final report. EU project no: FI4P-CT95-0022 (2000).
- A9 Avila, R., K.J. Johanson and R. Bergström. Model of the seasonal variations of fungi ingestion and Cs-137 activity concentrations in roe deer. *J. Environ. Radioact.* 46(1): 99-112 (1999).
- A10 Abramov, V.I., O.M. Fedorenko and V.A. Shevchenko. Genetic consequences of radioactive contamination for populations of *Arabidopsis*. *Sci. Total Environ.* 112(1): 19-28 (1992).
- A11 Arkhipov, N.P., N.D. Kuchma, S. Askbrant et al. Acute and long-term effects of irradiation on pine (*Pinus silvestris*) strands post-Chernobyl. *Sci. Total Environ.* 157(1-3): 383-386 (1994).
- A12 Astasheva, N.P., N.M. Lazarev, L.K. Khramtsova et al. Influence of radiation released during the Chernobyl NPP accident on clinical and physiological status of agricultural animals. p. 176-180 in: *Problems of Agricultural Radiology*. UIAR, Kiev, 1991. (In Russian).
- A13 Adam, C. Genotoxic effects of radionuclides on aquatic organisms. State of the art and critical review of existing methods. Report DEI/SECRE 2004-022. IRSN 2007/81 (2007).
- A14 Anderson, S.L., N.M. Belfiore and F. Harrison. Genotoxic effects in aquatic organisms: methodologies, field-related applications and the role of genetic diversity. Report prepared for the Atomic Energy Control Board, Ottawa, Canada (1998).
- A15 Anderson, S.L. and F.L. Harrison. Predicting the ecological significance of exposure to genotoxic substances in aquatic organisms. p. 81-97 in: *In Situ Evaluation of Biological Hazards of Environmental Pollutants* (S.S. Sandhu et al., eds.). Plenum Press, New York, 1990.
- A16 Adam, C., B. Fraysse, J. Garnier-Laplace et al. Impact of cadmium and zinc prior exposure on ^{110m}silver, ⁵⁸⁺⁶⁰cobalt and ¹³⁷cesium uptake by two freshwater bivalves during a brief field experiment. *Bull. Environ. Contam. Toxicol.* 68(3): 428-435 (2002).
- A17 Ausseil, O., C. Adam, J. Garnier-Laplace et al. Influence of metal (Cd and Zn) waterborne exposure on radionuclide (¹³⁴Cs, ^{110m}Ag, and ⁵⁷Co) bioaccumulation by rainbow trout (*Oncorhynchus mykiss*): A field and laboratory study. *Environ. Toxicol. Chem.* 21(3): 619-625 (2002).
- A18 Au, W.W., M.-Y. Heo and T. Chiewchanwit. Toxicological interactions between nickel and radiation on chromosome damage and repair. *Environ. Health Perspect.* 102 (Suppl. 9): 73-77 (1994).
- A19 Alonzo, F., R. Gilbin, S. Bourrachot et al. Effects of chronic internal alpha irradiation on physiology, growth and reproductive success of *Daphnia magna*. *Aquat. Toxicol.* 80(3): 228-236 (2006).
- A20 Al-Sabti, K. Micronuclei induction in pike (*Esox lucius*) in Swedish lakes contaminated with radio-caesium. *Cytobios.* 70(280): 27-32 (1992).
- A21 Al-Sabti, K. Monitoring the genotoxicity of radio-contaminants in Swedish lakes by fish micronuclei. *Cytobios.* 70(281): 101-106 (1992).
- A22 Anspaugh, L.R. Retention by vegetation of radionuclides deposited in rainfall — A literature summary. Lawrence Livermore National Laboratory, UCRL-53810 (1987).
- A23 Amiro, B.D. Effect of gamma-radiation dose rate and total dose on stem growth of *Pinus banksiana* (Jack pine) seedlings. *Environ. Exp. Bot.* 26(3): 253-257 (1986).
- A24 Alexakhin, R.M., L.A. Buldakov, V.A. Gubanov et al. *Radiation Accidents*. Moscow, Izdat Publisher, 2004.
- A25 Antonio, E.J., B.L. Tiller, S.L. Domotor et al. U.S. Department of Energy's regulatory and evaluation framework for demonstrating radiation protection of the environment: Implementation at the Hanford site. p. 175-192 in: *Protection of the Environment from the Effects of Ionizing Radiation*. Proceedings of an International Conference, Stockholm, October 2003. STI/PUB/1229. IAEA, Vienna (2005).
- A26 Alonzo, F., T. Hertel-Aas, M. Gilek et al. Modelling the propagation of effects of chronic exposure to ionising radiation from individuals to populations. *J. Environ. Radioact.* 99(9): 1464-1473 (2008).
- A27 Alonzo, F., R. Gilbin, F.A. Zeman et al. Increased effects of internal alpha irradiation in *Daphnia magna* after chronic exposure over three successive generations. *Aquat. Toxicol.* 87(3): 146-156 (2008).

- A28 Antropova, Z.G., E.I. Belova, I.K. Dibobes et al. A Review of Studies and Experience in Eliminating Consequences of the Accidental Contamination of the Territory with Uranium Fission Products (A.I. Burnazyan, ed.). Energoatomizdat, Moscow, 1990.
- A29 Alexakhin, R.M., N.I. Sanzharova, S.V. Fesenko et al. Chernobyl radionuclide distribution, migration, and environmental and agricultural impacts. *Health Phys.* 93(5): 418-426 (2007).
- B1 Bird, S., R.N. Coulson and D.A. Crossley Jr. Impacts of silvicultural practices on soil and litter arthropod diversity in a Texas pine plantation. *For. Ecol. Manage.* 131(1-3): 65-80 (2000).
- B2 Berger, M.J. Distribution of absorbed dose around point sources of electrons and beta particles in water and other media. *J. Nucl. Med.* 12 (Suppl. 5): 5-23 (1971).
- B3 Berger, M.J. Energy deposition in water by photons from point isotropic sources. *J. Nucl. Med.* 9 (Suppl. 1): 17-25 (1968).
- B4 Brownell, G.L., W.H. Ellett and A.R. Reddy. Absorbed fractions for photon dosimetry. *J. Nucl. Med.* 9 (Suppl. 1): 29-39 (1968).
- B5 Bacq, Z.M. and P. Alexander. *Fundamentals of Radiobiology*, 2nd Edition. page 562. Pergamon Press, Oxford, 1961.
- B6 Bakker, K. Some general remarks on the concepts "population" and "regulation". p. 565-567 in: *Dynamics of Populations: Proceedings of the Advanced Study Institute on Dynamics of Numbers in Populations*, Oosterbeek, 1970. Centre for Agricultural Publishing and Documentation, Wageningen, 1970.
- B7 Bond, V.P., T.M. Flidner and J.O. Archambeau. *Mammalian Radiation Lethality*. Academic Press, New York, 1965.
- B8 Bell, M.C. Radiation effects on farm animals: a review. p. 656-669 in: *Survival of Food Crops and Livestock in the Event of Nuclear War* (D.W. Bensen and A.H. Sparrow, eds.). AEC Symposium Series 24 (1971).
- B9 Blaylock, B.G. and J.R. Trabalka. Evaluating the effects of ionizing radiation on aquatic organisms. p. 103 in: *Advances in Radiation Biology*, Volume 7 (J.T. Lett and H. Adler, eds.). Academic Press, New York, 1978.
- B10 Blaylock, B.G. Chromosomal polymorphism in irradiated natural populations of *Chironomus*. *Genetics* 53(1): 131-136 (1966).
- B11 Bostrack, J.M. and A.H. Sparrow. Radiosensitivity of gymnosperms. II. On the nature of radiation injury and cause of death of *Pinus rigida* and *P. strobus* after chronic gamma irradiation. *Radiat. Bot.* 10: 131-143 (1970).
- B12 Blaylock, B.G., M.L. Frank and B.R. O'Neal. Methodology for estimating radiation dose rates to freshwater biota exposed to radionuclides in the environment. ES/ER/TM-78. Prepared for the U.S. Department of Energy (1993).
- B13 Brodo, I.M. Field studies of the effects of ionizing radiation on lichens. *Bryologist* 67(1): 76-87 (1964).
- B14 Baker, D.A. and J.K. Soldat. Methods for estimating doses to organisms from radioactive materials released into the aquatic environment. PNL-8150 (1992).
- B15 Bustad, L.K., L.A. George Jr., S. Marks et al. Biological effects of I-131 continuously administered to sheep. *Radiat. Res.* 6(3): 380-413 (1957).
- B16 Budarkov, V.A., A.S. Zenkin, N.I. Arkhipov et al. Effects of iodine-131 in sheep depending on the content of stable iodine in the diet. *Radiobiologiya* 32(3): 451-458 (1992). (In Russian).
- B17 Beresford, N.A. and B.J. Howard. Deliverable D9: Application of FASSET framework at case study sites. ERICA (Contract number: F16R-CT-2003-508847) European Commission (2005).
- B18 Barnthouse, L.W. Effects of ionizing radiation on terrestrial plants and animals: A workshop report. ORNL/TM-13141 (1995).
- B19 Belova, N.V., B.V. Verigin, N.G. Yemel'yanova et al. Radiobiological analysis of silver carp (*Hypophthalmichthys molitrix*) from the cooling pond of Chernobyl nuclear power station in the post-disaster period. 1. Reproductive system of fish exposed to radioactive contamination. *J. Ichthyol.* 34(1): 814-828 (1994).
- B20 Barci-Funel, G., J. Dalmasso, V.L. Barci et al. Study of the transfer of radionuclides in trees at a forest site. *Sci. Total Environ.* 173/174: 369-373 (1995).
- B21 Bunzl, K., H. Kofuji, W. Schimmack et al. Residence times of global weapons testing fallout ^{237}Np in a grassland soil compared to $^{239+240}\text{Pu}$, ^{241}Am and ^{137}Cs . *Health Phys.* 68(1): 89-93 (1995).
- B22 Barendsen, G.W. RBE for non-stochastic effects. *Adv. Space Res.* 12(2-3): 385-392 (1992).
- B23 Belov, A.D. and V.A. Kirshin. *Veterinary Radiobiology*. Atomizdat, Moscow, 1987. (In Russian).
- B24 Bartell, S.M., G. Lefebvre, G. Kaminski et al. An ecosystem model for assessing ecological risks in Québec rivers, lakes, and reservoirs. *Ecol. Model.* 124(1): 43-67 (1999).
- B25 Bartell, S.M., K.R. Campbell, C.M. Lovelock et al. Characterizing aquatic ecological risks from pesticides using a diquat dibromide case study III. Ecological process models. *Environ. Toxicol. Chem.* 19(5): 1441-1453 (2000).
- B26 Brown, J.E., H. Thørring and A. Hosseini. The "EPIC" impact assessment framework: Towards the protection of the Arctic environment from the effects of ionising radiation. A deliverable report for EPIC (Environmental Protection from Ionising Contaminants in the Arctic). Contract no.: ICA2-CT-2000-10032. Fifth Framework Programme, European Commission (2003).
- B27 Barnett, C.L., N.A. Beresford, P.L. Self et al. Radio-caesium activity concentrations in the fruit-bodies of macrofungi in Great Britain and an assessment of dietary intake habits. *Sci. Total Environ.* 231(1): 67-83 (1999).

