Radioprotection of the environment: recent advances in nuclear ecotoxicology research

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Abstract:
Funding for radioecology in Europe escalated after the Chernobyl accident, and remained elevated for some 15 years. The enhanced funding permitted Europeans to explore new directions in radioecology, particularly in the area of effects to non-human biota. Herein we highlight several recent advances: 1) an attempt to merge environmental risk analysis methods for radioactive contamination with those for other pollutants using species sensitivity distributions; 2) attempts to extrapolate damage observed in individual organisms to potential effects in their populations; and 3) the use of advanced models to estimate and explain changes in an individual's energy allocation as a result of exposure to low doses of radionuclides. We conclude by presenting the radioecology Alliance: an international network whose goal is to integrate resources in order to efficiently fill knowledge gaps in radioecology and improve risk assessments tools that support both human and environmental radioprotection.

1 BACKGROUND

1.1 Basic lines

Radioecology is a branch of environmental sciences devoted to a specific category of stressors *i.e.* natural and artificial radioactive substances. This science includes key issues that are (i) common with other groups of pollutants, particularly metals (*e.g.,* transport, fate, speciation, bioavailability, biological effects at various organisational levels) and (ii) specific to radionuclides (*e.g.,* external irradiation pathway, radiation dosimetry, decay products) [1].

From an operational point of view, radioecology gathers all the environmental-related knowledge necessary to provide the key elements to perform an assessment of the impact or risk of radioactive substances on man and the environment. Ideally, integrated Environmental Impact (Risk) Assessment (EIA/ERA) may be done in parallel for both non-human species (demonstrating the protection of the ecosystem *per se*) and for humans (and for both chemicals and radioactive substances). Ecological (Human) Risk is an estimation of the probability (or incidence) and magnitude (or severity) of the adverse effects likely to occur in an ecosystem or its sub-organisational levels (in human individuals or groups), together with identification of uncertainties. The Environmental Impact (or Risk) Assessment is generally implemented through a tiered-approach, from the initial screening tier using simple models and conservative assumptions, to higher tiers using site specific models and data associated with Sensitivity/Uncertainty analysis for a proper interpretation of the impact or risk. The basic components of any EIA (or ERA) are presented in Figure 1. They comprise exposure and effects analyses integrated through risk characterisation. Today, even if existing knowledge on transport, transfer, dosimetry and biological effects are extensively used to implement an ERA-type approach, many major research challenges still remain in radioecology. This paper only deals with one of the discipline of radioecology, *i.e.* nuclear ecotoxicology; in which the operational outcomes are useful for regulatory needs in the field of environmental radioprotection.

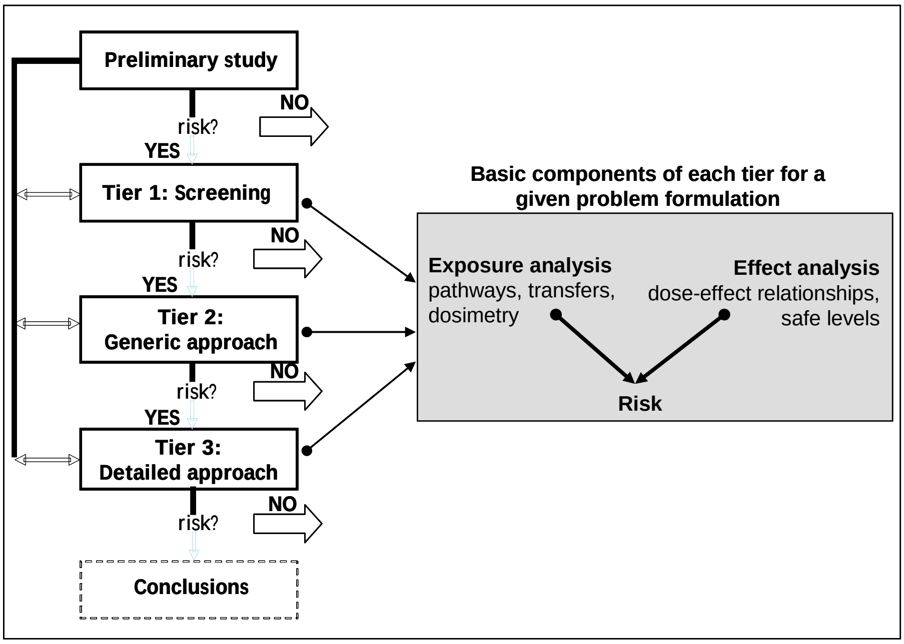

Figure 1: *General scheme of a tiered approach (left side) and its basic components (right side) used for Environmental Impact or Risk assessment regardless if the object of protection is humans or ecosystems and if the category of pollutants is stable or radioactive substances.*

