## Session 9: Radiation protection of the biota

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Low dose radiation-induced non targeted effects – How the changing paradigm impacts radiation protection of biota?

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Abstract

Ever since the grudging acceptance that non-targeted effects (NTE) can be measured in unirradiated cells or distant progeny of irradiated cells, the discussion has raged about the relevance of these effects for radiation protection and risk assessment. Arguments will be made in this presentation, that NTE may call into question radiation effects pillars such as the LNT model. They may also have relevance to wider mechanisms in cancer biology, population ecology and evolutionary biology concerning process of selection, the transmission of heritable traits, the relevance of “social” interactions between cells, organisms and populations and the mechanism by which cells/organisms respond rapidly to environmental stress. This presentation will also argue that a key consequence of findings in NTE biology is that at any given level of organization, from gene to ecosystem – communication of stress signals and heritability of stress adaptations provide the bridges linking one hierarchical level to the next and enable the rapid propagation of change triggered by stress at one level, resulting in change at a higher (or lower?) level. This addresses a major problem in evolutionary biology because while the molecular mechanisms of natural selection are fairly well understood a major knowledge gap exists in translating mutational drift at the level of the individual cell to natural selection at the ecological level where sociobiological factors are so important. The existence of the mechanisms discovered in the NTE field provides a glimpse of a major way that evolution could be regulated through communicated signals between cells, individuals, and populations. These control and optimize responses at the level of the population and coordinate the emergence of exquisitely tuned systems which can adapt rapidly to micro or macro environmental change. Radiation protection strategies for biota mean that an understanding of the driving mechanisms is vital.
The activities of the IAEA in developing standards on radiological protection of the environment

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Abstract
Radiological protection of the environment is an issue that has been intensively discussed for more than one decade. A great deal of progress has been made during this time regarding the capabilities: (i) of estimating the uptake of radionuclides by flora and fauna in different habitats and ecosystems; (ii) in the development of dosimetric models that allow the calculation of internal and external exposures for a wide range of terrestrial and aquatic organisms; and (iii) in investigating and analysing the effects of radiation exposures to biota.

This paper gives an overview of the IAEA’s activities in this field and it describes the interactions with UNSCEAR, the ICRP and other national and international bodies and institutions with regard to the work on analysis and evaluation of exposures to flora and fauna. The current status of the discussion on the integration of environmental protection into the radiation protection system is also summarized. Results of case studies are presented that assess the radiological impact to flora and fauna due to discharges of radionuclides to terrestrial and aquatic environments.

Finally, the paper discusses the factors, assumptions and considerations that are regarded as important for risk characterisation and decision making in relation to radiation exposures to biota. It explores the remaining challenges related to the integration in regulating and controlling dischargeable waste.

Introduction
For a long time, the management of radionuclides entering the environment was in general based on the assessment and evaluation of the radiological impact to humans. However, in the last decades, with an increasing awareness of environmental issues, concerns were raised that flora and fauna might be affected by radionuclides released into the environment; it is now considered necessary to demonstrate that the environment is appropriately protected against ionizing radiation (ICRP, 2007).

Considerations on protection of the environment from ionizing radiation started in the 1960s and 1970s (IAEA, 1961, 1975, 1979; IMO, 1972), one important reason for this interest was the practice of disposing of low-level radioactive waste into the oceans.
Concerns rose that this could harm marine flora and fauna, which initiated detailed investigations on the effects of ionizing radiation to biota.

This original scientific interest has been accompanied by new and developing international policies and agreements. Important milestones were the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Convention) (IMO, 1972) and the Declaration of the United Nations Conference on Environment and Development of 1992 (UNCED, 1992), which stimulated the development of policies and approaches to specifically address impacts of radioactive substances on non-human species.

Nevertheless, for a long time risk assessment and management of radionuclides released into the environment were based on radiological impacts to humans alone. In 1990, the International Commission on Radiological Protection (ICRP) (ICRP, 1991), the view is held that — as is also the case in the 1977 recommendations (ICRP, 1977) — the environment implicitly is afforded adequate protection by application of standards that provide for adequate protection of humans. The main problem is related to situations where man is absent or not exposed as in e.g., unpopulated areas or in the sea. In the meantime, this indirect approach is considered insufficient (e.g., Strand and Larsson, 2001) and in the most recent ICRP recommendations (ICRP 2007), the development of a framework is proposed to explicitly demonstrate radiological protection of the environment. The IAEA is following progress in this area and is exploring the need for those cases where it could be considered necessary because of an actual radiological risk, as well as the form and content of any improved international standards.

**Current status**

**Objectives of radiation protection of the environment**

The objectives of the radiation protection of humans are to avoid deterministic effects and to limit stochastic effects to individuals (e.g., IAEA, 1996; ICRP, 2007). However, the objectives for the protection of the environment are more complex. The protection of individual organisms is not an issue, approaches in environmental protection always target protection on the population and community levels. Therefore, there is a consensus that the objectives of protection of the environment are related to the conservation of species, the maintenance of biodiversity and the protection of habitats, communities and ecosystems (IAEA, 1999, 2002, 2006; ICRP, 2003, 2007, 2008).

**Scientific background**

Much work has been done in recent years to develop methodologies to assess and evaluate exposures to flora and fauna, taking into account both the terrestrial and aquatic environments (Figure 1). The European Union has launched two projects, FASSET and ERICA (Larsson, 2004, 2008) in order to develop a framework for assessment and evaluation of radiological impacts to biota from radionuclides discharged to, or already existing in, the environment. In 2005, the ICRP established a Committee dedicated to Protection of the Environment with the aim of setting up a framework for assessment and evaluation of exposures to biota. This work has been supported by the approaches developed during the EU projects FASSET and ERICA.
Due to the enormous variability of nature, it is impossible to take all species into account. For this purpose, within FASSET and ERICA a set of Reference Organisms has been defined representing terrestrial, freshwater and marine ecosystems. With the same intention, ICRP developed, in accordance with the system for the protection of humans from ionizing radiation, a set of 12 Reference Animals and Plants (RAPs) covering plants and animals, and different habitats (ICRP, 2008).

During these activities, models and databases were developed that allow for the:
- estimation of activity concentrations in reference organisms from measured or predicted radionuclide concentrations in soil, water or sediments;
- estimation of internal and external doses to aquatic and terrestrial; and
- setup of relationships between exposure and adverse effects to animals and plants.

**Fig. 1. Overview of the steps to estimate and evaluate exposures to biota in the aquatic and terrestrial environments.**

A key issue in considerations on protection of the environment is the evaluation of exposure in relation to effects. However, whereas the objectives of the radiation protection of humans are to avoid deterministic effects and to limit stochastic effects to individuals, the objectives for the protection of the environment are related to the population and community level; as formulated in the ICRP 2007 recommendations, the targets are conservation of species, and to protect habitats, communities and ecosystems.

For this purpose, ICRP has derived a set of Derived Consideration Reference Levels (DCRL) for the 12 RAPs; which usually cover one order of magnitude (Fig. 2). The DCRLs represent bands of doses that are associated with no or very little adverse effects.

Within the EU-funded project PROTECT (Andersson et al., 2009), and on the basis of a statistical analysis of dose-effects relationships, screening levels were derived for vertebrates, invertebrates and plants of 2, 200 and 70 µGy h⁻¹ respectively, and a
generic screening value of 10 μGy h\(^{-1}\) was derived. Due to the approaches used during their derivation, they represent values that can be used to screen out exposure conditions of no concern. These screening values are generally in agreement with the DCRLs.

DCRLs do not represent dose limits, they should be considered as zones of doses at which a more detailed evaluation of the situation would be warranted. Therefore, DCRLs should be applied in a similar way as reference levels for existing and emergency exposure situations.

For this evaluation of the exposure conditions, factors should be taken into account as, e.g., the type of exposure situation (planned, existing, emergency), the size of area that is affected, the time period for such exposures, the fraction of a population of a species that is exposed to such dose levels, the appropriateness of the database used for the dose estimation, and the degree of precaution that is needed for the assessment.

Examples of exposures to biota as derived from case studies
During recent years, a number of studies were performed to estimate doses to biota under different field conditions. Some results are summarized in Table 1. It should be noted, however, that this list is not complete. The selection given is intended to cover a wide range of contamination situations. Very high exposures are only observed during the early phase of a nuclear accident as illustrated by the examples given for the Techa River, Chernobyl or Kyshtym (Kryshev et al., 1998; Sazykina et al., 1999).

Recently estimated doses to biota in the Chernobyl exclusion zone vary widely as the contaminations vary. The peak values refer to a few highly contaminated areas.

The exposure of biota in Finnish lakes contaminated by the Chernobyl fallout depends on the habitat, i.e., exposures in the water column are low, whereas organisms...
living on or in the sediments are still exposed at levels of a few µGy h\(^{-1}\) due to the persistent contamination of lake sediments with \(^{137}\text{Cs}\).

Table 1. Exposures to biota as estimated in selected studies.

<table>
<thead>
<tr>
<th>Site and Year</th>
<th>Source of contamination</th>
<th>Radionuclides involved, Organism</th>
<th>Exposure (µGy h(^{-1}))</th>
<th>Reference</th>
</tr>
</thead>
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<tr>
<td>Techa river, 1951</td>
<td>Nuclear weapons industry</td>
<td>Fish</td>
<td>up to 25000</td>
<td>Kryshev et al., (1998), Sazykina et al. (1999), Brechignac (2003)</td>
</tr>
<tr>
<td>Kyshtym, 1957/1958</td>
<td>Nuclear weapons industry</td>
<td>Pines Fish</td>
<td>up to 90000, up to 1000</td>
<td></td>
</tr>
<tr>
<td>Chernobyl 1986</td>
<td>Chernobyl accident, 3 selected sites</td>
<td>Pines, rodents</td>
<td>up to 10000</td>
<td></td>
</tr>
<tr>
<td>Chernobyl exclusion zone, 2005</td>
<td>Chernobyl accident, 3 selected sites</td>
<td>Small mammals</td>
<td>12-810</td>
<td>Beresford et al, 2008</td>
</tr>
<tr>
<td>Lakes, Finland, 2003</td>
<td>Chernobyl fallout</td>
<td>(^{134}\text{Cs}, (^{137}\text{Cs}, (^{90}\text{Sr}) \begin{align*} \gamma\text{-dose rate} &amp;= 2 - 31 \text{ µGy h}^{-1} \end{align*} ) (\text{Cs in soil}: \text{7-100 kBq kg}^{-1}) Fish, waterplants</td>
<td>0.03-0.85</td>
<td>Vettiko and Saxen, 2008</td>
</tr>
<tr>
<td>Loire river, 1999</td>
<td>Chinon Nuclear Power Plant</td>
<td>(^{3}\text{H}, (^{14}\text{C}, (^{131}\text{I}, (^{134/137}\text{Cs})} \begin{align*} \gamma\text{-dose rate} &amp;= 2 - 31 \text{ µGy h}^{-1} \end{align*} ) (\text{Cs in soil}: \text{7-100 kBq kg}^{-1}) Various plants and animals</td>
<td>1<em>10^{-6} - 5</em>10^{-5}</td>
<td>Beresford and Howard, (2005)</td>
</tr>
<tr>
<td>Norway 2003</td>
<td>Oil and gas rigs</td>
<td>(^{226/228}\text{Ra}, (^{210}\text{Pb}, (^{210}\text{Po}) \begin{align*} \gamma\text{-dose rate} &amp;= 2 - 31 \text{ µGy h}^{-1} \end{align*} ) (\text{Cs in soil}: \text{7-100 kBq kg}^{-1}) Fish, molluscs, phyto- and zooplankton</td>
<td>5<em>10^{-3} - 7</em>10^{-2}</td>
<td></td>
</tr>
<tr>
<td>La Hague, 1996</td>
<td>La Hague reprocessing plant</td>
<td>(^{14}\text{H}, (^{16/18}\text{O}, (^{129/131}\text{Co}, (^{134/137}\text{Cs}, \begin{align*} \gamma\text{-dose rate} &amp;= 2 - 31 \text{ µGy h}^{-1} \end{align*} ) (\text{Cs in soil}: \text{7-100 kBq kg}^{-1}) Crustaceans, mollusks, round and flat fish, algae</td>
<td>0.05</td>
<td>Chambers et al. 2005</td>
</tr>
<tr>
<td>OSPAR region (2005)</td>
<td>Nuclear industry</td>
<td>(^{99}\text{Tc}, (^{131/137}\text{Cs}, \begin{align*} \gamma\text{-dose rate} &amp;= 2 - 31 \text{ µGy h}^{-1} \end{align*} ) (\text{Cs in soil}: \text{7-100 kBq kg}^{-1}) Macroalgae, crustaceans, vertebrates</td>
<td>10^{-3} - 10^{-1}</td>
<td>OSPAR (2008)</td>
</tr>
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</table>

Exposures to biota due to routine discharges of radionuclides, as reported for the Loire River and La Hague, are low. In the latter case, this is also due to strong sea currents at this part of the English Channel, i.e., within a distance of 500 m from the discharge point, the concentrations decrease by a factor of 100 000 (Chambers et al., 2005). Exposures to biota reported for the vicinity of oil and gas rigs are low. In OSPAR (2008), dose rates to marine flora and fauna were estimated; in 2005, the highest estimated dose rates due to radionuclides discharged by the nuclear industry were in the order of 0.1 µGy h\(^{-1}\).

The results indicate that doses to biota above a level of 10 µGy h\(^{-1}\) may hardly be achieved under planned exposure situations, since those dose rates are only possible for contamination levels that do not comply with the 1 mSv a\(^{-1}\) dose limit for public exposure.
IAEA activities on the development of Safety Guides and Safety Standards in relation to protection of the environment

The IAEA has been active in this field since a long time (e.g., IAEA, 1975, 1988, 1992). One important step during the last decade refers to the Conference “Protection of the Environment from the Effects of Ionizing Radiation” which was held in Stockholm, Sweden in 2003 in cooperation with the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), the European Commission (EC) and the International Union of Radioecology (IUR). The main objective of the Conference was to stimulate the development of an international policy on the protection of the environment from the effects of ionizing radiation (IAEA, 2005).

The findings of this Conference provided the basis for the 2005 “IAEA Plan of Activities on the Radiation Protection of the Environment: An International Action Plan on the Protection of the Environment against the Detrimental Effects Attributable to Radiation Exposure”. This plan was developed in cooperation with UNSCEAR, the ICRP, OECD/NEA, the EC and a number of other International organizations and was approved by the IAEA’s Board of Governors and General Conference in September 2005. The Plan of Activities is targeted at:

- Fostering the cooperation of relevant international organizations in considering radiation protection of the environment;
- Supporting IAEA Members States in their efforts to protect the environment;
- Elaborating how protection of the environment may be integrated into the system of protection from adverse effects of ionizing radiation.

The main recent activities related to these issues are summarized in Table 2. An important step was achieved in 2006 when the IAEA published the Fundamental Safety Principles as these include explicitly the protection of people and the environment, present and future, against radiation risks (IAEA, 2006). It is important to note that the Fundamental Safety Principles are binding for IAEA activities and constitute a key document for the development of IAEA safety standards for protection against adverse effects of ionizing radiation.

Currently, the BSS (Basic Safety Standards for Protection against Ionizing Radiation and the Safety of Sources) (IAEA, 1996) are under revision; the current draft includes requirements that, subject to national decisions, protection of the environment needs to be taken into account during:

- registration and licensing of activities;
- setting of discharge limits for nuclear facilities; and
- optimization of existing and emergency exposure situations.

These issues will be considered in three IAEA safety guides that are currently under development:

- The first is dedicated to guidance on the application of the Fundamental Safety Principles and the requirements of the revised BSS in relation to protection of the public and environment in planned, existing and emergency exposure situations. This is essential to ensure a consistency of approaches that include an integrated consideration of the radiation...
protection of the public and the environment. It should be noted that the radiological impact to biota under existing and emergency situations is considered as one factor – among many others – during the optimization process, when planning remediation or mitigating actions.

- A further safety guide is under development to give detailed guidance on the assessment of the radiological impact to the environment arising from authorized discharges to terrestrial or aquatic environments. The preparation of a radiological environmental impact analysis is a key component for demonstrating radiological protection of the environment: For this purpose, a graded approach is proposed in order to ensure that the efforts dedicated to safety are commensurate with the radiation risks. The guide will facilitate the development of a standardised approach; it will promote a common understanding of the process, definitions and methodologies, and it will consider environmental aspects in all stages of the life cycle of a facility.