- B28 Burkart, W. and B. Ogorek. Genotoxic action of cadmium and mercury in cell cultures and modulation of radiation effects. *Toxicol. Environ. Chem.* 12(3-4): 173-183 (1986).
- B29 Baker, R.J., A.M. Bickham, M. Bondarkov et al. Consequences of polluted environments on population structure: the bank vole (*Clethrionomys glareolus*) at Chernobyl. *Ecotoxicology* 10(4): 211-216 (2001).
- B30 Barillet, S., A. Devaux and C. Adam. Assessment of bioaccumulation, oxidative stress and neurotoxicity in the teleostean *Danio rerio* exposed to different isotopic compositions of uranium. *Environ. Toxicol. Chem.* 26(3): 497-505 (2007).
- B31 Bird, G.A., P.A. Thompson, C.R. Macdonald et al. Assessment of the impact of radionuclide releases from Canadian nuclear facilities on non-human biota. p. 241-247 in: Proceedings of the Third International Symposium on the Protection of the Environment from Ionising Radiation (SPEIR 3), Darwin, Australia, 22-26 July 2002. IAEA, Vienna (2003).
- B32 Brown, J.E., S.R. Jones, R. Saxén et al. Radiation doses to aquatic organisms from natural radionuclides. *J. Radiol. Prot.* 24(4A): A63-A77 (2004).
- B33 Bouffler, S.D., B.A. Bridges, D.N. Cooper et al. Assessing radiation-associated mutational risk to the germline: repetitive DNA sequences as mutational targets and biomarkers. *Radiat. Res.* 165(3): 249-268 (2006).
- B34 Blaylock, B.G. Cytogenetic study of a natural population of Chironomus inhabiting an area contaminated by radioactive waste. p. 835-846 in: Disposal of Radioactive Wastes into Seas, Oceans and Surface Waters. Proceedings of a Symposium. STI/PUB/126. IAEA, Vienna (1966).
- B35 Bickham, J.W., B.G. Hanks, M.J. Smolen et al. Flow cytometric analysis of the effects of low-level radiation exposure on natural populations of slider turtles (*Pseudemys scripta*). *Arch. Environ. Contam. Toxicol.* 17(6): 837-841 (1988).
- B36 Bechtel Jacobs Company LLC. Radiological benchmarks for screening contaminants of potential concern for effects on aquatic biota at Oak Ridge National Laboratory, Oak Ridge, Tennessee. BJC/OR-80. Prepared for the U.S. Department of Energy (1998).
- B37 Bothwell, M.L., D.M.J. Sherbot and C.M. Pollock. Ecosystem response to solar ultraviolet-B radiation: Influence of trophic-level interactions. *Science* 265(5168): 97-100 (1994).
- B38 Bréchnignac, F. Protection of the environment: how to position radioprotection in an ecological risk assessment perspective. *Sci. Total Environ.* 307(1): 35-54 (2003).
- B39 Boonstra, R., R.G. Manzon, S. Mihok et al. Hormetic effects of gamma radiation on the stress axis of natural populations of meadow voles (*Microtus pennsylvanicus*). *Environ. Toxicol. Chem.* 24(2): 334-343 (2005).
- B40 Bakri, A., N. Heather, J. Hendrichs et al. Fifty years of radiation biology in entomology: Lessons learned from IDIDAS. *Ann. Entomol. Soc. Am.* 98(1): 1-12 (2005).
- C1 Coppelstone, D., S. Bielby, S.R. Jones et al. Impact assessment of ionising radiation on wildlife. R&D publication 128. Environment Agency, Bristol, UK (2001).
- C2 Chambers, D.B., E. Muller, S. Saint-Pierre et al. Assessment of marine biota doses arising from radioactive discharges to the sea by the COGEMA La Hague facility. p. 159-174 in: Protection of the Environment from the Effects of Ionizing Radiation. Proceedings of an International Conference, Stockholm, October 2003. STI/PUB/1229. IAEA, Vienna (2005).
- C3 Chipman, W.A. Ionizing radiation. p. 1578 in: Marine Ecology, A Comprehensive Integrated Treatise on Life in Oceans and Coastal Waters, Volume 1/3 (O. Kinne, ed.). Wiley, Interscience, 1972.
- C4 Committee on the Biological Effects of Ionizing Radiations. The Effects on Populations of Exposure to Low Levels of Ionizing Radiation. National Academy of Sciences, National Research Council. National Academy Press, Washington D.C., 1972.
- C5 Chambers, D.B., R.V. Osborne and A.L. Garva. Choosing an alpha radiation weighting factor for doses to non-human biota. *J. Environ. Radioact.* 87(1): 1-14 (2006).
- C6 Canadian Environmental Protection Act. Consolidated Statutes and Regulations of Canada, Chapter 33. CEPA, Canada, 1999.
- C7 Casadesus, J., T. Sauras, M.A. Gonze et al. A nutrient-based mechanistic model for predicting the root uptake of radionuclides. p. 209-239 in: Radioactive Pollutants: Impact on the Environment (F. Brechnignac and B.J. Howard, eds.). EDP Sciences, Les Ulis, 2001.
- C8 Chamberlain, A.C. Interception and retention of radioactive aerosols by vegetation. *Atmos. Environ.* 4(1): 57-58 (1970).
- C9 Carini, F. Radionuclide transfer from soil to fruit. *J. Environ. Radioact.* 52(2-3): 237-279 (2001).
- C10 Committee Examining Radiation Risks of Internal Emitters (CERRIE). Report of the Committee Examining Radiation Risks of Internal Emitters. www.cerrie.org. ISBN 0-85951-545-1, London (2004).
- C11 Coppelstone, D., I. Zinger and D. Jackson. The challenge of protecting non-human biota from exposure to ionising radiation. In: The Society for Radiological Protection 40th Anniversary Meeting: ALARP: Principles and Practices, St. Catherine's College, Oxford, 2003.
- C12 Coppelstone, D., J. Hingston and A. Real. The development and purpose of the FREDERICA radiation effects database. *J. Environ. Radioact.* 99(9): 1456-1463 (2008).
- C13 Cai, L., M. Satoh, C. Tohyama et al. Metallothionein in radiation exposure: its induction and protective role. *Toxicology* 132(2): 85-98 (1999).

- C14 Cai, L. and M.G. Cherian. Adaptive response to ionizing radiation-induced chromosome aberrations in rabbit lymphocytes: Effect of pre-exposure to zinc, and copper salts. *Mutat. Res.* 369(3/4): 233-241 (1996).
- C15 Cai, L. and M.G. Cherian. Zinc-metallothionein protects from DNA damage induced by radiation better than glutathione and copper- or cadmium-metallothioneins. *Toxicol. Lett.* 136(3): 193-198 (2003).
- C16 Canadian Nuclear Safety Commission (CNSC). Releases of radionuclides from nuclear facilities (impact on non-human biota). Second Priority Substances List (PSL2), Canadian Environmental Protection Act (CEPA) (2001).
- C17 Caratero, A., M. Courtade, L. Bonnet et al. Effect of a continuous gamma irradiation at a very low dose on the life span of mice. *Gerontology* 44(5): 272-276 (1998).
- C18 Carnes, B.A. and T.E. Fritz. Continuous irradiation of beagles with gamma rays. *Radiat. Res.* 136(1): 103-110 (1993).
- C19 Coppenger, C.J. and S.O. Brown. The gross manifestations of continuous gamma irradiation on the prenatal rat. *Radiat. Res.* 31(2): 230-242 (1967).
- C20 COGEMA Resources Inc. McClean Lake Operation, Sue E Project, Environmental Impact Statement. Main Document. Saskatoon, Canada, November 2004.
- C21 Copplestone, D., B.J. Howard and F. Bréchnignac. The ecological relevance of current approaches for environmental protection from exposure to ionizing radiation. *J. Environ. Radioact.* 74(1-3): 31-41 (2004).
- C22 Ciffroy, P., K. Beaugelin-Seiller, M. Luck et al. Protection of non-human biota against radiation in freshwater — Effect of time dependence in tiered exposure assessment. *Ecol. Model.* 206(3-4): 360-368 (2007).
- C23 Crow, M.E. and F.B. Taub. Designing a microcosm bioassay to detect ecosystem level effects. *Int. J. Environ. Stud.* 13(2): 141-147 (1979).
- D1 Davey, D.R. and R.A. Jeffree. Ocean dumping of low-level radioactive waste. p. 245-254 in: *Radiation Protection in Nuclear Energy, Volume 2*. IAEA, Vienna (1988).
- D2 Dobson, R.L. and T.C. Kwan. The tritium RBE at low-level exposure—variation with dose, dose rate, and exposure duration. *Curr. Top. Radiat. Res. Q.* 12(1-4): 44-62 (1978).
- D3 Dubrova, Y.E. and M.A. Plumb. Ionising radiation and mutation induction at mouse minisatellite loci. The story of the two generations. *Mutat. Res.* 499(2): 143-150 (2002).
- D4 Dubrova, Y.E., M. Plumb, J. Brown et al. Stage specificity, dose response, and doubling dose for mouse minisatellite germ-line mutation induced by acute radiation. *Proc. Natl. Acad. Sci U.S.A.* 95(11): 6251-6255 (1998).
- D5 Dubrova, Y.E., M. Plumb, J. Brown et al. Induction of minisatellite mutations in the mouse germline by low-dose chronic exposure to gamma radiation and fission neutrons. *Mutat. Res.* 453(1): 17-24 (2000).
- D6 DeAngelis, D.L., S.M. Bartell and A.L. Brenkert. Effects of nutrient recycling and food-chain length on resilience. *Am. Naturalist* 134(5): 778-805 (1989).
- D7 Doi, M., I. Kawaguchi, N. Tanaka et al. Model ecosystem approach to estimate community level effects of radiation. *Radioprotection* 40 (Suppl. 1): s913-s919 (2005).
- D8 Dallas, C.E., S.F. Lingenfelter, J.T. Lingenfelter et al. Flow cytometric analysis of erythrocyte and leukocyte DNA in fish from Chernobyl-contaminated ponds in the Ukraine. *Ecotoxicology* 7(4): 211-219 (1998).
- E1 Environmental Risk from Ionising Contaminants: Assessment and Management (ERICA). Developed under EU 6th Framework Programme. Contract no. FI6R-CT-2004-508847. www.ERICA-project.org (2003).
- E2 Environment Canada/Health Canada. Second priority substances list assessment report (PSL2). Releases of radionuclides from nuclear facilities (Impact on non-human biota). Environment Canada and Health Canada, Ottawa (2003).
- E3 Environment Canada. Priority substances list assessment report (PSL2). Releases of radionuclides from nuclear facilities (impact on non-human biota). Environment Canada and Health Canada, Ottawa (2000).
- E4 ECOMatters Inc. Effect of radionuclides on plants. Prepared for the Chemical Evaluation Division, Commercial Chemicals Evaluation Branch, Environment Canada by ECOMatters Inc., Pinawa, Manitoba (1999).
- E5 Environment Canada. Environmental assessments of priority substances under the Canadian Environmental Protection Act (EPS/2/CC/3E). Guidance manual version 1.0 — March 1997. Chemicals Evaluation Division, Commercial Chemicals Evaluation Branch, Hull, Quebec (1997).
- E6 Ehlsen, S. and G. Kirchner. Environmental processes affecting plant root uptake of radioactive trace elements and variability of transfer factor data: a review. *J. Environ. Radioact.* 58(2): 97-112 (2002).
- E7 Ertel, J. and H. Ziegler. Cs-134/137 contamination and root uptake of different forest trees before and after the Chernobyl accident. *Radiat. Environ. Biophys.* 30(2): 147-157 (1991).
- E8 Expert Group on Environment (EGE). Environmental consequences of the Chernobyl accident and their remediation: Twenty years of experience. Report of the Chernobyl Forum Expert Group “Environment”. STI/PUB/1239. IAEA, Vienna (2006).
- E9 Ewing, D. Synergistic damage from H₂O₂ and OH radicals in irradiated cells. *Radiat. Res.* 94(1): 171-189 (1983).
- E10 Erickson, R.C. Effects of chronic irradiation by tritiated water on *Poecilia reticulata*, the Guppy. p. 1091-1099 in: *Radionuclides in Ecosystems. Proceedings of the Third National Symposium on Radioecology*, Oak Ridge, Tennessee, 1971, Volume 2 (D.J. Nelson, ed.). CONF-710501-P2 (1973).

