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Comparative radiation impact on biota and man in the area affected by the accident at the Chernobyl nuclear power plant

S.V. Fesenko[a,b,*], R.M. Alexakhin[a], S.A. Geras'kin[a], N.I. Sanzharova[a], Ye.V. Spirin[a], S.I. Spiridonov[a], I.A. Gontarenko[a], P. Strand[c]

[a]*Russian Institute of Agricultural Radiology and Agroecology, Kievskoe shosse, Kaluga region, Obninsk 249020, Russia*
[b]*International Atomic Energy Agency, Agency's Laboratories, Seibersdorf A-2444, Austria*
[c]*Norwegian Radiation Protection Authority, steras, Norway*

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Abstract

A methodological approach for a comparative assessment of ionising radiation effects on man and non-human species, based on the use of *Radiation Impact Factor* (RIF) – ratios of actual exposure doses to biota species and man to critical dose is described. As such doses, radiation safety standards limiting radiation exposure of man and doses at which radiobiological effects in non-human species were not observed after the Chernobyl accident, were employed. For the study area within the 30 km ChNPP zone dose burdens to 10 reference biota groups and the population (with and without evacuation) and the corresponding RIFs were calculated. It has been found that in 1986 (early period after the accident) the emergency radiation standards for man do not guarantee adequate protection of the environment, some species of which could be affected more than man. In 1991 RIFs for man were considerably

* Corresponding author. Tel.: +43 1 2600 28247; fax: +43 1 2600 28222.
E-mail address: s.fesenko@iaea.org (S.V. Fesenko).

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(by factor of 20.0–1.1 × 10^5) higher compared with those for selected non-human species. Thus, for the long term after the accident radiation safety standards for man are shown to ensure radiation safety for biota as well.

Keywords: Radiation protection; Chernobyl accident; Radiation impact; Non-human species; Man

1. Introduction

A major trend in the evolution of the current system of radiation protection is the development of principles to ensure protection of non-human species from ionising radiation (Alexakhin and Fesenko, 2004). Over the last decades the scientific grounds of radiation protection of biota are based on the postulate originally formulated in ICRP Publication 26 (ICRP, 1977) and reproduced with minor changes in ICRP Publication 60 (ICRP, 1991): "The Commission believes that the standards of environmental control needed to protect man to the degree currently thought desirable will ensure that other species are not put at risk. Occasionally, individual members of non-human species might be harmed, but not to the extent of endangering whole species or creating imbalance between species".

Overall, based on this principle, the system for radiation protection indirectly provided protection of non-human species. However, it should be stressed that the above statement of ICRP was related only to the routine practice and was never extended to accidental situations.

This approach to radiation protection has received wide acceptance in the last quarter of the XX century and been reflected in legal documents on protection of the environment of many countries (IAEA, 1992a, 2000).

Some changes in the principles of radiation protection of biota as compared with Publications 26 and 60 are evident in the ICRP activity, which has prepared Publication 91 "A Framework for Assessing the Impact of Ionising Radiation on Non-Human Species" (ICRP, 2003a). In the framework of ICRP a task group has been established aimed at substantiating a representative set of critical species and indicators for estimating radiation effects (Williams, 2003). Also evident are changes in the IAEA position pointing recently to the importance of a comprehensive approach to the problem of radiation protection of biota (IAEA, 1999, 2000, 2002). In the last 5–10 years much effort to fill this conceptual gap in the radiation protection system was made by the International Union of Radioecology (IUR, 2003).

The need to develop criteria and standards aimed at including non-human species to the radiation protection system is based on a number of arguments. Firstly, the lack in the current system of radiation protection of internationally approved criteria for non-human species makes impossible an answer to the question: are biota adequately protected in radiological situations when man is absent in the environment? Among such situations are sites of radioactive waste disposals in seas and oceans, deep geological formations, areas contaminated after radiation accidents, in particular, the head part of the East Urals radioactive trail (Burnazyan, 1990; Sokolov and Krivolutsky, 1993) and the Exclusion Zone after the Chernobyl accident (IAEA, 1992b) in the long term after these accidents. Secondly, the current regulatory system of radiation effects implicitly supposes that low exposure doses to the population automatically ensure low doses to other living beings. This, however, does not always represent the facts (Romanov and Spirin, 1991). Considering close radiosensitivity of man and some edificators responsible for functioning and resistance of ecosystem species (coniferous trees, most of mammals), it becomes clear that such a ratio of doses absorbed by man and other living beings requires special attention to the protection of some plants, animals and their communities.

A considerable contribution to the estimation of the thesis correctness "if radiation standards protect man, then biota are also adequately protected from ionising radiation" is made by comparing exposure doses to human and non-human species found in the same area. However, for the moment there is a lack of a direct information on a comparative impact of radioactive contamination on non-human species and man as well as a common approach for such comparison and no adequate results have been obtained which allow the conclusion in which radioecological situations radiation standards for biota should be applied and on what basis.

One of the occasions helpful for such evaluations was formed after the Chernobyl NPP accident where in the early phase after the accident the situation is a classical example of intervention after the contamination event and in the long term it can be classified as a routine practice (case of radiation legacy). On the other hand these estimates, including also an early stage after the accidental release, are important for the evolution of current concepts related to the comparison of radiation impact on biota species and man. Such an analysis using data of long-term radioecological and radiation-hygienic investigations in the Chernobyl affected area was the prime objective of the present paper.

2. Materials and methods

2.1. A framework for a comparative analysis of the radiation impact on man and non-human species

2.1.1. The approach

The dose ratio of man (D_{h}) and non-human species (D_{b}) and critical dose, respectively to man ($\mathrm{CDV_h}$) and biota ($\mathrm{CDV_b}$), termed *Radiation Impact Factor* ($\mathrm{RIF_{h,b}}$), was applied to compare effects of ionising radiation on man and biota:

$$\mathrm{RIF_{h,b}} = \frac{D_{\mathrm{h,b}}}{\mathrm{CDV_{h,b}}}$$

In the framework of the above views if $\mathrm{RIF_{h,b}} > 1$ for man or biota, they may be considered as unprotected and if $\mathrm{RIF_{h,b}} < 1$, as protected from ionising radiation. The evaluation of $\mathrm{RIF_{h,b}}$ values for man and biota representatives in the same radiological situation allows a direct comparison of radioactive impact on non-human species and man. In both cases, if $RIF_h > RIF_b$ man is less protected from irradiation than biota and if $RIF_h < RIF_b$ human being is more protected.

Debatable when analyzing the correctness of the thesis "if man is protected then biota are also protected" is the interpretation of the notion "radiation protection of man". When irradiation of man is above the dose limits a system of protective measures is introduced that provides for dose decrease, however, non-human species in this situation can be exposed to radiation above the levels ensuring the absence of adverse impacts in them. In these conditions the thesis "if man is protected then biota are also protected" seems to be interpreted only bearing in mind that the introduction of countermeasures for reducing doses to humans is not envisaged. Thus, under the situation with an accidental radioactive contamination of the environment the use of the thesis "if man is protected then biota are also protected" is hardly possible, since accidental situations imply the introduction of the system of countermeasures for man, for instance sheltering, evacuation, reduction in the diet of contaminated products, decrease of radionuclide activity concentrations in these products, etc. All these countermeasures are not applicable for biota (an exception may be the relocation of farm animals and their protection through changing the maintenance regime and ration). It is worth noting that the above measures of radiation protection of the livestock were actually applied in mitigating consequences of the Chernobyl accident (Alexakhin and Korneyev, 1992). In accidental situations we see little reason for using additional dose limits to biota (among a few of exceptions may be farm animals for which "an active protection" is possible by implementing of countermeasures) and general values should be applied for all contamination events.

