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Using an Ecosystem Approach to complement protection schemes based on organism-level endpoints

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Abstract

Radiation protection goals for ecological resources are focused on ecological structures and functions at population-, community-, and ecosystem-levels. The current approach to radiation safety for non-human biota relies on organism-level endpoints, and as such is not aligned with the stated overarching protection goals of international agencies. Exposure to stressors can trigger non-linear changes in ecosystem structure and function that cannot be predicted from effects on individual organisms. From the ecological sciences, we know that important interactive dynamics related to such emergent properties determine the flows of goods and services in ecological systems that human societies rely upon. A previous Task Group of the IUR (International Union of Radioecology) has presented the rationale for adding an Ecosystem Approach to the suite of tools available to manage radiation safety. In this paper, we summarize the arguments for an Ecosystem Approach and identify next steps and challenges ahead pertaining to developing and implementing a practical Ecosystem Approach to complement organism-level endpoints currently used in radiation safety.

Keywords: Complex ecological systems, Ecological dynamics, Indirect effects, Species interactions, Non-linearity, Wildlife

1. Introduction

Ecosystem processes underpin a range of services that are vital to the sustainability of human societies such as flood control, pollination of crops, mineral recycling, maintenance of food web structure, and climate control (MEA, 2003). Under the pressure of environmental managers and policy makers, international legislation currently expresses management goals of protection in ecological terms featuring integrated objectives of protection such as maintaining ecosystem structure (biodiversity) and functions (life support, etc.). The Convention on Biological Diversity for example recommends adopting an "Ecosystem Approach" and has identified several principles to support it (CBD, 2000). Consistent with ecosystem-oriented policies, environmental scientists in fields such as fisheries and forestry are actively developing technical tools to support ecosystem management. Overall, this trend is now rooted in a broad consensus that environmental protection is best served by methods and concepts targeting populations and their interactions with other biota and abiotic components of ecological systems or other methods that holistically consider the ecosystem level.

The emerging focus on ecosystems is not yet reflected in the current approaches for protecting the environment (i.e. non-human biota, other biota or wildlife) against radiation advocated by the ICRP (ICRP, 2008) or other similar approaches (ERICA, 2007; US DOE, 2002). All such approaches take a limited set of reference organisms as in the "Reference Animals and Plants" of ICRP (abbreviated as RAPs) mimicking the concept of "reference person" used in human radiological protection (ICRP, 2007). The ICRP RAPs were chosen using various taxonomic and practical criteria to serve as points of comparison in ecological risk assessments. The radiosensitivity of each reference organism is documented (from a wide literature survey of radio-toxicological data) in terms of radiation-induced dose–response curves for four individual organism-level endpoints: early mortality, morbidity, reproductive success, and mutation frequency. Simple dosimetric models have been developed to map measured or derived activity concentrations of radionuclides in organisms and their habitat on to absorbed dose-rates. Dose rate bands for RAPs within which certain effects have been noted, or might be expected, are then used to construct a scale of risk (ICRP, 2008) to help decision makers. The components of the system provide the basis for relating exposure to dose, and dose to radiation effects, for different types of animals and plants in an internally consistent manner. One key aspect of this method, directly evolving from traditional toxicology, is to emphasize individual organisms rather than populations or ecosystems.

As a consequence, the existing approach to radiation protection, as best illustrated by recent ICRP developments (ICRP, 2008), is based on a conceptual method linked to individual reference organisms. This approach could be sufficient to protect ecosystems only if the suite of reference organisms included the most sensitive and most highly exposed species within the ecosystem. Since it will never be possible to test the radiosensitivity of all life stages of every species and since radiation exposures are likely to vary over even very small spatial scales, we can never guarantee that the reference organism approach will protect all components of an ecosystem. Moreover, exposure to stressors can trigger non-linear changes in ecosystem structure and function that cannot be predicted from effects on individual organisms. For these reasons, the reference organism approach and the resulting protection system is largely inconsistent with respect to current management goals (Fig. 1). Development of an Ecosystem Approach to radiation protection would eliminate this inconsistency.