- E11 Environment Canada. Technical guidance document in support of Commission Directive 93/67/EEC on risk assessment for new notified substances and Commission Regulation (EC) No. 1488/94 on risk assessment for existing substances, Directive 98/8/EC of the European Parliament and of the Council concerning the placing of biocidal products on the market. Part II. EUR 20418 EN/2. Office for Official Publication of the European Communities, Luxembourg (2003).
- E12 Environment Agency. An investigation into the effects of chronic radiation on fish. R&D technical report P3-053/TR. Environment Agency, Bristol, UK (2002).
- E13 Environment Agency. Habitats regulations for stage 3 assessments: radioactive substances authorisations. R&D technical report P3-101/SP1a. Environment Agency, Bristol, UK (2003).
- E14 Erickson, B.H. and P.G. Martin. Effects of continuous prenatal gamma radiation on the pig and rat. p. 111-117 in: Biological and Environmental Effects of Low-Level Radiation, Proceedings Series, Volume I. STI/PUB/409. IAEA, Vienna (1976).
- E15 Erickson, B.H. and P.G. Martin. Reproductive and genetic effects of continuous prenatal irradiation in the pig. *Teratology* 30(1): 99-106 (1984).
- E16 Erickson, B.H. Effect of continuous gamma-radiation on the stem and differentiating spermatogonia of the adult rat. *Mutat. Res.* 52(1): 117-128 (1978).
- E17 Ershoff, B.H. and V. Brat. Comparative effects of prenatal gamma radiation and x-irradiation on the reproductive system of the rat. *Am. J. Physiol.* 198(5): 1119-1122 (1960).
- E18 Eliseeva, K.G., A.M. Voïtovich, M.V. Ploskaia et al. The genetic monitoring of populations of brown frogs inhabiting radionuclide-contaminated regions of the Republic of Byelarus. *Radiats. Biol. Radioecol.* 34(6): 838-846 (1994). (In Russian).
- E19 Eliseeva, K.G., N.A. Kartel, A.M. Voïtovich et al. Chromosome aberrations in different tissues of the murine rodents and amphibians from radionuclide-contaminated regions of Belarus. *Tsitol. Genet.* 30(4): 20-25 (1996).
- E20 Ermakova, O.V. Compensatory-recovery processes in the endocrine system of voles in conditions of radioactive contamination of the environment. p. 58-76 in: Effects of Radioactive Contamination on Terrestrial Ecosystems in the Chernobyl Affected Area. Proceedings No. 145, Vol. 1. Komi Science Center, Ural Branch of the Russian Academy of Sciences. Syktyvkar, 1996. (In Russian).
- E21 Ewing, D. The directed evolution of radiation resistance in *E. coli*. *Biochem. Biophys. Res. Commun.* 216(2): 549-553 (1995).
- E22 EcoMetrix Incorporated. McArthur river operation: environmental risk assessment 2005. Prepared for Cameco Corporation (December 2005).
- E23 EcoMetrix Incorporated. Ecological effects review of Chalk river laboratories. Prepared for Atomic Energy of Canada Limited (January 2005).
- F1 Framework for Assessment of Environmental Impact (FASSET) Final report. Developed under EC 5th Framework Programme. Contract no. FIGE-CT-2000-00102. www.ERICA-project.org. (2004).
- F2 Framework for Assessment of Environmental Impact (FASSET). Deliverable 2: Part 1: Formulating the FASSET assessment context; Part 2: Overview of programmes for the assessment of risks to the environment from ionising radiation and hazardous chemicals (C.M. Larsson, E. Brewitz, C. Jones et al., eds.) (2002).
- F3 Framework for Assessment of Environmental Impact (FASSET). Radiation Effects Database, Vol. 1^o. Environmental Research and Consultancy, University of Liverpool (2002).
- F4 Framework for Assessment of Environmental Impact (FASSET). Deliverable 3: Dosimetric models and data for assessing radiation exposures to biota (G. Pröhl, ed.) (2003).
- F5 Framework for Assessment of Environmental Impact (FASSET). Deliverable 4: Radiation effects on plants and animals (D. Woodhead and I. Zinger, eds.) (2003).
- F6 Framework for Assessment of Environmental Impact (FASSET). Deliverable 5: Handbook for assessment of the exposure of biota to ionising radiation from radionuclides in the environment (Main report); Appendix 1, Transfer factors and dose conversion coefficient look-up tables; Appendix 2, Underpinning scientific information (life history sheets, empirical data and models) (J. Brown, P. Strand, A. Hosseini et al., eds.) (2003).
- F7 Frissel, M.J. An update of the recommended soil-to-plant transfer factors of Sr-90, Cs-137 and transuranics. p. 16-25 in: VIIIth Report of the Working Group Soil-to-Plant Transfer Factors. IUR Pub R-9212-02. International Union of Radioecologists, Balen, 1992.
- F8 Frissel, M. Soil to plant transfer of radionuclides in (sub-)tropical areas. Results of an IAEA-coordinated research programme. p. 130-137 in: Proceedings of International Meeting on Influence of Climatic Characteristics upon Behaviour of Radioactive Elements (Y. Ohmoto and N. Sakurai, eds.). Institute for Environmental Sciences, Rokkasho, Japan, 1997.
- F9 Forbes, V.E. and P. Calow. Population growth rate as a basis for ecological risk assessment of toxic chemicals. *Philos. Trans. R. Soc. Lond. Ser. B: Biol. Sci.* 357(1425): 1299-1306 (2002).
- F10 Fedotov, I.S., V.A. Kal'chenko, E.V. Igoninna et al. Radiation and genetic consequences of ionizing irradiation on population of *Pinus sylvestris* L. within the zone of the Chernobyl NPP. *Radiats. Biol. Radioecol.* 46(3): 268-278 (2006). (In Russian).
- F11 Frissel, M.J., D.L. Deb, M. Fathony et al. Generic values for soil-to-plant transfer factors of radiocaesium. *J. Environ. Radioact.* 58(2-3): 113-128 (2002).

- F12 Fesenko, S., P. Jacob, R. Alexakhin et al. Important factors governing exposure of the population and counter-measure application in rural settlements of the Russian Federation in the long-term after the Chernobyl accident. *J. Environ. Radioact.* 56(1-2): 77-98 (2001).
- F13 Fesenko, S.V., R.M. Alexakhin, S.I. Spiridonov et al. Dynamics of ¹³⁷Cs concentration in agricultural products in areas of Russia contaminated as a result of the accident at the Chernobyl nuclear power plant. *Radiat. Prot. Dosim.* 60(2): 155-166 (1995).
- F14 Fielitz, U. Untersuchungen zum Verhalten von Radio-cäsium in Wildschweinen und anderen Biomedien des Waldes. Final report of the research project StSch 4324. Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, Bonn, Berlin, 2005. (In German).
- F15 Fraysse, B., J.P. Baudin, J. Garnier-Laplace et al. Effects of Cd and Zn waterborne exposure on the uptake and depuration of ⁵⁷Co, ^{110m}Ag and ¹³⁴Cs by the Asiatic clam (*Corbicula fluminea*) and the zebra mussel (*Dreissena polymorpha*): whole organism study. *Environ. Pollut.* 118(3): 297-306 (2002).
- F16 Fan, Y.J., Z. Wang, S. Sadamoto et al. Dose-response of a radiation induction of a germline mutation at a hypervariable mouse minisatellite locus. *Int. J. Radiat. Biol.* 68(2): 177-183 (1995).
- F17 Fesenko, S.V., R.M. Alexakhin, S.A. Geras'kin et al. Comparative radiation impact on biota and man in the area affected by the accident at the Chernobyl nuclear power plant. *J. Environ. Radioact.* 80(1): 1-25 (2005).
- F18 Ferens, M.C. and R.J. Beyers. Studies of a simple laboratory microecosystem: effects of stress. *Ecology* 53(4): 709-713 (1972).
- F19 Fuma, S., H. Takeda, K. Miyamoto et al. Effects of γ -rays on the populations of the steady-state ecological microcosm. *Int. J. Radiat. Biol.* 74(1): 145-150 (1998).
- F20 Framework for Assessment of Environmental Impact (FASSET). Deliverable 1: Identification of candidate reference organisms from a radiation exposure pathways perspective (P. Strand, N. Beresford, R. Avila et al., eds.) (2001).
- G1 Gragtmans, N.J., D.K. Myers, J.R. Johnson et al. Occurrence of mammary tumors in rats after exposure to tritium beta rays and 200-kVp x rays. *Radiat. Res.* 99(3): 636-650 (1984).
- G2 Groupe Radioecologie Nord-Cotentin, Groupe de Travail n°2. *Revue Critique des mesures dans l'environnement*. Tome 1-2, France (1999).
- G3 Garnier-Laplace, J. and R. Gilbin. Deliverable 5: Derivation of predicted-no-effect-dose-rate values for ecosystems (and their sub-organisational levels) exposed to radioactive substances. ERICA, Contract number: F16R-CT-2004-508847 (2006).
- G4 Guillitte, O., A. Fraiture and J. Lambinson. Soil-fungi radiocaesium transfers in forest ecosystems. p. 468-476 in: *Transfer of Radionuclides in Natural and Semi-Natural Environments* (G. Desmet, P. Nassimbeni and M. Belli, eds.). Elsevier Applied Science, London, 1990.
- G5 Goor, F. and Y. Thiry. Processes, dynamics and modelling of radiocaesium cycling in a chronosequence of Chernobyl-contaminated Scots pine (*Pinus sylvestris* L.) plantations. *Sci. Total Environ.* 325(1-3): 163-180 (2004).
- G6 Garger, E.K., F.O. Hoffman, K.M. Thiessen et al. Test of existing mathematical models for atmospheric resuspension of radionuclides. *J. Environ. Radioact.* 42(2): 157-175 (1999).
- G7 Gillett, A.G. and N.M.J. Crout. A review of ¹³⁷Cs transfer to fungi and consequences for modelling environmental transfer. *J. Environ. Radioact.* 48(1): 95-121 (2000).
- G8 Gaichenko, V.A., V.I. Kryzhzhanovsky, V.N. Stovbchaty et al. Ecological situation in the 30-km zone of Chernobyl NPP and its alteration over last 3 post-accidental years. Reports of the Second All-Union scientific and technical meeting on the results of elimination of consequences of the accident at the Chernobyl NPP. *Chernobyl* 6(3): 4-11 (1990). (In Russian).
- G9 Gaschak, S.P., A.A. Zalissky, D.A. Vishnevsky et al. Fauna of vertebrates in the Chernobyl zone of Ukraine. Preprint of the International Chernobyl Center for Nuclear Safety, Radioactive Waste and Radioecology, Slavutysh, 2002. (In Ukrainian).
- G10 Geraskin, S.A., V.G. Dikarev, Y.Y. Zyablitskaya et al. Genetic consequences of radioactive contamination by the Chernobyl fallout to agricultural crops. *J. Environ. Radioact.* 66(1): 155-169 (2003).
- G11 Garnier-Laplace, J., D. Coppelstone, R. Gilbin et al. Issues and practices in the use of effects data from FREDERICA in the ERICA integrated approach. *J. Environ. Radioact.* 99(9): 1474-1483 (2008).
- G12 Grodzinsky, D.N. and I.N. Gudkov. Radiobiological effects on plants in the contaminated territory. p. 325-377 in: *The Chernobyl Exclusion Zone*. National Academy of Sciences, Ukraine, Kiev, 2001.
- G13 Guthrie, J.E. and J.R. Dugle. Gamma-ray irradiation of a boreal forest ecosystem: the Field Irradiator-Gamma (FIG) facility and research programs. *Can. Field Nat.* 97: 120-128 (1983).
- G14 Grueter, H. Radioactive fission product ¹³⁷Cs in mushrooms in W. Germany during 1963-1970. *Health Phys.* 20(6): 655-657 (1971).
- G15 Garnier-Laplace, J., C. Della-Vedova, R. Gilbin et al. First derivation of predicted-no-effect values for freshwater and terrestrial ecosystems exposed to radioactive substances. *Environ. Sci. Technol.* 40(20): 6498-6505 (2006).
- G16 Garnier-Laplace, J., M. Gilek, S. Sundell-Bergman et al. Assessing ecological effects of radionuclides: data gaps and extrapolation issues. *J. Radiol. Prot.* 24(4A): A139-A155 (2004).
- G17 Garnier-Laplace, J., A. Boudou, C. Adam et al. Is it relevant to take into account the multipollution context in freshwater radioecology? ECORAD 2001: The Radioecology-ecotoxicology of Continental and Estuarine Environments, Aix en Provence, France, 3-7 September 2001. *Radioprotection-colloques* 37(1): C1-185/C1-196 (2002).