In the estimation of consequences of radioactive contamination is essential in the situation when the release contains radionuclides of iodine. Since iodine is selectively accumulated in the thyroid, the estimation of consequences from a release of radionuclides mixture containing radioiodine into the environment must take into account both the effective dose and that absorbed by the thyroid. In this situation radiation effects on man can be estimated by the maximum RIF_h calculated from the effective dose and dose to the thyroid (concept of critical exposure pathway). Radiation impact in this case also might be estimated by summing up RIF_h for the both pathways (concept of additive exposure effects). However, since radiation effects connected with the thyroid irradiation are poorly related to the whole body dose, the first approach was adopted in the current study. However, in some situations the second variant may be of certain importance, which offers rather conservative evaluation of the effects. A similar approach was used for estimating radiation effects on some biota species (mammals) in which damage to the thyroid is crucial in manifestation of the radiation impact.

When comparing radiation induced effects in humans and biota, it is often of great importance, along with correct dose estimation, to justify those exposure levels that do not cause reliable registered effects of radiation exposure, i.e. to make a correct CDV selection.

Since the study area was affected by the radiation accident, for the first period after the accident standards that restrict exposure of man in these situations were used, including the national radiation standards (100 mSv a^{-1}) for the population protection being in force during the liquidation of the Chernobyl consequences in the USSR (MHR, 1986). However, according to the ICRP recommendations (ICRP, 1993), in the accidental situations the radiation safety standards vary within 50–500 mSv a^{-1}. As a result, for a comparative analysis of the impact of the accidental radionuclide release on man and non-human species in 1986, 50 and 100 mSv a^{-1} were adopted as CDV_h. For the long-term period, CDV_h dose limit for the public 1 mSv a^{-1} was taken (MHR, 1999) which is similar to dose limit recommended by international organisations (ICRP, 1991; IAEA, 1996). As CDV_h for the thyroid, an absorbed dose of 5 Gy was employed adopted in the USSR (Russia) for limiting radiation exposure of human beings (MHR, 1999). A similar dose limit is also recommended by the ICRP (2003b).

More complex and undeveloped is the problem of estimating critical exposure doses to biota (CDV_b). This is mainly connected with uncertainty in establishing critical endpoints and significant gaps in the information on radiobiological responses of plants and animals. Thus, the radiation safety standards for man are developed based on the principle of maximum possible restriction of stochastic effects (radiation induced cancer, genetic effects). As to endpoints for biota, to date no consensus has been achieved and CDV_b are established by the method of expert estimates. In this case dominant (Brechignac, 2003) is the opinion that radiation protection of non-human species must be realized at the population and cenotic levels rather than at the organism level. However, this approach has not yet assumed the shape suitable for practical introduction.

As the most common endpoints for biota, it is generally agreed to use the following: early mortality, morbidity, reduced reproduction success and deleterious heredity effects (Pentreath, 1999, 2002; Pentreath and Woodhead, 2001; Robinson, 2003). A number of attempts have been undertaken up to now to estimate exposure doses to biota which non-excess guarantees the absence of radiation induced effects (UNSCEAR, 1996; Sazykina and Kryshev, 1999; CNSC, 2001). In particular, some publications (Bird et al., 2000, 2002; CNSC, 2001) have suggested using *ENEV* (*Expected No Effect Value*), and the numerical values have been calculated for this parameter. However, our efforts in using these parameters to evaluate consequences of the Chernobyl accident for non-human species have demonstrated its limitations. This is mainly because of the fact that *ENEV* have been provided for a wide range of conditions, and this often predetermined a rather conservative character of the derived estimates. At the same time, in some cases underestimated *ENEV*, in particular for coniferous trees, has been suggested in these publications thus showing a need for further amending this approach.

In the present paper, dose burdens causing significant, from the ecological point of view, radiation induced changes in plants and animals in the Chernobyl affected area, were taken as CDV_b.

2.1.2. Selection of representative biota species

When choosing reference non-human species to evaluate consequences of the contamination the following features were considered: (1) role in functioning of ecosystems, (2) abundance, (3) availability of biologic and radiobiologic information, (4) radiosensitivity, (5) possibility of induction and severity of adverse effects manifestation in different scenarios of radioactive contamination of the environment, (6) economic value, and (7) availability of adequate dosimetric models and capabilities for correct estimation of doses to critical organs in various radiological situations.

In the framework of these studies, doses have been estimated resulting from the Chernobyl accident to 10 selected biota species that belong to four main types of natural, semi-natural and artificial ecosystems in the environment: (1) aquatic (phytoplankton, zooplankton, zoobenthos, fish); (2) forest (coniferous trees); (3) meadow (meadow grasses, mouse-like rodents and soil mesofauna); and (4) agricultural (cereal crops and cattle).

2.2. Methods for estimating doses to man and biota

2.2.1. Population

The reconstruction of doses to the population evacuated from the 30 km ChNPP zone is a great challenge. Most of estimates made immediately after the accident and being the basis for a political decision to evacuate the population were conservative and overestimated the real doses (IAEA, 1992b). Sometime later these estimates were improved (Iljin and Gubanov, 2001). Therefore, for the reconstruction of effective dose to the population of the study area and dose to the human thyroid, the methodological guides based on the above experience and approved by the Russian Federation Health Ministry (MHR, 1996, 2001) were applied.

2.2.2. Non-human species

2.2.2.1. Coniferous trees. Dose burdens to coniferous trees were calculated based on the approach presented elsewhere (Tikhomirov, 1972; Fesenko et al., 1993). To calculate doses to the woody storey of the forest located in the study area, the data on the deposition density for biologically important radionuclides recalculated at the time of maximum fallout were used. In assessing the radionuclides activity concentrations in the trees' compartments, processes related to the forest self-clearing were taken into account along with the processes influencing the retention and redistribution of radionuclides. The effective period of half-clearing was taken to be identical for all radionuclides, 90 days; this corresponded to a conservative assessment for this value (Tikhomirov and Shcheglov, 1994). When estimating doses to trees, the contributions of radionuclides from the forest soil as well as radionuclides distributed in the tree canopy were calculated. In both cases, contributions of both β- and γ-radiations to the total tree exposure were considered.

2.2.2.2. Herbaceous plants. To calculate doses to critical organs of herbaceous plants, a complex of methods were used (Spirin, 2002) that took into account changes with time of the radionuclides distribution between various plant compartments and soil as well as biometric characteristics of plants during the vegetation period (Spirin, 1997). A botanic composition of the herbaceous phytocenoses (meadow grasses) is much diversified. Therefore, for dose estimation, the simplest irradiation geometry has been chosen where a source of irradiation is a flat layer and radiosensitive tissues are located at a height of 5 cm above the source.