2. Scientific limits of current approaches

In addition to being inconsistent with evolving environmental management goals, organism-level approaches to radiation protection only partially address potential environmental effects of ionizing radiation, especially ecosystem-level effects. Ecologists have long known that perturbations induced by stressors such as harvesting (Fogarty and Murawski, 1998), species introductions (Mack et al., 2000), nutrient addition (Carpenter et al., 1998) or chemical discharges (Fleeger et al., 2003) cannot be entirely grasped from knowledge of the stressor's effects on individual organisms or single-species populations, even when addressed through statistical approaches such as species sensitivity distributions (Forbes and Calow, 2002; Garnier-Laplace et al., 2013; Posthuma et al., 2001). Such effects may act as triggers of perturbation, which propagate through higher levels of biological organization within ecosystems, with ultimate system consequences that may differ radically from those expected based on effects observed at the organism-level. In extreme cases, irreversible changes in ecosystem structure and function, termed "regime shifts," can occur (Holling, 1973; Scheffer et al., 2001, and see Section 4). These phenomena are particularly relevant when considering the potential long-term ecological effects of chronic exposure to radiation, as such impacts may not be manifested as the result of direct radio-toxicological effects on individual organisms, but rather as the consequence of indirect effects resulting from differences in sensitivity of different species, potentially leading to changes in habitat structure or altered trophic relationships (Geras'kin et al., 2008; Woodwell, 1967). For example, in an area of pine-birch forest severely affected by releases of radionuclides following an accident in the Southern Urals, the amount of light energy reaching the earth's surface increased by up to a factor of 5 and the air temperature increased by 1–2 °C. Also, at Chernobyl, changes in the microclimate and structure of grassy communities within the area of dead pine stands and severely affected birch stands led to a 2–3 fold increase of grass-cover biomass (Alexakhin et al., 2004).

Such shortcomings in the protection frameworks have already been recognized and discussed in other fields of environmental protection (Tannenbaum, 2005), and have also been stressed in the area of radiological protection (Bréchignac, 2003; Bréchig-

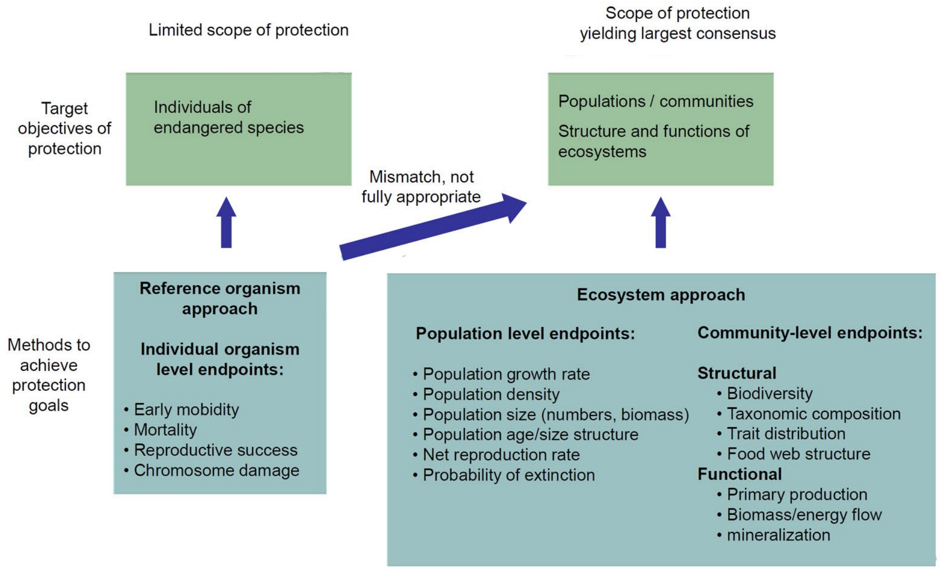

Figure 1. Target objectives of environment protection versus methods to achieve them.

nac, 2009; Bréchignac et al., 2012; Doi et al., 2005; Fuma et al., 2003; Hinton and Bréchignac, 2005). Methods for managing indirect effects and for detecting adverse changes in ecosystems before they become severe are now being developed (Forbes and Calow, 2013; Knights et al., 2013; Scheffer et al., 2009).