1.2 Focus on the radioprotection of the environment

The need for a system to protect the environment from ionising radiation has, over the past decade, been recognised internationally. The ICRP has addressed environmental protection as an element of the revision of its recommendations [2] and released underlying concepts [3]. Environmental protection is now referred to in the International Atomic Energy Agency's Fundamental Safety Principles [4]. Moreover, both the International and Euratom Basic Safety Standards (BSS) currently under revision, consider the inclusion of radioprotection of the environment. Within Europe only the UK, Sweden and Finland appear to currently regulate specifically to protect the environment rather than relying on previous ICRP statements. The recommendations of the ICRP and changes in both the IAEA and the Euratom BSS are likely to lead to a change in this situation. As more member states regulate specifically for the environment in forthcoming years, regulators and industry will require the support of radioecological expertise.

Within this framework, this paper reports on some major advances in: 1) making environmental risk analysis methods for radioactive contaminants consistent with those for other pollutants; 2) extrapolating damage observed in individual organisms to potential effects in their populations; the latter being more relevant with regard to ecological protection. Additionally, we list the lines of research that have been prioritized to enhance our capability of predicting environmental effects of radionuclides under the realistic conditions in which organisms are actually exposed, i.e. mainly chronic low dose exposure to muti-contaminants.

2 SOME RECENT ADVANCES IN NUCLEAR ECOTOXICOLOGY

A major overarching challenge for nuclear ecotoxicology is to develop efforts to align environmental risks assessments from radiological exposures with the methods used in ecotoxicology for other types of contaminants [5]. The science of ecotoxicology, however, is also troubled with procedural difficulties, large uncertainties, and the current need to extrapolate results generated on individual organisms to predicted responses at the population and community levels [6]. To counter the uncertainty, extrapolation factors (also called Assessment Factors AFs) are used to incorporate precautionary safety in the risk estimates. AFs increase the conservatism in risk estimates by safety factors up to 10000, and indicate the level of uncertainty in predicting environmental effects. Reducing extrapolation and the associated conservatism in environmental risk assessments has been identified as a major research need in environmental sciences [7]. New knowledge and methods are needed in both ecotoxicology and radioecology that will permit the development of science-based rules experimentally validated for confidently extrapolating from simple to more complex biological/ecological systems [8].

2.1 How to integrate environmental risk assessment methods for radionuclides and chemicals?

In Europe, the technical guidance document for chemicals [9] and recently the ERICA integrated approach for radionuclides [10], recommend the use of a Screening Tier (or Screening Level Ecological Risk Assessment, SLERA) as the initial step in a risk assessment. SLERA can be used to evaluate the potential for contaminants emissions to put the receptor ecosystems at risk or not. Beyond this ERA-type approach, one major challenge still remaining is to gain the capability for assessing radiological impact in a comparative unbiased way to what is done for other stressors such as chemical substances. Recently we proposed to adapt a Life Cycle Assessment derived methodology to solve this issue [11]. Conducting a SLERA for releases from nuclear facilities under authorization is a challenging task because of (1) the large number of substances, (2) the various quantities that may be emitted to the ecosystems and (3) the various environmental situations to be considered. This task must be performed for two categories of pollutants, radionuclides and chemicals, each exhibiting specificities in terms of concentration in the exposure medium (- or dose) - effect relationships.

Briefly, the method calculates the ecotoxicological impacts in ecosystems (*e.g.,* freshwaters). It comprises a fate-analysis step described by a fate factor (calculation of the change in exposure from a given release) and an effect-analysis step described by an effect factor (calculation of the change in effect per unit change of exposure) [11, 12]. Ecotoxicological exposure-response is based primarily on Species Sensitivity Distributions (SSD) and the potentially affected fraction (PAF) of species as an indicator of ecosystem damages. The PAF value expresses the toxic pressure put on ecosystems due to the presence of a given pollutant and can be easily calculated homogeneously regardless the category of stressors. For example, the method allowed us to rank the routinely released substances from nuclear power plants alongside the Rhône river, on the basis of the associated ecotoxicological hazard for the watercourse and therefore to identify high-risk chemicals and/or radioactive substances for ecosystems (Figure 2). This comparative method represents a first step towards an integrated impact assessment whatever the category of stressors considered. The next step is to take account for potential interactions between the different types of stressors.