- G18 Geras'kin, S.A., V.G. Dikarev, A.A. Udalova et al. The combined effect of ionising irradiation and heavy metals on the frequency of chromosome aberrations in spring barley leaf meristem. *Genetika (RU)* 32(2): 246-254 (1996).
- G19 Gilyarov, M.S. and D.A. Krivolutsky. Radioecological studies in soil zoology. *Zool. J.* 50(3): 329-342 (1971).
- G20 Greenwood, L.N. and J.F. Knowles. Effect of chronic irradiation on the humoral immune response of a marine fish, the eelpout (*Zoarces viviparus L.*). *Int. J. Radiat. Biol.* 67(1): 71-77 (1995).
- G21 Gómez-Ros, J.M., G. Pröhl and V. Taranenko. Estimation of internal and external exposures of terrestrial reference organisms to natural radionuclides in the environment. *J. Radiol. Prot.* 24(4A): A79-A88 (2004).
- G22 Gilbin, R., F. Alonzo and J. Garnier-Laplace. Effects of chronic external gamma irradiation on growth and reproductive success of *Daphnia magna*. *J. Environ. Radioact.* 99(1): 134-145 (2008).
- G23 Gustavino, B., K.A. Scornajenghi, S. Minissi et al. Micronuclei induced in erythrocytes of *Cyprinus carpio* (teleostei, pisces) by X-rays and colchicine. *Mutat. Res.* 494(1): 151-159 (2001).
- G24 George, L.S., C.E. Dallas, I.L. Brisbin Jr. et al. Flow cytometric DNA analysis of ducks accumulating ¹³⁷Cs on a reactor reservoir. *Ecotoxicol. Environ. Saf.* 21(3): 337-347 (1991).
- G25 Grahn, D., G.A. Sacher, R.A. Lea et al. Analytical approaches to and interpretations of data on time, rate and cause of death of mice exposed to external gamma irradiation. p. 43-58 in: *Late Biological Effects of Ionizing Radiation, Vol. II. Proceedings of a Symposium, Vienna, 13-17 March 1978.* IAEA, Vienna (1978).
- G26 Geras'kin, S.A., S.V. Fesenko and R.M. Alexakhin. Effects of non-human species irradiation after the Chernobyl NPP accident. *Environ. Int.* 34(6): 880-897(2008).
- G27 Garisto, N.C., S.L. Fernandes, M. Monabbati et al. Screening "no-effect concentrations" for radionuclides in the abiotic environment from a generic ecological risk perspective: derivation and application to the Pickering Nuclear Site. *The 2nd International Conference on Radioactivity in the Environment, 2-6 October 2005, Nice, France, 2005.*
- H1 Holdway, D.A. Uranium toxicity to two species of Australian tropical fish. *Sci. Total Environ.* 125: 137-158 (1992).
- H2 Harrison, J.D. and J.W. Stather. The gastrointestinal absorption of protactinium, uranium, and neptunium in the hamster. *Radiat. Res.* 88(1): 47-55 (1981).
- H3 Harrison, F. Radiobiological endpoints relevant to ecological risk assessment. p. 39-52 in: *Symposium on Radiological Impacts from Nuclear Facilities on Non-human Species, Ottawa, Ontario, 1-2 December 1996.* Canadian Nuclear Society, Toronto, Ontario, 1997.
- H4 Hoffman, F.O., C.W. Miller, D.L. Shaeffer et al. Computer codes for the assessment of radionuclides released to the environment. *Nucl. Saf.* 18(3): 343-354 (1977).
- H5 Hoffman, F.O., K.M. Thiessen and B. Watkins. Opportunities for the testing of environmental transport models using data obtained following the Chernobyl accident. *Health Phys.* 70(1): 5-7 (1996).
- H6 Heinemann, K. and K.J. Vogt. Measurements of the deposition of iodine onto vegetation and of the biological half-life of iodine on vegetation. *Health Phys.* 39(3): 463-474 (1980).
- H7 Hosker Jr., R.P. and S.E. Lindberg. Review: Atmospheric deposition and plant assimilation of gases and particles. *Atmos. Environ.* 16(5): 889-910 (1982).
- H8 Haselwandter, K., M. Berreck and P. Brunner. Fungi as bioindicators of radiocaesium contamination: pre- and post-Chernobyl activities. *Trans. Br. Mycol. Soc.* 90(2): 171-174 (1988).
- H9 Haas, G., R. Schupfner and A. Müller. Radionuclide uptake and long term behavior of Cs-137, Cs-134 and K-40 in tree rings of spruce. *J. Radioanal. Nucl. Chem.* 194(2): 277-282 (1995).
- H10 Hinton, T.G., M. McDonald, Y. Ivanov et al. Foliar absorption of resuspended ¹³⁷Cs relative to other pathways of plant contamination. *J. Environ. Radioact.* 30(1): 15-30 (1996).
- H11 Hyodo-Taguchi, Y. Effects of chronic gamma-irradiation on spermatogenesis in the fish *Oryzias latipes* with special reference to the regeneration of testicular stem cells. p. 91-104 in: *Radiation Effects on Aquatic Organisms (N. Egami, ed.).* Japan Scientific Societies Press, Tokyo, 1980.
- H12 Hinton, T.G., D.P. Coughlin, Y. Yi et al. Low dose rate irradiation facility: initial study on chronic exposures to medaka. *J. Environ. Radioact.* 74(1-3): 43-55 (2004).
- H13 Hagger, J.A., F.A. Atienzar and A.N. Jha. Genotoxic, cytotoxic, developmental and survival effects of tritiated water in the early life stages of the marine mollusc, *Mytilus edulis*. *Aquat. Toxicol.* 74(3): 205-217 (2005).
- H14 Hinton, T.G., J. Bedford, J. Congdon et al. Determining significant endpoints for ecological risk analyses. Final Report, Project ID No. 55410, US DOE (2000).
- H15 Harrison, F.L. and D.W. Rice. Effect of low cobalt-60 dose rates on sister chromatid exchange incidence in the benthic worm *Neanthes arenaceodentata*. p. 28 in: *UCRL-53205* (1981).
- H16 Hyodo-Taguchi, Y. and N. Egami. Damage to spermatogenic cells in fish kept in tritiated water. *Radiat. Res.* 71(3): 641-652 (1977).
- H17 Hyodo-Taguchi, Y. and H. Etoh. Vertebral malformations in medaka (teleost fish) after exposure to tritiated water in the embryonic stage. *Radiat. Res.* 135(3): 400-404 (1993).
- H18 Hupp, E.W., J.W. Austin, G.M. Krise et al. Survival of Spanish goats exposed to continuous or acute irradiation. *Int. J. Radiat. Biol. Relat. Stud. Phys. Chem. Med.* 20(5): 475-484 (1971).

- H19 Hupp, E.W. Effects of continuous lifetime irradiation on Spanish goats. p. 119-126 in: *Biological and Environmental Effects of Low-Level Radiation*, Proceedings Series, Volume I. STI/PUB/409. IAEA, Vienna (1976).
- H20 Hinton, T.G. and F. Bréchnac. A case against biomarkers as they are currently used in radioecological risk analyses: a problem of linkage. In: *ECORAD 2004: The Scientific Basis for Environment Protection Against Radioactivity*, Aix-en-Provence, France, 6-10 September (2004).
- H21 Health Protection Agency (HPA). Review of risks from tritium. Report of the independent advisory group on ionising radiation. Documents of the Health Protection Agency, Radiation, Chemical and Environmental Hazards, RCE-4 (2007).
- H22 Hertel-Aas, T., D.H. Oughton, A. Jaworska et al. Effects of chronic gamma irradiation on reproduction in the earthworm *Eisenia fetida* (Oligochaeta). *Radiat. Res.* 168(5): 515-526 (2007).
- H23 Hingston, J.L., M.D. Wood, D. Copplestone et al. Impact of chronic low-level ionising radiation exposure on terrestrial invertebrates. *Radioprotection* 40 (Suppl. 1): S145-S150 (2005).
- H24 Hutchinson, T.C. and H. Czynska. Heavy metal toxicity and synergism to floating aquatic weeds. *Verh. Int. Ver. Theor. Angew. Limnol.* 19(3): 2102-2111 (1975).
- H25 Hinton, T.G., R. Alexakhin, M. Balonov et al. Radiation-induced effects on plants and animals: findings of the United Nations Chernobyl forum. *Health Phys.* 93(5): 427-440 (2007).
- H26 Hoffman, F.O., K.M. Thiessen, R.M. Rael. Comparison of interception and initial retention of wet-deposited contaminants on leaves of different vegetation types. *Atmos. Environ.* 29(15): 1771-1775 (1995).
- I1 International Atomic Energy Agency. Draft plan of activities on the radiation protection of the environment. IAEA, GOV/2005/49 (24 August 2005).
- I2 International Atomic Energy Agency. Effects of ionizing radiation on aquatic organisms and ecosystems. Technical Reports Series No. 172. IAEA, Vienna (1976).
- I3 International Atomic Energy Agency. Assessing the impact of deep sea disposal of low level radioactive waste on living marine resources. Technical Reports Series No. 288. IAEA, Vienna (1988).
- I4 International Atomic Energy Agency. Effects of ionizing radiation on plants and animals at levels implied by current radiation protection standards. Technical Reports Series No. 332. IAEA, Vienna (1992).
- I5 International Commission on Radiological Protection. 1990 Recommendations of the International Commission on Radiological Protection. ICRP Publication 60. *Annals of the ICRP* 21(1-3). Pergamon Press, Oxford, 1991.
- I6 Ingram, M. Biological effects on ionizing radiation. An annotated bibliography covering the years 1898-1957. TID-3097 (1966).
- I7 International Commission on Radiological Protection. Recommendations of the International Commission on Radiological Protection (As Amended 1959 and Revised 1962). Pergamon Press, Oxford, 1964.
- I8 International Commission on Radiological Protection. Recommendations of the International Commission on Radiological Protection. ICRP Publication 26. *Annals of the ICRP* 1(3). Pergamon Press, Oxford, 1977.
- I9 International Commission on Radiological Protection. A Framework for Assessing the Impact of Ionizing Radiation on Non-human Species. ICRP Publication 91. *Annals of the ICRP* 33(3). Pergamon Press, Oxford, 2003.
- I10 International Commission on Radiological Protection. Environmental Protection: the Concept and Use of Reference Animals and Plants. ICRP Publication 108. *Annals of the ICRP* 38(4-6). Elsevier, Oxford, 2008.
- I11 International Atomic Energy Agency. Generic models for use in assessing the impact of discharges of radioactive substances to the environment. Safety Reports Series No. 19. IAEA, Vienna (2001).
- I12 International Commission on Radiological Protection. Recommendations of the International Commission on Radiological Protection. ICRP Publication 103. *Annals of the ICRP* 37(2-4). Elsevier, Oxford, 2007.
- I13 International Commission on Radiological Protection. Radionuclide Transformations: Energy and Intensity of Emissions. ICRP Publication 38. *Annals of the ICRP* 11-13. Pergamon Press, Oxford, 1983.
- I14 International Atomic Energy Agency. Quantification of radionuclide transfer in terrestrial and freshwater environments for radiological assessments. IAEA-TECDOC-1616. IAEA, Vienna (2009).
- I15 International Commission on Radiation Units and Measurements. Photon, electron, proton and neutron interaction data for body tissues. ICRU Report 46 (1991).
- I16 International Atomic Energy Agency. Handbook of parameter values for the prediction of radionuclide transfer in temperate environments. Technical Reports Series No. 364. IAEA, Vienna (1994).
- I17 Ipatyev, V., I. Bulavik, V. Baginsky et al. Forest and Chernobyl: forest ecosystems after the Chernobyl nuclear power plant accident: 1986-1994. *J. Environ. Radioact.* 42(1): 9-38 (1999).
- I18 Ilyazov, R.G., A.N. Sirotkin et al. Ecological and Radiobiological Consequences of the Chernobyl Catastrophe for Stock-Breeding and Ways of its Overcoming (R.G. Ilyazov, Fan, Kazan, eds.). 2002. (In Russian).
- I19 International Atomic Energy Agency. Protection of the environment from the effects of ionizing radiation. A report for discussion. IAEA-TECDOC-1091. IAEA, Vienna (1999).

- I20 International Atomic Energy Agency. Sediment distribution coefficients and concentration factors for biota in the marine environment. Technical Reports Series No. 422. IAEA, Vienna (2004).
- I21 Iosjpe, M., J. Brown and P. Strand. Modified approach to modelling radiological consequences from releases into the marine environment. *J. Environ. Radioact.* 60(1-2): 91-103 (2002).
- I22 Ilyinskikh, N.N., E.N. Ilyinskikh and I.N. Ilyinskikh. Micronucleated erythrocytes frequency and radiocesium bioconcentration in pikes (*Esox lucius*) caught in the Tom River near the nuclear facilities of the Siberian Chemical Complex (Tomsk-7). *Mutat. Res.* 421(2): 197-203 (1998).
- I23 International Atomic Energy Agency. Summary report on the post-accident review meeting on the Chernobyl accident. Safety Series No. 75-INSAG-1. IAEA, Vienna (1991).
- I24 International Atomic Energy Agency. The international Chernobyl project: an overview. STI/PUB/884. IAEA, Vienna (1991).
- J1 Jones, D., S. Domotor, K. Higley et al. Principles and issues in radiological ecological risk assessment. *J. Environ. Radioact.* 66(1-2): 19-39 (2003).
- J2 Jones, D.S. and P.A. Scofield. Implementation and validation of a DOE standardized screening method for evaluating radiation impacts to biota at long-term stewardship sites. U.S. Department of Energy, Oak Ridge National Laboratory. ORNL/TM-2003/76 (2003).
- J3 Johanson, K.J. and R. Bergström. Radiocaesium transfer to man from moose and roe deer in Sweden. *Sci. Total Environ.* 157(1-3): 309-316 (1994).
- J4 Jha, A.N., Y. Dogra, A. Turner et al. Impact of low doses of tritium on the marine mussel, *Mytilus edulis*: genotoxic effects and tissue-specific bioconcentration. *Mutat. Res.* 586(1): 47-57 (2005).
- J5 Jarvis, R.B. and J.F. Knowles. DNA damage in zebrafish larvae induced by exposure to low-dose rate gamma-radiation: detection by the alkaline comet assay. *Mutat. Res.* 541(1-2): 63-69 (2003).
- J6 Journal of Environmental Radioactivity. The ERICA Project, Environmental risk from ionising contaminants: assessment and management. *J. Environ. Radioact.* 99(9): 1361-1518 (2008).
- K1 Kozubov, G.M. and A.I. Taskaev (eds.). The Radiation Influence on the Coniferous Forests in the Region of the Catastrophe at the Chernobyl Atomic Power Station. Siktivkar, USSR, 1990.
- K2 Kocher, D.C. and J.R. Trabalka. On the application of a radiation weighting factor for alpha particles in protection of non-human biota. *Health Phys.* 79(4): 407-411 (2000).
- K3 Knowles, J.F. and L.N. Greenwood. A comparison of the effects of long-term beta and gamma irradiation on the reproductive performance of a marine invertebrate ophryotrocha diadema (*Polychaeta*, *Dorvilleidae*). *J. Environ. Radioact.* 34(1): 1-7 (1997).
- K4 Kinnersley, R.P., A.J.H. Goddard, M.J. Minski et al. Interception of caesium-contaminated rain by vegetation. *Atmos. Environ.* 31(8): 1137-1145 (1997).
- K5 Kirchner, G. Transport of iodine and cesium via the grass-cow-milk pathway after the Chernobyl accident. *Health Phys.* 66(6): 653-665 (1994).
- K6 Krouglov, S.V., A.S. Filipas, R.M. Alexakhin et al. Long-term study on the transfer of ¹³⁷Cs and ⁹⁰Sr from Chernobyl-contaminated soils to grain crops. *J. Environ. Radioact.* 34(3): 267-286 (1997).
- K7 Kocher, D.C. and G.G. Killough. Global cycling of tritium and I-129 in the biosphere. Presented in: Seminar on the Cycling of Long-lived Radionuclides in the Biosphere: Observations and Models, Madrid, Spain, 15-19 September 1986.
- K8 Kiefer, P., G. Pröhl, H. Müller et al. Factors affecting the transfer of radiocaesium from soil to roe deer in forest ecosystems of southern Germany. *Sci. Total Environ.* 192(1): 49-61 (1996).
- K9 Kryshev, I.I. and T.G. Sazykina. Radiological consequences of radioactive contamination of the Kara and Barent Seas. *J. Environ. Radioact.* 29(3): 213-223 (1995).
- K10 Kozubov, G.M. and A.I. Taskaev. Radiobiological and Radioecological Investigations of Woody Plants. Nauka, St. Petersburg, 1994. (In Russian).
- K11 Krivolutsky, D., V. Martushov and I. Ryabtsev. Influence of radioactive contamination on fauna in the area of the Chernobyl NPP during first years after the accident (1986-1988). p. 106-122 in: Bioindicators of Radioactive Contamination. Nauka, Moscow, 1999. (In Russian).
- K12 Kryshev, I., R. Alexakhin, K. Makhonko et al. Radiocological Consequences of the Chernobyl Accident. Nuclear Society, Moscow, 1992.
- K13 Krivolutzkii, D.A. and A.D. Pokarzhevskii. Effects of radioactive fallout on soil animal populations in the 30 km zone of the Chernobyl atomic power station. *Sci. Total Environ.* 112(1): 69-77 (1992).
- K14 Kryshev, I. Radioactive contamination of aquatic ecosystems following the Chernobyl accident. *J. Environ. Radioact.* 27(3): 207-219 (1995).
- K15 Karavaeva, Y.N., N.V. Kulikov, I.V. Molchanova et al. Accumulation and distribution of long-living radionuclides in the forest ecosystems of the Kyshtym accident zone. *Sci. Total Environ.* 157(1-3): 147-151 (1994).
- K16 Knowles, J.F. Long-term irradiation of a marine fish, the plaice *Pleuronectes platessa*: an assessment of the effects on size and composition of the testes and of possible genotoxic changes in peripheral erythrocytes. *Int. J. Radiat. Biol.* 75(6): 773-782 (1999).
- K17 Knowles, J.F. The effect of chronic radiation on the humoral immune response of rainbow trout (*Oncorhynchus mykiss Walbaum*). *Int. J. Radiat. Biol.* 62(2): 239-248 (1992).
- K18 Kryshev, I.I. and T.G. Sazykina. Radioecological effects on aquatic organisms in the areas with high levels of radioactive contamination: environmental protection criteria. *Radiat. Prot. Dosim.* 75(1): 187-191 (1998).