- Furthermore, the IAEA will integrate the requirements formulated by the Safety Fundamentals and the revised Basic Safety Standards during revision of the safety guide on the regulatory control of radioactive releases (IAEA, 2000).

These activities are accompanied by efforts to stimulate the scientific exchange on protection of the environment: In 2009, IAEA launched the programme Environmental Modelling for Radiation Safety (EMRAS II), which is intended to act as a scientific forum to stimulate model development and testing to improve capabilities for assessments of radiological impacts to the public and the environment from radioactivity in the environment. The programme is scheduled to run until 2011. A total of 9 Working Groups were setup within EMRAS II, three of which work on issues related to protection of the environment:

- Working Group 4 “Biotas Modelling” focuses on testing and comparison of dosimetric and radioecological models being applied to assess exposures to biota.
- Working Group 5 “Wildlife Transfer Coefficient Handbook” focusses on the collection, analysis and evaluation of transfer parameters being used for the estimation of exposure to biota
- Working Group 6 “Biotas Dose Effects Modelling” concentrates on the analysis of the effects of ionizing radiation to flora and fauna, the derivation of dose effect relationships and the impact of ionizing radiation on populations.

For many years the has IAEA advised the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Convention) (IMO, 1972) and the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention) on questions related to radioactivity in the marine environment and the possible radiological impact to man as well as to marine flora and fauna.
Table 2. Summary of recent IAEA activities in relation to protection of the environment.

<table>
<thead>
<tr>
<th>Item</th>
<th>Activity</th>
<th>Remark</th>
</tr>
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<tbody>
<tr>
<td>Safety Standards</td>
<td>Draft of revised BSS: Consider Protection of the Environment during • Registration and licensing • Setting discharge limits • Optimization in existing and emergency exposure situations</td>
<td>Draft sent out in January 2010 to Member States for Comments</td>
</tr>
<tr>
<td></td>
<td>Implement requirements related to protection of the environment as defined in the Safety Fundamentals and the new BSS in new Safety Standards on: • Regulatory Control of the Releases of Radioactive Material from Facilities and Activities • Radiological Environmental Impact Analysis for Facilities and Activities • Radiation Protection of the Public and the Environment</td>
<td>Development initiated in 2010</td>
</tr>
<tr>
<td>Advisory Work</td>
<td>Giving advice in questions related to radioactivity in the oceans and resulting exposures to man and biota to: • Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Convention) • Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention)</td>
<td></td>
</tr>
</tbody>
</table>

The development of safety standards as specified above requires the integration of issues related to environmental protection into the system for radiation protection of humans. A scheme of an approach for protection of humans and the environment is shown in Figure 3. For all three exposure situations (planned, existing and emergency) the assessment of exposures to both humans and biota start with the radionuclide concentrations in the environment. Exposures are calculated for reference persons and reference animals and plants respectively. Decisions needing to be made in relation to human exposure are guided by comparison with dose limits and constraints for planned exposures and with reference levels for existing and emergency exposure situations. Exposures to biota may be evaluated by comparison with Derived Consideration Reference Levels (DCRLs), taking into account the specific conditions of the exposure situations.

If the releases of radioactivity lead to exposures of the public that comply with the dose limits, it is very unlikely that there is any concern with regard to the exposure to biota at the same location. The situation is more complex if the exposure to biota needs...
to be evaluated for unpopulated areas. Even in such a case, the radiological impact to biota cannot be considered in isolation since on a planet with a population of nearly 7 billion people also the (unpopulated) environment is at least to some extent always part of the human habitat — or it could become so in the future — and therefore needs to be explored as a actual or potential source of exposures to humans.

**Fig. 3. Scheme for estimating and evaluating exposures to humans and biota (according to ICRP, 2008).**

**Discussion and conclusions**

Radiological protection of the environment is a topic that has been intensively discussed in the last years. Much progress has been made on the development of methodologies to estimate exposures flora and fauna and to evaluate exposures to biota with regard to adverse effects induced by ionizing radiation. Derived Consideration Reference Levels derived by the ICRP for chronic exposure represent bands of dose that indicate the need for a detailed consideration of the exposures and its circumstances. For the most sensitive group of References Animals and Plants, this zone ranges from 4-40 µGy h⁻¹. This agrees very well a screening value of 10 µGy h⁻¹ to be applied to identify exposure conditions of no concern for biota.

Doses to biota above a level of 10 µGy h⁻¹ may hardly be achieved under planned exposure situations. If doses to humans and biota are assessed for the same habitat, it is difficult to imagine that conditions leading to such dose rates for biota could comply with the 1 mSv a⁻¹ dose limit for public exposure.

The development and application of International Safety Standards to ensure protection of the public and environment is a key activity of the IAEA. Currently special emphasis is given to integrate issues related to environmental protection into the system for radiation protection of humans in a manner that is coherent with the ICRP Recommendations and the input of the IAEA Member States.
References
Beresford, N. Howard, B. (2005): Application of FASSET framework at case study sites, ERICA Deliverable D9, wiki.ceh.ac.uk/display/rpemain/ERICA+reports.


Dose rates to freshwater biota in Finnish lakes

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Abstract
In recent years there has been growing international interest in the assessment of doses and risks from ionising contaminants to biota. Incremental dose rates to biota in freshwater ecosystems in Finland mainly resulting from exposure to the Chernobyl-derived radionuclides $^{137}$Cs, $^{134}$Cs and $^{90}$Sr were estimated using the ERICA Assessment Tool developed within the EC 6th Framework Programme. Data sets consisting of measured activity concentrations in fish, aquatic plants, lake water and sediment for three selected lakes located in a region with high $^{137}$Cs deposition were applied in the assessment. The selected lakes are among those having the highest activity concentrations found in Finland and therefore represent the highest exposure to biota in freshwater ecosystems affected by the Chernobyl fallout. The dose rates to most species studied were clearly below the screening level of 10 $\mu$Gy h$^{-1}$, indicating no significant impact of the Chernobyl fallout on these species. However, the possibility of higher dose rates to certain species living on or in the bottom sediment cannot be excluded based on this assessment. In addition, dose rates from $^{210}$Pb and $^{210}$Po to selected organisms were calculated. Dose rates from these radionuclides were negligible in comparison with the screening level. In the ERICA Tool the parameter “occupancy factor”, defining the fraction of time the studied organism spends in a given habitat, can have a considerable impact on the dose rate estimates. The values set for this parameter should be as realistic as possible with respect to the use of the habitat of the studied organisms.

Introduction
In recent years there has been growing international interest in the assessment of doses and risks from ionising contaminants to biota (Andersson et al. 2008; ICRP 2003, 2007, 2009; Larsson 2008). Several models are now available that enable the assessment of radiological risk to biota (Beresford et al. 2008a; Vives I Battle et al. 2007). In this study one of the models, the ERICA Assessment Tool (Brown et al. 2008), was applied to estimate dose rates to biota in freshwater ecosystems in Finland.

The ERICA Tool allows the estimation of dose rates for terrestrial, freshwater and marine ecosystems for a set of default reference organisms or, alternatively, user-defined organisms. The Tool includes databases on radionuclide transfer (Beresford et al. 2008b; Hosseini et al. 2008) and dose conversion coefficients (Ulanovsky et al. 2008a).
2008) enabling dose calculation to be performed from input data on radionuclide concentrations in biota and/or environmental media such as soil or water.

The aim of this assessment was to estimate incremental dose rates to biota from the late 1980s to the 2000s, as affected by the Chernobyl fallout in 1986. In addition, dose rates from $^{210}$Pb and $^{210}$Po to selected organisms were calculated.

**Material and methods**

**Study sites and the data**

Selection and characterisation of the study sites have been described in Vetikko and Saxén (2010). Existing data sets consisting of measured activity concentrations of $^{137}$Cs, $^{134}$Cs and $^{90}$Sr in fish, aquatic plants, lake water and sediment for three selected lakes located in a region with high $^{137}$Cs deposition were applied in the assessment. The selected lakes Päijänne, Siikajärvi and Vehkajärvi are among those having the highest activity concentrations found in Finland and therefore represent the highest exposure to biota in freshwater ecosystems affected by the Chernobyl fallout. Sampling, sample treatment and analyses of the different sample types have been described in Saxén et al. (1996) and Saxén and Ilus (2008). Activity concentrations of $^{137}$Cs, $^{134}$Cs and $^{90}$Sr in perch (*Perca fluviatilis*), pike (*Esox lucius*), bream (*Abramis brama*), lake water and sediment for Lake Päijänne are presented in Table 1. For Lakes Siikajärvi and Vehkajärvi, activity concentrations of $^{137}$Cs in perch, pike, water horsetail (*Equisetum fluviatile*), water lily (*Nymphaea candida*), yellow water lily (*Nuphar lutea*), lake water and sediment are provided in Table 2.

The mean activity concentration of $^{210}$Po in lake water collected in 2007 from several lakes was 0.0019 Bq kg$^{-1}$ and that of $^{210}$Pb 0.0032 Bq kg$^{-1}$. The corresponding activity concentrations in roach (*Rutilus rutilus*) sampled in 2005 from Lake Päijänne were 1.45 Bq kg$^{-1}$ f.w. for $^{210}$Po and 0.24 Bq kg$^{-1}$ f.w. for $^{210}$Pb.

**Application of the ERICA Assessment Tool**

The ERICA Assessment Tool, version 1.0 (April 2008, available from: http://www.project.facilia.se/ERICA/download.html) was used for estimating dose rates to biota. The ERICA Tool allows the input of site-specific measured activity concentrations in biota and/or environmental media at Tiers 2 and 3 of the three tiers in the model (Brown et al. 2008). In this assessment Tier 2 was used. Best estimate values of measured activity concentrations in biota, lake water and/or sediment were used as inputs at Tier 2, as recommended by Brown et al. (2008). For the geometries and dimensions of the biota, default reference organisms were used in the model, so that for the fish species the reference organism selected was “pelagic fish” and for aquatic plants it was “vascular plant”.

In case of missing activity concentrations in sediment, the model uses concentrations in water and a distribution coefficient (Kd, L kg$^{-1}$) to calculate the concentrations in sediment needed for estimation of the dose rate. Default Kd values provided by the Tool were used in such cases.

The ERICA Tool contains a parameter “occupancy factor”, which defines the fraction of time an organism spends in a given location in its habitat. For aquatic ecosystems, the possible locations are the water surface, water column, sediment
surface and sediment. As a default in the model, the occupancy factor for vascular plants is entirely assigned to the sediment surface to maximise the dose rate (Oughton et al. 2008). For pelagic fish the default occupancy factor is 1 for the water, which means that fish only occupy the water column. In this study alternative occupancy factors were also used to provide lower and upper estimates of the dose rates.

The Tool performs dose rate calculations from the input data by applying dose conversion coefficients (µGy h⁻¹ per Bq kg⁻¹ fresh weight; see Ulanovsky et al. 2008) and weighting factors for various components of radiation (10 for alpha, 3 for low energy beta and 1 for beta, gamma as default). A default uncertainty factor of three at Tier 2 was used in the model to account for uncertainties in the assessment method (Oughton et al. 2008).

Table 1. Activity concentrations of ¹³⁷Cs, ¹³⁴Cs and ⁹⁰Sr in fish (Bq kg⁻¹ fresh weight) and water (Bq l⁻¹) sampled in 1986, 1988, 1998 and in 2000 - 2006 (mean values), and in sediment (Bq kg⁻¹ dry weight) sampled in 1997 from Lake Päijänne (Saxén et al. 1996). Activity concentrations in fish are for edible parts.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Sampling time</th>
<th>¹³⁷Cs</th>
<th>¹³⁴Cs</th>
<th>⁹⁰Sr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perch</td>
<td>August 1986</td>
<td>1700</td>
<td>870</td>
<td>5.5</td>
</tr>
<tr>
<td></td>
<td>December 1986</td>
<td>2200</td>
<td>1070</td>
<td>5.5</td>
</tr>
<tr>
<td></td>
<td>1988</td>
<td>2250</td>
<td>625</td>
<td>5.5</td>
</tr>
<tr>
<td></td>
<td>1998</td>
<td>346</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>2000 - 2006</td>
<td>270</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Pike</td>
<td>August 1986</td>
<td>970</td>
<td>500</td>
<td>0.27</td>
</tr>
<tr>
<td></td>
<td>December 1986</td>
<td>1600</td>
<td>720</td>
<td>0.27</td>
</tr>
<tr>
<td></td>
<td>1988</td>
<td>4100</td>
<td>1300</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>1998</td>
<td>376</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>2000 - 2006</td>
<td>250</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Bream</td>
<td>August 1986</td>
<td>1400</td>
<td>660</td>
<td>5.0</td>
</tr>
<tr>
<td></td>
<td>December 1986</td>
<td>1800</td>
<td>900</td>
<td>5.0</td>
</tr>
<tr>
<td></td>
<td>1988</td>
<td>1080</td>
<td>310</td>
<td>5.0</td>
</tr>
<tr>
<td></td>
<td>1998</td>
<td>212</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>2000 - 2006</td>
<td>110</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Water</td>
<td>August 1986</td>
<td>1.65</td>
<td>0.77</td>
<td>0.024</td>
</tr>
<tr>
<td></td>
<td>December 1986</td>
<td>0.6</td>
<td>0.2</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>1988</td>
<td>0.322</td>
<td>0.089</td>
<td>0.017</td>
</tr>
<tr>
<td></td>
<td>1998</td>
<td>0.05</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>2000 - 2006</td>
<td>0.025</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Sediment</td>
<td>1997</td>
<td>18530</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
At Tier 2 the results are given as total, internal and external weighted whole body absorbed dose rates (Brown et al. 2008). The total (internal and external summed) dose rates are compared directly to the selected screening dose rate to enable assessment of the risk to biota from ionising radiation (Brown et al. 2008). A default screening dose rate of 10 µGy h⁻¹ provided by the Tool and suggested by Andersson et al. (2008), Beresford et al. (2007) and Garnier-Laplace et al. (2008) was used in the model.

Table 2. Activity concentrations of ¹³⁷Cs in fish and aquatic plants (Bq kg⁻¹ fresh weight), in water (Bq l⁻¹) and in sediment (Bq kg⁻¹ dry weight) sampled from Lakes Siikajärvi and Vehkajärvi (Saxén and Ilus 2008). Activity concentrations in fish are for edible parts.

<table>
<thead>
<tr>
<th>Lake</th>
<th>Sample</th>
<th>Year of sampling</th>
<th>¹³⁷Cs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Siikajärvi</td>
<td>Perch</td>
<td>2003</td>
<td>4710</td>
</tr>
<tr>
<td></td>
<td>Pike</td>
<td>2003</td>
<td>3610</td>
</tr>
<tr>
<td></td>
<td>Water horsetail</td>
<td>2003</td>
<td>1720</td>
</tr>
<tr>
<td></td>
<td>Water lily</td>
<td>2003</td>
<td>350</td>
</tr>
<tr>
<td></td>
<td>Yellow water lily</td>
<td>2003</td>
<td>1100</td>
</tr>
<tr>
<td></td>
<td>Water</td>
<td>2003</td>
<td>0.290</td>
</tr>
<tr>
<td></td>
<td>Sediment</td>
<td>2003</td>
<td>14 942</td>
</tr>
<tr>
<td>Vehkajärvi</td>
<td>Perch</td>
<td>1998</td>
<td>1558</td>
</tr>
<tr>
<td></td>
<td>2000 - 2004</td>
<td>2070</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pike</td>
<td>1998</td>
<td>2300</td>
</tr>
<tr>
<td></td>
<td>2000 - 2004</td>
<td>2134</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Water horsetail</td>
<td>2003</td>
<td>633</td>
</tr>
<tr>
<td></td>
<td>Water lily</td>
<td>2003</td>
<td>248</td>
</tr>
<tr>
<td></td>
<td>Yellow water lily</td>
<td>2003</td>
<td>264</td>
</tr>
<tr>
<td></td>
<td>Water</td>
<td>1998</td>
<td>0.332</td>
</tr>
<tr>
<td></td>
<td>Sediment</td>
<td>2002 - 2003</td>
<td>0.304</td>
</tr>
<tr>
<td></td>
<td>2003</td>
<td>18 396</td>
<td></td>
</tr>
</tbody>
</table>

Results and discussion

Dose rates from ¹³⁷Cs, ¹³⁴Cs and ⁹⁰Sr to perch in Lake Päijänne varied from 0.05 to 0.6 µGy h⁻¹ (Vetikko and Saxén 2010). For pike the dose rates were between 0.05 and 1 µGy h⁻¹ (Vetikko and Saxén 2010). The maximal dose rate for perch was observed in December 1986, followed by a small decrease in 1988, and declined to one tenth in 1998 and in the 2000s (Figure 1). For pike the maximal dose rate was shown in 1988, followed by a decline to a level almost two orders of magnitude lower in 1998 and in the 2000s (Figure 1). This temporal variation in the dose rates was associated with the changes in the activity concentrations in fish and water from August 1986 to the 2000s. The missing contributions of ¹³⁴Cs and ⁹⁰Sr to the dose rates in 1998 and from 2000 to 2006 may also have influenced the lower dose rates then observed.