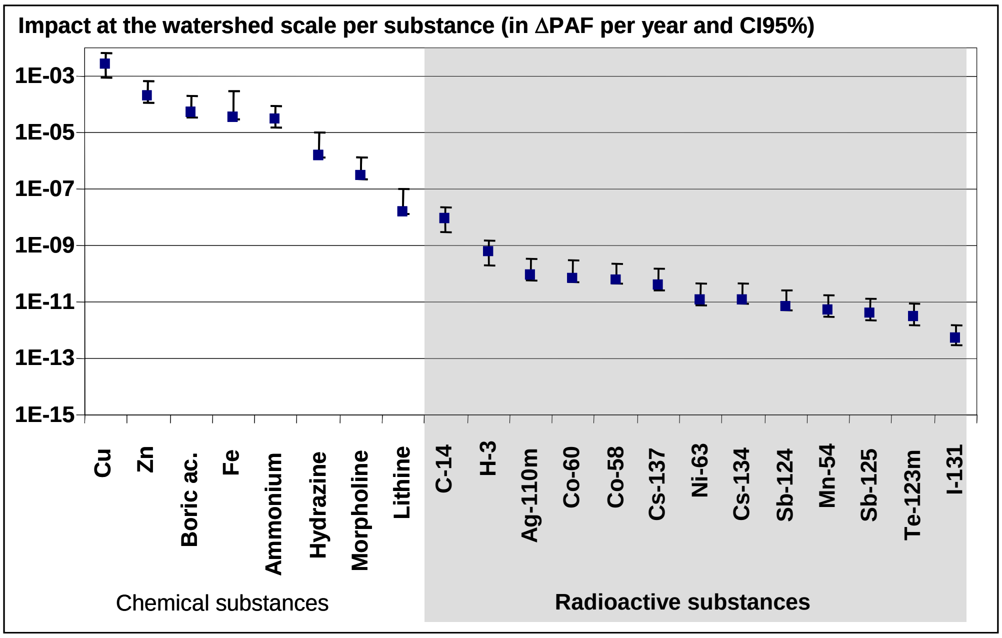

Figure 2: *Ranking of the substances realeased in the year 2005 from electronuclear power plants alongside the Rhône river according to their calculated impact at the watershed scale expressed in change of potentially affected fraction (PAF) of species.*

2.2 How to extrapolate damages observed in individual organisms to potential effects at population level?

EU regulations for protecting the environment target protection of populations and ecosystems; yet, most laboratory research on toxic effects is carried out at an individual level (*e.g.,* responses in growth, reproductive capacity, survival). One of the most important challenges is to extrapolate measured effects from the individual level to the population level (*e.g.,* responses in abundance, age or size structure, population growth rate, carrying capacity, genetic diversity). From a management perspective, those population-level endpoints are ecologically more relevant than health or survival of individual organisms, except when endangered species must be considered. Focusing only on individuals can lead to inaccurate estimates of risk to populations, due to the complexity and nonlinearity in the relationship between effects on individual survival, reproduction or growth and population dynamics [13].

One approach recently adopted at IRSN and currently applied to a limited number of stressors combines the use of Dynamic Energy Budget (DEB) theory and Leslie matrices. Based on simple rules for metabolism [14], the DEB theory describes how individual organisms acquire energy from food and allocate it to survival, growth, maturity and reproduction and how underlying physiological functions are perturbated under toxicant exposure. Traditionnally used to simulate population dynamics, Leslie matrices allow an integration of effects on individual survival and reproduction in terms of population growth rate. Here, we combined both approaches to predict consequences of increasing dose rates for population dynamics based on survival, growth and reproduction responses measured at the individual level. As an example, we report briefly on effects of multigenerational exposure to waterborne uranium in a freshwater invertebrate (*Daphnia magna).* Under controlled laboratory conditions, toxic effects on daphnid life history and physiology increased over a 3-generation period [15]. Uranium's primary mechanism of toxicity was identified as an inhibition of food assimilation, with strong consequences for somatic growth and reproduction. Combining DEBtox-Leslie matrix approaches, we integrated effects and predicted changes in population growth rate (λ) over the range of uranium concentration. In the second offspring generation, exposure to uranium caused toxic effects above a concentration of 2 µg.L^{-1}, the resulting decline in λ leading to population extinction above 39 µg.L^{-1} (Figure 3). A combination of the DEBtox and matrix population models has already been successfully applied to metals and organics (see *e.g.,* [16,17]). This combined approach represents a powerful tool to identify and compare underlying modes of toxic action among stressors and to assess ecotoxic consequences at the individual and the population levels. This work will be followed up under the STAR EC-funded Network of Excellence with a comparative investigation of the population consequences of chronic external gamma exposure *vs*. alpha irradiation.