When estimating doses to cereal farm crops, the apical cone of plant has been assumed to be located in the soil for 20 days after sowing. During the following 20 days the height of the plant apical meristem above the ground is linearly increasing from 0 to 10 cm. Over another 60 days the plant height is linearly increasing from 10 to 100 cm. During the last stage (20 days) the plant ear height above the ground remains unchanged.

2.2.2.3. Cattle. The exposure dose formed by β- and γ-radiations of incorporated nuclides and γ-radiation of nuclides located in the gastro-intestinal tract was calculated to the whole body of animals and to the thyroid. The calculation model took into account variations in the content of radionuclides in pasture grass with time due to a physical decay of radionuclides, weathering and increment of the grass biomass, following the procedure described in MAR (2001).

2.2.2.4. Mouse-like rodents. The absorbed dose of γ-radiation in the body of mouse-like rodents from external sources was calculated based on the radionuclide composition of deposits in the assumption that the irradiation source is contaminated soil with an exponential distribution of radionuclides in the soil profile with a drop constant with depth of $0.7\ cm^2\ a^{-1}$. Calculations of the absorbed dose in the body of animals took into account residence of rodents on the soil surface, in holes and passages into holes. The ratio of doses to rodents over the residence time in the above places was determined experimentally using lithium fluoride thermoluminescent detectors located in holes and near them. Doses of internal exposure were calculated from measurements of specific activity in animal carcasses but ignored in the further analysis because of low values compared to doses of external irradiation (Ryazanov et al., 1989).

2.2.2.5. Soil invertebrates. Similar approach was used for the calculation of the doses to soil invertebrates. Thus, these were calculated with the account of radionuclide distribution and their migration in the soil upper horizon treated as a three-dimensional source (thick plate) of β- and γ-irradiations of soil invertebrates with a thickness of 5 cm. Internal doses were calculated by the methods described in Mashkovich (1982) and accumulation factors given in Iljin and Gubanov (2001).

2.2.2.6. Hydrobionts. To estimate an impact of the Chernobyl fallout on aquatic ecosystems, the data on the radionuclide deposition density on the water table of the reservoir found at the test site were used. For a reconstruction of the kinetics of radionuclides activity concentrations in water and their redistribution in the bottom sediments, a model for radionuclides migration in freshwater ecosystems was used (Fesenko, 1985). Empirical values for accumulation factors obtained in this zone

(Iljin and Gubanov, 2001) were employed to assess radionuclides activity concentrations in hydrobionts.

Dose burdens were estimated in phytoplankton, zooplankton, fish and macrozoobenthos organisms concentrated in the upper layer of bottom sediments. Doses of external γ- and β-radiations were calculated from a three-dimensional infinite source (water layer containing radionuclides). Following the principle of a conservative estimation, doses were determined in the middle of the source – the site where these are maximal. In addition to external exposure doses, internal irradiation of aquatic organisms was also calculated from the uptake of β- and γ-emitting nuclides by these organisms from the ambient medium.

2.3. General characteristics of the study area

2.3.1. Characteristics of the environment

The study area is situated in the Byelorussian Polesyes at a distance of 10–16 km to the north-west of the ChNPP (Fig. 1). It includes settlement of Borshchovka surrounded by agricultural lands, forests, meadows and a water body.

The total area of agricultural lands includes 720 ha of arable land, 920 ha of hayland, 7100 ha of pasture. The agriculture was mainly of a meat–dairy orientation. The main agricultural plants were cereals (winter wheat, rye and oats) as well as potato and various vegetables.

The major part of the area is occupied by alluvial (floodplain) soddy and alluvial (floodplain) soddy swampy (47.7%), soddy-podzolic (19.1%), soddy-podzolic swampy (14.2%), peat-boggy lowland (14.3%) soils. By mechanical composition, soils are mainly sandy and sandy loam. The bulk of the territory is occupied by natural meadows – dry, floodplain and boggy. The dominant species of grass are meadow fescue (*Festuca pratensis*), herd's grass (*Agrostis alba*), matgrass (*Nardus stricta*), yellow bedstraw (*Gallium verum*), turfted hairgrass (*Deschampsia caespitose*).

Pine trees dominate in the forest where both old trees and stands aged 15–30 years are found. The pine forest (motley grass, green-mossy pine forest) mainly (80%) contains Scots pine (*Pinus sylvestris*) with the age of 50–80 years with a small admixture (20%) of birch (*Betula pendula*) and isolated aspen (*Populus tremula*) specimens. The soil is inhabited by more than 700 species of different invertebrate groups. The mesofauna is dominated by coleopterans – 272 species; these are followed by bugs – 54 species (Krivolutsky et al., 1990). Field vole (*Microtus arvalis*) can be distinguished as the most widespread among mouse-like rodents.

The water body is a cut-off lake in the floodplain of the river Pripyat. The most abundant fish species are bleak (*Alburnus alburnus*), goldfish (*Carasius gibelio*), carp (*Cyprinus carpio*), bream (*Abramis brama*) and perch (*Perca flavescens*) (Ryabov, 1992).

2.3.2. Contamination of the environment

The formation of radioactive trails after the accident had a complex nature because of superposition of deposits with different physical–chemical properties. The

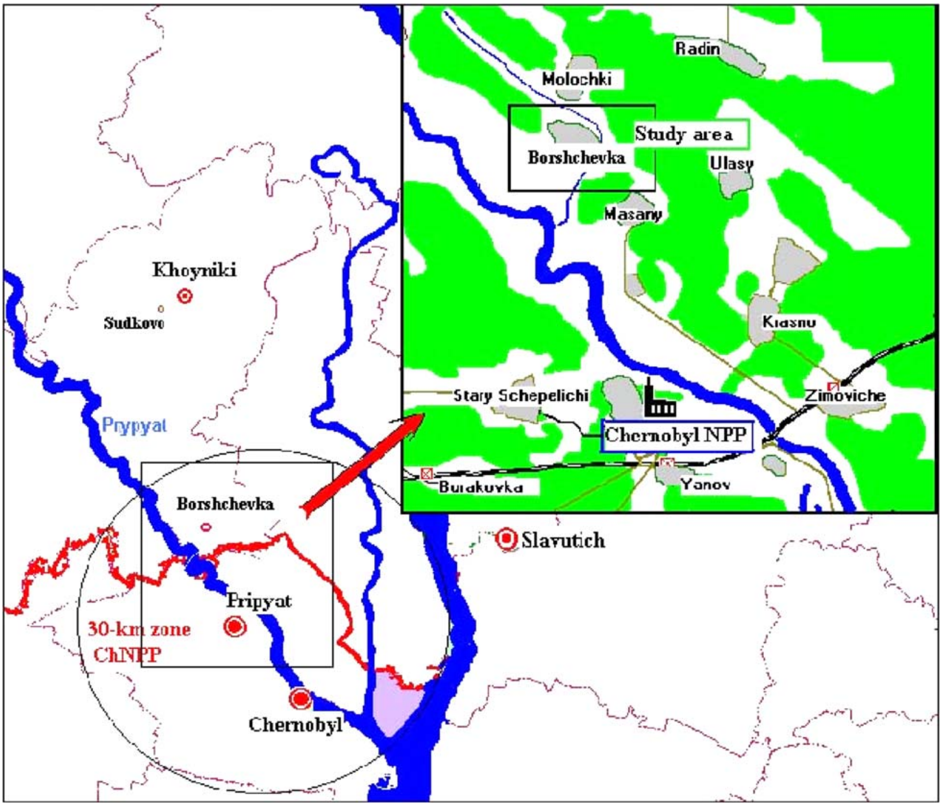

Fig. 1. Location of the study area.

fallout radionuclide composition was determined in the top 0–2 cm soil layer on May 8, 1986 (Table 1).