- K19 Knowles, J.F. An investigation into the effects of chronic radiation on fish. R&D Technical Report P3-053/TR. Environment Agency, Bristol (2001).
- K20 Kozubov, G.M. and A.I. Taskaev. Characteristics of morphogenesis and growth processes of conifers in the Chernobyl nuclear accident zone. *Radiats. Biol. Radioecol.* 47(2): 204-223 (2007).
- K21 Kozubov, G.M. and A.I. Taskaev. Radiobiology Investigations of Conifers in Region of the Chernobyl Disaster (1986-2001). PPC "Design Information Cartography", Moscow, 2002. (In Russian).
- K22 Kozubov, G.M., A.I. Kastaev, E.I. Ignatenko et al. Radiation Exposure of the Coniferous Forest in the Area Exposed to the Chernobyl Contamination. Komy Scientific Centre of the Academy of Sciences, Syktyvkar, 1990.
- K23 Krivolutsky, D.A., B.L. Usachev, A.I. Arkhireyeva et al. Changes in the structure of animal populations (above-ground and soil invertebrates) as affected by contamination of land with strontium-90. p. 241-249 in: *Ecological Consequences of Radioactive Contamination in the Southern Urals*. Nauka Publishers, Moscow, 1993.
- K24 Kryshev, I.I. Contamination of aquatic ecosystems in the areas of nuclear power plants and other nuclear facilities in Russia. *Radiochim. Acta* 74: 199-202 (1996).
- K25 Kryshev, I.I., G.N. Romanov, L.N. Isaeva et al. Radioecological state of lakes in the Southern Urals impacted by radioactivity release of the 1957 radiation accident. *J. Environ. Radioact.* 34(3): 223-235 (1997).
- K26 Kryshev, I.I. (ed.). *Environmental Risk Analysis for the Ural Radioactive Pattern*. Russian Nuclear Society, Moscow, 1997.
- K27 Kryshev, I.I. (ed.). *Radioactive Contamination of the Areas Around NPP*. Nuclear Society, Moscow, 1990. (In Russian).
- K28 Kryshev, I.I., T.G. Sazykina, I.N. Ryabov et al. Model testing using Chernobyl data: II. Assessment of the consequences of the radioactive contamination of the Chernobyl nuclear power plant cooling pond. *Health Phys.* 70(1): 13-17 (1996).
- L1 Larsson, C.M. and P. Strand. The FASSET and EPIC Projects – Development of conceptual and practical approaches to environmental assessment and protection. p. 275-290 in: *Protection of the Environment from the Effects of Ionizing Radiation*, Proceedings of an International Conference, Stockholm, October 2003. STI/PUB/1229. IAEA, Vienna (2005).
- L2 Laskey, J.W., J.L. Parrish and D.F. Cahill. Some effects of lifetime parental exposure to low levels of tritium on the F₂ generation. *Radiat. Res.* 56(1): 171-179 (1973).
- L3 Leonard, A., M. Delpoux, R. Meyer et al. Effect of an enhanced natural radioactivity on mammal fertility. *Sci. Total Environ.* 45: 535-542 (1985).
- L4 Larsson, C.M. The FASSET Framework for assessment of environmental impact of ionising radiation in European ecosystems — an overview. *J. Radiol. Prot.* 24(4A): A1-A12 (2004).
- L5 Lockhart, W.L., R. Wagemann, B. Tracy et al. Presence and implications of chemical contaminants in the freshwaters of the Canadian Arctic. *Sci. Total Environ.* 122(1-2): 165-245 (1992).
- L6 Laskey, J.W. and S.J. Bursian. Some effects of chronic tritium exposure during selected ages in the rat. *Radiat. Res.* 67(2): 314-323 (1976).
- L7 Lorenzelli, R., A. Zambonelli, F. Serra et al. ¹³⁷Cs content in the fruit bodies of various Tuber species. *Health Phys.* 71(6): 956-959 (1996).
- L8 Lingenfelser, S.F., C.E. Dallas, C.H. Jagoe et al. Variation in DNA content of blood cells of largemouth bass from contaminated and uncontaminated waters. *Environ. Toxicol. Chem.* 16(10): 2136-2143 (1997).
- L9 Little, M.P. and B.E. Lambert. Systematic review of experimental studies on the relative biological effectiveness of tritium. *Radiat. Environ. Biophys.* 47(1): 71-93 (2008).
- L10 Lingenfelser, S.K., C.E. Dallas, C.H. Jagoe et al. Variation in blood cell DNA in *Carassius carassius* from ponds near Chernobyl, Ukraine. *Ecotoxicol.* 6(4): 187-203 (1997).
- L11 Lamb, T., J.W. Bickham, J. Whitfield Gibbons et al. Genetic damage in a population of slider turtles (*Trachemys scripta*) inhabiting a radioactive reservoir. *Arch. Environ. Contam. Toxicol.* 20(1): 138-142 (1991).
- M1 Myers, D.K. The general principles and consequences of environmental radiation exposure in relation to Canada's nuclear fuel waste management concept. AECL-9917 (1989).
- M2 Muller, H.J. Our load of mutations. *Am. J. Hum. Genet.* 2(2): 111-176 (1950).
- M3 Macdonald, C.R. The effects of radiation exposure on wildlife. Report to the Commercial Chemicals Evaluation Branch, Environment Canada. Northern Environmental Consulting and Analysis, Pinawa, Manitoba (1998).
- M4 Müller, H. and G. Pröhl. ECOSYS-87: a dynamic model for assessing radiological consequences of nuclear accidents. *Health Phys.* 64(3): 232-252 (1993).
- M5 Meyers-Schöne, L., L.R. Shugart, J.J. Beauchamp et al. Comparison of two freshwater turtle species as monitors of radionuclide and chemical contamination: DNA damage and residue analysis. *Environ. Toxicol. Chem.* 12(8): 1487-1496 (1993).
- M6 Moiseenko, V.V., A.J. Walker and W.V. Prestwich. Energy deposition pattern from tritium and different energy photons — a comparative study. *Health Phys.* 73(2): 388-392 (1997).
- M7 Mueck, K., M. Suda, M. Gerzabek et al. Ingestion dose response to the deposition date in the first year after radionuclide deposition. *Radiat. Prot. Dosim.* 42(2): 103-114 (1992).
- M8 Miller, C.W. and F.O. Hoffman. An examination of the environmental half-time for radionuclides deposited on vegetation. *Health Phys.* 45(3): 731-744 (1983).

- M9 Mitchel, R.E.J., J.S. Jackson, D.P. Morrison et al. Low doses of radiation increase the latency of spontaneous lymphomas and spinal osteosarcomas in cancer-prone, radiation-sensitive *Trp53* heterozygous mice. *Radiat. Res.* 159(3): 320-327 (2003).
- M10 Moiseenko, V.V., A.J. Waker, R.N. Hamm et al. Calculation of radiation-induced DNA damage from photons and tritium beta-particles. Part II: Tritium RBE and damage complexity. *Radiat. Environ. Biophys.* 40(1): 33-38 (2001).
- M11 Mihok, S. Chronic exposure to gamma radiation of wild populations of meadow voles (*Microtus pennsylvanicus*). *J. Environ. Radioact.* 75(3): 233-266 (2004).
- M12 Matson, C.W., B.E. Rodgers, R.K. Chesser et al. Genetic diversity of *Clethrionomys glareolus* populations from highly contaminated sites in the Chernobyl region, Ukraine. *Environ. Toxicol. Chem.* 19(8): 2130-2135 (2000).
- M13 Mole, R.H. and A.M. Thomas. Life-shortening in female CBA mice exposed to daily irradiation for limited periods of time. *Int. J. Radiat. Biol.* 3(5): 493-508 (1961).
- M14 Muramatsu, S., T. Sugahara, T. Tsuchiya et al. Effects of chronic low-dose irradiation for three successive generations on the breeding behaviour of mice. *Int. J. Radiat. Biol.* 8(6): 523-531 (1964).
- M15 Muramatsu, S., T. Sugahara and Y. Okazawa. Genetic effects of chronic low-dose irradiation on mice. *Int. J. Radiat. Biol.* 6(1): 49-59 (1963).
- M16 Muramatsu, S., T. Tsuchiya and H. Hanada. Effects of continuous gamma radiation on the reproductivity of mice. p. 191-198: Late Biological Effects of Ionizing Radiation. Proceedings of a Symposium. Volume II. IAEA, Vienna (1978).
- M17 Møller, A.P., T.A. Mousseau, G. Milinevsky et al. Condition, reproduction and survival of barn swallows from Chernobyl. *J. Anim. Ecol.* 74(6): 1102-1111 (2005).
- M18 Møller, A.P. and T.A. Mousseau. Mutation and sexual selection: a test using barn swallows from Chernobyl. *Evolution* 57(9): 2139-2146 (2003).
- M19 Møller, A.P. and T.A. Mousseau. Biological consequences of Chernobyl: 20 years on. *Trends Ecol. Evol.* 21(4): 200-207 (2006).
- M20 Møller, A.P., T.A. Mousseau, F. de Lope et al. Elevated frequency of abnormalities in barn swallows from Chernobyl. *Biol. Lett.* 3(4): 414-417 (2007).
- M21 Makeeva, A.P., N.G. Emelianova, N.V. Belova et al. Radiobiological analysis of silver carp *Hypophthalmichthys molitrix* in the cooling pond of the Chernobyl NPP in the post-accidental period. II. Development of the reproductive system in offsprings of the first generation. *J. Ichthyology* 34(5): 681-696 (1994). (In Russian).
- M22 Materiy, L.D. Dynamics of morphological manifestations of the affection and recovery processes in the hemopoietic system of small mammals from the 30 km ChNPP zone. p. 12-40 in: Effects of Radioactive Contamination on Terrestrial Ecosystems in the Chernobyl Affected Areas. Proceedings of the Komi Research Center of Ural Branch of the Russian Academy of Sciences, Syktyvkar, 1996. (In Russian).
- M23 Monte, L., P. Boyer, J.E. Brittain et al. Review and assessment of models for predicting the migration of radionuclides through rivers. *J. Environ. Radioact.* 79(3): 273-296 (2005).
- M24 Mosser, J.L., N.S. Fisher and C.F. Wurster. Polychlorinated biphenyls and DDT alter species composition in mixed cultures of algae. *Science* 176(4034): 533-535 (1972).
- M25 Muramatsu, Y., S. Yoshida, T. Ban-nai et al. Behaviour of iodine in the soil-plant system. *Radioprotection (Colloques)* 37: C1-479-484 (2002).
- N1 National Council on Radiation Protection and Measurements. Effects of ionizing radiation on aquatic organisms. NCRP Report No. 109 (1991).
- N2 National Research Council of Canada. Radioactivity in the Canadian aquatic environment. NRCC Report No. 19250 (1983).
- N3 National Council on Radiation Protection and Measurements. Radiological assessment: predicting the transport, bioaccumulation and uptake by man of radionuclides released to the environment. NCRP Report No. 76 (1984).
- N4 Nisbet, A.F. and R.F. Woodman. Soil-to-plant transfer factors for radiocesium and radiostrontium in agricultural systems. *Health Phys.* 78(3): 279-288 (2000).
- N5 Nisbet, A.F., B. Salbu and S. Shaw. Association of radionuclides with different molecular size fractions in soil solution: implications for plant uptake. *J. Environ. Radioact.* 18(1): 71-84 (1993).
- N6 Nuclear Energy Agency. The future policy for radiological protection. A stakeholder dialogue on the implications of the ICRP proposals. Summary report, Lanzarote, Spain, 2-4 April 2003. NEA No. 4421. OECD (2004).
- N7 Naito, W., K. Miyamoto, J. Nakanishi et al. Evaluation of an ecosystem model in ecological risk assessment of chemicals. *Chemosphere* 53(4): 363-375 (2003).
- N8 National Council on Radiation Protection and Measurements. Extrapolation of radiation-induced cancer risks from nonhuman experimental systems to humans. NCRP Report No. 150 (2005).
- N9 Nikipelov, B.V., G.N. Romanov, L.A. Buldakov et al. Accident in the Southern Urals on 29 September 1957. IAEA-INFIRC-368 (1989).
- O1 Oak Ridge National Laboratory. Radiological benchmarks for screening contaminants of potential concern for effects on aquatic biota at Oak Ridge National Laboratory, Oak Ridge, Tennessee. BJC/OR-80. Prepared for the U.S. Department of Energy, Office of Environmental Management (1998).
- P1 Pierce, C.M. The effects of radiation and radioisotopes on the life processes. An annotated bibliography. TID-3098 (1963).

