

Review

Addressing ecological effects of radiation on populations and ecosystems to improve protection of the environment against radiation: Agreed statements from a Consensus Symposium[☆]

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ABSTRACT

This paper reports the output of a consensus symposium organized by the International Union of Radioecology in November 2015. The symposium gathered an academically diverse group of 30 scientists to consider the still debated ecological impact of radiation on populations and ecosystems. Stimulated by the Chernobyl and Fukushima disasters' accidental contamination of the environment, there is increasing interest in developing environmental radiation protection frameworks. Scientific research conducted in a variety of laboratory and field settings has improved our knowledge of the effects of ionizing radiation on the environment. However, the results from such studies sometimes appear contradictory and there is disagreement about the implications for risk assessment. The Symposium discussions therefore focused on issues that might lead to different interpretations of the results, such as laboratory versus field approaches, organism versus population and ecosystemic inference strategies, dose estimation approaches and their significance under chronic exposure conditions. The participating scientists, from across the spectrum of disciplines and research areas, extending also beyond the traditional radioecology community, successfully developed a constructive spirit directed at understanding discrepancies. From the discussions, the group has derived seven consensus statements related to environmental protection against radiation, which are supplemented with some recommendations. Each of these statements is contextualized and discussed in view of contributing to the orientation and integration of future research, the results of which should yield better consensus on the ecological impact of radiation and consolidate suitable approaches for efficient radiological protection of the environment.

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1. Introduction

Radiological protection is evolving from a system focused only on humans, to one that encompasses non-human biota and the environment itself. In 2001, the International Union of Radioecology (IUR) arranged a Consensus Conference on Environmental Radiological Protection which crystallized a broad agreement on the need to address the environmental impacts of ionizing radiation (IUR, 2002a). Since then, scientific research in both the laboratory and the field has significantly improved our knowledge of radiological impacts, yet there is a feeling of divergence rather than convergence in current opinion:

- Laboratory studies have reduced uncertainties related to impacts on individual non-human organisms, notably but not exclusively through application of the reference organism approach (IUR, 2000, 2002b; ICRP, 2003, 2008; FASSET, 2004; ERICA, 2007; Sazykina and Kryshev, 2003, 2006) and the development of practical dose assessment tools. To assess risk to non-human biota, various approaches use sophisticated

dosimetry tools to estimate radiation dose to individuals and infer the corresponding effects based on dose-response data gathered from the literature. Considerable gains in knowledge have been made in the last ten years through these initiatives. However, the reference organism approach and other evolving frameworks still need to be refined for more realistic application at the ecological level (Carroll, 2009; IUR, 2012; Bradshaw et al., 2014). For example, mainly acute exposure is studied in the laboratory whereas the field situation, even for humans, is one of chronic exposure.

- Meanwhile, new information and increasing uncertainties have emerged from recent field studies, often conducted in areas contaminated by nuclear accidents (e.g., Beresford and Copplestone, 2011; Murphy et al., 2011; Hiyama et al., 2012; Geras'kin et al., 2013; Mousseau and Møller, 2014; Taira et al., 2014; Møller and Mousseau, 2015; Møller et al., 2015; Deryabina et al., 2015; Pryakhin et al., 2016). These studies have mostly focused on large-scale correlations among estimated exposures and natural history observations in the field at the level of individuals, populations, or of communities of

species interacting within the ecosystem. Their findings sometimes appear to contradict predictions made under the traditional laboratory paradigm (Beresford et al., 2012). However, recent efforts have attempted to bridge the different approaches and offered a number of explanations for divergence in findings (Garnier-Laplace et al., 2013, 2015).

Contrasted results from the laboratory and the field, and resulting disagreement about their respective implications for risk assessment and management, are currently stimulating a need for refinement of international assumptions and findings relevant to environmental radiological protection systems (UNSCEAR, 2015). Nuclear accidents, most recently the Fukushima disaster, provide a strong impetus to better address the very diverse situations and ecosystems (potentially) affected by planned or unplanned releases of ionizing radiation.

An *ecocentric approach* to environmental protection offers a means for such refinement, reconciling understanding of radiation impacts developed mainly under acute exposure in the laboratory with more recent observations under chronic exposure in the field. However, while there is increasing awareness of the need to embrace not only the individual level but also population, community and ecosystem impacts, radiation protection institutions are only starting to engage the range of expertise that can conceptualize and conduct the relevant research. A new consensus on the need and means to achieve an ecocentric approach might stimulate dialogue, foster a more integrated research program, and facilitate national and international efforts to work toward a more comprehensive system of protection. More broadly, such consensus might contribute to societal understanding of radioecology and greater credibility in the eyes of decision makers, funding agencies, and ultimately the public.