For bream in Lake Päijänne the dose rates varied from 0.1 µGy h⁻¹ in the 2000s to 15 µGy h⁻¹ in August 1986 (Figure 2). The result for bream was based on activity
concentrations in water and on the default Kd parameter provided by the ERICA Tool, not on measured data for the sediment surface, as the only available data on activity concentrations in sediments of Lake Päijänne were from the year 1997. Therefore a more site-specific assessment for the year 1986 was prevented and the exceeding of the screening dose rate to bream could not be confirmed.

![Graph 1](image1.png)

Fig. 1. Absorbed dose rate (µGy h\(^{-1}\)) from \(^{137}\)Cs, \(^{134}\)Cs and \(^{90}\)Sr to perch and pike in Lake Päijänne (Assumption: Occupancy factor 1 for the water column was used for both fish species.).

![Graph 2](image2.png)

Fig. 2. Absorbed dose rate (µGy h\(^{-1}\)) from \(^{137}\)Cs, \(^{134}\)Cs and \(^{90}\)Sr to bream in Lake Päijänne (Assumptions: Occupancy factor 0.8 for the water column and 0.2 for the sediment surface were used. Default values for the Kd parameter were used so that the Kd was 137 000 L kg\(^{-1}\) for Cs and 2000 L kg\(^{-1}\) for Sr.).
In the short term after the deposition, short-lived nuclides also caused a radiation dose to biota. However, this was mainly external exposure during a short period and therefore not significant for the incremental dose (Vetikko and Saxén 2010).

For perch and pike the absorbed total dose rate consisted almost entirely of the internal dose rate, whereas for bream the external dose rate was more pronounced due to exposure to radiation from the bottom sediment reflected by the parameter “occupancy factor” that for bream was assumed to have a component related to the surface sediment in addition to the water column (Table 3).

Table 3. External, internal and total dose rates (µGy h⁻¹) from ¹³⁷Cs, ¹³⁴Cs and ⁹₀Sr to fish in Lake Päijänne in August and December 1986, calculated using Tier 2 of the ERICA Tool (Vetikko and Saxén 2010).

<table>
<thead>
<tr>
<th>Sample</th>
<th>Sampling time</th>
<th>Occupancy factor</th>
<th>External dose rate</th>
<th>Internal dose rate</th>
<th>Total dose rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perch</td>
<td>August 1986</td>
<td>Water column = 1</td>
<td>1.09E-3</td>
<td>4.92E-1</td>
<td>4.93E-1</td>
</tr>
<tr>
<td></td>
<td>December 1986</td>
<td>Water column = 1</td>
<td>3.32E-4</td>
<td>6.24E-1</td>
<td>6.24E-1</td>
</tr>
<tr>
<td>Pike</td>
<td>August 1986</td>
<td>Water column = 1</td>
<td>1.09E-3</td>
<td>2.80E-1</td>
<td>2.81E-1</td>
</tr>
<tr>
<td></td>
<td>December 1986</td>
<td>Water column = 1</td>
<td>3.32E-4</td>
<td>4.39E-1</td>
<td>4.40E-1</td>
</tr>
<tr>
<td>Bream</td>
<td>August 1986</td>
<td>Water column = 0.8 Sediment surface = 0.2</td>
<td>1.49E1</td>
<td>3.94E-1</td>
<td>1.53E1</td>
</tr>
<tr>
<td></td>
<td>December 1986</td>
<td>Water column = 0.8 Sediment surface = 0.2</td>
<td>4.54E0</td>
<td>5.16E-1</td>
<td>5.06E0</td>
</tr>
</tbody>
</table>

¹³⁷Cs accounted for 62-75% of the total dose rate to perch and pike, while 24-38% was due to ¹³⁴Cs (Vetikko and Saxén 2010). However, for bream ¹³⁷Cs accounted only for 45% in August 1986 when the contribution of ¹³⁴Cs to the dose was 55%. Later ¹³⁷Cs exceeded ¹³⁴Cs as a contributor to the dose. The contribution of ⁹₀Sr to the dose rate of all fish species was only 0.02-0.7% (Vetikko and Saxén 2010).

Dose rate from ²¹⁰Po and ²¹⁰Pb to roach in Lake Päijänne was 0.045 µGy h⁻¹ (Assumptions: Occupancy factor 1 for the water column was used.).

For Lakes Siikajärvi and Vehkajärvi, two sets of occupancy factors for fish and aquatic plants were used to provide lower and upper estimates of the dose rates (Vetikko and Saxén 2010). Dose rate from ¹³⁷Cs to perch in Lake Siikajärvi varied from 0.8 to 1.3 µGy h⁻¹, depending on the occupancy factor (Figure 3). For pike the dose rates were between 0.7 and 1.1 µGy h⁻¹ (Figure 3). The corresponding values for perch of Lake Vehkajärvi were 0.3 and 1.6 µGy h⁻¹ and those for pike 0.4 and 1.7 µGy h⁻¹ (Figure 4). These dose rates were slightly higher than those for Lake Päijänne due to higher activity concentrations in fishes and water in Lakes Siikajärvi and Vehkajärvi.

The absorbed dose rate also to aquatic plants varied according to the values set for the occupancy factor (Vetikko and Saxén 2010). It should be noted that the lower values of the dose rates are based on the assumption that the whole plant is located in water, therefore excluding the exposure of roots in the sediment and resulting in unrealistically low dose rates (Figure 3, 4). The upper values of the dose rates, on the other hand, represent the maximum, whereas more realistic exposure of plants will be obtained between the two values.
Fig. 3. Absorbed dose rate (µGy h⁻¹) from ¹³⁷Cs to fish and plant species in Lake Siikajärvi in 2003 (OF = occupancy factor).

Fig. 4. Absorbed dose rate (µGy h⁻¹) from ¹³⁷Cs to fish and plant species in Lake Vehkajärvi (year of sampling given in brackets; OF = occupancy factor).
The roots of aquatic plants can receive higher dose rates via external exposure to contaminated sediment compared to the other plant parts located in the water column or on the water surface. For example, Nedveckaite et al. (2007) reported a ten times higher dose rate to the roots of submerged hydrophytes (0.044 µGy h⁻¹) compared to the above-sediment plant parts (0.0044 µGy h⁻¹) from ⁵⁴Mn, ⁶⁰Co, ¹³⁷Cs and ⁹⁰Sr in the cooling pond of Ignalina nuclear power plant in Lithuania.

Conclusions
The dose rates from ¹³⁷Cs, ¹³⁴Cs and ⁹⁰Sr to most species studied were clearly below the screening level of 10 µGy h⁻¹, indicating no significant impact of the Chernobyl fallout on these species. However, the possibility of higher dose rates to certain species living on or in the bottom sediment cannot be excluded based on this assessment.

The screening dose rate was exceeded for bream in Lake Päijänne in August 1986 due to external exposure to radiation from the sediment surface. However, the dose rate to bream did not differ from the levels of natural background radiation generally reported in the literature (see Zinger et al. 2007). This leads to the assumption that the likely risk to bream from ionising radiation in August 1986 was also minimal.

In the ERICA Tool the values set for the occupancy factor can have a considerable impact on the dose rate. The occupancy factors should be as realistic as possible with respect to the use of the habitat of the studied organisms.

References


Vetikko V, Saxén R. Application of the ERICA Assessment Tool to freshwater biota in Finland. Journal of Environmental Radioactivity 2010; 101: 82-87.


Effects of radioactive contamination on plant populations and radiation protection of biota

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Abstract
An assessment of the state of plant and animal populations inhabiting polluted territories and the analysis of mechanisms of their adaptation to adverse environmental conditions undoubtedly have general biological importance. Consequently, studies that examine biological effects on non-human biota in natural settings provide a unique opportunity for obtaining information about the potential biological hazard associated with radioactive contamination. Nevertheless, up to now there is a distinct lack of quantitative data on the real long-term biological consequences of chronic radiation exposure lasting a long period of time. Actually, few studies exist that are directly relevant to understanding the responses of plant and animal populations to radioactive substances in their natural environment. The results of long-term field experiments in the Bryansk Region affected by the Chernobyl accident and in the Semipalatinsk Test Site, Kazakhstan that have been carried out on different species of plants are discussed. Although radionuclides cause primary damage at the molecular level, there are emergent effects at the level of populations, non-predictable solely from knowledge of elementary mechanisms of the pollutants’ influence. Plant populations growing in areas with relatively low levels of pollution are characterized by the increased level of both cytogenetic disturbances and genetic diversity. Radioactive contamination of the plants environment activates genetic mechanisms, changing a population’s resistance to exposure. However, in different radioecological situations, genetic adaptation to extreme edaphic conditions in plant populations could be achieved with different rates.

Introduction
The majority of abiotic stress studies performed under controlled laboratory conditions does not reflect the actual situations that occur in the field. Therefore, to understand effects of contaminant exposure properly we must pay attention to what is actually going on in natural conditions. Field studies are particularly useful for assessing long-term biological effects induced by chronic low dose-rate and multi-pollutant exposure at contaminated sites. Although radionuclides and heavy metals cause primary damage at the molecular level, there are emergent effects at the level of populations that are not predictable solely from knowledge of elementary mechanisms of the pollutants’
influence. Up to now we have known little about responses of plant and animal populations to environmental pollutants in their natural environments. These data gaps imply that the protection of the environment from ionizing radiation will require more experimental data related to effects of chronic low-level exposure to radionuclides at the population level. Previously completed and ongoing field studies that have been carried out in Laboratory of Plant Ecotoxicology, RIARAE in different species of wild and agricultural plants are briefly summarized in Table 1. A wide range of radioecological situations and climatic zones have been covered in frames of this work. To illustrate the main findings, two field studies are discussed here in more detail.

Table 1. Field studies on wild and agricultural plants.

<table>
<thead>
<tr>
<th>Species</th>
<th>Site &amp; Time</th>
<th>Assay and/or endpoints</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter rye and wheat,</td>
<td>10-km ChNPP zone (12-454 MBq/m²), Ukraine, 1986-1989</td>
<td>Morphological indices of seeds viability, cytogenetic disturbances in intercalary seedling root meristem (Geras'kin et al. 2003a)</td>
</tr>
<tr>
<td>spring barley and oats</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scots pine,</td>
<td>30-km ChNPP zone (2.5-27 μGy/h), Ukraine, 1995</td>
<td>Cytogenetic disturbances in seedling root meristem (Geras'kin et al. 2003b)</td>
</tr>
<tr>
<td>couch-grass</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scots pine</td>
<td>Radioactive waste storage facility, Leningrad Region, Russia, 1997-2002</td>
<td>Cytogenetic disturbances in needle and seedling root meristems (Geras'kin et al. 2005)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scots pine</td>
<td>Bryansk Region radioactively contaminated in the Chernobyl accident (0.6-3.5 μGy/h), Russia, 2003-2009</td>
<td>Cytogenetic disturbances in seedling root meristem, enzymatic loci polymorphism, abortive seeds (Geras'kin et al. 2008; Geras'kin et al. 2009a)</td>
</tr>
<tr>
<td>Crested hairgrass</td>
<td>Semipalatinsk Test Site (0.7-36 μGy/h), Kazakhstan, 2005-2008</td>
<td>Cytogenetic disturbances in coleoptiles of germinated seeds (Geras'kin et al. 2009b)</td>
</tr>
</tbody>
</table>

Material and methods

In 2005-2008 seeds of crested hairgrass (*Koeleria gracilis* Pers.) were collected from six sites of the Semipalatinsk Test Site (Kazakhstan). Radiation background at the sites and specific activity of the main dose-forming radionuclides in soil samples were measured. Doses to generative organs of crested hairgrass were calculated. Squashed slides for cytogenetic analysis were prepared of coleoptiles (2-5 mm in length) of germinated seeds. In every slide, all ana-telophase cells (4800-11900 ana-telophases in 30-90 slides) were scored to calculate frequency of aberrant cells. Detailed description of methods used is given in (Geras'kin et al. 2009b).

To study biological effects in Scots pine (*Pinus sylvestris* L.) populations experiencing chronic radiation exposure, six test sites were chosen in the Bryansk region radioactively contaminated as a result of the Chernobyl accident. Pine cones were collected in autumns of 2003-2007. Specific activities of radionuclides in soil samples were measured, and doses to the pine trees’ generative organs were estimated. Aberrant cells were scored in root meristem of germinated seeds in ana-telophases of the first mitosis. The method of isozymic analysis of megagametophytes was used for an estimation of genetic variability in populations of Scots pine. Five enzymatic loci (GDH, LAP, MDH, DIA, and 6-PGD) were studied in endosperms of the seeds.
collected in 2005. Detailed description of materials and methods used can be found in (Geras’kin et al. 2008; Geras’kin et al. 2009a).

Results and discussion

In the Semipalatinsk Test Site (STS), 116 atmospheric and ground-surface explosions for nuclear and hydrogen bomb testing were carried out between 1949 and 1963. A study of crested hairgrass (*Koeleria gracilis* Pers.) populations, a typical wild crop for Kazakhstan, showed that the frequency of cytogenetic disturbances in coleoptiles of germinated seeds increases proportionally to the dose absorbed by plants (Fig. 1). The agreement between findings from four years of study (2005-2008), different in weather conditions, suggests the leading role of radioactive contamination in an occurrence of cytogenetic effects. Severe disturbances of single and double bridges as well as laggard chromosomes contribute mainly to the observed cytogenetic effect (Geras’kin et al. 2009b).

Fig. 1. Frequency of aberrant cells in coleoptiles of germinated seeds of crested hairgrass collected in the Semipalatinsk Test Site, Kazakhstan in 2005-2008 in dependence on annual dose absorbed. Ref1 and Ref2 are the reference sites in 2005-2007 and 2008, respectively. Significant difference from the corresponding reference site: * - p < 0.10; ** - p < 0.05.

Dose rate in the epicentre of nuclear tests amounts to 36 μGy/h, which is more than 3 fold of the predicted no-effect dose rate of 10 μGy/h derived in the EC ERICA project (Andersson et al. 2009). It is, however, well below the threshold for statistically significant effects (100 μGy/h) derived at the FASSET Radiation Effects Database analysis (Real et al. 2004). It is not surprising, than, that in the STS study there are found significant cytogenetic effects in crested hairgrass populations but no morphological alterations. Thus, the finding obtained are in agreement with the
benchmark values proposed in the FASSET and ERICA projects to restrict radiation impact on biota.

Forest trees have gained much attention in recent years as nonclassical model eukaryotes for population, evolutionary and ecological studies (Gonzalez-Martinez et al. 2006). Because of their potential to affect many other species, any responses to selection pressures that are exerted on such keystone species as forest trees are especially important to quantify. The low domestication, large open-pollinated native populations and high sensitivity to environmental exposure make conifers almost an ideal species for the study of environmental effects of radioactive contamination.

In Fig. 2, the 5-year results of long-term (2003-2009) study of cytogenetic effects in Scots pine populations growing in the Bryansk region radioactively contaminated as a result of the Chernobyl accident are presented. Populations under investigation have not shown any significant difference between years, so our results are robust and replicable over time. Aberrant cell frequency in root meristem of germinated seeds collected from these populations significantly exceeds reference level and shows statistically significant correlation to specific activity of $^{137}$Cs, the main dose-forming radionuclide, in pine cones during all five years of study. Although there is a tendency for aberrant cells occurrence to increase with dose absorbed by the pine trees’ generative organs, it is not always significant. Compiled with data from other our studies (Geras’kin et al. 2003a; Geras’kin et al. 2003b; Geras’kin et al. 2005), these findings indicate that an increased level of cytogenetic disturbances is a typical...
phenomenon for plant populations growing in areas with relatively low levels of pollution.