- P2 Polikarpov, G.G. Radioecology of Aquatic Organisms. (Translated from Russian by Scripta Technica, English translation edited by V. Schultz and A.W. Klement). Reinhold Publishing Corp., New York, 1966.
- P3 Purdom, C.E. Radiation and mutation in fish. p. 861-867 in: Disposal of Radioactive Wastes into Seas, Oceans and Surface Waters. Proceedings of a Symposium. STI/PUB/126. IAEA, Vienna (1966).
- P4 Pesch, G.G. and J.S. Young. Baseline study of effects of ionizing radiation on the chromosomes of the marine worm, 'Neanthes arenaceodentata'. Technical report PB-82-131517. Surveillance and Emergency Preparedness Division, Office of Radiation Programs, ORP/SEPD-81-1. Washington, D.C. (1981).
- P5 Purdom, C.E. and D.S. Woodhead. Radiation damage in fish. p. 67-73 in: Genetics and Mutagenesis of Fish (J.H. Schroder, ed.). Springer-Verlag, Berlin, 1973.
- P6 Pentreath, R.J. and D.S. Woodhead. A system for protecting the environment from ionising radiation: selecting reference fauna and flora, and the possible dose models and environmental geometries that could be applied to them. *Sci. Total Environ.* 277(1-3): 33-43 (2001).
- P7 Power, M. and L.S. McCarty. A comparative analysis of environmental risk assessment/ management frameworks. *Environ. Sci. Technol.* 32(9): 224A-231A (1998).
- P8 Pinon-Lataillade, G., J.F. Vélez de la Calle, M.C. Viguier-Martinez et al. Influence of germ cells upon Sertoli cells during continuous low-dose rate gamma-irradiation of adult rats. *Mol. Cell. Endocrinol.* 58(1): 51-63 (1988).
- P9 Puigdomenech, I. and U. Bergström. Calculation of distribution coefficients for radionuclides in soils and sediments. *Nucl. Saf.* 36(1): 142-154 (1995).
- P10 Pröhl, G. and F.O. Hoffman. Radionuclide interception and loss processes in vegetation. p. 9-47 in: Modelling of Radionuclide Interception and Loss Processes in Vegetation and of Transfer in Semi-natural Ecosystems. IAEA-TECDOC-857. IAEA, Vienna (1996).
- P11 Pröhl, G., H. Müller and F.O. Hoffman. Interception and post-deposition retention of radionuclides by vegetation and their importance for dose assessment. p. 275-288 in: Environmental Impact of Radioactive Releases. STI/PUB/971. IAEA, Vienna (1995).
- P12 Putyrskaya, V., E. Klemt, H. Paliachenka et al. ¹³⁷Cs accumulation in *Elaphomyces granulatus* Fr. and its transfer to wild boar. p. 1-5 in: Proceedings of XXXIII Annual Meeting of ESNA/Jointly Organised with IUR Working Group Soil-to-Plant Transfer (Working Group 3) (N. Mitchell, V. Licina and G. Zibold, eds.) Viterbo, Italy, 27-31 August 2003. Fachhochschule Ravensburg-Weingarten University of Applied Sciences, Germany, 2003.
- P13 Pentreath, R.J. Effects of ionising radiation on aquatic organisms and ecosystems. p. 124-135 in: Protection of the Natural Environment. International Symposium on Ionising Radiation. Swedish Radiation Protection Institute, Stockholm, 1996.
- P14 Päsler-Sauer, J. Description of the atmospheric dispersion model ATSTEP. RODOS report; Decision support for nuclear emergencies. RODOS(RA2)-TN(03)-01 (2003).
- P15 Pinon-Lataillade, G. and J. Maas. Continuous gamma-irradiation of rats: dose-rate effect on loss and recovery of spermatogenesis. *Strahlentherapie* 161(7): 421-426 (1985).
- P16 Pomerantseva, M.D., L.K. Ramaiya and A.V. Chekhovich. Genetic disorders in house mouse germ cells after the Chernobyl catastrophe. *Mutat. Res.* 381(1): 97-103 (1997).
- P17 Prister, B.S. Consequences of the Accident at the Chernobyl NPP for Agriculture of Ukraine. Center of Privatisation and Economic Reform, Kiev, 1999. (In Russian).
- P18 Prister, B.S., V.A. Shevchenko and V.A. Kalchenko. Genetic effects of radionuclides on agricultural crops. p. 138-148 in: Progress of Modern Genetics. USSR Academy of Science, Moscow, 1982.
- P19 Prister, B.S., N.A. Loschilov, O.F. Nemets et al. Fundamentals of Agricultural Radiology, 2nd edition. Urozhay, Kiev, 1991. (In Russian).
- P20 Pechkurenkov, V.L. The effect of the accident at the Chernobyl atomic electric power station in 1986 on the fish population of a cooling pond. *Radiobiologiya* 31(5): 704-708 (1991). (In Russian).
- P21 Pinon-Lataillade, G., M.C. Viguier-Martinez and J. Maas. Endocrinological and histological changes induced by continuous low dose gamma-irradiation of the rat testis. *Acta Endocrinol.* 109(4): 558-562 (1985).
- P22 Patel, B. and S. Patel. Techniques for detecting radiation effects on biochemical and physiological systems in aquatic organisms. p. 237-265 in: Methodology for Assessing Impacts of Radioactivity on Aquatic Ecosystems. Technical Reports Series No. 190. IAEA, Vienna (1979).
- P23 Polikarpov, G.G. Effects of ionising radiation upon aquatic organisms (chronic irradiation). p. 25-46 in: Atti della Giornata sul Tema 'Alcuni Aspetti di Radioecologia'. XX Congresso Nazionale, Associazione Italiana di Fisica Sanitaria e Protezione contro le Radiazioni, 1977, Bologna, Parma Poligrafici (1978).
- P24 Pradines, C., V. Wiktor, V. Camilleri et al. Development of biochemical methods to estimate the subcellular impact of uranium exposure on *Chlamydomonas reinhardtii*. *Radioprotection* 40 (Suppl. 1): S163-S168 (2005).
- R1 Ross, H.A. Genetic changes in an irradiated population of wild meadow voles (*Microtus pennsylvanicus*). *Can. J. Zool.* 64(3): 698-703 (1986).
- R2 Rose, K.S.B. Lower limits of radiosensitivity in organisms, excluding man. *J. Environ. Radioact.* 15(2): 113-133 (1992).
- R3 Røed, K.H. and M. Jacobsen. Chromosome aberrations in Norwegian reindeer following the Chernobyl accident. *Mutat. Res.* 346(3): 159-165 (1995).

- R4 Rafferty, B., M. Brennan, D. Dawson et al. Mechanisms of ^{137}Cs migration in coniferous forest soils. *J. Environ. Radioact.* 48(2): 131-143 (2000).
- R5 Rönnbäck, C. Effect on fertility of continuous gamma-irradiation during the suckling period in mice. *Acta Radiol. Ther. Phys. Biol.* 6(1): 53-60 (1967).
- R6 Rahman, M.M. and G. Voigt. Radiocaesium soil-to-plant transfer in tropical environments. *J. Environ. Radioact.* 71(2): 127-138 (2004).
- R7 Römmelt, R., L. Hiersche, G. Schaller et al. Influence of soil fungi (basidiomycetes) on the migration of Cs-134/137 and Sr-90 in coniferous forest soils. p. 152-160 in: *Transfer of Radionuclides in Natural and Semi-Natural Environments* (G. Desmet, P. Nassimbeni and M. Belli, eds.). Elsevier Applied Science, London, 1990.
- R8 Rühm, W., S. Yoshida, Y. Muramatsu et al. Distribution patterns for stable ^{133}Cs and their implications with respect to the long-term fate of radioactive ^{134}Cs and ^{137}Cs in a semi-natural ecosystem. *J. Environ. Radioact.* 45(3): 253-270 (1999).
- R9 Real, A., S. Sundell-Bergman, J.F. Knowles et al. Effects of ionising radiation exposure on plants, fish and mammals: relevant data for environmental radiation protection. *J. Radiol. Prot.* 24(4A): A123-A137 (2004).
- R10 Ryabov, I.N. Evaluation of the effect of the radioactive contamination of hydrobionts in the 30-kilometer control zone of the accident at the Chernobyl NPP. *Radiobiologiya* 32(5): 662-667 (1992). (In Russian).
- R11 Rantavaara, A. and M. Ammann. Description of the forest food chain and dose model FDMF in RODOS PV6.0. RODOS report; Decision support for nuclear emergencies. RODOS(RA3)-TN(04)-01 (2004).
- R12 Rönnbäck C. Effects of continuous irradiation during gestation and suckling periods in mice. *Acta Radiol. Ther. Phys. Biol.* 3: 169-176 (1965).
- R13 Rönnbäck, C. Effects on foetal ovaries after protracted, external gamma irradiation as compared with those from internal depositions. *Acta Oncol.* 22(6): 465-471 (1983).
- R14 Russell, W.L. and E.M. Kelly. Specific-locus mutation frequencies in mouse stem-cell spermatogonia at very low radiation dose rates. *Proc. Natl. Acad. Sci. U.S.A.* 79(2): 539-541 (1982).
- R15 Reyners, H., E. Gianfelici de Reyners, F. Poortmans et al. Brain atrophy after foetal exposure to very low doses of ionizing radiation. *Int. J. Radiat. Biol.* 62(5): 619-626 (1992).
- R16 Raabe, O.G., S.A. Book, N.J. Parks et al. Lifetime studies of ^{226}Ra and ^{90}Sr toxicity in beagles — a status report. *Radiat. Res.* 86(3): 515-528 (1981).
- R17 Ryabokon, N.I. and R.I. Goncharova. Transgenerational accumulation of radiation damage in small mammals chronically exposed to Chernobyl fallout. *Radiat. Environ. Biophys.* 45(3): 167-177 (2006).
- R18 Ryabov, I.N. and I.I. Kryshev. Assessments of the level of fluctuating asymmetry and doses to fish from the sea cooling pond of NPP. *Probl. Ichthyol.* 30(3): 519-522 (1990). (In Russian).
- R19 Ruan, M., C. Lu, S. Zhang et al. Adaptive response to and its time effect on radiation-induced chromosome aberrations in mouse embryonic cells pre-exposed to cadmium chloride. *Chin. J. Radiol. Med. Prot.* 18(3): 151-152 (1998).
- S1 Sparrow, A.H., S.S. Schwemmer and P.J. Bottino. The effects of external gamma radiation from radioactive fallout on plants with special reference to crop production. *Radiat. Bot.* 11(2): 85-118 (1971).
- S2 Sparrow, R.C. and A.H. Sparrow. Relative radiosensitivities of woody and herbaceous spermatophytes. *Science* 147(3664): 1449-1451 (1965).
- S3 Sparrow, A.H. and G.M. Woodwell. Prediction of the sensitivity of plants to chronic gamma irradiation. p. 257-270 in: *Proceedings of the First National Symposium on Radioecology* (V. Schultz and A.W. Klement, eds.). Reinhold Publishing Corp., New York and American Institute of Biological Sciences, Washington, 1963.
- S4 Sparrow, A.H., S.S. Schwemmer, E.E. Klug et al. Woody plants: changes in survival in response to long-term (8 years) chronic gamma irradiation. *Science* 169(3950): 1082-1084 (1970).
- S5 Suter II., G.W. *Ecological Risk Assessment*. Lewis Publishers, Chelsea, Michigan, 1993.
- S6 Searle, A.G., C.V. Beechey, D. Green et al. Comparative effects of protracted exposures to ^{60}Co gamma-radiation and ^{239}Pu alpha-radiation on breeding performance in female mice. *Int. J. Radiat. Biol. Relat. Stud. Phys. Chem. Med.* 37(2): 189-200 (1980).
- S7 Spalding, J.F., J.R. Prine and G.L. Tietjen. Late biological effects of ionizing radiation as influenced by dose, dose rate, age at exposure and genetic sensitivity to neoplastic transformation. p. 3-11 in: *Late Biological Effects of Ionizing Radiation*. Proceedings Series. Vol. II. IAEA, Vienna (1978).
- S8 Sinclair, W.K. The present system of quantities and units for radiation protection. *Health Phys.* 70(6): 781-786 (1996).
- S9 Straume, T. and A.L. Carsten. Tritium radiobiology and relative biological effectiveness. *Health Phys.* 65(6): 657-672 (1993).
- S10 SENES Consultants Limited. Assessment of marine biota doses arising from the radioactive sea discharges of the COGEMA La Hague Facility. Final Report, Volumes 1-3. SENES Consultants Limited, Ontario (2003).
- S11 Sazykina, T.G. and I.I. Kryshev. Assessment of the impact of radioactive substances on marine biota of north European waters. Report of working subgroup D*. Annex F in: *MARINA II. Update of the MARINA Project on the Radiological Exposure of the European Community from Radioactivity in North European Marine Waters*. European Commission (2002).