Organism-level endpoints (including reference organisms) or Species Sensitivity Distributions (SSDs) constructed upon organism-level data cannot capture the dynamic interactions between populations or forecast effects due to multiple stressors acting concurrently or sequentially in typical environmental settings. Almost all tests are performed under optimal or near optimal conditions for the test organisms, are often based on acute exposures and on time scales that do not provide information about multigenerational effects or indirect effects in the ecosystem. For example, De Laender et al. (2008) performed standard SSD analyses for 1000 hypothetical toxicants in a six-species ecosystem computational model and compared these with modified SSDs where species interactions were included. For 25% of the toxicants, the values for PNEC and NOEC (Predicted No Effect Concentration, No Observed Effect Concentration) varied by a factor of ten between the two models.

3. Key elements of the Ecosystem Approach as suggested by IUR

Possible guidelines for the application of an Ecosystem Approach are currently under development at the incentive of the International Union of Radioecology (Bréchignac et al., 2012). This approach is designed to better cover population- and ecosystem-level effects and harmonize radiological protection with the ecosystem-scale approaches now being employed in the management of other types of environmental stressors. This harmonization could lead to consistency of management approaches across stressors and will enable radioecologists to take advantage of scientific advances being made in other related fields.

A conceptual model is the central organizing principal for any ecological risk assessment. The conceptual model identifies the source(s) of the stressor being evaluated, the key ecological receptors of interest for the assessment, and the exposure pathways linking the source(s) to the receptors. The conceptual model underlying an organism-level (including RAPs) approach, like classical ecotoxicology, focuses on individual organisms and attempts to define radiological doses that will be protective of individual organisms belonging to representative species, with further attempts to extrapolate to the population level resulting in large uncertainties (Lance et al., 2012). To effectively implement the Ecosystem Approach advocated by IUR, the conceptual model must be changed to focus on the community of interacting species exposed to radiation rather than on a small set of species considered in isolation.

The effects endpoints considered in a reference organism approach consist of organism-level and cellular-level characteristics and processes that could be impaired by exposure to ionizing radiation, for example, early mortality, morbidity, reduced growth, reduced fecundity, or increased chromosome breakage rate. Some of these endpoints have only tenuous, sometimes theoretical links to population or ecosystem-level endpoints. Moreover, they have often not been demonstrated empirically to link exposure and effects (Hinton and Bréchignac, 2005). In an Ecosystem Approach, an expanded set of endpoints are available to more closely align assessments with radiation protection goals (Fig. 1).

Two complementary methodologies exist for using the above endpoints as part of the Ecosystem Approach: (1) formal mathematical models that express the relationship between radiation exposure and the value of the endpoint being measured in terms of the processes that link exposures to effects, and (2) empirical indices or statistical models that express the relationship between exposures and effects based on comparisons between exposed and unexposed ecosystems.

None of the above endpoints or methods is unique to radiation protection. All of them have been used with varying degrees of success in ecological risk assessment or resource management. Yet there seems to be wider acceptance of the limitations of organism-level approaches for risk assessment of chemicals than currently exists for radiation risk assessment, and more attempts to find ways to use higher level approaches. One goal of the IUR effort is to foster a willingness to extend the scope of assessments to population and ecosystem levels for radiation risk assessments.