In this light, IUR launched a new consensus effort, with the intention to revisit the statement published in 2002, and to assess the status of current research. A group of 30 scientists from different disciplines and research areas extending beyond the historical radioecology community came together for three days in Miami in November 2015. They were invited to present and discuss scientific work from the laboratory and the field, identify areas of agreement, explore reasons for disagreement about conceptual approaches, and review different interpretations of the results as well as their implications for environmental protection.

The 2015 Miami Consensus Symposium assembled scientists from diverse areas of interest and perspectives who work with different methods and points of reference. The group successfully developed a constructive spirit directed at understanding discrepancies rather than arguing disagreements. This particular achievement allowed the formulation of seven statements, supported by observations and practical recommendations, which have been endorsed by the entire group.¹

The seven consensus statements are gathered below, then contextualized and developed in more detail. The program of presentations heard at the Miami Consensus Symposium, and notes on the discussion questions and process, are provided in an appendix.

2. Consensus statements

Statement 1: Successful protection of the environment depends on the protection of natural populations, their dynamics, species

interactions and contributions to ecosystem functioning. Ecosystem approaches are needed to support these protection goals.

Statement 2: Improved terminology for referring to environmental protection criteria, operational outcomes and standardized methods is required.

Statement 3: Field studies and experiments, especially those focusing on populations, make a vital contribution to the scientific background necessary to achieve the environmental protection goals. Field data are essential to account for realistic exposure scenarios, as well as to investigate how exposure to radionuclides interacts with other environmental factors to determine the effects on natural populations.

Statement 4: Better continuity between laboratory and field studies should be developed to advance protection of the environment. Hypotheses should ideally be tested through an iterative strategy integrating field and laboratory studies, and modeling efforts.

Statement 5: Strategies need to be developed to disentangle the direct and indirect effects of radiation on (populations of) biota in natural ecosystems, as well as the confounding factors that prevent clear interpretation of the results.

Statement 6: Reference organism approaches represent an important first step to characterize doses to biota, but they have significant limitations. More effort should be placed on understanding mechanisms and processes of how radiation effects are manifested in natural ecosystems, and on quantifying dose in the field.

Statement 7: Research programs and studies should encourage a multidisciplinary approach among radioecologists, radiobiologists, ecologists, evolutionary biologists, statisticians, modelers and geneticists. Field study design should encompass methods and approaches established in ecology and address a diverse range of sites and cases with preferably experimental approaches.

3. Contextualizing the consensus statements

3.1. Protection goals; need for improved conceptualization and terminology

It is now widely acknowledged that protection standards aimed uniquely at humans do not necessarily ensure adequate protection of non-human biota and related ecosystems (FASSET, 2004; ERICA, 2007; NEA, 2007). Moving away from the old paradigm assuming that protection of man would *ipso facto* also protect the environment, IUR's 2001 consensus statement (IUR, 2002a) recognized that "man is part of the environment" but gave no detailed explanation of what this actually meant or implied. A better conceptualization of this statement is now needed.

A general conceptual model is proposed (Fig. 1) highlighting the fact that *Homo sapiens* is actually interacting with (and often out-competing) other species within an ecosystem. Man is but one predator species, while our agronomic species belong to ecological categories such as primary producers (e.g., terrestrial plants) and primary consumers (e.g., herbivorous mammals). Recognition of the interdependency of man and other ecosystem components is a prerequisite for properly addressing how human and environmental radiological protection can be integrated.

Statement 1: Successful protection of the environment depends on the protection of natural populations, their dynamics, species interactions and contributions to ecosystem

¹ One meeting participant does not appear among the authors because the required employer validation procedure was judged to be prohibitively long. That participant, and one other, chose to endorse the seven statements presented here by personally co-signing the short IUR note (2016) limited to those statements.