Absorbed doses in generative organs of pine trees are assessed with a dosimetric model (Fig. 2). In 22 years after the ChNPP accident, the annual doses are about thirty times below dose rate of 10 mGy/day proposed by IAEA (International… 1992) as safe for terrestrial plants. On the other hand, dose rates for two most contaminated sites are exceed the ERICA generic predicted no-effect value of 10 μGy/h (Andersson et al. 2009). From this comparison we can suppose that radiation exposure at the study sites is strong enough to induce cytogenetic but not morphologic disturbances in the exposed populations. Indeed, aberrant cell frequency in root meristem of germinated seeds collected from experimental populations significantly exceeded reference level during all five years of study (Fig. 2). It should be noted that, in the STS study, a wide range of doses from 4 to 265 mGy absorbed by the plants was studied, and dependence of cytogenetic effects on dose was revealed. On the contrary, in the Bryansk region, the range of doses absorbed by the pine trees at the study sites is much narrower; this could be the reason for an absence of statistically significant increase of biological effect with the dose absorbed in some years of observations.

It is becoming increasingly clear that cytogenetic disturbances detected in our studies might only be tip of an iceberg, reflecting global structural and functional rearrangements induced by radiation in exposed populations. An increase in mutation rate can affect the population genetic structure by producing new alleles or genotypes, and thereby has ecologically relevant effect. Alterations in the genetic make-up of populations are of primary concern because somatic changes, even if they lead to a loss of some individuals, will not be critical in populations with a large reproductive surplus. To analyze whether an exposure to radionuclides causes changes in population genetic structure, we evaluated frequencies of three different types of mutations (null allele, duplication and changing in electrophoretic mobility) of enzymatic loci in endosperm and embryos of pine trees from the studied populations. It is found that chronic radiation exposure results in the significant increase of total occurrence of enzymatic loci mutations. In particular, frequencies of mutations for loss of enzymatic activity increase with a dose absorbed by generative organs of pine trees (Fig. 3).

Fig. 3. Frequency of null alleles in enzymatic loci of endosperms (2005) in dependence on annual dose absorbed by generative organs of pine trees.
There are plenty of theoretical interpretations of evolution, but what is important is to see what happens in practice. Mutations in plant or animals are not necessary bad events when they do not adversely affect the population fitness. Mutation is one of the mechanisms that maintains genetic variation within a natural population and thus enables that population to cope with an adversely changing environment. Indeed, phenotypic variability in the exposed pine tree populations, estimated via Zhivotovsky index (Zhivotovsky 1980), significantly exceeds the reference level and increases with dose absorbed by generative organs of pine trees (Fig. 4).

![Fig. 4. Phenotypic variability estimated via the Zhivotovsky index in dependence on annual dose absorbed by generative organs of pine trees.](image)

A decrease in heterozygosity within individuals has been associated (Theodorakis 2001) with decreased resistance to diseases, decreased growth rates, and decreased fertility. This would suggest that variations in individual heterozygosity may affect population growth and recruitment. The observed heterozygosity in pine tree populations at the radioactively contaminated sites is essentially higher then the expected one and increases with dose absorbed by generative organs of pine trees (Fig. 5).

From the data presented we can conclude that the relationship between radioactive contamination and genetic variability provides evidence of adaptation which optimizes the physiological response of a population to environmental changes. Keeping in mind all the data mentioned, it could be concluded that a high level of mutation occurrence is intrinsic for descendants of pine trees in the investigated populations, and genetic diversity in the populations is essentially conditioned by radiation exposure. So, in spite of their low values, dose rates observed can be considered as a factor able to modify genetic structure of population. Furthermore, an increased genetic diversity within the population of keystone species is likely to be positively correlated with increased species diversity of the depended community (Whitham et al. 2006).
Fig. 5. Heterozygosity in endosperms of Scots pines in dependence on annual dose absorbed by generative organs of pine trees. Significant difference from the Ref population: * - $p < 0.01$.

Fig. 6. Portion of abortive seeds in chronically exposed Scots pine populations. * - difference from Ref is significant, $p < 0.05$.

Although great progress has been made in understanding the nature of mutations, too little is yet known about the way in which mutations can lead to effects at the level of an organism and population. The effect of severe conditions on an organism is often considered to eliminate individuals. However, the alternative effect is to change the number of offspring produced by individuals without killing them. The plasticity of plants, and the fact that their reproductive organs are usually the terminal points of a branching structure, means that they tend to respond to environmental stresses by...
variation in reproductive rate without death. It is true that a much larger number of seeds are produced than developed into adult plants, and that the changes in frequency of the different genotypes occur due to a greater death of some genotypes than others. This is a form of response to selection, and a very powerful one (Valladares et al. 2007). From the results gathered a question arises: what could be an effect of high mutation rates revealed in our study on a reproductive potential of pine trees? From Fig. 6 it is clear that chronic exposure within the range of dose rates studied has virtually no effect on reproductive ability of pine trees from the exposed populations.

Conclusions
A basic level of concern within a newly developing system for radiological protection of the environment is a population. Of special importance in this context are studies on plant and animal populations inhabiting sites with contrasting levels and spectra of radioactive contamination. Special attention should be paid to population-level effects such as radioadaptation, changes in sexual, age and genetic structure of populations, since knowledge of elementary mechanisms of the radionuclides’ impact is insufficient to predict them. Corresponding studies are likely to increase in importance as the rate at which we change the environment worldwide continues to accelerate. The findings presented here clearly indicate that plant populations growing in areas with relatively low levels of pollution are characterized by an increased level of both cytogenetic disturbances and genetic diversity. Concordant responses between changes in population genetic structure and elevated levels of cytogenetic damage provide evidence that the population genetic changes are influenced by exposure to radionuclides. Effects of contaminants on genetic diversity within a population are important because the level of genetic diversity affects a population’s ability to adapt or the rate of adaptation to changes in the environment. Therefore, the amount of genetic variation within a population can influence its relative susceptibility to extinction. Finally, in spite of the wealth of information collected so far, much more still remains to be explained in order to fully understand the basis of plant populations’ adaptations to a harmful environment.

References


Unusual damaging effects of low radiation:
Model experiments with protozoa and invertebrates

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Abstract
The importance of peculiar disturbing effect of low radiation, observed previously by Bychkovskaya et al in protozoa and in tissues of rats (http://irbb.ucoz.ru) was studied in the model experiments on aquatic invertebrates water flea Daphnia magna. During these experiments we were able to show that the probability of animals’ death increases even at a dose of 0.1 Gy which is a thousand times lower than predicted as lethal dose (100 Gy). The process was registered for the greater part of daphnia’s lifetime. The frequency of death of irradiated animals did not increase with dose increasing from 0.1 to 20 Gy.

The negative effect of low radiation (0.01 Gy) we also observed on the aquatic unicellular ciliates Spirostomum ambiguum. Modal experiments of the laboratory population of Spirostomum showed that these protozoa are highly sensitive to gamma-irradiation by spontaneous motor activity (SMA) criterion. We observed the reliable effect of SMA decrease right after the irradiation in doses 1 sGy. It was approximately on the similar level (about 40% below control) in a broad variety of doses. These changes were mass, did not dependent on dose in a wide range and were transmitted to the descendants of irradiated cells. Changes had been inherited not only through the vegetative reproduction of organisms, but also through the sexual reproduction (water flea daphnids). Due to the fact that the cellular dose-independent effects induced by low doses were found on the different organisms (including rats), we assumed that these effects might be widespread in nature. Molecular-genetic mechanism of these changes still remains unknown; mass character and non-linear nature of these changes can not be attributed to the mutations. Generally, they can be classified as epigenetic changes which attract more and more attention.

This work is directed to the ecological problem. We have witnessed and detected the decline of the viability and functional activity of aquatic organisms in the interval of doses that are lower than considerably dangerous ones.
Introduction

In the plural studies of the subjects of various species (amoebas, ciliates, cells of different low regenerating tissue of rats) we found (Bychkovskya 1986; Bychkovskya et al 2006) the peculiar negative cellular effects of low radiation which do not fit the general concept of stochastic nature of radiation. One of the typical manifestations of these effects was the high prolonged increase of the possibility of damage and cells death compared with the control level. Unlike the widely studied genotoxic changes, these effects: i) are mass; ii) are already registered at the doses which are very low for the subjects; iii) do not increase with further increasing of radiation dose; iv) inherited; v) may be caused by exposure to the nucleus as well as the cytoplasm of cells (experiments on amoeba).

In this paper, the possibility of this unusual form of damage was confirmed in experiments conducted at new subjects – unicellular and multicellular aquatic organisms. Let’s consider these materials.

Material and methods

Ciliates Spirostomum ambiguum Ehrbg were cultured in laboratory tubes with separated dechlorinated water at a temperature of 20±2°C. The ciliates were fed nutritional yeast once a week. It is known that ciliates refer to highly radio resistant organisms. LD_{50/30} is around 1000 and more of Gray (Choppin et al 1995). Spirostomum were irradiated in masscult in tubes with 6 ml of water for “Gamma-cell” radiator (Canada, ^{60}Co; 0.15 Gy/min) at doses 0.01, 0.1 and 1 Gy and “Issledovatel” radiator (Russia, ^{60}Co; 36 Gy/min) at dose 20 and 50 Gy at 28±2°C as an additional negative factor. The control groups were in the same conditions as experimental, but without irradiation. The effect of irradiation was estimated by reduce the ciliates’ motor activity in the experimental groups. These changes were measured immediately just after irradiation and at 2, 4 and 7 days after that. To do this, the ciliates from irradiated groups and from the control groups were placed individually in special plastic plate with holes of 5 mm in diameter and 1-2 mm in depth. Motor activity of each ciliate was observed under the microscope. At the eyepiece of the microscope were did two lines crossing each other perpendicularly. A quantitative measure of each ciliate’s motor activity was the number of intersections of the lines for 1 min. It was held for 5 series of observations at each dose with coding of the samples. The effect was manifested not only in reducing the SMA of irradiated ciliates, but also in the appearance of essential disorders of motion as a function of reaction – “death prognosticators” – convulsive twitching of the body, changes in moving patterns from the normal lineal to abnormal twirling and rolling, backward movements or total body immobility. Additionally, we took in the account the number of individuals (organisms) with motion pathologies. The frequency of pathological movement forms for ciliate was measured in % of the total investigated ciliates.

In the experiments we also used aquatic invertebrates’ water flea Daphnia magna. They were born from females of the same age and irradiated on the first day after birth. They were irradiated for 5 individuals in biological tubes with 6 ml of water for “Gamma-cell” radiator at doses 0.1 and 1 Gy and “Issledovatel” radiator at dose 20, 100, 250 and 600 Gy. Based on literature data, radiation doses around 10^2 Gy are lethal for the class Crustacea (Choppin et al 1995). Control animals were in the same
conditions as experimental, but were not irradiated. Then, the control and irradiated groups were cultured in the laboratory glasses for 5 individuals per 100 ml of separated dechlorinated water at a temperature about 20±2°C. Daphnia were fed algae suspension once a day at a rate of 0.1 ml (density of 600–1000 million cells per ml) per 100 ml of water. Water in the experimental and the control glasses was refreshed every week; daphnia were transferred using a plastic pipette. In these conditions daphnids’ lifetime were not much longer than 3 months.

Animals’ death had been checked every day for 30 days. We presented the combined data collected in the 4th (embryonic period), 14th and 30th (reproductive period) days after the irradiation. We estimated the number of surviving daphnids as % of their original number or % from control groups for the corresponding period of observations. It was held for 4 series of observations at each dose.

The reliability assessment of the experimental data was carried out by the nonparametric Fisher test.

**Results and discussion**

**Experiments with ciliates**

Consider Table 1, which demonstrated the data of ciliates’ SMA in control and at various periods after γ-irradiation at doses of 0.01–50 Gy (absolute value).

### Table 1. Values ciliates’ SMA (in absolute value) in control and at doses of 0.01–50 Gy at various periods after γ-irradiation.

<table>
<thead>
<tr>
<th>Dose, Gy</th>
<th>0</th>
<th>2</th>
<th>4</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (Control)</td>
<td>2.1±0.2</td>
<td>1.8±0.1</td>
<td>1.8±0.1</td>
<td>1.9±0.1</td>
</tr>
<tr>
<td>0.01</td>
<td>1.4±0.2*</td>
<td>1.2±0.1*</td>
<td>1.2±0.3*</td>
<td>1.3±0.1*</td>
</tr>
<tr>
<td>0.1</td>
<td>1.4±0.1*</td>
<td>1.1±0.2*</td>
<td>1.0±0.2*</td>
<td>0.8±0.2*</td>
</tr>
<tr>
<td>1</td>
<td>1.5±0.2*</td>
<td>0.9±0.2*</td>
<td>1.0±0.1*</td>
<td>1.1±0.3*</td>
</tr>
<tr>
<td>20</td>
<td>1.1±0.3*</td>
<td>1.0±0.1*</td>
<td>1.1±0.1*</td>
<td>0.9±0.1*</td>
</tr>
<tr>
<td>50</td>
<td>1.5±0.1*</td>
<td>1.0±0.1*</td>
<td>1.0±0.1*</td>
<td>0.9±0.3*</td>
</tr>
</tbody>
</table>

*In the control, in each dose and at each period studied of 60 ciliates.

The effect is caused by exposure to a dose of 0.01 Gy and has not run-up even with 5 thousand times dose increase. Table clearly demonstrates the detected non-linear effects of radiation and underlines the effectiveness of low doses. Figure 1 presents the data for variations in the experimental ciliates’ SMA in percentage of the corresponding control with standard deviation for the percentages at various periods after irradiation.
Fig. 1. The changing in ciliates’ SMA (in % relative to controls) after \( \gamma \)-irradiation at dose of 0.01-50 Gy immediately (a) and in 2 (b), 4 (c) and 7 (d) days.

Figure 1 shows that the significant decrease (p<0.05) in SMA is approximately the same at all times (immediately and in distant periods after exposure) and at all doses. This effect already taken place by exposure at 0.01 Gy. The effect was recorded on the 7th days after irradiation. During that time the ciliates replaced about 3-4 generations (average length of the cell cycle was about 2 days). It follows that the effect can transmitted to descendants of irradiated cells.

The same change pattern was identified while we calculated the frequency of occurred pathological forms. Figure 2 shows these data. If in control groups pathology occurs very rarely or never recorded; but in the experiment it is expressed at each dose. It is seen that increasing the dose does not influence the degree of damage.

Fig. 2. The pathological forms of ciliates’ movement (in %) after \( \gamma \)-irradiation at doses of 0.01, 0.1, 1, 20 and 50 Gy immediately (a) and in 7 (b) days.

In controls, in each dose and at each period studied for 50 ciliates.
This data shows that changes of motion function occur after low radiation and are transmitted to descendants of irradiated cells in vegetative reproduction of protozoa. We observed noticeable deviations from control group in all doses. It shows the massive nature of the changes of the described type.

Experiments with daphnids
Consider figure 3 which shows the survival of daphnia at different times in the control and after irradiation at doses from 0.1 to 600 Gy, expressed as % of the original number of animals (60 animals for each curve).

![Fig. 3. Survival of daphnids during 30 days in the control (C) and after exposure at doses of 0.1, 1, 20, 100, 250 and 600 Gy in % of their original number (60).](image)

There are 4 categories of curves which respectively show the evidence of the daphnids viability in the control (C) and after irradiation at doses from 0.1 to 20 Gy, at 100 Gy (LD₀/₀/₃₀) and at absolutely lethal doses – 250 and 600 Gy (LD₁₀₀/₁₆ and LD₁₀₀/₄). Fig.3 shows that even at the lowest of doses – 0.1 Gy, as well as low for subject doses of 1 and 20 Gy there is a marked deviation from control. The effect does not increase with increasing dose in this dose range and by the end of the period of observation at all doses the effect is about 20%. At the same time, unlike the actions in higher doses, there is a constant extension in the time of the death of individuals, rather than the death of the population in the relatively early time.

In the follow up experiments we studied the changes of daphnids' survival on the 30th day because the maximum differences from the control after the irradiation in relatively low doses were achieved at that time. In these experiments we discovered the possibility of inheritance of the studied forms of damage in the descendants of irradiated animal. Figure 4a shows the evaluation of survival of daphnids-parents at 30th day after the irradiation at doses of 0.1, 1 and 20 Gy.
In these experiments, we see almost the same results as in the first case (fig.3). The survival of daphnids-parents, irradiated at low for the subject doses (including 0.1 Gy), is significantly lower than in the control, and the effect does not increase even with a very large increase in radiation exposure (at 200 times).

These results enabled us to proceed to study the viability of the 1st generation offspring born from the daphnids-irradiated. The data is presented in Figure 4b. Likewise, we see that in this case the survival of experimental animals is lower than in control, and that the effect does not increase with the increasing doses.