The soil contamination density by ^{137}Cs ranged from 1850 to 8300 kBq m^{-2} with a mean of 5500 kBq m^{-2}. As for ^{90}Sr, the soil contamination density varied between 440 and 1800 kBq m^{-2} with a mean of 1100 kBq m^{-2}.

In the early period after the accident the main pathway of radionuclide uptake by plants was aerial one. Soils, plants and animals were contaminated by a large set of short-, medium- and long-lived radionuclides. The maximum content of radionuclides in biota was reported in the first several weeks after the accident (Iljin and Gubanov, 2001). Agricultural production on the study territory was suspended and the public was evacuated on May 4, 1986. Therefore, the calculation of the radionuclide content in farm products for the given region (provided the production has not been suspended) was made based on the data obtained in the settlement of Sudkovo located 40–45 km northward of the ChNPP.

The settlement of Sudkovo (Fig. 1) located within the same radioactive trail as Borshchovka was subject to contamination to a lesser extent (average ^{137}Cs

Table 1
The radionuclide composition of soil within the Borshchovka study area (May 8, 1986)

Radionuclide	Radionuclide activity per unit area, $kBq\ m^{-2}$	Radionuclide	Radionuclide activity per unit area, $kBq\ m^{-2}$
^{89}Sr	12,650	^{131}I	33,440
^{90}Sr	1100	^{134}Cs	2860
^{95}Zr	36,600	^{137}Cs	5500
^{95}Nb	53,680	$^{140}Ba + ^{140}La$	58,700
^{103}Ru	44,000	^{141}Ce	32,560
^{106}Ru	5500	^{144}Ce	28,490

deposition density was 550 $kBq\ m^{-2}$) and its population was not evacuated and agricultural production was not discontinued. The soil–climatic and agricultural production conditions in this settlement were identical to those in Borshchovka situated in the same area.

Starting from the summer of 1986, agricultural countermeasures were applied in Sudkovo, which included radical improvement of meadows, liming and application of increased doses of potassium fertilizers. At the same time these protective measures were used only in part of the agricultural land, thus allowing estimation of ^{90}Sr and ^{137}Cs transfer factors from soil to farm crops in both conditions, with and without countermeasures application based on the information given elsewhere (Sanzharova et al., 1995). Simultaneously this made it possible to reconstruct doses to the population in the study area also for these both conditions.

2.4. Justification of critical dose values for a comparative analysis of the radiation impact on biota and man

As noted earlier, for assessing doses which could be potentially safe for the non-human species (CDV_b) the results from our analysis of the data on the effects of irradiation of different biota species for the conditions specific for the Chernobyl area were applied (Table 2). In each case the values derived were compared to the similar data given elsewhere (UNSCEAR, 1996; Bird et al., 2000; CNSC, 2001, etc.) and the principle discrepancies found were analysed.

2.4.1. Coniferous trees

Forest ecosystems are known to be the most radiosensitive components in the biosphere. A high vulnerability of the forest biocenoses to radiation impact in the cases when radioactive fallout acts as a source of ionising radiation is not only determined by a high radiosensitivity of the woody storey but also by a high retention capacity and slow self-clearing of radionuclides after the deposition (Tikhomirov and Shcheglov, 1994; Kozubov and Taskaev, 1995).

The minimum dose at which morphologic effects in the Chernobyl zone (reduction in the shoots growth of pine trees, appearance of morphoses in the year following the accidental one) was reported to be 0.43 $Gy\ a^{-1}$ (Sidorov, 1994). The experience in studying the radiation effects in coniferous plants accumulated in

Table 2
Review of CDV_b for non-human species inhabiting the study area, $Gy\,a^{-1}$

Non-human species	CDV_b used in the current study	Literature data
Terrestrial ecosystems		
Coniferous trees (pine)	0.40	0.4 (Sazykina and Kryshev, 1999), 0.88 (CNSC, 2001), 3.65 (UNSCEAR, 1996)
Herbaceous plants (meadow grasses)	3.00	0.4 (Sazykina and Kryshev, 1999, 2002), 0.88 (CNSC, 2001), 3.65 (UNSCEAR, 1996)
Herbaceous plants (cereals)	3.00	0.4 (Sazykina and Kryshev, 1999, 2002), 0.88 (CNSC, 2001), 3.65 (UNSCEAR, 1996)
Cattle	0.60 (50[a])	0.4 (Sazykina and Kryshev, 2002), 0.90 (CNSC, 2001)
Mouse-like rodents	0.40	0.05 (Sazykina and Kryshev, 1999), 0.07 (Sazykina and Kryshev, 2002), 0.37 (CNSC, 2001), 0.37 (UNSCEAR, 1996), 1.0 (Bird et al., 2002)
Soil invertebrates	0.90	0.4 (Sazykina and Kryshev, 1999, 2002), 0.88 (CNSC, 2001), 2.0 (Bird et al., 2002)
Aquatic ecosystems		
Phytoplankton	3.00	0.88 (CNSC, 2001), 1.0 (Bird et al., 2002)
Zooplankton	2.50	0.88 (CNSC, 2001), 1.0 (Bird et al., 2002)
Zoobenthos	0.90	0.6 (CNSC, 2001), 2.0 (Bird et al., 2002)
Fish	0.60	0.1 (Sazykina and Kryshev, 1999), 0.2 (CNSC, 2001), 0.2 (Bird et al., 2002), 3.65 (US DOE, 2002)

[a] Dose to the thyroid, Gy.

radiobiology and radioecology during more than half of a century provides evidence that at lower doses a determined registration of only cytogenetic rather than morphologic effects can be expected. Therefore, a dose of $0.4\,Gy\,a^{-1}$ (see Table 2) was taken as CDV_b for the coniferous trees surrounding the ChNPP. This value is about two times lower than ENEV ($0.88\,Gy\,a^{-1}$) proposed by Bird et al. (2000, 2002) and in the CNSC report (2001) and about nine times lower than threshold dose ($3.65\,Gy\,a^{-1}$) presented in the UNSCEAR report (1996) for terrestrial plants. Such discrepancies can be explained mainly by the fact that in these publications threshold doses were established as generic values for all terrestrial plants.