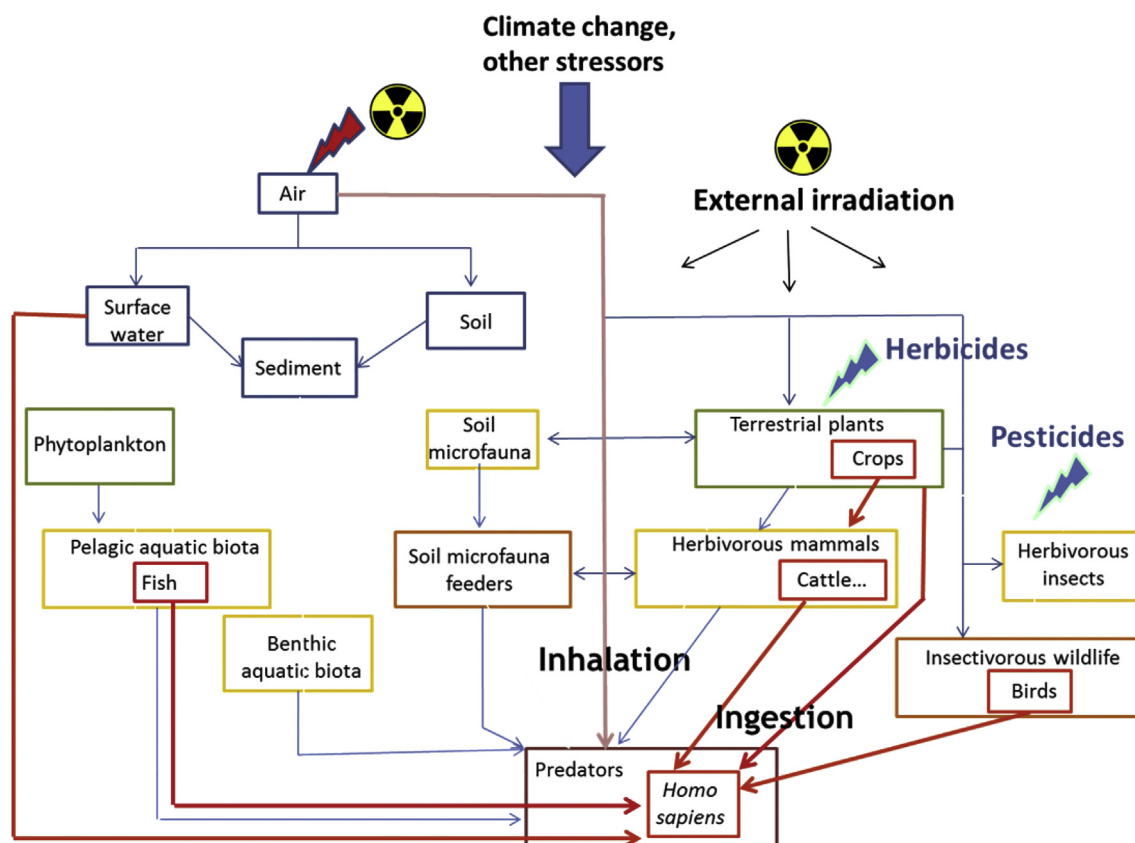


Fig. 1. “Man is part of the environment”: Conceptual model for a scenario of release of radioactivity to the air, integrating the various ecosystem components that include 1) abiotic media (blue boxes), 2) various functional categories of wildlife accounting for primary producers (green boxes), primary consumers (yellow boxes), secondary consumers (orange boxes), predators (brown box) and parasites (not shown) together with 3) *Homo sapiens* and companion agricultural species (red boxes), each being a subset of these ecological categories. Arrows represent radionuclides transfer through these ecosystem components to top predators, highlighted in red when these are directed at *H. sapiens*. Depicting the ecological relationships that link the natural trophic network for wildlife and the agronomic network for *H. sapiens*, this illustration indicates how man boosts ecological processes toward his own food production by using herbicides and pesticides to outcompete natural populations (adapted from Bréchnac, 2016).

processes. Ecosystem approaches are needed to support these protection goals.

There is a need for new methods and approaches to achieve the goals of protecting not only *H. sapiens*, but also the ecosystems of which humans are a part. The traditional approaches used today, which largely rely on extrapolation from individual to population/ecosystem level effects, are flawed. Better approaches would include direct consideration of population and ecosystem attributes.

Recent field studies on radiation effects demonstrate the limitations of exclusive reliance on models based solely on laboratory experiments and methods based upon reference organisms. There is a difference between physiological (individual organismal level) and ecological effects and between the consequences of these effects. Ecological effects include interactions at population level among species and also between these species and their environment, potentially governed by emergent properties of these systems (Fig. 2). Because they lack ecological realism, models based on findings from artificial laboratory contexts have been shown in at least one case to be inaccurate in prediction by an order of magnitude (Garnier-Laplace et al., 2013). Similar phenomena have been seen in other fields of protection and the science of ecology as a whole (Cairns et al., 1996; Newman, 2001; Tannenbaum, 2005).