Significant deviations from control observed for daphnids-parents and for unexposed descendants of the first generation show the mass nature of the disruption of the described type. However, we haven’t seen valid deviations between control and experimental groups for second and third generations of daphnids.

**Conclusions**

Similar dose-independent inheritable mass damage was found in different species after low radiation. The results support the idea of the universal nature of this unusual form of reaction (Bychkovskaya 1986, Bychkovskaya I.B. et al 2006). Innovative materials are obtained showing that the phenomenon can manifest itself in violation of important physiological functions (experiments on ciliates) (Sarapultseva 2008) and on the organism level of integration (experiments on daphnids) (Sarapultseva et al 2009). In the experiments on daphnids the inheritance of the effect in F1 confirmed previously observed effect on rats (Bychkovskaya et al 2006). It also showed the elimination of damage in subsequent generations.

The features of this effect, including unusual for radiobiology dose-independent character, cannot be related to mutations. In general this phenomenon can be related to a category of epigenomic alterations (Jablonka et al 2008).

This research can be applied to the low radiation risks’ assessment.
References


Impact assessment of elevated levels of natural/technogenic radioactivity on wildlife of the North – INTRANOR

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Abstract

Arctic and boreal regions are often considered to be vulnerable to exposures from contaminants and therefore merit special attention in relation to the application of environmental impact assessment methodologies. The INTRANOR project has focussed specifically on environmental assessments for radiation exposure through application of existing methodologies and their adaptation to quantify transfer, exposure and effects in Boreal/Arctic ecosystems. Non-parametric statistical methods have been applied in order to estimate the threshold dose rates above which radiation effects can be expected in vertebrate organisms. The effects considered in the analyses include morbidity, reproduction, and life shortening and the approach has drawn upon data collations pertaining to databases on effects of chronic low-LET radiation exposure. In addition, industrial areas contaminated by uranium mill tailings and radium production wastes, in the Komi Republic, Russia, were selected as suitable study sites to study further the effects of exposure to radiation under boreal conditions. Dose–effect relationships have been established for natural Vicia cracca L. populations inhabiting this area. The various endpoints considered include chromosome aberration frequency in seedling root meristem, frequency of embryonic lethal mutation in legumes, germination of seeds and survival rate of sprouts of seeds. Analyses of data have allowed a benchmark to be established below which no decrease in reproductive capacity could be observed. Other work performed within the project includes the collation of data in relation to naturally occurring radionuclides and application of existing methodologies to characterise background radiation exposures. These dose-rates used in conjunction with dose rates known to have specific biological effects on individuals/populations may be a suitable means of contextualising the exposure attributable to enhanced dose-rates arising from human activities.
Introduction
At a European regional level, methodologies to assess the impact of exposure to ionising radiation on flora and fauna in European temperate and Arctic environments have been developed in two European collaborative projects “FASSET - Framework for Assessment of Environmental Impact” (Larsson et al., 2004) and “EPIC - Environmental Protection from Ionizing Contaminants in the Arctic” (Brown et al., 2003) respectively. These studies were superseded by the project “ERICA - Environmental Risk from Ionising Contaminants: Assessment and Management” wherein risk assessment methodologies have been developed and issues relevant to decision making in the context of the management of environmental impacts of radioactivity have been addressed (Larsson, 2008). Of particular relevance to the Arctic is the project EPIC which provides a number of the foundation stones that are prerequisite in the process of developing a robust assessment methodology. However, the development of the EPIC framework was curtailed at a point that did not incorporate risk characterisation or concomitant management options. With this in mind, the central rationale behind the INTRANOR project was to build upon the recent advances in environmental impact assessments, as detailed in the abovementioned research programmes, with focus on adapting the systems for Arctic/boreal environments, developing the risk characterisation component of the analysis and testing the assessments for actual situations. Some of the activities in the project are presented below.

Further development of Environmental Impact Assessment methodologies
The Environmental Impact Assessment methodologies outlined above are constructed around the concept of Reference organism, definitively specified in Larsson (2004) as ‘a series of entities that provide a basis for the estimation of radiation dose rate to a range of organisms which are typical, or representative, of a contaminated environment. These estimates, in turn, would provide a basis for assessing the likelihood and degree of radiation effects’. The approach was designed to be compatible with the methodology adopted by the International Commission on Radiological Protection, ICRP (2008) and as such some of the geometries that had been proposed for the ICRP’s “Reference Animals and Plants” were used as defaults in the ERICA Approach. Reference organisms were defined and used for the derivation of geometric relationships between radiation sources and organisms, as well as for considerations of the dosimetry of both external and internal exposure (further discussed by Ulanovsky et al., 2008). The concept of reference organism also includes the consideration of transfer to the plant or animal and occupancy of the organism at locations within their habitat. With regards the former, this is achieved through the application of default concentration ratios, based on literature review or the use of suitable analogues or models, in order to derive body concentrations from media concentrations (e.g. see Hosseini et al., 2008). Occupancy factors, i.e. the time spent by an organism at a particular location within its habitat, have often been defined to maximise the dose-rate. A further intended use of reference organisms was that they could be used for pooling some of the effects data generated for a range of species. In addition, the selection of reference organisms was made with the intention of making it...
possible to address most protected species within Europe (and therefore be of applicability to envisaged requirements for environmental impact assessment). In view of the fact the ICRP are in the process of developing a data set that are references in the truest sense, the organism lists in EPIC and ERICA might be more appropriately referred to as representative organisms (Pentreath, 2009) which implies an application within site specific situations much in the same way as the ICRP suggest using the representative person with habits typical for those of a small number of (human) individuals who are most highly exposed within a given assessment.

Work conducted in the INTRANOR project has led to the conclusions that: Although the EPIC reference organism suite would seem to provide us with a reasonable starting point in selecting region-specific organisms for the estimation of doses and radiation impact on wildlife of the North, there are severe limitations in the existing organism suite. In particular, the fact that in many cases the reference data either do not exist, as is the case for freshwater reference organisms, or are few (much of the transfer data) means that it is a moot point whether they should be regarded as reference points at all. This of course is immediately mitigated if we consider the EPIC suite to be ‘representative’ (as oppose to ‘reference’) organisms. Several years of additional work leads to the clear observation that the transfer data in ERICA are far superior to those collated in EPIC and, in many cases, the EPIC data have been incorporated into the much larger ERICA datasets. Furthermore, ERICA allows derivation of transfer and exposure for a much broader suite of radionuclides and provides an indication of uncertainty for overall exposure estimates through the collation of detailed statistical information for concentration ratios. Additionally, with regards transfer there appears to be little justification, in most cases, for using smaller Arctic/boreal specific data sets in lieu of more comprehensive global data sets. In fact, following the arguments of Sheppard (2005), not drawing on larger generic data sets (as typified by ERICA) may be counter-productive. In the few named examples where studies have been undertaken to demonstrate a significant difference between Arctic/boreal and temperate data (see Brown et al., 2004a), then work should be done to provide these alternative values for use within an Environmental Impact Assessment. A cursory examination of the dosimetric models for ERICA also suggests that they may be suitably applied to the Arctic. This reflects the fact that the ERICA dosimetric models are based on highly generic organism categories, e.g. pelagic fish, bird etc. (Table 1) and it is therefore non-problematic to illustrate that such types of biota will be present in Arctic/boreal regions (and in most ecosystems for that matter).

For the sake of simplicity it seems reasonable to recommend, in relation to conducting environmental impact assessment in the Arctic, using the organism suite applied in the ERICA approach. This might be supplemented by a representative organism suite for application in the Arctic/boreal environment where this is deemed necessary. The system for performing an impact assessment for an Arctic site would therefore involve:

- the use of ICRP Reference Animals and Plants and guidance to allow, inter alia, site specific assessment to be more readily compared to other assessments.
- the use of the ERICA integrated approach (Larsson, 2008) supported by the ERICA Tool (Brown et al., 2008) to provide screening tools and generic
data sets to perform the assessment. The ERICA dataset might be regarded as providing data for ‘representative organisms’. In this way the approach might be considered as a management tool to be applied for authorisations/compliance, for example, and as providing a pool of information to allow a more comprehensive assessment where clearer links can be made to (and relevant data derived for) actual species of interest.

- If required, to collate and undertake a site specific investigation drawing on tools available in the ERICA Tool, e.g. defining site specific geometries and occupancy factors, conducting probabilistic model runs etc. Furthermore, site specific activity concentration and transfer data should be collated and for the transfer data Bayesian methods might be implemented in refining the information (e.g. see Barrera et al. 2007), i.e. allow the assessor to utilise the more comprehensive datasets available from ERICA in tandem with newly acquired site specific information.

Table 1. Boreal/Arctic Representative organisms for application in an Environmental Impact Assessment – from the ERICA Tool (Brown et al., 2008) - in italics within brackets = the corresponding ICRP Reference Animals and Plants, for which the ERICA Tool uses the proposed ICRP geometries as default.

<table>
<thead>
<tr>
<th>Freshwater</th>
<th>Marine</th>
<th>Terrestrial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amphibian (frog)</td>
<td>(Wading) bird (duck)</td>
<td>Amphibian (frog)</td>
</tr>
<tr>
<td>Benthic fish</td>
<td>Benthic fish (flat fish)</td>
<td>Bird (duck)</td>
</tr>
<tr>
<td>Bird (duck)</td>
<td>Bivalve molluscs</td>
<td>Bird egg (duck egg)</td>
</tr>
<tr>
<td>Bivalve molluscs</td>
<td>Crustacean (crab)</td>
<td>Detritivorous invertebrate</td>
</tr>
<tr>
<td>Crustacean</td>
<td>Macroalgae (brown seaweed)</td>
<td>Flying insects (bee)</td>
</tr>
<tr>
<td>Gastropod</td>
<td>Mammal</td>
<td>Gastropod</td>
</tr>
<tr>
<td>Insect larvae</td>
<td>Pelagic fish</td>
<td>Grasses and herbs (wild grass)</td>
</tr>
<tr>
<td>Mammal</td>
<td>Phytoplankton</td>
<td>Lichen and bryophytes</td>
</tr>
<tr>
<td>Pelagic fish (salmonid/trout)</td>
<td>Polychaete worm</td>
<td>Mammal (rat, deer)</td>
</tr>
<tr>
<td>Phytoplankton</td>
<td>Reptile</td>
<td>Reptile</td>
</tr>
<tr>
<td>Vascular plant</td>
<td>Sea anemones/true corals</td>
<td>Shrub</td>
</tr>
<tr>
<td>Zooplankton</td>
<td>Vascular plant</td>
<td>Soil invertebrate (worm) (earthworm)</td>
</tr>
<tr>
<td>Zooplankton</td>
<td></td>
<td>Tree (pine tree)</td>
</tr>
</tbody>
</table>

Statistical analyses of dose-effects data
There have been recent efforts to derive predicted no effects dose-rates for wild-life based on the construction of species sensitivity distributions (SSD) that are in turn constructed from effective Dose-rate 10 % (EDR$_{10}$) data from individual experiments (Garnier-Laplace et al., 2008, Andersson et al., 2009). Although such methods are well established in the ecotoxicological sciences (see EC, 2003), their application within the field of radiological protection is relatively new and not without deliberation. One important limitation is the fact that the criteria used in the selection of appropriate data for construction of the SSD are extremely strict which results in the loss of a large dataset that may have great utility in informing the derivation of appropriate dose-rate
benchmarks. For this reason, alternative methods for analysing dose-effects data have been explored within the INTRANOR project. Non-parametric statistical methods have been applied in order to estimate the threshold dose rates above which radiation effects can be expected in vertebrate organisms by Sazykina et al. (2009). The effects considered in the analyses include morbidity, reproduction, and life shortening and the approach has drawn upon data collations pertaining to databases on effects of chronic low-LET radiation exposure. Radiation thresholds dose-rates in vertebrate animals subjected to chronic low-LET exposure were estimated to be $2.1 \times 10^{-4}$ Gy/day, $4.1 \times 10^{-4}$ Gy/day and $1.1 \times 10^{-3}$ Gy/day for the endpoints of morbidity, reproduction and life-shortening respectively. This means that the generic screening value suggested by Andersson et al. (2009), based on SSD analysis corresponds to the lowest level for morbidity effects in mammals based on the non-parametric analyses of data proposed in INTRANOR by Sazykina et al. (2009). Further work may be required to establish whether additional uncertainty factors should be applied to generic benchmarks to account for the (perceived) greater sensitivity of Arctic systems to impacts of radioactivity.

**Estimating the impacts of ionising radiation on natural plant populations**

The work described above by Sazykina et al. (2009); Andersson et al. (2009) and others essentially involves an assimilation of data for dose-effects relationships for many different species of organism. In many cases of plants and animals this relationship between exposure and effects is poorly characterised or unknown. Many of the available data pertain to laboratory studies and there are few published data reporting the occurrence of biological effects in natural populations of plants and animals located within areas with enhanced concentrations of naturally occurring radionuclides. In this light, experiments have been conducted on herbaceous vegetation, Tufted vetch (*Vicia cracca*) within a boreal environment contaminated with radionuclides from $^{238}$U and $^{232}$Th decay chains to investigate the effects of different dose regimes (Evseeva et al., 2009). The following endpoints were selected in this study:

- chromosome aberration frequency in seedling root meristem,
- frequency of embryonic lethal mutation in legumes,
- germination of seeds and
- survival rate of sprouts of seeds.

The latter three parameters were selected as they reflect reproduction capacity in the studied organisms. A site near the Vodnyi settlement within the Komi Replublic was selected as a suitable field station. Detailed descriptions of the study area as well as results of previous radioecological investigations are presented by Geras'kin et al. (2007). The contamination of the site has been caused by storage of the uranium mill tailings and radium production wastes.

Doses to *V. cracca* plants from areas contaminated with radium production wastes, exceeded the natural background level (0.0007– 0.001 Gy) by a factor of 1.4–900. The main dose forming radionuclide was $^{226}$Ra. The study of relationships between biological effects observed and weighted absorbed dose for *V. cracca* seeds showed that nonlinear models fit experimental data better than linear ones. The relationship between
the frequency of the chromosome aberration in seedlings’ root tip cells and the absorbed dose was found to be quadratic (Figure 1).

![Graph showing the relationship between chromosome aberration frequency and absorbed dose](image)

Fig. 1. Plot of models showing the relationship between chromosome aberration frequency in meristematic root tip cells of seedlings and weighted absorbed dose for seeds (From Evseeva et al., 2009).

The exponential model provided the best result in describing the empirical dependence between the absorbed dose and both the germination capacity of seeds and the survival rate of sprouts of *V. cracca*. No significant relationship (p>F>0.05) was found between the embryonic lethal mutations frequency and the absorbed dose. For *V. cracca* plants inhabiting areas contaminated with uranium mill tailings and radium production wastes, a weighted absorbed dose for the aboveground part of plants of 0.2 Gy (weighting factor for alpha particles=5) during the vegetation period (120 days) can be considered to be a level below which no increase in genetic variability and decrease in reproductive capacity is observable. Evseeva et al.(2009) essentially derive a (weighted) no observable effect dose-rate of 1.66 mGy/day (0.2 Gy over 120 days) for *V. cracca* growing over a site contaminated by enhanced levels of naturally occurring radionuclides.

**Background dose rate characterisation**

In helping to assess the impacts of radiation exposure on organisms, Pentreath (2002) suggested that only two reference points can be utilised in a practicable way, these being natural background dose-rates and dose-rates known to have specific biological effects on individuals/populations. Building on this, the ICRP has suggested that it would be helpful for the decision-making process if information concerning effects on biota was set out in terms of multiples of the natural background dose-rates typically experienced by each type of Reference Animals and Plants (ICRP 2008). For such a structuring of data to be made, there is clearly a requirement to provide well characterised background dose-rate estimates for the selected Reference Animals and Plants. However, whilst data have been collated for terrestrial Reference Animals and
Plants (Beresford et al. 2008) information has not been collated with the express purpose of deriving background dose-rates to aquatic Reference Animals and Plants. Furthermore, there are significant limitations associated with earlier compilations of naturally occurring radionuclides in the context of deriving background dose-rates for aquatic wildlife. For example, no natural radionuclide data for European freshwater organisms were identified in the review of Brown et al. (2004b).