4. Inter-population relationships can lead to unexpected responses

Emerging properties of populations and communities reveal dynamic, non-linear relationships that result in non-intuitive outcomes. Organisms can interact in several ways directly (e.g., eating each other) or indirectly by affecting their environment (e.g., common use of resources). Irradiation of plants and animals with lethal and sublethal doses (direct or primary effects) results in the disruption of ecological relationships between the components of ecosystems and in further disturbances (indirect or secondary effects). For example, a simplification of the complex interrelations between populations in an ecosystem (Fig. 2) includes symbiosis, competition, predation and shelter, but also second order indirect effects, such as that competitors for a common resource indirectly affect a predator by affecting the prey.

The relationship between individual-level responses and population-level impacts of disturbance are tenuous and often counter-intuitive. Life-history differences, physiological requirements and tolerances, and interactions among species can be more important for determining inter-species differences in susceptibility to radiation than differences in radionuclide-specific dose-responses. This means that using ecological knowledge is essential to understanding the responses of populations to radiation.

Such indirect effects of irradiation are not purely theoretical; field examples exist. As described by Tikhomirov (1972); Krivolutskiy et al. (1988) for a coniferous forest affected by radiation,

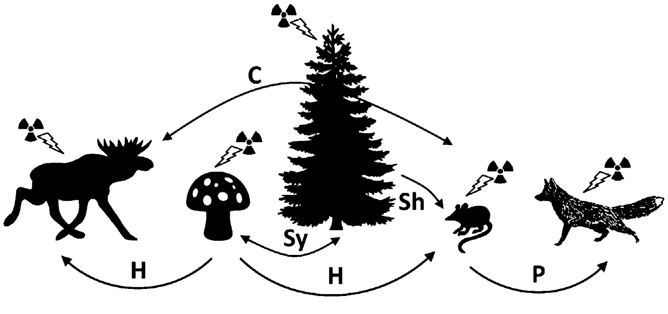

Figure 2. Examples of direct effects of a contaminant (radiation symbols) and indirect effects (lines) between populations (represented here for simplicity as single organisms) in an ecosystem. Indirect effects include: competition between populations (C) (in this case for food; fungus), predation (P), herbivory (H), symbiosis (Sy), shelter (Sh). A direct negative effect of radiation on the pine tree will for example create a number of indirect effects in the ecosystem: decreased shelter for the mouse and decreased symbiosis with the fungus. This in turn may lead to decreased food for the mouse and the moose, and increased competition between them for their more limited food resource. A direct negative effect of radiation on the fox will indirectly benefit the mouse since it will be less predated. This may in turn lead to higher consumption of fungus by the mouse, and that in turn to less food for the moose and decreased symbiosis with the pine tree.

the disturbances of ecological interrelations are caused by the following factors: (1) changes in microclimatic and edaphic conditions (because of improvement of both light and mineral nutrition conditions, more radio-resistant deciduous species are favored); (2) disturbances in the synchronism of seasonal phases in the development of ecologically connected groups of organisms (shifts in the time of leaves blossoming and eggs of leaf worms hatching); (3) imbalance in food interrelations between consumers and producers (decrease in food resources as a result of irradiation); (4) changes in biological pressure (i.e., competitive advantages) as a result of species differences in radio-resistance (changes towards prevalence of more radio-resistant species in meadow phytocoenoses; disturbances in both host-parasite and predator-prey relationships); (5) opening of ecological niches in radiation-affected communities that allow immigration of new species.

The importance of complex population interactions is likely to vary according to dose and dose rate. At the low end of the dose continuum we might expect a range of background radiation doses that may vary according to factors such as underlying geology (Fig. 3). In situations of exposure just above background radiation we expect few individuals in the populations to be affected beyond the generally random mutation rates experienced within organisms. Safety standards for existing and planned facilities typically set permissible releases at levels that remain well below those expected from background, based on human radiological protection criteria (IAEA, 1996; IAEA, 2011; SSM, 2008). Exposures resulting from routine releases would therefore normally fall within the variability of natural background. Furthermore, maximum permitted releases from facilities are often set at a level where human doses are as low as reasonably achievable, social and economic factors having been accounted for. At such low releases, exposure levels can be considered as posing low and likely indiscernible risk to human health. From these considerations we might superficially infer that ecosystem level effects would not be detectable at exposure levels typical for planned exposure situations.