- S12 Sparrow, A.H., A.G. Underbrink and R.C. Sparrow. Chromosomes and cellular radiosensitivity. I. The relationship of D_0 to chromosome volume and complexity in seventy-nine different organisms. *Radiat. Res.* 32(4): 915-945 (1967).
- S13 Simmonds, J.R. and G.S. Linsley. A dynamic modeling system for the transfer of radioactivity in terrestrial food chains. *Nucl. Saf.* 22(6): 766-777 (1981).
- S14 Sanzharova, N.I., S.V. Fesenko, R.M. Alexakhin et al. Changes in the forms of ^{137}Cs and its availability for plants as dependent on properties of fallout after the Chernobyl nuclear power plant accident. *Sci. Total Environ.* 154(1): 9-22 (1994).
- S15 Salbu, B., D.H. Oughton, A.V. Ratnikov et al. The mobility of ^{137}Cs and ^{90}Sr in agricultural soils in the Ukraine, Belarus and Russia, 1991. *Health Phys.* 67(5): 518-528 (1994).
- S16 Schimmack, W. and K. Bunzl. Transport of Sr-85, Co-60, Zn-65 and Cd-109 in two forest soils as observed in undisturbed soil columns. *Radiochim. Acta* 58/59: 297-303 (1992).
- S17 Sugg, D.W., R.K. Chesser, J.A. Brooks et al. The association of DNA damage to concentrations of mercury and radiocesium in largemouth bass. *Environ. Toxicol. Chem.* 14(4): 661-668 (1995).
- S18 Sugg, D.W., J.W. Bickham, J.A. Brooks et al. DNA damage and radiocesium in channel catfish from Chernobyl. *Environ. Toxicol. Chem.* 15(7): 1057-1063 (1996).
- S19 Skuterud, L., E. Gaare, T. Kvam et al. Concentrations of ^{137}Cs in lynx (*Lynx lynx*) in relation to prey choice. *J. Environ. Radioact.* 80(1): 125-138 (2005).
- S20 Swanson, S.M. Levels and effects of radionuclides in aquatic fauna of the Beaverlodge lake area (Saskatchewan). SRC Publication C-806-5-E-82. Saskatchewan Research Council, Saskatoon (1982).
- S21 Shevchenko, V.A., M.D. Pomerantseva, L.K. Ramaiya et al. Genetic disorders in mice exposed to radiation in the vicinity of the Chernobyl nuclear power station. *Sci. Total Environ.* 112(1): 45-56 (1992).
- S22 Shevchenko, V.A., V.I. Abramov, V.A. Kal'chenko et al. The genetic sequelae for plant populations of radioactive environmental pollution in connection with the Chernobyl accident. *Radiats. Biol. Radioecol.* 36(4): 531-545 (1996). (In Russian).
- S23 Suschenya, L.M. et al. (eds.). *Animal Kingdom in the Accident Zone of Chernobyl NPP. Navuka i technica*, Minsk, 1995. (In Russian).
- S24 Spalding, J.F., T.T. Trujillo and P. McWilliams. Dose rate effect on survival of mice during continuous (23-24 hr/day) gamma ray exposures. *Health Phys.* 10(10): 709-713 (1964).
- S25 Sazykina, T.G. and A.I. Kryshev. EPIC database on the effects of chronic radiation in fish: Russian/FSU data. *J. Environ. Radioact.* 68(1): 65-87 (2003).
- S26 Smith, J.T. Is Chernobyl radiation really causing negative individual and population-level effects on barn swallows? *Biol. Lett.* 4(1): 63-64 (2008).
- S27 Sato, M. and I. Bremner. Oxygen free radicals and metallothionein. *Free Radic. Biol. Med.* 14(3): 325-337 (1993).
- S28 Sazykina, T.G. A system of dose-effects relationships for the northern wildlife: radiation protection criteria. *Radioprotection* 40 (Suppl. 1): S889-S892 (2005).
- S29 Sokolov, V.E., I.N. Ryabov, I.A. Ryabtsev et al. Effect of Radioactive Contamination on the Flora and Fauna in the Vicinity of Chernobyl' Nuclear Power Plant. *Physiology and General Biology Reviews* (T.M. Turpaev et al., eds.). Volume 8, Part 2. Soviet Scientific Reviews / Section F. Harwood Academic Publishers, 1994.
- S30 Suvorova, L.I., D.A. Spirin, V.Z. Martyushev et al. Assessment of biological and ecological consequences of radioactive contamination of biogeocenoses. p. 321-325 in: *Radiation Aspects of the Chernobyl Accident*. Vol. 2 (Yu.A. Izrael, ed.). Hydrometeoizdat, St. Petersburg, 1993. (In Russian).
- S31 Smirnov E.G. and L.I. Suvorova. Estimation and prediction of biological effects of radioactive contamination on the plant cover in the Chernobyl affected area. p. 27-37 in: *Effects of Radioactive Contamination on Terrestrial Ecosystems in the Chernobyl Affected Areas*. Proceedings of the Komi Research Center of Ural Branch of the Russian Academy of Sciences, Syktyvkar, 1996. (In Russian).
- S32 SENES Consultants Limited. Ecological risk assessment of Pickering Nuclear, phase (ii) supporting document. Prepared for Ontario Power Generation. SENES Consultants Limited, Ontario (September 2000).
- S33 St-Pierre, S., D.B. Chambers, L.M. Lowe et al. Screening level dose assessment of aquatic biota downstream of the Marcoule nuclear complex in southern France. *Health Phys.* 77(3): 313-321 (1999).
- S34 Schevchenko, V.A., V.I. Abramov and V.L. Pechkurenkov. Genetic investigations in the Southern Urals radioactive trail. p. 258-303 in: *Ecological Consequences of Radioactive Contamination in the Southern Urals*. Nauka Publishers, Moscow, 1993.
- S35 Sazykina, T.G. and I.I. Kryshev. Radiation protection of natural ecosystems: primary and secondary dose limits to biota. p. 115-118 in: *Proceedings of the International Symposium on Radioactive Waste Disposal: Health and Environmental Criteria and Standards*, Stockholm, 1998. Stockholm Environment Institute, Sweden 1999.
- S36 Sazykina, T.G. and I.I. Kryshev. Methodology for radioecological assessment of radionuclides permissible levels in the seas—protection of human and marine biota. *Radioprotection* 37(1): 899-902 (2002).
- S37 Steiner, M., I. Linkov and S. Yoshida. The role of fungi in the transfer and cycling of radionuclides in forest ecosystems. *J. Environ. Radioact.* 58(2-3): 217-241 (2002).
- S38 Sheppard, S.C., J.E. Guthrie and D.H. Thibault. Germination of seeds from an irradiated forest: implications for waste disposal. *Ecotoxicol. Environ. Saf.* 23(3): 320-327 (1992).

- S39 SENES Consultants Limited. Overview of representative ecological risk assessments conducted for sites with enhanced radioactivity. Prepared for World Nuclear Association. SENES Consultants Limited, Ontario (2007).
- S40 Smirnov, Y.G. Living forms and radioecology of plants. p. 103-119 in: *Ecological Consequences of Radioactive Contamination in the Southern Urals*. Nauka Publishers, Moscow, 1993.
- T1 Thompson, P.M. Environmental monitoring for radionuclides in marine ecosystems: are species other than man protected adequately? *J. Environ. Radioact.* 7(3): 275-283 (1988).
- T2 Thomson, J.F. and D. Grahn. Life shortening in mice exposed to fission neutrons and gamma rays. VIII. Exposures to continuous gamma radiation. *Radiat. Res.* 118(1): 151-160 (1989).
- T3 Tanaka, I.B. 3rd, S. Tanaka, K. Ichinohe et al. Cause of death and neoplasia in mice continuously exposed to very low dose rates of gamma rays. *Radiat. Res.* 167(4): 417-437 (2007).
- T4 Tikhomirov, F.A. and G.N. Romanov. Doses of radiation to organisms under conditions of radioactive contamination of a forest. p. 13-20 in: *Ecological Consequences of Radioactive Contamination in the Southern Urals*. Nauka Publishers, Moscow, 1993.
- T5 Templeton, W.L., R.E. Nakatani and E.E. Held. Radiation effects. p. 223 in: *Radioactivity in the Marine Environment*. National Academy of Sciences, Washington, 1971.
- T6 Tsytsugina, V.G. and G.G. Polikarpov. Radiological effects on populations of Oligochaeta in the Chernobyl contaminated zone. *J. Environ. Radioact.* 66(1): 141-154 (2003).
- T7 Trivedi, A. and N.E. Gentner. Ecosimetry weighting factor (e_R) for non-human biota. Paper T-1-5, P-2a-114 in: IRPA-10. Proceedings of the International Radiation Protection Association, Japan, 14-19 May 2000. CD Rom (2002).
- T8 Tsytsugina, V.G. An indicator of radiation effects in natural populations of aquatic organisms. *Radiat. Prot. Dosim.* 75(1-4): 171-173 (1998).
- T9 Tice, R.R. and G.H.S. Strauss. The single cell gel electrophoresis/comet assay: a potential tool for detecting radiation-induced DNA damage in humans. *Stem Cells* 13 (Suppl. 1): 207-214 (1995).
- T10 Taranenko, V., G. Pröhl and J.M. Gomez-Ros. Absorbed dose rate conversion coefficients for reference terrestrial biota for external photon and internal exposures. *J. Radiol. Prot.* 24(4A): A35-A62 (2004).
- T11 Thorne, M. Assessing the radiological impact of releases of radionuclides to the environment. p. 391-446 in: *Radioecology — Radioactivity and Ecosystems* (E. Van der Stricht and R. Kirchmann, eds.). ISBN 2-9600160-0-1. Liege, Belgium, 2001.
- T12 Twining, J.R., T.E. Payne and T. Itakura. Soil-water distribution coefficients and plant transfer factors for (134)Cs, (85)Sr and (65)Zn under field conditions in tropical Australia. *J. Environ. Radioact.* 71(1): 71-87 (2004).
- T13 Tsukada, H. and Y. Nakamura. Transfer factors of 31 elements in several agricultural plants collected from 150 farm fields in Aomori, Japan. *J. Radioanal. Nucl. Chem.* 236(1-2): 123-131 (1998).
- T14 Theodorakis, C.W. Integration of genotoxic and population genetic endpoints in biomonitoring and risk assessment. *Ecotoxicology* 10(4): 245-256 (2001).
- T15 Tracy, B.L. and F.A. Prantl. 25 years of fission product input to Lakes Superior and Huron. *Water Air Soil Pollut.* 19(1): 15-27 (1983).
- T16 Taskaev, A. and B. Testov. Number and reproduction of mouse-like rodents in the Chernobyl accident area. p. 200-205 in: *Bioindicators of Radioactive Contamination*. Nauka, Moscow, 1999. (In Russian).
- T17 Tikhomirov, F.A., A.I. Shcheglov and V.P. Sidorov. Forests and forestry: radiation protection measures with special reference to the Chernobyl accident zone. *Sci. Total Environ.* 137(1-3): 289-305 (1993).
- T18 Tikhomirov, F.A. and A.I. Shcheglov. Main investigation results on the forest radioecology in the Kyshtym and Chernobyl accidents zones. *Sci. Total Environ.* 157(1-3): 45-57 (1994).
- T19 Trabalka, J.R. and C.P. Allen. Aspects of fitness of a mosquitofish *Gambusia affinis* population exposed to chronic low-level environmental radiation. *Radiat. Res.* 70(1): 198-211 (1977).
- T20 Theodorakis, C.W., B.G. Blaylock and L.R. Shugart. Genetic ecotoxicology I: DNA integrity and reproduction in mosquitofish exposed *in situ* to radionuclides. *Ecotoxicology* 6(4): 205-218 (1997).
- T21 Theodorakis, C.W. and L.R. Shugart. Genetic ecotoxicology II: population genetic structure in mosquitofish exposed *in situ* to radionuclides. *Ecotoxicology* 6(6): 335-354 (1997).
- T22 Theodorakis, C.W. and L.R. Shugart. Genetic ecotoxicology III: the relationship between DNA strand breaks and genotype in mosquito fish exposed to radiation. *Ecotoxicology* 7(4): 227-235 (1998).
- T23 Theodorakis, C.W., T. Elbl and L.R. Shugart. Genetic ecotoxicology IV: survival and DNA strand breakage is dependent on genotype in radionuclide-exposed mosquitofish. *Aquat. Toxicol.* 45(4): 279-291 (1999).
- T24 Taub, F.B. Demonstration of pollution effects in aquatic microcosms. *Int. J. Environ. Stud.* 10(4): 23-33 (1976).
- T25 Tanaka, S., I.B. Tanaka 3rd, S. Sasagawa et al. No lengthening of life span in mice continuously exposed to gamma rays at very low dose rates. *Radiat. Res.* 160(3): 376-379 (2003).
- T26 Tagami, K. and S. Uchida. Aging effect on technetium behaviour in soil under aerobic and anaerobic conditions. *Toxicol. Environ. Chem.* 56(1-4): 235-247 (1996).
- T27 Tikhomirov, F.A. Distribution and migration of radionuclides in the forests within the Southern Urals radioactive trail of fallout. p. 21-39 in: *Ecological Consequences of Radioactive Contamination in the Southern Urals*. Nauka Publishers, Moscow, 1993.