In light of these propositions, information on activity concentrations of naturally occurring primordial radionuclides for marine and freshwater ecosystems have been applied and appropriate dosimetry models used to derive absorbed dose-rates for Reference Animals and Plants. Although coverage of activity concentration data is comprehensive for sediment and water, few, or in some cases no, data were found for some organism groups, for most radionuclides. The activity concentrations for individual radionuclides in both organisms and their habitat often exhibit standard deviations that are substantially greater than arithmetic mean values, reflecting large variability in activity concentrations. The dominating radionuclides contributing to exposure in the Reference Animals and Plants are \(^{40}\text{K},^{210}\text{Po}\) and \(^{226}\text{Ra}\).

The mean unweighted and weighted dose-rates for aquatic Reference Animals and Plants are in the ranges \(0.07–0.39 \, \mu\text{Gy h}^{-1}\) and \(0.37–1.9 \, \mu\text{Gy h}^{-1}\) respectively. Typical results are shown in Figure 2.

![Fig. 2. Contributions of different radionuclides to internal, external and the total unweighted dose-rates for (marine) Flatfish. The vertical-orientated values are estimated internal and external dose-rates. Reproduced from Hosseini et al. (in press).](image-url)

The data compiled and the dose-rates estimates in this exercise pertain to specific organism types as defined by the ICRP and are not specifically related to Arctic organisms. Further studies are required to determine the differences in exposures of
boreal organisms compared to temperate organisms building on previous studies on this theme (Sazykina et al., 2003).

**Conclusions**

The INTRANOR project has dealt with many aspects relating to the development of a more robust methodology for assessing the impact of ionising radiation on wild-life. The general methodology itself has been reviewed with particular focus on the applicability of representative organisms in the context of boreal/Arctic systems and how these might relate to the reference animals and plants being developed by the ICRP. Dose response data from published literature has also been investigated by considering the applicability of different statistical methods in the derivation of generic benchmarks for application in protection systems. There are clearly deficiencies in relation to well characterised dose-response relationships for many organism types especially under field conditions. With this in mind, experimental studies have been conducted to investigate the dose response of herbaceous vegetation to exposures from naturally occurring radionuclides. This has allowed the shape of dose response relationship to be elucidated and information relating to no observable effects and lowest observable effects doses to be elaborated. Finally work has also been conducted in relation to the characterisation of naturally occurring radionuclides in aquatic ecosystems. By organising the data around the reference animals and plants considered by the ICRP, the data should have direct relevance as a point of reference for contextualising calculated dose-rates for any given impact assessment for ionising radiation.

**Acknowledgements**

This work was supported by the Norwegian Research Council (NFR) and forms part of the INTRANOR (Impact Assessment of Elevated Levels of Natural/Technogenic Radioactivity on Wildlife of the North) project, contract no.185134. The financial support of the NFR is gratefully acknowledged.

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Testing of linearity assumption of soil-to-plant transfer factors in boreal forest

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Abstract
The use of traditional transfer factors (TF) in radioecological modelling is based on the assumption that element concentrations in plant and soil are linearly related. We tested the validity of the linearity assumption for Mo, Ni, Pb, U and Zn in boreal forest using narrow buckler fern (Dryopteris carthusiana) as a model plant. Higher TFs were generally found in lower soil concentrations. A non-linear function was found to explain the relationship between TF and soil concentration significantly better than the linear assumption. The use of traditional TFs may be inadequate for estimating plant concentrations, and new approaches to modelling soil-to-plant transfer are thus needed.

Introduction
In radioecological modelling, the transfer of an element from soil to plants is commonly described by an element-specific transfer factor (TF), which is defined as the plant/soil ratio of the concentration of the element (IAEA 2010). The use of these TFs is based on the assumption that soil and plant concentrations are linearly related. However, this assumption is not valid for essential elements and has also been questioned for non-essential elements (Sheppard and Sheppard 1985; Simon and Ibrahim 1987).

From experience in other fields of science, such as studies on plant nutrition and uptake of heavy metals, it is known that concentration in plants as a function of concentration in soil generally shows a steep increase at low concentrations towards a plateau at high concentrations. Several mathematical functions have been used to describe this behaviour, e.g. the Freundlich equation (Martinez-Aguirre et al. 1997; Krauss et al. 2001; Yaylah-Abanuz and Tüysüz 2009) and the Langmuir equation (Wenger et al. 2002; Han et al. 2006; Redjala et al. 2010).

In this study the soil-to-plant transfers of three essential (Mo, Ni and Zn) and two non-essential (Pb, U) elements were studied in a boreal setting using narrow buckler fern (Dryopteris carthusiana) as a model species. Empirical data were used investigate the relationship between plant and soil concentrations. The total element concentrations rather than radionuclide concentrations were measured in this study. Radionuclides and stable isotopes of the same element are considered to behave similarly in ecosystems,
and stable isotopes can thus be used for modelling the behavior of radionuclides in the biosphere (IAEA 2010).

**Material and methods**

The study site was a uranium occurrence in a herb-rich forest (*Oxalis-Maianthemum* type) located in Nilsiä, Eastern Finland (N63°04', E27°54') (Fig 1).

![Fig 1. Overall view of the study site.](image)

The soil samples were collected from 29 systematically selected sampling points in June 2007. The topsoil was collected to the depth of 100 mm, which was considered to be the rooting depth of the understorey species, within an area of 100 mm x 100 mm. The soil samples were dried at 40 °C and sieved to diameter fractions < 2mm and > 2mm. The fraction < 2mm was used for analysis.

Plant samples were collected at the same time as soil samples. The collected plant species was narrow buckler-fern (*Dryopteris carthusiana*) which was present at 27 sampling points. The plant samples were divided into root (containing both rhizome and fine roots), petiole and leaf fractions. The plant samples were dried at 60 °C before analysis.

Inductively coupled plasma-mass spectroscopy (ICP-MS) measurements were carried out in the laboratory of Labtium Ltd. in Espoo, Finland providing pseudototal concentrations of Mo, Ni, Pb, U and Zn after nitric acid digestion (EPA 3051) in microwave oven. An estimate of mobile fraction of these elements in the soil samples was obtained by ICP-MS analyses after 1 M Ammonium acetate (NH₄Ac, buffered at pH 4.5) leach. Detection limits for Mo, Ni, Pb, U and Zn were 0.02; 0.3; 0.05; 0.01 and 0.4 mg/kg, respectively. If the concentration of an element was below detection limit the value of detection limit divided by two was used in calculations (EU 2008).

All the results were corrected to represent dry matter content (dw). TFs based on the IAEA (2010) definition for U, Mo, Ni, Pb and Zn were calculated separately for root, petiole and leaf as follows:
TF_{p,t} = \frac{\text{concentration (dw) of Mo, Ni, Pb, U or Zn in plant part } p (p= \text{root, petiole or leaf})}{\text{total concentration (dw) of Mo, Ni, Pb, U or Zn in soil}}

TF_{m,p} = \frac{\text{concentration (dw) of Mo, Ni, Pb, U or Zn in plant part } p (p= \text{root, petiole or leaf})}{\text{mobile concentration (dw) of Mo, Ni, Pb, U or Zn in soil}}

To investigate the relationship between TFs and soil concentrations, the data were fitted with non-linear functions. In this paper, we described results based on a Langmuir-tupe function. The Langmuir equation is of the form:

\[
C_p = \frac{a \ b \ C_s}{1 + b \ C_s},
\]

where \(a\) and \(b\) are experimentally determined constants, \(C_s\) is the concentration in soil, and \(C_p\) is the concentration in the plant. To allow fitting with data that suggested a slowly accumulating function at high soil concentrations, we added a linear term to the Langmuir equation and got what we call the Langmuir+ equation:

\[
C_p = \frac{a \ b \ C_s}{1 + b \ C_s} + c \ C_s
\]

To study the relationship between TF and element concentration in soil, the following equation was derived from the Langmuir+ equation:

\[
TF = \frac{C_p}{C_s} = \frac{a \ b}{1 + b \ C_s} + c
\]

Results

Soil concentrations

The medians and ranges of soil total and mobile concentrations of Ni, Pb, U and Zn are shown in Table 1. For Mo the majority of measured mobile concentrations were under the detection limit and thus only the range is shown in Table 1. Zn was the most abundant of these five elements followed by Pb, Ni, U and Mo, respectively, whether soil total or mobile concentration was considered.

Table 1. Medians and ranges of total and mobile Mo, Ni, Pb, U and Zn concentrations in soil (mg kg\(^{-1}\)).

<table>
<thead>
<tr>
<th></th>
<th>Mo</th>
<th>Ni</th>
<th>Pb</th>
<th>U</th>
<th>Zn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>0.83 (0.17-32)</td>
<td>9.0 (4.3-26)</td>
<td>8.7 (5.0-120)</td>
<td>1.6 (0.46-110)</td>
<td>27 (14-74)</td>
</tr>
<tr>
<td>Mobile</td>
<td>&lt;0.02-0.15</td>
<td>0.68 (&lt;0.3-7.7)</td>
<td>2.6 (0.56-17)</td>
<td>0.33 (0.04-66)</td>
<td>3.1 (0.72-12)</td>
</tr>
</tbody>
</table>

Soil-to-plant transfer factors (TFs)

A trend towards higher TFs at lower soil concentrations was systematically seen in the data for both essential and non-essential elements. Data for Pb are shown as an example in Fig. 2.
Fig. 2. TFs of Pb for different plant parts (root, petiole, leaf) as a function of soil total concentration. The line shows the fit with equation (3) (see Materials and Methods).

Non-linear and linear model
When equation (3) was fitted with the data, the goodness of fit ($R^2$) ranged from 7.68E-06 to 0.94 (average 0.44). The $R^2$-values for Pb are shown as an example in Fig. 2. In all cases the fits with the non-linear function were better than fits with linear assumption (constant TF), with produced $R^2$-values below 5.5E-16 (average 2.0E-17).
Discussion
Lack of linearity between soil and plant concentrations was clearly shown in this study for both essential and non-essential elements, in agreement with previous results (Sheppard & Sheppard 1985; Simon & Ibrahim 1987; Cook et al. 1994). Our results indicated that TFs are high at low soil concentrations and decrease towards a constant value at high soil concentrations. Therefore, the use of constant TFs may be justified at high soil concentrations but may lead to underestimation of plant concentrations in case of low soil concentrations (Martínez-Aguirre et al. 1997). For example, possible leaks from final disposal of spent nuclear fuel, will in all likelihood lead to low soil concentrations.

Empirically determined TFs, generally show very large variation, and published TF values therefore include a lot of uncertainty (Higley & Bytwerk 2007). Examination of the non-linear functions found in this study (Fig. 2) suggests that part of the variation (which has been traditionally assumed to be random) may in fact be systematic variation with soil concentration. Therefore, examining soil-to-plant transfer as a non-linear function might greatly improve the accuracy of predictions concerning plant concentrations.

Conclusions
The soil-to-plant transfer of both essential (Mo, Ni and Zn) and non-essential (Pb, U) elements is clearly non-linear. New approaches to model the soil-to-plant transfer are needed to improve the accuracy of model predictions.

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Application of ellipsoid geometry in dose assessment of forest plants

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Abstract
Posiva is implementing a deep repository for spent nuclear fuel in Olkiluoto, Finland. A site-specific safety case is being produced, and data has been acquired for the assessment models. In the dose assessment of other biota, international approaches are applied. However, determining geometry parameters for the variability of forest plants is a challenging task, not to mention coupling of the geometry to plant physiology. First, it is well known that physical dimensions of plants differ widely between plant species. Secondly, dimensions of certain plant species are dependent on growth conditions (e.g. weather, soil fertility), biological age and developmental stage of plant (e.g. many annual herbs have their highest biomass in largest extent during late summer). Furthermore, plant parts have different physiological tasks, and they should be taken into account as well (e.g. photosynthetically active green leaves compared to lignified brown stems). In this paper we illustrate problems in plant geometry using some key plant species of boreal forests and propose alternative geometries for assessment use.

Introduction
Posiva is implementing a deep repository for spent nuclear fuel in Olkiluoto, Finland. A site-specific safety case (Posiva 2008) is being produced, and data has been acquired for the assessment models (Hjerpø et al. 2010). In the dose assessment of other biota, international approaches are applied.

In all generic approaches (Copplestone et al. 2001, Brown et al. 2003, Larsson et al. 2004, Beresford et al. 2007, ICRP 2008) the basis of the dosimetric modelling is to select reference organisms that are represented by target geometry (a phantom). It has been widely acknowledged that identification of actual species or groups of species is helpful, if not even necessary, to derive the geometrical and radionuclide transport properties. However, selection of such species or group does not refer to any particular species or group of species (e.g. ICRP 2008).

Furthermore, the reference organisms can be considered to be typical of the environment "in the sense that one might expect to find them there" (ICRP 2008) or at least in the sense of being representative of the environment (Copplestone et al. 2001, Beresford et al. 2007). This is supposed to be also the meaning of the Finnish regulatory requirement to assess "typical radiation exposures" (YVL 8.4, YVL E-5).
Concerning the representatives of forest plants, roots, meristem, buds and/or seeds have been considered as the dosimetric target (Copplestone et al. 2002, Brown et al. 2003, Larsson et al. 2004), or "whole" plants have been used, as apparently in (Beresford et al. 2007). Whereas in these approaches the geometry is defined as an ellipsoid, the ICRP approach (ICRP 2008) considers pine tree as an ellipsoid for estimating the internal doses but for external doses uses a homogeneous canopy layer, and in (Larsson et al. 2004) buds and meristem of shrubs and trees are located in a canopy. Respectively ICRP also uses an ellipsoid for a spike of Wild grass, but its meristem as homogeneous layer on the ground surface. In all these approaches the organisms are assumed to be homogeneous with a density of 1 g/cm³ and in an infinite water medium (ensuring sufficient secondary photon transport). The composition of the reference organism is best described to be a four-component tissue substitute (ICRP 2008).

However, determining geometry parameters for the variability of forest plants is a challenging task, not to mention coupling of the geometry to plant physiology. First, it is well known that physical dimensions of plants differ widely between plant species. Secondly, dimensions of certain plant species are dependent on growth conditions (e.g. weather, soil moisture and fertility), biological age and developmental stage of plant (e.g. many annual herbs have their highest biomass in largest extent during late summer). Growing density and competition between plant species (or between individual species) affect also size and shape of single species. Furthermore, plant parts have different physiological tasks, and they should be taken into account as well (e.g. photosynthetically active green leaves compared to lignified brown stems).

In this paper we illustrate problems in plant geometry using some key plant species of boreal forests and propose alternative geometries for assessment use.

**Material and methods**

**Selection of representative plants and defining their dimensions**

Due to a large number of plant species and large variation in plant dimensions between different species it is impossible to cover dimensions of single plant species in dose assessment. A practical approach would be using of functional plant groups from which some typical key species are selected for detailed examination. However, two main problems still remain. First, what are the requirements and justifications for selection of key species from plant groups? Secondly, how to handle a huge variation inside plant species?

Plant species groups have been used in mapping of the nutrient status of the vegetation on Olkiluoto Island in 2005 (Tamminen et al. 2007). Plant groups were also used in determining biomass and chemical composition of the vegetation on the intensive forest monitoring plots at Olkiluoto in 2008 (Salemaa & Korpela 2009). The latter included six functional plant groups (some exemplars):

1) Evergreen dwarf shrubs (*Vaccinium vitis-idaea*)
2) Deciduous dwarf shrubs (*Vaccinium myrtillus*)
3) Lower herbs (*Maianthemum bifolium*, *Oxalis acetosella* and *Tridentalis europaea* (shoots die annually), and *Linnaea borealis* (perennial shoots)
4) Ferns (*Equisetum sylvaticum, Dryopteris carthusiana, Gymnocarpium dryopteris, Pteridium aquilinum* (shoots/leaves die annually))
5) Grasses (both perennial and annual leaves, *Deschampsia flexuosa*)
6) Mosses (lower parts die gradually, *Pleurozium schreberi, Hylocomium splendens*)

In this study selection of key plant species was based on earlier vegetation inventories at Olkiluoto (Tamminen et al. 2007, Salemaa & Korpela 2009), frequency of plant species and their importance in food chains. Hence bilberry (*Vaccinium myrtillus*) was selected to represent deciduous dwarf shrubs, chickweed wintergreen (*Trientalis europaea*) lower herbs, wavy hair-grass (*Deschampsia flexuosa*) grasses and red-stemmed feather-moss (*Pleurozium schreberi*) mosses. All the selected plant species belong to a group of ten most common plant species in Southern-Finland (Reinikainen et al. 2000). Red-stemmed feather-moss also is commonly used as a bioindicator species in environmental studies. Scots pine and Norway spruce dominate forests on Olkiluoto Island (Saramäki & Korhonen 2005). Because appearance of Scots pine differs clearly from that of Norway spruce (i.e. tree crown forms separate part in the older trees), pine was selected to represent tree species in this case study.