2.4.2. Herbaceous plants

A threshold dose of $3\,Gy\,a^{-1}$ (Table 2) has been suggested as CDV_b for herbaceous plants that are rather close to the similar value presented in UNSCEAR report (1996). Such doses in the Chernobyl zone caused an increase in the yield of cytogenetic disturbances and point mutations in herbaceous plants. However, the increased sterility and decreased germination rate of seeds, as well as morphologic anomalies next year following the accident were observed at much higher doses (more than $10\,Gy\,a^{-1}$) (Suvorova et al., 1993). Overall, almost 10-fold increase in the CDV_b for herbaceous plants compared to coniferous trees fits a known radiosensitivity ratio of phylogenetically more ancient gymnosperms and evolutionary younger angiosperms (Sarapultsev and Geras'kin, 1993). It should be noted in this context that CNSC (2001) suggests a single ENEV for all terrestrial plants, which can hardly be considered as an acceptable decision taking into account significant differences in radiosensitivity between angiosperms and gymnosperms.

2.4.3. Cattle

For cattle, we have suggested a threshold dose to the whole body of 0.6 Gy a^{-1}. It is getting clear from the experience derived that the key moment for the Chernobyl accident in the radiation damage to farm animals is the thyroid affection due to the radioiodine accumulation in the thyroid. Problems connected with the role of radioiodine in the formation of radiation induced effects in mammals will be treated separately. It should be noted that in estimation of a CDV_b for cattle we relied on the data presented by Alexakhin et al. (1992) and Budarkov et al. (1996) taking into account differences in rates of metabolic and reproductive processes in mouse-like rodents and large mammals. As for iodine radionuclides, based on the analysis of radiation effects in the Chernobyl affected zone (Astasheva, 1991) a value of 50 Gy was taken as a complimentary CDV_b for cattle.

2.4.4. Mouse-like rodents

For mouse-like rodents a CDV_b of 0.4 Gy a^{-1} has been suggested (Table 2). After the Chernobyl accident, the pathological changes in the hemopoietic system and inner organs of mouse-like rodents were observed at doses of above 1 Gy (Ermakova, 1996; Matery and Goncharov, 1996) which correspond to ENEV adopted by Bird et al. (2002). At the same time, there is information indicating that acute irradiation of mouse-like rodents at doses of 0.4–0.8 Gy reduces their fertility (Sokolov et al., 1994). Bearing in mind differences in the effectiveness of acute and chronic exposure, it may be inferred that a CDV_b of 0.4 Gy a^{-1} is fairly realistic. Threshold dose (0.37 Gy a^{-1}) close to this value was also adopted in UNSCEAR (1996) and CNSC (2001) reports. About 6–8 times lesser critical doses (0.05 and 0.07 Gy a^{-1}) reported by Sazykina and Kryshev (1999, 2002) are mainly based on early hemopoietic and genetic effects and are likely too conservative for the objectives of the current study.

2.4.5. Soil invertebrates

Radiosensitivity of soil invertebrate species (LD_{50}) varies widely, from 20 to 5000 Gy, and depends largely on the developmental stage of organisms. The minimum LD_{50} was reported for common chickweed (20 Gy), the maximum – for some insect species (5000 Gy). A disorder in the reproduction process resulting in a drop of the mesofauna organism's number occurs at doses of 10% of LD_{50} (Krivolutsky, 1994).

According to Krivolutsky et al. (Krivolutsky et al., 1990; Krivolutsky, 1994), a noticeable reduction in the numbers of invertebrates inhabiting the forest litter (earth mites, earthworms, polypods, etc.) in the Chernobyl affected area was observed at a dose of about 8 Gy. Considering that during ontogenesis radiosensitivity of invertebrates can vary more than two orders of magnitude (Sarapultsev and Geras'kin, 1993) and that the inhibition of the reproductive processes usually occurs at doses by an order of magnitude lower than LD_{50}, we have suggested a dose of 0.9 Gy a^{-1} as a CDV_b for soil invertebrates which is similar to the value (0.88 Gy a^{-1}) adopted in the CNSC report (2001). It should be noted that this value lies between the estimates (0.4 and 2.0 Gy a^{-1}) suggested by Sazykina and Kryshev (1999, 2002) and Bird et al. (2002) on the basis of other data.

2.4.6. Hydrobionts

The threshold values of irradiation for algae and macrophytes (0.88 and 1 Gy a^{-1}) suggested in the CNCS report (2001) and by Bird et al. (2002) (Table 2) were the same as for terrestrial plants, because of the lack of available information. On the other hand, a comparison of data (UNSCEAR, 1996) on radioresistance (LD_{50}) for algae (100–2000 Gy) with that of coniferous plants (5–20 Gy) allows a conclusion to be made that the suggested threshold values are much too conservative. Therefore, as CDV_b for these aquatic organisms, the following values were used: phytoplankton – 3 Gy a^{-1}, zooplankton – 2.5 Gy a^{-1} (Table 2). Zoobenthos shows higher variability in radiosensitivity LD_{50} (30–2500 Gy) and, despite the data reported in CNSC report (2001) – 0.6 Gy a^{-1} and by Bird et al. (2002) – 2 Gy a^{-1}, a dose of 0.9 Gy a^{-1} was chosen in the current study as CDV_b for this group of species.

As proposed in the literature threshold doses for fish vary from rather low values 0.1 Gy a^{-1} (Sazykina and Kryshev, 1999), 0.2 Gy a^{-1} (CNSC, 2001; Bird et al., 2002) to 3.65 Gy a^{-1} (US DOE, 2002) dependent on the endpoint and conservatism used in establishing these values. Thus, the minimal values are based on early genetic, hemopoietic effects while bigger values are mainly based on reduction of fertility. Fish are generally characterised by a higher radiosensitivity than plankton and zoobenthos (UNSCEAR, 1996). In spite of this, even in the contaminated cooling pond and other water bodies located close to the ChNPP where doses reached several Gy in 1986, radiobiological effects in fish were not significant and restricted themselves to minor disorders in the reproductive and hemopoietic systems, elevated level of fluctuating asymmetry and cytogenetic disturbances (Ryabov, 1992; Makeyeva et al., 1995). Therefore, taking into account CDV_b described earlier for other non-human species, it is expedient using for fish a CDV_b of 0.6 Gy a^{-1} as most applicable for the objectives of the current study.

2.5. Doses and radiation impact on the population and selected species of biota

2.5.1. Population

The population of Borshchovka was evacuated on May 4, 1986. However, to compare impacts of the ChNPP accident release on man and non-human species in different time periods after the accident and regularities in their changing, a hypothetical situation was also considered when the inhabitants of the settlement were allowed to live in this area at least up to 1992. The food habits and the other conditions for dose calculations were chosen as these were at the time of the accident. The doses to the inhabitants of this settlement were estimated for three time intervals: from April 26 to May 4, 1986 (real exposure); from April 26 to September 15, 1986 (reconstructed exposure); and during 1991 (reconstructed exposure). Both

Table 3
Effective doses to the population, mSv

Dose	Before relocation	26.04–15.09.86	1991
External	41.2[a]	216.3[a]	10.7
Internal	13.1	77.2	10.7 (27.3[b])
Total	54.3	293.5	21.4 (38.0[b])
To the thyroid, mGy	2750	4520	–

[a] Including dose from the cloud.
[b] Without countermeasures application.

doses to the thyroid from radioiodine and effective doses from external and internal exposure of the population were calculated (Table 3).