- U1 United Nations. Effects of Ionizing Radiation. Volume I: Report to the General Assembly, Scientific Annexes A and B; Volume II: Scientific Annexes C, D and E. United Nations Scientific Committee on the Effects of Atomic Radiation, UNSCEAR 2006 Report. United Nations sales publications E.08.IX.6 (2008) and E.09.IX.5 (2009). United Nations, New York.
- U3 United Nations. Sources and Effects of Ionizing Radiation. Volume I: Sources; Volume II: Effects. United Nations Scientific Committee on the Effects of Atomic Radiation, 2000 Report to the General Assembly, with scientific annexes. United Nations sales publications E.00.IX.3 and E.00.IX.4. United Nations, New York, 2000.
- U4 United Nations. Sources and Effects of Ionizing Radiation. United Nations Scientific Committee on the Effects of Atomic Radiation, 1996 Report to the General Assembly, with scientific annex. United Nations sales publication E.96.IX.3. United Nations, New York, 1996.
- U5 United Nations. Sources and Effects of Ionizing Radiation. United Nations Scientific Committee on the Effects of Atomic Radiation, 1994 Report to the General Assembly, with scientific annexes. United Nations sales publication E.94.IX.11. United Nations, New York, 1994.
- U9 United Nations. Ionizing Radiation: Sources and Biological Effects. United Nations Scientific Committee on the Effects of Atomic Radiation, 1982 Report to the General Assembly, with annexes. United Nations sales publication E.82.IX.8. United Nations, New York, 1982.
- U17 Ulanovsky, A. and G. Pröhl. A practical method for assessment of dose conversion coefficients for aquatic biota. *Radiat. Environ. Biophys.* 45(3): 203-214 (2006).
- U18 Ulsh, B.A., M.C. Mühlmann-Díaz, F.W. Whicker et al. Chromosome translocations in turtles: a biomarker in a sentinel animal for ecological dosimetry. *Radiat. Res.* 153(6): 752-759 (2000).
- U19 Ulsh, B., T.G. Hinton, J.D. Congdon et al. Environmental biodosimetry: a biologically relevant tool for ecological risk assessment and biomonitoring. *J. Environ. Radioact.* 66(1-2): 121-139 (2003).
- U20 Ulanovsky, A. and G. Pröhl. Tables of dose conversion coefficients for estimating internal and external radiation exposures to terrestrial and aquatic biota. *Radiat. Environ. Biophys.* 47(2): 195-203 (2008).
- U21 Upton, A.C., M.L. Randolph and J.W. Conklin. Late effects of fast neutrons and gamma rays in mice as influenced by the dose rate of irradiation: Life shortening. *Radiat. Res.* 32(3): 493-509 (1967).
- U22 United Nations. Rio declaration on environment and development. Annex I. Report of the United Nations Conference on Environment and Development, Rio de Janeiro, 3-14 June 1992. United Nations, A/CONF.151/26 (Vol. I) (1992).
- U23 United Nations. Convention on biological diversity (with annexes). Concluded at Rio de Janeiro on 5 June 1992. Multilateral No. 30619. United Nations Conference on Environment and Development. Treaty series, United Nations (1993).
- U24 Uchida, S., K. Tagami and I. Hirai. Soil-to-plant-transfer factors of stable elements and naturally occurring radionuclides: (1) Upland field crops collected in Japan. *J. Nucl. Sci. Technol.* 44(4): 628-640 (2007).
- U25 Uchida, S., K. Tagami and I. Hirai. Soil-to-plant transfer factors of stable elements and naturally occurring radionuclides: (2) Rice collected in Japan. *J. Nucl. Sci. Technol.* 44(5): 779-790 (2007).
- U26 United States Department of Energy. A graded approach for evaluating radiation doses to aquatic and terrestrial biota. DOE-STD-1153-2002. U.S. DOE, Washington DC (2002).
- V1 Viarengo, A., B. Burlando, N. Ceratto et al. Antioxidant role of metallothioneins: a comparative review. *Cell. Mol. Biol.* 46(2): 407-417 (2000).
- V2 Vives i Batlle, J., S.R. Jones and J.M. Gomez-Ros. A method for calculation of dose per unit concentration values for aquatic biota. *J. Radiol. Prot.* 24(4A): A13-A34 (2004).
- W1 Woodhead, D.S. Contamination due to radioactive materials. p. 1111 in: *Pollution and Protection of the Seas - Radioactive Materials, Heavy Metals and Oil*, Volume 5, Part 3 (O. Kinne, ed.). John Wiley and Sons, New York, 1984.
- W2 Woodhead, D.S. Methods of dosimetry for aquatic organisms. p. 43-96 in: *Methodology for Assessing Impacts of Radioactivity on Aquatic Ecosystems*. Technical Reports Series No. 190. IAEA, Vienna (1979).
- W3 Whicker, F.W. and T.B. Kirchner. PATHWAY: a dynamic food chain model to predict radionuclide ingestion after fallout deposition. *Health Phys.* 52(6): 717-737 (1987).
- W4 Woodwell, G.M. and L.N. Miller. Chronic gamma radiation affects the distribution of radial increment in *Pinus rigida* stems. *Science* 139(3551): 222-223 (1963).
- W5 Woodwell, G.M. Radiation and the patterns of nature. Sensitivity of natural plant populations to ionizing radiation seems to follow known ecological patterns. *Science* 156(774): 461-470 (1967).
- W6 Whicker, F.W. and V. Schultz. *Radioecology: Nuclear Energy and the Environment*, Volume II. CRC Press, Inc., Boca Raton, Florida, 1982.
- W7 Woodhead, D.S. The effects of chronic irradiation on the breeding performance of the guppy, *Poecilia reticulata* (Osteichthyes: Teleostei). *Int. J. Radiat. Biol. Relat. Stud. Phys. Chem. Med.* 32(1): 1-22 (1977).
- W8 Whicker, F.W. and L. Fraley. Effects of ionizing radiation on terrestrial plant communities. p. 317 in: *Advances in Radiation Biology*, Volume 4. Academic Press, New York, 1974.

- W9 Woodwell, G.M. and J.K. Oosting. Effects of chronic irradiation on the development of old field plant community. *Radiat. Bot.* 5/3: 205 (1965).
- W10 Woodhead, D.S. A possible approach for the assessment of radiation effects on populations of wild organisms in radionuclide-contaminated environments? *J. Environ. Radioact.* 66(1-2): 181-213 (2003).
- W11 Whicker, F.W. Impacts on plants and animals. p. 74-84 in: *Health Impacts of Large Releases of Radionuclides—Symposium No. 203*. CIBA Foundation Symposium. John Wiley & Sons, 1997.
- W12 Wang, C.-J., S.-Y. Lai, J.-J. Wang et al. Transfer of radionuclides from soil to grass in Northern Taiwan. *Appl. Radiat. Isot.* 48(2): 301-303 (1997).
- W13 Wang, J.-J., C.-J. Wang, C.-C. Huang et al. Transfer factors of ⁹⁰Sr and ¹³⁷Cs from paddy soil to the rice plant in Taiwan. *J. Environ. Radioact.* 39(1): 23-34 (1998).
- W14 Williams, R.B. and M.B. Murdoch. The effects of continuous low-level gamma radiation on estuarine microcosms. p. 1213-1221 in: *Radionuclides in Ecosystems. Proceedings of the Third National Symposium on Radioecology*, Oak Ridge, Tennessee, 1971, Volume 2 (D.J. Nelson, ed.). CONF-710501-P2 (1973).
- W15 Woodwell, G.M. Design of the Brookhaven experiment on the effects of ionizing radiation on a terrestrial ecosystem. *Radiat. Bot.* 3: 125-133 (1963).
- W16 Whicker, F.W. and T.G. Hinton. Effects of ionizing radiation on terrestrial ecosystems. p. 109-123 in: *Protection of the Natural Environment*. Swedish Radiation Protection Institute, Stockholm, 1996.
- W17 Woodhead, D.S. The impact of radioactive discharges on native British wildlife and the implications for environmental protection. p. 80 in: *R&D Technical Report P135*. Environment Agency, Bristol (1998).
- W18 Woodwell, G.M. and T.P. Gannutz. Effects of chronic gamma irradiation on lichen communities of a forest. *Am. J. Bot.* 54(10): 1210-1215 (1967).
- W19 Wismer, D.A., N.C. Garisto and F.J. Bajurny. Application of ecological risk assessment to establish non-human environmental protection at nuclear generating stations in Ontario, Canada. *Radioprotection* 40 (Suppl. 1): S695-S700 (2005).
- W20 Wilkes, F.G. Laboratory microcosms for use in determining pollutant stress. p. 309-321 in: *Aquatic Pollutants: Transformation and Biological Effects* (O. Hutzinger, I.H. van Lelyveld and B.C.J. Zoeteman, eds.). Pergamon, Oxford, 1978.
- Y1 Yoshida, S. and Y. Muramatsu. Use of stable elements for predicting radionuclide transport. p. 41-49 in: *Contaminated Forests: Recent Developments in Risk Identification and Future Perspectives* (I. Linkov and W.R. Schell, eds.). Kluwer Academic Publishers Group, Amsterdam, 1999.
- Y2 Yamamoto, O., T. Seyama, H. Itoh et al. Oral administration of tritiated water (HTO) in mouse. III: Low dose-rate irradiation and threshold dose-rate for radiation risk. *Int. J. Radiat. Biol.* 73(5): 535-541 (1998).
- Y3 Yanagisawa, K. and Y. Muramatsu. Transfer of technetium in the soil-rice plant system. *J. Radioanal. Nucl. Chem.* 197(1): 203-210 (1995).
- Y4 Yoshida, S., Y. Muramatsu and M. Ogawa. Radiocesium concentrations in mushrooms collected in Japan. *J. Environ. Radioact.* 22(2): 141-154 (1994).
- Y5 Yoshida, S. and Y. Muramatsu. Accumulation of radiocesium in basidiomycetes collected from Japanese forests. *Sci. Total Environ.* 157(1-3): 197-205 (1994).
- Y6 Yoshida, S., Y. Muramatsu, A.M. Dvornik et al. Equilibrium of radiocesium with stable cesium within the biological cycle of contaminated forest ecosystems. *J. Environ. Radioact.* 75(3): 301-313 (2004).
- Z1 Zibold, G., J. Drissner, S. Kaminski et al. Time-dependence of the radiocaesium contamination of roe deer: measurement and modelling. *J. Environ. Radioact.* 55(1): 5-27 (2001).
- Z2 Zainullin, V.G., V.A. Shevchenko, E.N. Myasn'yankina et al. The mutation frequency of *Drosophila melanogaster* populations living under conditions of increased background radiation due to the Chernobyl accident. *Sci. Total Environ.* 112(1): 37-44 (1992).