However, drawing from observations of areas with mineralized soils, we know that differences in relative sensitivities (or tolerance) such as exist in metal-rich serpentine soils results in a different array of plant communities compared to adjacent non-serpentine soils (Alexander et al., 2007). This characteristic has also been used to prospect for uranium (Canon, 1957). Many studies of adaptation have demonstrated acquired tolerance to metals can occur within a few generations (Rahavi et al., 2011). Thus, it would be little more than conjecture without a more rigorous examination to confirm that background doses of radiation have no ecological consequences.

At much higher dose rates, differences in the sensitivities of different taxa to radiation (Whicker and Schultz, 1982; Copplestone et al., 2008) create the possibility of competitive advantages for resistant organisms within a taxon, and among populations of interacting taxa. This means that life history traits, responses to a change in resources and generation time all play a role in determining radiation effects, in addition to differences in radiosensitivity of individual organisms. Such higher exposures may exist during or after emergency situations (i.e., accidents or necessary temporary releases to minimize dangers, spills etc.).

As dose rates rise to those observed after major accidents such as Chernobyl, responses at population-, community-, and ecosystem levels are expected to be more pronounced. Even so, in such situations, human occupation of the contaminated areas often decreases or is eliminated, resulting in a rebound effect with respect to the ecosystem structure as the pressures from human use ease. The simultaneous positive effects on ecosystems of less human activity and potentially negative effects from high radiation exposure can complicate efforts to identify radiation-specific effects in the exposed ecosystems in terms of species abundance, diversity, and other ecological endpoints.

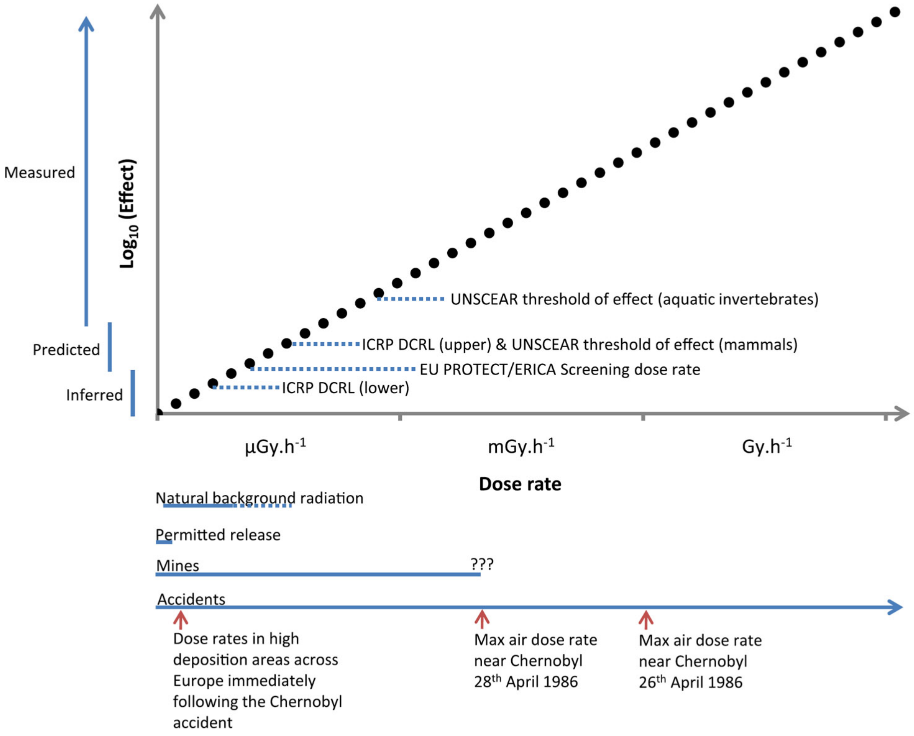

Figure 3. Generalized radiation doses that occur in relation to biological responses and the sources of radiation across background and anthropogenic activities involving radionuclides. Dose rates for Chernobyl exposures are from Jaworowski (2010).