It follows from Table 3 that the evacuation of the population from the settlement was an effective protective measure that reduced the dose by more than 80% by the end of the first year after the accident. At the same time, the population of the test area received a considerable dose to the thyroid, 2.75 Gy, prior to the evacuation; this value comprises more than 50% of the potential annual dose. The average effective dose to the population in the study area could have been rather high in 1991 as well. Without the public relocation and application of agricultural countermeasures this dose could have amounted to 38 mSv with the prevailing contribution from internal exposure (71%).

2.5.2. Non-human species

The doses to non-human species were calculated for a period of the active growth and development of plants, from 26 April through September 15, 1986 (Table 4). For correctness of the comparison, similar periods for dose calculations were used for animals and man.

2.5.2.1. Coniferous trees. To calculate doses to the woody storey of the forests located at the experimental site, the data on the radionuclides deposition densities

Table 4
Calculated doses to selected species of biota inhabiting the study area, Gy

Biota species	1986 (26.04–15.09)	1991
Terrestrial ecosystems		
Coniferous trees (pine)	3.7	0.03
Herbaceous plants (meadow grasses)	15	0.04
Herbaceous plants (cereals)	8.0	0.04
Cattle	1.6 (150[a])	0.06
Mouse-like rodents	0.6	0.06
Soil invertebrates	4.6	0.15
Aquatic ecosystems		
Phytoplankton	0.06	3.4×10^{-4}
Zooplankton	0.18	6.3×10^{-4}
Zoobenthos	0.7	0.23
Fish	0.4	0.04

[a] Dose to the thyroid.

(Table 1) were recalculated at the time of the maximum fallout. The doses accumulated by coniferous trees in 1986 amounted to a value of 3.7 Gy, which was significantly higher than the values at which no radiation effects were observed after the ChNPP accident (Table 4). Most of the dose was delivered during the first two weeks after the accident when more than 80% of the dose was due to short-lived radionuclides (such as ^{95}Zr and ^{95}Nb, ^{140}Ba and ^{140}La, iodine radionuclides and some others). The calculations based on the mathematical model of radiation damage to forest ecosystems (Alexakhin et al., 1994) indicated that from 3 to 7% of pine trees were expected to die in this area within 3–5 years.

The doses to the trees from the radioactive fallout rapidly decreased with time and did not exceed 0.4 Gy a^{-1} in 1987 and 0.03 Gy a^{-1} in 1991. So, it may be concluded that the period of a considerable radiation impact on the woody storey was limited to the first months of 1986 while the post-radiation recovery of trees had been completed by 1991.

2.5.2.2. Herbaceous plants (meadow grasses). The resulting dose of 15 Gy in 1986 to herbaceous plants can cause negative effects in phytocenoses. The partial sterility and reduced germination rate of seeds of dandelion and arabidopsis were observed (Suvorova et al., 1993) at doses of about 10 Gy over the first month after the accident. The next year at such doses numerous and various anomalies could appear, such as fasciation and branching of stems, doubling, changes in flower clusters, colour and size of blades and flowers.

2.5.2.3. Herbaceous plants (cereals). At the study site in 1986 cereals received a dose to the apical cone of about 8 Gy. The results of the investigations carried out on cereals in the 10 km ChNPP zone in 1986 (Suvorova et al., 1993; Zjablitzkaja et al., 1996) show that such doses do not cause significant phenotypic effects although the increase of yield of cytogenetic disturbances in the root meristem of seedlings, starting from a dose of 3 Gy was observed.

The calculations have shown that in the first year after the accident the main contributor to the dose burden to plants is β-radiation, and depending on the plant development stage the contribution of β-radiation exceeds that of γ-radiation by factors of 5–10.

In 1991 a source of irradiation of plants was a ploughed soil layer with a uniform radionuclide distribution over the profile. A dose of 0.04 Gy absorbed in the study area over the growth season of 1991 by cereal crops would hardly cause a significant increase in the frequency of genetic disorders. Certainly, no radiation induced phenotypical effects can be expected at such doses.

2.5.2.4. Cattle. The dose burden to the thyroid of cattle (150 Gy) markedly exceeds that to the whole body (1.6 Gy) and is practically completely formed in the first month after the accident. The internal doses of γ-radiation in the body of animals over the first month mainly result from the radionuclides in the gastro-intestinal tract. The external exposure contribution to the total dose to animals amounts to

0.5 Gy. A dose of 0.06 Gy to cattle absorbed in the study area in 1991 would hardly result in any radiation effects.

2.5.2.5. Mouse-like rodents. Mouse-like rodents have a high reproduction potential, thereby causing high variability in their numbers (increase or decrease hundred times) during 3–6 months under changes in the environment (Bondarenko et al., 1977).

At relatively low doses ionising radiation can cause temporary or constant sterility of individuals, which affects the reproduction rates of the population. According to Ilyenko and Krapivko (1989), depending on the rodent species, LD_{50} value is within the 5–10 Gy range. Doses of 1–2 Gy induce temporary sterility, 0.4–0.8 Gy – reduced fertility (Krivolutsky, 1983).

The estimated dose for 1986 with the account of residence time on the soil surface and in holes (0.6 Gy) is not lethal; this is not expected to result in any pathological changes in the hemopoietic system, the liver, the adrenals and the thyroid (such effects need doses over 1 Gy). This dose, however, can induce a prolonged (up to 3–5 months) delay in the reproduction processes. The estimation of the external β-radiation doses to the skin of rodents has demonstrated that their values can be higher than doses to the whole body by a factor of 2. In 1991, the dose to mouse-like rodents amounted to 0.06 Gy. Such exposure doses do not cause significant genetic and especially ecological effects of irradiation.

2.5.2.6. Soil invertebrates. Soil is a natural depot for radionuclides released into the environment; therefore doses to soil inhabitants are often noticeably higher than to organisms living on its surface. The time of the Chernobyl accident coincided with the most radiosensitive stage of development of soil inhabitants: the period of reproduction and moulting after a winter dormancy and spring warming up of soil. The calculation results show that over the period considered soil invertebrates received a dose of about 4.6 Gy. It has been shown (Krivolutsky et al., 1990) that such a dose, even during a longer period, causes the reduction in the numbers of mesofauna representatives (earth mites, earthworms, polypods, etc.), i.e. can produce adverse ecological effects. In 1991, after a decay of the bulk of short- and medium-lived radionuclides, the annual dose to soil invertebrates amounted to 0.15 Gy; that is lower than doses at which radiation damage to soil mesofauna can be observed.

2.5.2.7. Hydrobionts. The calculations have shown that in 1986 the maximum doses to aquatic organisms were typical for bottom fish (0.4 Gy) and benthic organisms (0.7 Gy). At such levels of radiation exposure, noticeable radiobiological effects are difficult to be expected, though the frequency of cytogenetic disturbances in actively dividing tissues can be significant (Pechkurenkov, 1991; Ryabov, 1992). The dose burdens to zooplankton over 1986 amounted to 0.18 Gy and to phytoplankton – to 0.06 Gy, i.e. much lower than level when radiation effects in phytoplankton could be observed (Bird et al., 2000). Following the decay of short- and medium-lived radionuclides, the main contributors to irradiation of hydrobionts in the early period after the accident, the dose burdens to aquatic organisms reduced considerably. The maximum doses in 1991 (0.23 Gy) are characteristic of zoobenthos.