Selection criteria for the reference organisms include ecological niche, intrinsic radiosensitivity, radioecological sensitivity, distribution (e.g. presence year-round), suitability to research and monitoring and protected status (IAEA 2010). It seems that the criteria are quite well in accordance with the key species we have selected for this study. However, intrinsic radiosensitivity of the selected species is an uncertain issue, especially regarding long-lived radionuclides characteristic to releases from deep repositories.

Determination of ellipsoid geometries was attempted to base on literature where, however, only plant heights were available. Therefore some estimates were created for plant width and length. For bilberry a demonstrative sampling was carried out. Three samples of bilberry in different developmental stages (i.e. age of plant) were subjectively collected and the dimensions measured (Fig. 2). Some results based on expert judgment during Olkiluoto Biosphere Description 2009 process (Haapanen et al. 2009) were also included. In addition, a few applications of determination ellipsoid geometries for certain plant species were proposed and discussed.

**Evaluation of impacts on doses to plants**

In this contribution, the effect of varying sizes of ellipsoids representing plants has been preliminary studied using the ERICA Assessment Tool (Beresford et al. 2007), version 1.0, May 2009. Default values have been used except for the organism dimensions (Table 1) and the concentration ratios, which were taken from Helin et al. (2010). The activity concentration in the soil was taken from the biosphere assessment simulations, corresponding the maximum exposure in terrestrial systems (case Sh4Q-C, dried area of Mäntykarinjärvi Lake, year 12020; Hjerpe et al. 2010). As the needed C-14 concentration in air was not easily extractable from the simulation data, it was omitted here, similarly to Pd-107 and Sn-126 not supported by the ERICA Assessment Tool. Due to the pathway, contribution of C-14 is believed not to invalidate the results below.
The contribution of the two other omitted radionuclides would be insignificantly small anyway.

Fig. 1. Examples on Scots pine heights in different developmental stages. From left to right: young seedling (1-year-old, height 0.1 m), advanced seedling (<10 yrs, h= 5 m), mature pine tree (100-yrs-old, h= 22 m) and old mature pine tree (150-yrs-old, h= 25 m). Drawing: A. Hamari /Metla.

Fig. 2. Examples on bilberry of different developmental stages growing in mesic heath forest during winter season. Maximum dimensions (width x length x height, cm) from left to right: 18 x 10 x 25 (A), 6 x 4 x 18 (B) and 25 x 30 x 35 (C).
Results and discussion

Plant dimensions and ellipsoid geometry

A variety of plant dimensions are presented in Table 1. Typically only plant heights were found in literature. Those heights represent different growth conditions of plants, e.g., *Trientalis europaea* appears in wide range of habitats from xeric heat forests to herb-rich forests, and *Deschampsia flexuosa* and *Vaccinium myrtillus* from sub-xeric to herb-rich heat forests (Reinikainen et al. 2000). *Pleurozium schreberi* is the most common plant species in Finland and has the largest range of habitats among forest mosses (Reinikainen et al. 2000). In many cases plants reach their highest dimensions in the most fertile sites.

The age of plant (i.e. developmental stage) determines also plant size. Illustrative figures are shown for *Pinus sylvestris* and *Vaccinium myrtillus* (Table 1, Figs. 1 and 2). Some examples on determination of ellipsoids for pine are also demonstrated (Fig. 1). There are two options: consider tree crown and stem below crown separately, or consider the whole tree. ICRP (2008) also suggested that tree crown could be analysed as a one-level sheet.

Table 1. Dimensions (cm) of selected key plant species.

<table>
<thead>
<tr>
<th>Species</th>
<th>Class/source</th>
<th>Width</th>
<th>Length</th>
<th>Height</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Pinus sylvestris</em></td>
<td>1-year-old seedling</td>
<td>3^1</td>
<td>3^1</td>
<td>10^1</td>
</tr>
<tr>
<td></td>
<td>&lt;10 yrs old</td>
<td>200^1</td>
<td>200^1</td>
<td>500^1</td>
</tr>
<tr>
<td></td>
<td>&lt;100 yrs old</td>
<td>500^1</td>
<td>500^1</td>
<td>1200^1</td>
</tr>
<tr>
<td></td>
<td>150 yrs old</td>
<td>800^1</td>
<td>800^1</td>
<td>1000^1</td>
</tr>
<tr>
<td></td>
<td>BSD2009, crown^2</td>
<td>100</td>
<td>100</td>
<td>475</td>
</tr>
<tr>
<td></td>
<td>BSD2009, stem^2</td>
<td>10</td>
<td>10</td>
<td>475</td>
</tr>
<tr>
<td><em>Vaccinium myrtillus</em></td>
<td>BSD2009^2</td>
<td>15^2</td>
<td>15^2</td>
<td>20^2</td>
</tr>
<tr>
<td><em>Trientalis europaea</em></td>
<td>Literature</td>
<td></td>
<td></td>
<td>5 – 20^4</td>
</tr>
<tr>
<td><em>Deschampsia flexuosa</em></td>
<td>BSD2009^2</td>
<td>50</td>
<td>50</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>Literature</td>
<td></td>
<td></td>
<td>30 – 70^4</td>
</tr>
<tr>
<td><em>Pleurozium schreberi</em></td>
<td>BSD2009^2</td>
<td>2^2</td>
<td>3.5^2</td>
<td>2^2</td>
</tr>
<tr>
<td></td>
<td>Literature</td>
<td></td>
<td></td>
<td>5 – 10^5</td>
</tr>
<tr>
<td></td>
<td>Part of population^6</td>
<td>60^6</td>
<td>80^6</td>
<td>5 – 10^5</td>
</tr>
</tbody>
</table>

1^ Hypothetical dimensions for crown of tree including part of stem
2^ Haapanen et al. 2009; crown= crown of tree including part of stem, stem= stem of tree below crown
3^ Measured samples, see Fig. 2
4^ Hämet-Ahti et al. 1986, Mossberg & Stenberg 2005
5^ Jahns 1980
6^ E.g. on stone surface
Fig. 3. Examples of ellipsoid geometry for *Trientalis europaea* (with rhizomes, on the left side) and *Deschampsia flexuosa* (perennial grass, on the right side). Drawing: A. Hamari / Metla.

Fig. 4. Red-stemmed feather-moss (*Pleurozium schreberi*) population on the left side and few individual mosses on the right side (Photos: L. Aro / Metla).

Challenges in determination geometries for species that have plant parts with distinctively features are presented in Figure 3. *Trientalis europaea* grows annually one to three superficial rhizomes which should be included in ellipsoid geometry. *Deschampsia flexuosa* is a typical example of perennial grasses with narrow leaves growing from the base and inflorescences with stems. In the case of this grass ellipsoids...
can be considered separately for inflorescences and leaves, or consider the whole plant which may be difficult due to the unbalanced biomass distribution in the grass.

Many plant species grow in dense populations, such as *Pleurozium schreberi* (Fig. 4). In this case ellipsoids can be determined for single moss or for a part of moss population. If the approach of single moss is used then neighbouring effect of other mosses should also be considered in dose assessment.

**Implications for dose assessment**

By keeping the other parameters constant and varying the size of *Vaccinium myrtillus* according to Table 1 (18·4·6, 20·15·15, 25·10·18, 35·25·30 cm), the dose conversion coefficients (DCC) for internal low beta or external radiation do not change, but those for internal beta/gamma radiation increase 0.1 to 130% from the smallest to the largest ellipsoid. For the two nuclides contributing most to the dose rate, Cl-36 and I-129, the increase is 1 and 17%, respectively.

Concerning the total absorbed dose rate to the different sizes of *Vaccinium myrtillus*, similar trend is observed but in more modest extent: compared to the smallest, the dose rate to the largest ellipsoid is 1% higher.

Similarly, for the *Pleurozium schreberi* the DCC for internal beta/gamma radiation and the total dose rate are higher for the part of the population (10·60·80 cm) compared to the ellipsoid representing an individual (2·3·5·2 cm; see also Fig. 4): The increase in the DCC is 0.4 to 190% (Cl-36 4%, I-129 27%) and the increase in the total dose rate is 4%, mostly explained by the contribution of chlorine and iodine.

It needs to be noted that these results are for the latest Posiva's assessment case producing highest exposure to the terrestrial biota (see above), and not for unit activity concentrations most commonly applied with the biosphere part decoupled from the rest of the safety assessment.

Anyway, even if the uncertainty from the organism size in the total dose rate remains much smaller than the notoriously large overall uncertainties in the biosphere assessments, there is an effect – provided that the ellipsoidal geometry assuming a phantom density of 1 g/cm³ and a substitute-material composition (ICRP 2008) is valid. For the external exposure the size does not matter, in this case, but the variation in the DCC of internal radiation infers that the geometry might have a role. At least, if the ellipsoids are used to represent also plants of varying actual shape, it appears that appropriate ellipsoid dimensions could be obtained only by careful scaling and bearing in mind the composition of the phantom and the role of the combined effect of concentration ratio and weight in the case of internal exposure. However, for screening purposes the simple ellipsoids and their casual dimensioning seem to produce robust enough results, provided that the screening limits are then set appropriately.

**Conclusions**

In the selection of the representative species and estimating their size should be done in the context of the site conditions. Furthermore the life stage, or age, of the plant should be taken into account. This means that ideally the sizes should be weighted with site type and plant age distributions of the area of the dose assessment, which actually is out of any reasonable resources. However, despite of large variation in plant dimensions and consequently in ellipsoids derived from them, differences in calculated doses
remained quite minor in comparison with the overall uncertainties in the dose assessment. However, to improve the overall confidence to the assessment, some site-specific measurements of the selected reference species should be carried out.

It seems that the approach of using ellipsoids to represent plants in the dose assessment is reasonably robust especially for screening purposes. Still, in a graded approach to assessment, the level of conservativeness (overestimation of the doses) should decrease and realism increase with subsequent tiers. In the case of plants, there appears to be little justification for the use of the geometry – showing that size does not matter in a context of a dogmatic use of fixed geometries does not self-validate the approach; it only shows that the output is not sensitive to the dimensions. As the discussion is lacking at least from the main level documentation of the recent methodological descriptions, it is difficult to find confidence on that using an ellipsoidal geometry also for plants, of which many actually looks very different in shape, would be more conservative than a more characteristic geometry (e.g. a plate or a set of slabs). This is especially when the question comes to scaling the plant's physical dimensions to correspond the ellipsoid of uniform 1 g/cm³ matter substitute.

Even though the doses to biota are expected to remain small in the case of deep geological repositories (at maximum in the order of $10^{-3} \, \mu$Gy/h to terrestrial organisms in the plausible calculation cases of Posiva (Hjerpe et al. 2010), i.e. three orders of magnitude below the screening value recommended by Beresford et al. (2007)), further work on the dose assessment for plants seems useful at least to improve the conceptual basis and confidence to the approach. It is required that the assessment shall overestimate the consequences, but it shall not be overly conservative (YVL 8.4, YVL E-5); a better conception of the degree of realism of estimating doses to plants would have its use.

References


Assessment of critical doses for reproduction and survival of cultivated plants

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Abstract
The aim of the study is to estimate radiation doses that are critical for sustainability of agrocenosis. Available information on dose dependences in such umbrella endpoints as reproductive potential, survival, morbidity, alterations in morphological and biochemical processes, genetic effects in crops, vegetables, fruit trees, etc are gathered from papers issued mainly in Russian scientific press during last 50 years. Data are maintained as database in MS Access that contains about 7000 entries; the work is ongoing. Quantitative data obtained from different sources are transformed in relative units, which makes possible analysing unified arrays referred to specific endpoints. As critical, there are considered doses producing 50% changes of biological effect at acute impact, or dose rates resulting in 10% changes at chronic exposure of plants. There are three main exposure situations for plants: acute irradiation of seeds, acute and chronic exposure of vegetating plants. Critical doses and dose rates are assessed from dose-effect dependences constructed with data sets, referred to indexes of reproduction and survival. It is found that data on survival collected so far are rather insufficient to estimate critical dose (rates) for species of cultivated plants. From the available information, the predicted no-effect doses and dose rates for agrocenosis are estimated basing on reproduction endpoint. They range within 67÷80 and 15÷17 Gy at acute exposure of the most radiosensitive species in dormant and vegetation periods, correspondingly, and 3÷10 mGy/h at chronic exposure of vegetating plants. The estimates obtained are going to be improved with further development of the database and treatment approaches.

Introduction
In recent years many efforts have been undertaken to develop a system of radiation protection for non-human biota (ICRP 2003, 2009). Agrarian ecosystems are of special concern from the viewpoint of establishing safe levels of radiation impact on the environment. On one hand, their contamination can affect human health via radionuclide uptake with food. On other hand, agroecosystems are ones of the most sensitive to a number of environmental impacts including ionising radiation (Agricultural radioecology 1991). While the existing system of radiation standards (ICRP 2007) is effective in providing radiation protection of human and restricts...
radionuclides content in food chains, there are no guidelines on setting any limitations to directly protect agrarian ecosystems from negative effect of radiation. The aim of this work is to develop methods for an assessment of critical doses and dose rates that can result in significant radiation-induced effects in agroecosystems. This is realized on an example of cultivated plants which are one of the main components of agroecosystems since cultured plants not only contribute essentially to food production but also fulfil an important ecological function in agrarian biocenosis.

**Material and methods**

Available information on radiation-induced effects in cultured plants are being gathered from papers issued mainly in Russian scientific press during last 50 years; the work is ongoing. Data are maintained as database in MS Access that now contains about 2000 records from 134 original sources. There are available about 7000 entries which are pairs of “exposure level – biological effect” data accompanied with information on experimental design, species and its life stage, exposure parameters and conditions. Most information collected concern radiation effects in crops, vegetables and roots, as well as legumes – 39%, 22% and 17% of all entries, correspondingly.

Biological responses are grouped under umbrella endpoints of reproduction, survival, morbidity, morphological changes, biochemical changes, and (cyto)genetic effects. Only data on reproduction and survival endpoints are presented here. The first group pools traits of biological productivity (seed and straw mass, dry and wet biomass, number of plants per 1 m², etc) and reproductive potential (portion of fertile pollen seeds, fertility/sterility, number or portion of male and female flowers, etc). The later group indexes are germination rate (in field or in laboratory), survival of germinated seeds or plants by certain time/day, etc. To standardize the data sets, biological responses are expressed as percentages of corresponding controls, which makes possible analysing unified arrays formed of data obtained from different original sources.

Reproduction and survival data are estimated for three possible scenarios of radiation impact on cultivated plants: acute exposure of seeds, acute or chronic exposure of plants during vegetation. Following an approach proposed by (Garnier-Laplace et al 2006, 2008), the dose giving 50% change in observed effect (ED₅₀) is considered as the critical dose for acute exposure, and the critical dose rate for chronic exposure is defined as the dose rate resulting in 10% change of observed effect (EDR₁₀). Dose(rate)-response dependences are reconstructed for individual species using the linear model as the simplest approximation. An assessment of uncertainties in estimated critical doses is illustrated in Fig. 1 on an example of data on reproduction in wheat after seeds’ acute exposure. The main effect is fitted with a linear dose-effect function. For every dose value, a 95% confidence interval (CI) for predicted response is calculated (Draper & Smith 1981). A CI width is not constant but increases along with shifting up or down from the median dose. Dose dependences for the upper and down margins of CIs (dotted lines in Fig. 1) are fitted with linear-quadratic model, and their intersections with the 50% effect level (dashed line in Fig. 1) are found. Thus, for the example in Fig. 1 the ED₅₀ = 182.3 Gy, 95% CI = 167.3÷202.8 Gy. In several cases the linear-quadratic fit of the upper CI margin always is over the 50% effect level. Then, a linear model is used to fit the CI margins; these cases are marked below.
Assessment of critical doses for reproduction and survival of cultivated plants

**Results**

**Acute exposure of seeds**

Information on acute exposure of seeds, bulbs, tubers, and other planting stock for cultivated plants is respectively well represented in Russian scientific literature because of a period of radiobiological researches when a pre-sowing irradiation was considered as a possible mean to increase harvest, resistance to diseases and other economical benefits for farming. In the database, 1124 records (4028 pair entries) refer to this exposure scenario which is about 67% of data used to reconstruct dose dependences. A short description of corresponding data collected so far including maximum dose used in original works and numbers of records and paired entries for crops, legumes, vegetables and other cultivated plant species are presented in Tables 1 for reproduction and survival endpoints. Fig. 2 illustrates data on reproduction in crops and their linear fittings. For most species, a linear model fits the data well (p<5%).