5. Discussion and way forward

The ultimate aim of this Ecosystem Approach work is to suggest practical ways to implement a holistic, ecosystem-oriented process for radiation protection. It is intended to complement the current reference organism approach and is structured to align methods with the high-level objectives established in numerous international conventions dealing with the environment. This is needed because the reductionist approach used in organism-level based methods is not sufficient for evaluation of system interactions.

5.1. Advantages arising from an Ecosystem Approach

In the case of field investigations and assessments in contaminated areas, a focus on higher levels (ecosystem) enables implicit consideration of the net effects of contamination, integrating all direct and indirect effects (multiple stressors/contaminants, species interactions, different responses to different types of radiation, spatial and temporal issues and natural variation) without needing to address them specifically. The possibility of missing aspects of potential importance not covered by more reductionist approaches would then be prevented. Field studies can occur either as experimental manipulations (e.g., Krivolutskiy et al., 1988; Tikhomirov, 1972; Woodwell, 1967) or as forensic investigations following a release (e.g., Geras'kin et al., 2008). Modelling risks associated with releases projected under a range of scenarios across heterogeneous landscapes will benefit in using an Ecosystem Approach, i.e. one that considers not only ranges of exposure and corresponding organism-level responses, but incorporates probabilities of each and importantly factors in the types of species interactions that occur in complex ecological settings.

In contrast to an individual-based approach, the Ecosystem Approach is consistent and compatible with the Ecosystem Services concept which has increasingly been applied in other areas of environmental protection over the last 10 years (Apitz et al., 2006; FAO, 2005; UNEP, 2004). Ecosystem Services are "the benefits people obtain from ecosystems" (Millennium Ecosystem Assessment, 2003), and thus describe processes or services that are necessary for human well-being. In that sense they are anthropocentric, but the sub-category "supporting services" covers those "necessary for the production of all other ecosystem services" (MEA, 2003), such as primary production and nutrient cycling and thus includes processes that may not obviously be of direct use to humans. Ecosystem Services are also more meaningful for people than more abstract ecosystem endpoints, and are thus a useful communication tool in environmental protection. Valuing ecosystems and their services (using economical or other methods) also more easily allows holistic comparisons and trade-offs to be made.

The Ecosystem Approach complements the reference organism concept by enhancing their ecological contextualization; for example keystone species can be identified that could be focused upon, using a reference (or representative) organism approach. However, instead of stopping the analysis at the organism-level, the Ecosystem Approach explicitly considers the dynamic interactions that occur in complex systems.

5.2. Challenges ahead for an Ecosystem Approach

A serious hurdle to applying the Ecosystem Approach in radiation protection is the current lack of good experimental and field data to evaluate ecosystem-level effects (Bréchignac et al., 2011; Bréchignac et al., 2012). In particular, studies where both ecosystem and lower level (such as at the population, individual or cellular level) effects are measured are scarce. The few examples of such studies are mostly from high dose field experiments (e.g., Krivolutskiy et al., 1988; Tikhomirov, 1972; Woodwell, 1967) and from the South Urals (Krivolutskiy et al., 1988; Tikhomirov, 1972) and Chernobyl accidents (Geras'kin et al., 2008). This lack of data limits our ability to compare effects across organizational levels and identify ecosystem-specific effects.