2.6. Radiation impact on man and non-human species

The impact of radioactive releases on biota and man is not only determined by the exposure dose but also by their radiosensitivity and the *Radiation Impact Factors* (RIFs) were calculated based on the data given in Tables 2 and 4 to provide such a comparison (Tables 5 and 6).

It is seen that in the case of evacuation, RIF_hs are 1.1 and 0.54, i.e. man was practically protected from ionising radiation (in this case due to the evacuation). In the event of non-evacuation of the population from the study area the radiation impact would have been dependent on the effective dose rather than irradiation of the thyroid. Thus, RIF_h calculated from the effective dose is 3.3 (for CDV_h 100 mSv a^{-1}) and 6.5 (for CDV_h 50 mSv a^{-1}) times higher than RIF_h estimated from the dose to the thyroid. At the same time RIF_h calculated for a real case (the evacuation of the population on May 4, 1986) is by 20% more than the similar value estimated from the effective dose, thereby signalling a need to use RIF_h calculated from the dose to the thyroid (0.64). Hence, for a comparative assessment of the radiation impact on man and biota in most of cases, except for cattle and the evacuated population (CDV_h 100 mSv a^{-1}), $RIF_{h,b}$ estimates were used made from the dose to the whole body.

It follows from these calculations that the terrestrial ecosystems were affected by the Chernobyl accident more than aquatic ones. RIF_b values for all terrestrial species are above 1 (1.5–9.3). RIF_b values for aquatic species were much less (0.020–0.78). Among hydrobionts the lowest RIF_b values are typical of phytoplankton (0.020), followed by zooplankton (0.072) and then fish (0.67) and benthos species (0.78).

The maximum RIF_b values in 1991 were obtained for benthic organisms (0.26), as well as for mouse-like rodents (0.15) and soil invertebrates (0.17). This is mainly connected with the redistribution of radionuclides in ecosystems and concentration in natural depots of radioactive substances – bottom sediments in aquatic ecosystems and soil in terrestrial ones. The maximum RIF_h in 1991 was 38.0 while calculated from the current radiation safety standards (CDV_h 1 mSv a^{-1}) and 4.3 while

Table 5
RIF_h values calculated for population of the study area, dimensionless

CDV_h	1986		1991	
	Before evacuation (May 4, 1986)	26.04–15.09	With countermeasures	No countermeasures
1 mSv/a	–	–	21.4	38.0
5 mSv/a	–	–	4.3	7.6
50 mSv/a	1.1 (0.64[a])	5.9 (0.9[a])	–	–
100 mSv/a	0.54 (0.64[a])	2.9 (0.9[a])	–	–

[a] Dose to the thyroid.

Table 6
RIF_b values calculated for non-human species in the study area, dimensionless

Biota species	1986	1991
Terrestrial ecosystems		
Coniferous trees (pine)	9.3	0.08
Herbaceous plants (meadow grasses)	5.0	0.013
Herbaceous plants (cereals)	2.7	0.013
Cattle	3.0[a] (2.7)	0.10
Mouse-like rodents	1.5	0.15
Soil invertebrates	5.1	0.17
Aquatic ecosystems		
Phytoplankton	0.020	1.1×10^{-4}
Zooplankton	0.072	2.5×10^{-4}
Zoobenthos	0.78	0.26
Fish	0.67	0.067

[a] Dose to the thyroid.

estimated from the standards valid in 1986 (CDV_h 5 mSv a^{-1}) in the case if agricultural countermeasures in 1991 would be applied. These are $20.0 - 1.1 \times 10^5$ times higher than RIF_b for the selected biota representatives. Such a significant difference between man and biota species in this period is mainly connected with the extremely conservative radiation safety standards adopted for man (CDV_h).

3. Discussion

In the first year after the accident (1986) doses to biota species varied significantly (up to 250 times) (Table 4) and this was mainly connected with peculiarities of radionuclides distribution in ecosystems. The maximum doses are reported in herbaceous plants on meadows and crop fields, the aboveground parts of which were contaminated by radioactive fallout. These high doses result from the fact that critical organs of herbaceous plants are close to the contaminated soil surface. A high capacity of crowns of the woody plants to retain radionuclides has caused the development of rather high doses, though these were about 3–4 times lower than in herbaceous plants.

The soil invertebrates inhabiting the upper soil layer and forest litter where the bulk of the deposits is concentrated have also received considerable doses comparable with those to woody plants and 2–3 times lower than doses absorbed by meadow and farm crops. The minimum among the terrestrial species studied (albeit rather high in terms of biological consequences) doses was received by mammals, farm animals and mouse-like rodents. Doses to aquatic organisms were markedly lower, with the highest doses to hydrobionts being in zoobenthos and fish, the minimum – to plankton.

Dose burdens to non-human species and the public within the study area in 1986 normalised to the effective dose to the population from the moment of fallout till September 15, 1986 in the non-evacuation case (0.294 Sv) can be ranked as follows

($Gy\,Sv^{-1}$ for non-human species): relocated population (0.18) < phytoplankton (0.20) < zooplankton (0.61) < non-relocated population (1.0) < fish (1.4) < mouse-like rodents (2.1) < zoobenthos (2.4) < cattle (5.5) < coniferous trees (13) < soil invertebrates (16) < herbaceous plants (cereals) (27) < herbaceous plants (meadow grasses) (51).

All the considered biota species received doses 1.1–270 times higher than the relocated population. If the relocation has not been performed (i.e. doses to man and biota were calculated for the same period, from April 26 till September 15, 1986), these differences could have been much less, and doses to man would have been only about 50 times lower than the maximum doses to biota species. In this situation man is no longer the least irradiated component of the ecosystems, his doses are higher than in the least affected components, phytoplankton and zooplankton.

In 1991, due to the decay of short-lived radionuclides and migration of the remaining ones in the trophic chains, the radiological situation changed drastically. Firstly, doses to non-human species as well as the population dropped significantly, in terrestrial biota 10 (mouse-like rodents) to 200–375 (farm and meadow plants) times. Secondly, series of the selected biota representatives by the irradiation level changed. Thus, in the early period (1986) the highest doses were received by woody and herbaceous plants as well as the soil mesofauna, i.e. biota representatives which either intercept radioactive depositions themselves or inhabit the sites that retain radioactive substances. In 1991, the maximum doses were received by organisms inhabiting the natural depot of radionuclides – soil in terrestrial ecosystems and bottom sediments in hydrobiocenoses: soil invertebrates and zoobenthos. It should be noted that while in the early period after the accident, due to countermeasures, man was the "protected representative" of the biosphere and received the lowest doses, in the long-term period doses to many of non-human species and man became rather close and in biota species they can be even lower than in man. This had resulted from the redistribution of radionuclides over the components of natural and agricultural biocenoses and specific features of trophic chains of radionuclide transfer in the environment, thereby changing the role of different radionuclides and various pathways in dose formation in man and biota.