On reproduction, carrot appears to be the most radioresistant (ED_{50}=1244.6 Gy). The radiosensitive species are onion and potato as an acute exposure of tubers and bulbs before germination to estimated critical doses of 33.8 Gy and 66.6 Gy, correspondingly, would result in the 50% loss of their productivity. Legumes are also quite sensitive, since bean reproduction reduces twice after 57.0 Gy of acute seeds exposure. Crops show intermediate radiosensitivity with ED_{50}=180-350 Gy.

On survival, carrot is most resistant again (ED_{50}=902.5 Gy). Cotton plants are also very resistant at seeds irradiation (ED_{50}=629.7 Gy). Wheat and corn show the level of radiosensitivity (ED_{50}=222-230 Gy) similar to that on reproduction. There are obtained the very low estimated critical doses for barley and rye (the 95% CIs are within 14÷24 Gy); it is because of very little information taken from a single paper only, and a narrow dose range studied – only up to 5 Gy, which is completely

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**Fig. 1.** Standardized data (% of control) on reproduction in wheat after seeds’ acute exposure, and estimation of the ED_{50} and its uncertainty.
insufficient. For other cultivated plants data volumes on survival indexes are also very limited (N<10, Table 1) which often results in poor fitting (p>10%).

Table 1. Critical doses ED_{50} for reproduction and survival at acute exposure of planting stock.

<table>
<thead>
<tr>
<th>Species</th>
<th>Reproduction</th>
<th>Survival</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crops</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barley</td>
<td>200</td>
<td>20</td>
</tr>
<tr>
<td>Wheat</td>
<td>200</td>
<td>26</td>
</tr>
<tr>
<td>Rye</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corn</td>
<td>100</td>
<td>8</td>
</tr>
<tr>
<td>Legumes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bean</td>
<td>50</td>
<td>4</td>
</tr>
<tr>
<td>Peas</td>
<td>80</td>
<td>4</td>
</tr>
<tr>
<td>Soya</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Vegetables and roots</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carrot</td>
<td>1500</td>
<td>2</td>
</tr>
<tr>
<td>Cucumber</td>
<td>400</td>
<td>16</td>
</tr>
<tr>
<td>Onion</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Tomato</td>
<td>30</td>
<td>76</td>
</tr>
<tr>
<td>Pepper</td>
<td>18</td>
<td>8</td>
</tr>
<tr>
<td>Beet</td>
<td>50</td>
<td>6</td>
</tr>
<tr>
<td>Potato</td>
<td>30</td>
<td>16</td>
</tr>
<tr>
<td>Others</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cotton</td>
<td>300</td>
<td>82</td>
</tr>
<tr>
<td>Sunflower</td>
<td>200</td>
<td>36</td>
</tr>
<tr>
<td>Tobacco</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

D_{max} – maximum dose; N – number of records; N_p – number of entries presenting pairs of “exposure level – biological effect” data; (i) – a linear model is used to fit the CI margins; NE – value could not be estimated; goodness-of-fit on the Fisher test: * - p<10%, ** - p<5%, *** - p<1%.
For several species (barley, soya, beet, sweet pepper, and tomato at reproduction analysis, and cucumber at survival analysis) critical doses could not be estimated because of a) dose ranges of negative radiation effect are not covered in the works available, or b) large data variance and poor fittings (p>10%).

Despite respectively large in number, data on radiation effects in plants after acute exposure of seeds and other planting stock are not well suited for a purpose of a critical radiotoxicity values estimation, since original researches were mainly aimed at studying hormetic effects of radiation and often do not cover doses producing negative effects in plants. Thus, a better reproduction or lower survival in comparison to a control is shown by about 37% of the database entries refered to the scenario of seeds exposure. Stimulation could reach up to 500%. Although from the viewpoint of developing safety standards at radiation exposure of biocenoses, biological effects of low doses are of special interest, however, a correct interpretation of this kind of data is possible only when detailed information on radiation effect in the whole dose range – from stimulating to harmful – is available.

**Acute exposure of plants during vegetation**

Studies of radiation effects at total or partial exposure of plants during ontogenetic development are not very large in number. There are certain limitations for such researches such as an availability of special equipment at γ-fields or in greenhouse experiments, providing homogeneous radiation fields, dose and dose rate measurements, etc. At the moment, reproduction in the database is presented by 330 pair entries that mainly refer to radiation effect in crops (Table 2); survival was studied only in one work with cherry tree cuttings’ irradiation. Study design in these works was more homogeneous than at acute seeds exposure. Mostly, γ-sources are used, and dose ranges studied are similar. Radiosensitivity of plants much depends on a stage of ontogenesis at the moment of irradiation, but unfortunately, the available data are not enough to analize dose dependences for an every development stage. Radiation resulted in decreasing of reproduction and survival in all studied species excluding apple tree,
where acute exposure of pollen produced a better ability of trees to set fruits and seeds.

For reproduction data, the linear fitting appears good for all species (Table 2). The less sensitive species is potato (ED$_{50}$=45.8 Gy) in the first and second generation after parent plants’ acute exposure at different stages of ontogenesis. Cotton plants also shows high resistance with the estimated critical dose of 36.8 Gy. In crops variety, an assessment of doses leading to 50% loss of productivity gives the similar values (Fig. 3, Table 2). The most and the less radiosensitive are barley (95% CI = 14.6±16.6 Gy) and rye (95% CI = 25.7±37.5 Gy), respectively.

Table 2. Critical doses ED$_{50}$ and dose rates EDR$_{10}$ for reproduction and survival at acute and chronic exposure of vegetating plants.

<table>
<thead>
<tr>
<th>Species</th>
<th>Acute exposure</th>
<th>Chronic exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$D_{\text{max}}$, Gy</td>
<td>N</td>
</tr>
<tr>
<td>Reproduction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crops</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barley</td>
<td>30</td>
<td>46</td>
</tr>
<tr>
<td>Oats</td>
<td>45</td>
<td>10</td>
</tr>
<tr>
<td>Rye</td>
<td>35</td>
<td>5</td>
</tr>
<tr>
<td>Wheat</td>
<td>60</td>
<td>31</td>
</tr>
<tr>
<td>Others</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Apple</td>
<td>90</td>
<td>9</td>
</tr>
<tr>
<td>Black-currant</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cherry</td>
<td>20</td>
<td>5</td>
</tr>
<tr>
<td>Grape</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peas</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Potato</td>
<td>30</td>
<td>23</td>
</tr>
<tr>
<td>Survival</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cherry</td>
<td>30</td>
<td>9</td>
</tr>
<tr>
<td>Peas</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rye</td>
<td>0.3</td>
<td>1</td>
</tr>
<tr>
<td>Wheat</td>
<td>0.2</td>
<td>4</td>
</tr>
</tbody>
</table>

$DR_{\text{max}}$ – maximum dose rate. Other designations and marks are the same as in Table 1.
Assessment of critical doses for reproduction and survival of cultivated plants

Chronic exposure of plants during vegetation

Works on chronic exposure of vegetating plants are the most scarce. In the database, only 63 and 7 records refer to reproduction and survival, respectively, for this exposure scenario (Table 2). Experimental design varies: plants’ exposure in γ-field, soil contamination with radionuclides in controlled conditions or growing plants at territories contaminated in radiation accidents. Dose and dose rates range up to 4-5 orders of magnitude – from 10 mGy to 20 Gy, and from 1 μGy/h up to 500 mGy/h. But, the case of chronic exposure is the most interesting in terms of establishing the critical radiotoxicity values. Data on reproduction indexes gathered for cultivated plants are shown in Fig. 4. To fit dose rate – effect dependence, a linear model is used as before. The estimated critical dose rates giving the 10% decrease in biological response are presented in Table 2. In most species, chronic exposure decreases reproduction and survival (Fig. 4). Stimulating effect is observed in rye and cherry trees on reproduction, and in wheat on survival, but data volumes in these cases are limited.

For reproduction endpoint, the least value of $EDR_{10}=3.2$ mGy/h is obtained for grape in which the number of fruiting branches decreased after two-year growing at γ-field. In crops, the critical dose rates for wheat ($EDR_{10}=3.3\pm10$ mGy/h) and barley ($EDR_{10}=173.3\pm310.7$ mGy/h) differ by a factor of 30. Possible reasons could be different study designs and incomplete dosemetric information. Thus, wheat plants were exposed in γ-field while barley data refer to both external irradiation in γ-field and mixed exposure from $^{90}$Sr-contaminated soil. In the last case, internal doses were not estimated. The other species are close in radiosensitivity and the estimated critical dose rates range from 5.9 to 11.9 mGy/h (Table 4).

Survival indexes are taken from 3 papers, but neither of them gives a good example of a study on chronic radiation effect in vegetating plants. For rye, data on a germinating ability of seeds collected in August, 1986 from the 10-km zone of the Chernobyl NPP are used. The estimated critical dose rate of $EDR_{10}=0.24$ mGy/h is very low. To understand this data properly, it should be taken into that the parent plants not

Fig. 3. Standardized data (% of control) on reproduction in crops after acute exposure of vegetating plants and their fittings with a liner model.
only experienced chronic radiation with dose rate dramatically changing during the whole period of vegetation, but also they were acutely irradiated in the initial period after the Chernobyl accident (May-June). At the moment of harvesting, contamination density of soils with $^{137}$Cs at the study sites reached 800 MBq/m$^2$. So, this case should not be used to estimate derived radiation levels of chronic exposure. For peas, data are considered on the 24-day survival of seedlings after 12-hour imbibition of germinated seeds in $^{90}$Sr solution, and $EDR_{10}=158.6$ mGy/h is obtained. However, duration of radiation impact is too short in comparison to life time to consider these data as useful for establishing critical radiotoxicity values.

In total, there is a lack of acceptable information on effects of chronic radiation in cultivated plants. The data available are few and scarce, methods and study designs are very different, dosemetric information is incomplete. A part of studies do not contain calculated and measured doses and dose rates. In some works, only data on radioactive contamination are presented (radionuclide activity in soil or plant tissues, contamination density, etc). Internal exposure is rarely taken into account at dose assessments.

![Graph showing standardized data on reproduction in crops after chronic exposure of vegetating plants and their fittings with a linear model.](image)

**Fig. 4. Standardized data (% of control) on reproduction in crops after chronic exposure of vegetating plants and their fittings with a linear model.**

**Discussion**

The estimated critical doses and dose rates can be used to derive the predicted no-effect dose (PNED) and dose rate (PNEDR). The lowest short-term ED$_{50}$ and long-term EDR$_{10}$, which characterize radioresistance of the most sensitive species on the most affected umbrella endpoint, can be considered as the first approximation for the PNED and PNEDR in argocenosis. However, the quality and quantity of the primary data influence the safety of the estimated levels. Datasets collected from the original sources are very heterogeneous both in terms of materials and methods used and the data volumes available. To provide a certain confidence in the PNED and PNEDR values,
an additional requirement of a minimal number of records $N \geq 10$ is applied to select the ‘well-defined’ values of $ED_{50}$ and $EDR_{10}$. In Table 3 the minimal $ED_{50}$ and $EDR_{10}$’s are presented that fulfill the agreed requirement for the three radiation scenarios.

Table 3. Critical doses and dose rates for the most sensitive species for different scenarios of radiation impact on cultivated plants, and the corresponding PNED and PNEDR values.

<table>
<thead>
<tr>
<th>Exposure scenario</th>
<th>Reproduction</th>
<th>Survival</th>
<th>PNED(R)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acute exposure of seeds</td>
<td>$ED_{50} = 182.3 \pm 202.8$ Gy at wheat seeds exposure</td>
<td>$ED_{50} = 221.9 \pm 241.6$ Gy at corn seeds exposure</td>
<td>$170 \pm 200$ Gy</td>
</tr>
<tr>
<td></td>
<td>$ED_{50} = 66.6 \pm 79.9$ Gy at potato tubers exposure</td>
<td></td>
<td>$67 \pm 80$ Gy</td>
</tr>
<tr>
<td>Acute exposure of vegetating plants</td>
<td>$ED_{50} = 15.6 \pm 16.6$ Gy for barley</td>
<td>No data</td>
<td>$15 \pm 17$ Gy</td>
</tr>
<tr>
<td>Chronic exposure of vegetating plants</td>
<td>$EDR_{10} = 6.8 \pm 10.0$ mGy/h for wheat</td>
<td>No data</td>
<td>$3 \pm 10$ mGy/h</td>
</tr>
</tbody>
</table>

Minimal $ED_{50}$ and $EDR_{10}$ are chosen from Tables 1 and 2 following the requirement of $N \geq 10$.

From the above consideration it is obvious that data on survival collected so far are rather insufficient to estimate the critical radiotoxicity values. Radiosensitivity of two umbrella endpoints analysed (reproduction and survival) could be compared only for the case of acute seeds exposure (Table 3). According to the findings of this work, reproduction is more sensitive criteria than survival. It is well known that half-lethal doses often result in the full loss of productivity for most domesticated plants (Agricultural radioecology 1991). In terrestrial plants, the dose reducing survival by 10% is roughly equivalent to the dose reducing the yield by 50% (UNSCEAR 1996). (UNSCEAR 2008) also considers that reproductive changes are a more sensitive indicator of radiation effect than mortality. So, reproduction endpoint is used to derive PNED(R)s in this study. Consequently, at acute exposure of the most radiosensitive species in dormant and vegetation periods the PNEDs for agroecoses amounts to $67 \pm 80$ and $15 \pm 17$ Gy, correspondingly, according to the data gathered so far. At chronic exposure, the PNEDR is within $3 \pm 10$ mGy/h.

There is a number of uncertainties that influence the estimates derived. They emerge from pooling field and laboratory based studies, different ontogenetic phases, various biological effects under one umbrella endpoints, etc. There are also some shortages in dose (rate) determination and data statistical confidence for certain datasets. Typically, the safety factors method is applied to assure a security of finally derived safe levels of radiation impact.

Authorized international organisations proposed guideline dose rates below which a population level effect in wildlife is unlikely to be induced. According to the last recommendations (UNSCEAR 2008) chronic dose rates of less than 0.1 mGy/h for terrestrial communities and acute exposure of non-human biota at doses below about 1 Gy would be unlikely to have significant effects. The PNEDR equal to 10 $\mu$Gy/h was derived with the ERICA Integrated Approach (Garnier-Laplace et al. 2008). At this, mammals are regarded as the most sensitive of all non-human organisms. Taking into account that cultured plants discussed are commonly more resistant than mammals as well as the further lowering of the estimated PNED(R) due to their dividing by a safety
factor, the findings of this work can be considered non-contradictory to the existing guidelines.

The estimates presented here are the first derivation of PNED(R)s for agrarian biocenoses. They are going to be improved with further development of the database and methods for data treatment. In particular, other endpoints are expected to be analysed, and different fitting models, including logistic, would be applied.

References


Preliminary results on Cernavoda NPP operation impact on terrestrial and aquatic biota

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2 National Institute R&D for Cryogenic and Isotopic Technologies, Rm. Valcea, ROMANIA

Abstract
Recently, the awareness of the vulnerability of the environment has increased and the need to protect it against industrial pollutants has been recognized. The concept of sustainable development, requires new and developing international policies for environmental protection. (Protection of the environment from the effects of ionizing radiation. IAEA-TECDOC-1091. International Atomic Energy Agency, Vienna.). As it is recommended in “Cernavoda Unit #2 NPP Environmental Impact Assessment it is Cernavoda NPP responsibility to conduct an Ecological Risk Assessment study, mainly to assess the impact of Nuclear power plant operation on terrestrial and aquatic biota. Long records from normal operation of Cernavoda Unit 1, wind pattern, meteorological conditions, and upgread source terms data were used to evaluate areas of interest for environmental impact, conducting to a circle of 20 km radius around mentioned nuclear objective. The screening campaign established tritium level (because Cernavoda NPP is a CANDU type reactor, and tritium is the most important radioisotope evacuated in the environment) in air, water, soil and vegetation, focusing the interest area on particular ecosystem. Using these primary data it was evaluated which are the monitored ecological receptors and which are the measurement endpoints. This paper presents the Ecological Risk Assessment at Cernavoda NPP technical requirements, and the preliminary results of evaluating criteria for representative ecosystem components at Cernavoda NPP.