From the limited data that are available from both the radioecological and ecotoxicological fields, and from a substantial amount of ecological literature, it is clear that non-linear effects are common at the ecosystem level (Folke et al., 2004; Scheffer et al., 2001). Though methods exist to measure and to model interactions, there has not been widespread use of these tools (Forbes and Calow, 2013; Knights et al., 2013; Scheffer et al., 2009; Wootton, 1994). In contrast to the field situation where the net impacts of contamination are implicitly considered in the ecosystem approach, modelling and prediction of ecosystem effects may need to explicitly consider ecosystem complexity or be able to model emergent properties of ecosystems (Forbes and Calow, 2013). What is apparently needed is a focused effort to demonstrate how such tools including modelling approaches can be used effectively to characterize risks in terms of ecosystem-level responses to radiation exposure.

Modelling approaches and tools however face several challenges. Firstly, many existing models assume equilibrium conditions. Considering multi-species systems requires dynamic modelling approaches, particularly for scenarios where ecosystem-oriented approaches may be especially relevant, e.g., for short-term environmental releases of radionuclides (Vives i Batlle et al., 2008). Thus, the development of ecosystem-oriented approaches requires the improvement of individual models themselves. Secondly, the design of comprehensive inter-population or -species relationships in a given ecological system requires knowledge of many metabolic and ecological parameters that are not included in the organism-based approach, e.g. ingestion rates, assimilation rates, food preferences, trophic level, and territory size. Such information is largely unavailable for many organisms, though approaches such as allometry can be used for filling data gaps (Hendriks, 2007). Finally, given the high complexity of ecosystem-oriented models, it may be necessary to determine via sensitivity and uncertainty analysis which processes or compartments are most influential for the system as a whole (Ciric et al., 2012) or to use holistic methods that take a systems-level approach (e.g., Fath et al., 2007).

The concept of calculated threshold doses at which an effect will occur (or at least be detectable) may not be applicable to ecosystems as such. At the very least, they may be difficult or impossible to identify due to the large natural variability caused by spatial and temporal variation and complexity of ecosystem structure. As a consequence, the concept of a total dose to an ecosystem seems to be meaningless. It should also be acknowledged that, particularly at "lower" doses, ecological factors and variability can be more important than radiation effects. Altogether, this may lead to the need of adopting a different conceptual methodology to support the Ecosystem Approach. For example, it may require a site specific assessment of potential disturbances on the ecosystems, rather than using generic regulatory levels.

5.3. The way forward for the Ecosystem Approach

This IUR task group's primary objective is to develop practical methods to achieve ecological risk assessment in line with an Ecosystem Approach. In the initial phase of the work, we therefore plan to:

- Continue the literature mining started in the first IUR Ecosystem Approach task group (Bréchignac et al., 2011) to review studies that have investigated ecosystem-level effects of contaminants including radiation in order to form an overview of real data that demonstrates the importance (or otherwise) of indirect and unexpected effects. One important aspect where guidance is foreseen concerns the selection of a reasonably small suite of endpoints and exposure scenarios suitable to account for population-level, community-level and ecosystem-level effects. Special attention will need to be devoted to the goal of complementing organism-level based approaches in order to work towards the overall goal of improving the quality and efficiency of risk evaluation.

- Review models and tools that other fields of environmental protection have used that could be applicable to radiation protection, and also identify those that have had limited success so as to avoid making similar mistakes. Review the field of ecosystem modelling and ecological network analysis to identify approaches suitable for accounting for and detecting systems level processes.
- Theoretically explore, through different types of modelling and analysis, the importance of species/population interactions, connectivity, number of species (biodiversity) and differences in radiosensitivity between species for effects seen at the ecosystem-level. We hope to identify critical ecosystem configurations that might lead to greater susceptibility to radiological impacts at the ecosystem level than lower levels in the biological hierarchy, and quantitative relationships between the properties of ecosystems and the delivery of ecosystem services (i.e., ecosystem production functions).
- Use a scenario-based approach to explore potential ecosystem-level effects in real-life cases (e.g., accidental releases from mining sites/power plants rather than routine releases) to different types of ecosystems.
- Attempt to identify potential integrative endpoints to measure/monitor that are of relevance at the ecosystem level and also practicably feasible, drawing on existing work in other fields of environmental protection, and complementing organism-level based approaches.

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