In 1991, annual doses to man would have been at the level of doses received during the vegetation period by woody and herbaceous plants, as well as fish. These would have been higher than in phytoplankton and zooplankton, somewhat lower than in farm animals and mouse-like rodents and significantly lower than in soil invertebrates and zoobenthos.

By $RIF_{h,b}$ the impact on the selected non-human species and man in 1986 may be ranked as follows: phytoplankton (0.020) < zooplankton (0.072) < relocated population with CDV_h 100 $mSv\,a^{-1}$ (0.64[1]) < fish (0.67) < zoobenthos (0.78) < relocated population with CDV_h 50 $mSv\,a^{-1}$ (1.1) < mouse-like rodents (1.5) < herbaceous plants (cereals) (2.7) < non-relocated population with CDV_h 100 $mSv\,a^{-1}$ (2.9) < cattle (3.0[1]) < herbaceous plants (meadow grasses) (5.0) < soil invertebrates

[1] Dose to the thyroid.

(5.1) < non-relocated population with CDV_h 50 mSv a^{-1} (5.9) < coniferous trees (9.3).

Thus, soil mesofauna species (RIF_b amounts to 5.1) and coniferous trees (RIF_b amounts to 9.3) should be regarded as critical environmental species under the conditions of the Chernobyl accident.

As it was noted earlier the ICRP statement is related only to the routine practice and cannot be extended to the accidental situations. Therefore, the above ranks of man and non-human species based on $RIF_{h,b}$ values, calculated for 1986, allow only a comparison of the radiation impact on biota and man. It can be seen that the relocated population happens to be in the series considered close to the non-human species with the lowest impact, while the non-relocated population close to the non-human species with the highest radiation impact. However, even assuming the equivalent exposure conditions (no relocation) for man (RIF_h at CDV_h 50 and 100 mSv a^{-1} are, respectively, 5.9 and 2.9) and biota species, human being would not have been affected more than some non-human species, since coniferous trees have higher RIF_b (9.3).

These results were obtained for the case when to estimate radiation impact either dose to the whole body or dose to the thyroid were used. The RIF values based on an additive concept, which takes into account the sum of RIF_hs calculated on the basis of doses from radionuclides of iodine to the whole body and to the thyroid, were as follows: 5.7 for cattle, 1.7 and 1.2 for the relocated and 6.8 and 3.8 for non-relocated population at CDV_h of 50 and 100 mSv a^{-1}, respectively. So, even this, the most conservative estimation, does not alter the above conclusions.

Similar ranking by $RIF_{h,b}$ in 1991 gives the range: phytoplankton (1.1×10^{-4}) < zooplankton (2.5×10^{-4}) < herbaceous plants (cereals) (0.013) = herbaceous plants (meadow grasses) (0.013) < fish (0.067) < coniferous trees (0.08) < cattle (0.1) < mouse-like rodents (0.15) < soil invertebrates (0.17) < zoobenthos (0.26) < population with CDV_h 5 mSv a^{-1} (5.6) < population with CDV_h 1 mSv a^{-1} (38.0).

The data allow the conclusion that by 1991 RIF_b values for all the biota representatives compared to 1986 fell drastically (from 3 to 400 times) and were below unity. This shows that a period of important radiation stress for the environment after the Chernobyl accident was relatively short. It can be also seen that in 1991 benthic species, soil invertebrates and mouse-like rodents were the most affected among non-human species; much lesser was radiation impact on some aquatic species such as phytoplankton and zooplankton and other species happened to be in this series in the intermediate position.

An important procedure to verify the correctness of the principle "if man is protected then biota are also protected" is a comparative analysis of radiation effects on man and biota in various radioecological situations. Thus in Thorne et al. (2002) radiological impact on organisms other than man of various long-lived radionuclides of importance was evaluated in solid waste disposal sites (in geological repositories). Threshold dose rate for the induction of significant deleterious effects on communities is estimated and it has been found that compliance with the radiological protection standards appropriate to man ensures that such thresholds are not exceeded. This has allowed a conclusion about correctness of the anthropocentric principle. Thorne et al. (2002), however, adopted a common dose limit for all the selected non-human species (10 mGy day^{-1} or 3.65 Gy a^{-1}), which was considered to be an analogue of a dose of 1 mSv a^{-1} for man. In other words, in that paper less stringent standards of permissible biota exposure were adopted than in our investigation.

In accordance with the modern point of view the situation in the zone subjected to contamination after the ChNPP accident in 1991 can be classified as a routine practice (case of radiation legacy) and, therefore, can be used for the estimation of the ICRP thesis correctness "if radiation standards protect man, then biota are also adequately protected from ionising radiation". A considerable excess of RIF_h compared to RIF_b in the long term after the accident (1991) ($RIF_b < 1$ and $RIF_h > 1$) suggests that in the case considered in the current study (long term after the accident) man is not protected from irradiation and biota species, on the contrary, are protected, i.e. the thesis "if man is protected then biota are also protected" proves to be correct. At the same time, it should be stressed that this stems from the conservatism of standards currently adopted in the radiation protection of man.

4. Conclusion

The results of the current study allow the conclusion that in the early period after the Chernobyl accident (1986) for many biota species (primarily for terrestrial flora and fauna) in the most affected areas an excess of irradiation over the critical levels has been observed. Among them coniferous trees and soil mesofauna species can be regarded as critical environmental species under the conditions of the Chernobyl accident. However, in this case the irradiation of man (without evacuation) has also been above the levels permissible for emergencies. At these levels of human exposure pine, meadow plants and soil invertebrates were protected less than man and the levels of protection of other biota species (hydrobionts) were close to or exceeded that of man. On the contrary, in 1991 for all the considered non-human species RIF_b values were less than unity and from 17 to 3.4×10^5 times lesser than for man. Thus, for this case the statement "if radiation standards protect man, then biota are also adequately protected from ionising radiation" can be accepted even with some conservatism.

However, the environmental contamination in the Chernobyl affected area varied essentially in the contamination density, radionuclide composition, and physical–chemical properties of depositions. These resulted in a large variability in doses to man and various biota species even at the same contamination densities of territories. Therefore, the results presented in the current study although relating to the typical contamination area in the close vicinity of the ChNPP do not cover all possible radioecological situations in the accidental zone, and it is only a comprehensive analysis of similar situations on the basis of the suggested approach that can provide an adequate estimation of radiation impacts on man and biota after the ChNPP accident.

Even larger ratio of doses absorbed by man and non-human species in the regions contaminated mainly with β- or α-emitting radionuclides could be expected. Examples of such radioecological situations are the heavy radiation accidents at the "Mayak" radiochemical plant, regions with increased natural radiation background, areas of uranium mining and reprocessing plants.

The results obtained allow the conclusion that there are radioecological situations when the ratio of doses to humans and the radiation protection standards can be close enough to the ratio of doses to critical non-human species and the minimal doses at which negative effects can be observed. On the whole, this generates a need for a more detailed and comprehensive analysis of radiation impact on biota not only in the case of the ChNPP accident but also in other situations connected with contamination of the environment.

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