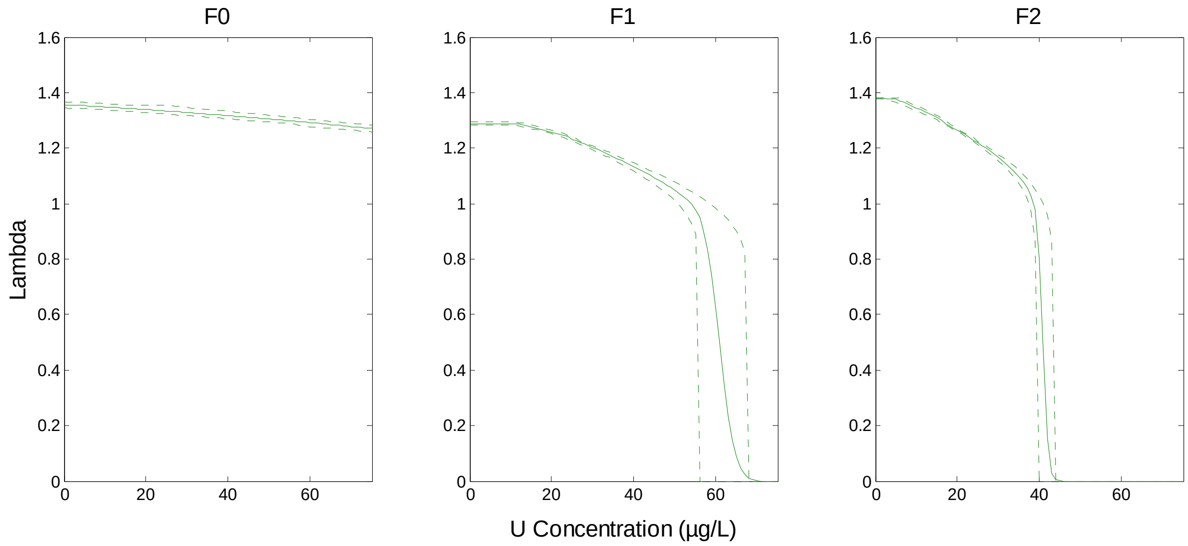

Figure 3: *Changes in population growth rate (λ) of D. magna at equilibium as a function of uranium water concentrations (µg/L) in 3 successive exposed generations. Threshold at which significant effects are detected at organismal level in F2 is 2.0 µg/L. Above this value, population grows at reduced rate and extincts at 39 µg/L (when λ<1) (from [15]).*

3 PERSPECTIVES UNDER THE EUROPEAN ALLIANCE IN RADIOECOLOGY

During the last decades, research in the field of radioecology has led to a widely recognized expertise in Europe. As pointed out in the FUTURAE project [1], there are today clear signs that key elements of this expertise are endangered. One major reason of this decline is that the research effort that was intensive during the years following the Chernobyl accident, is now regularly decreasing. Most of the National and EU funded radioecology programmes of the last decade have focused on modeling efforts and data summaries with very little attention given to the acquisition of new knowledge, especially through experiments. Although this situation has no visible consequences on the short term, it can be anticipated that, in middle and long term, the lack of competences and expertise in radioecology could have important consequences, for example in the case of a nuclear accident or for new nuclear builds. Moreover, given the worldwide so called “nuclear rennaissance” and the increased concern of the public for the impact of human activities on health and the environment, it is essential to ensure the long-term maintenance and enhancement of expertise, infrastructures and resources relating to radioecology.

In mid-2009, eight European organisations formed the European Alliance in Radioecology and agreed to operate a “revival” programme. The leaders of the eight organisations signed a memorandum of understanding for establishing a long-term strategic research agenda in order to (i) enhance the efficiency of radioecological research, (ii) share infrastructures, (iii) maintain and enhance radioecological expertise through education, training, mobility, knowledge management and dissemination. The first concrete action was to establish a proposal for a Network of Excellence in radioecology submitted in spring 2010 to the EC. The Alliance was successful and STAR, a Strategy for Allied Radioecology, will be launched in early 2011.

Several lines of research will be pursued over the next 10-15 years to address our current inability to accurately predict the environmental impacts of radioactive contaminants. Concerning more specifically nuclear ecotoxicology, we propose to focus on environmentally relevant low dose and low dose rates, including:

- multiple generational effects;
- comparative sensitivity among organisms with different life history traits; inter- and intra-species;
- comparative biological efficiency of different types of exposure pathways and radioactive emissions;
- primary modes of action from which effects are generated;
- propagation of effects to various levels of biological and ecological organisation;
- relationships of exposure concentrations (chemical speciation, bioavailability, dose) and effects
- mixed contaminants and multiple stressors.

The research conducted in this area by our Alliance will be based on hypothesis-driven laboratory and field work, with concomitant modeling and meta-analysis of data.

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