Both physiology and ecology must inform environmental

protection frameworks, recognizing that these are influenced as well by management systems, operational targets, philosophy, politics, international context, etc. Understanding ecological effects of radiation offers benefits for environmental preparedness, environmental stewardship, remediation actions, science, increasing credibility with the public, and putting radiation effects (of discharges, accidents, remediation, etc.) into context with other factors or effects.

To conclude, there is a need for environmental protection criteria that reflect the dynamics and processes responsible for ecosystem functioning (and resulting services). If protecting populations is a goal, methods and measurements must go beyond individual effects. Ecological and evolutionary theories address mechanisms that are highly relevant for generating realistic predictions of effects, and highlight the need for a new approach based on systematic, long-term monitoring and study of real life situations.

Statement 2: Improved terminology for referring to environmental protection criteria, operational outcomes and standardized methods is required.

Frameworks of environmental protection are being developed in areas outside the radiological protection field: protection of biodiversity, habitats, protection from physical/chemical stressors, etc. The supporting terminology comes essentially from ecology

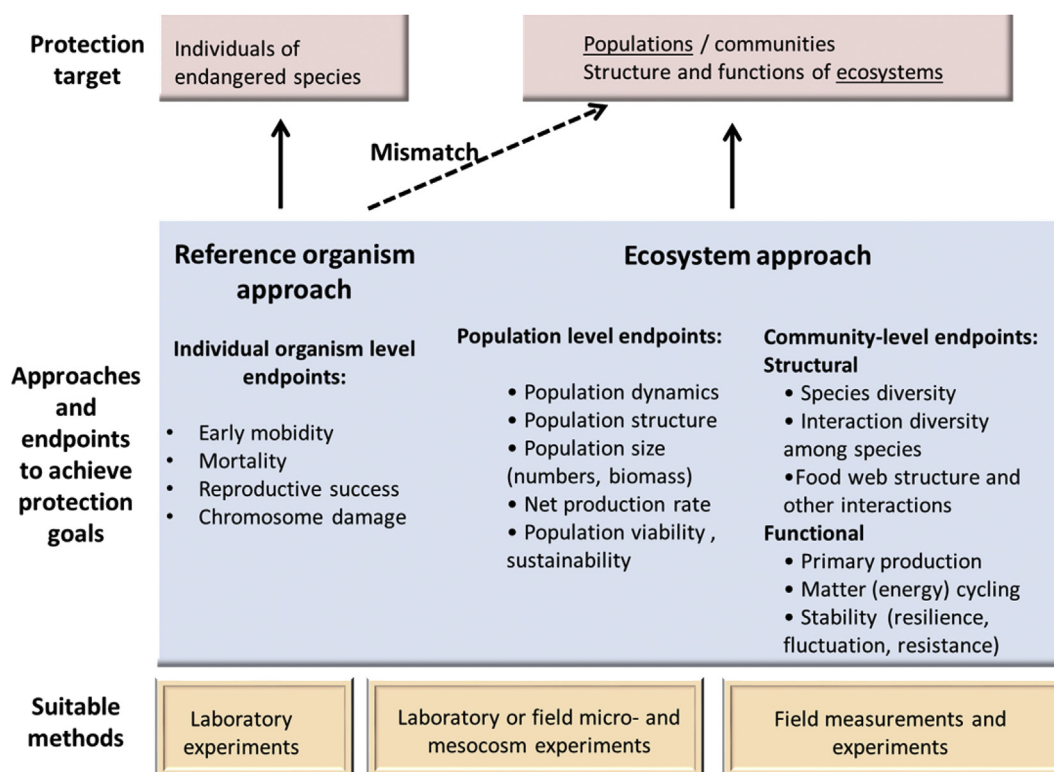


Fig. 2. Different targets of protection require proper alignment of the corresponding methodological approaches designed to achieve the associated goals. Reference organism approaches are mismatched with respect to protection goals set at population and ecosystem levels; these latter require development of ecosystem-oriented approaches. The former are usually supported by laboratory experiments whilst the latter can use laboratory and field micro- and mesocosm experiments as well as field measurements and experiments, to support this orientation (adapted from Bradshaw et al., 2014).

and environmental sciences regarding non-radiological stressors (chemicals, etc.). Radioecology should adopt the right terminologies in the right context to avoid errors and imprecision. “Objects, targets, endpoints” may have different meanings depending on the different levels of inquiry (measurement, assessment, etc.).

Our use of terminology must be sufficiently precise to help us identify gaps. For instance, the term “environmental protection” is widely used for current radiological protection systems (ICRP, 2003, 2008). In practice however, current approaches protect species only at the organismal level *stricto sensu*. Furthermore, abiotic media (i.e. air, water, soils and sediments) which form important components of the environment subject to potential contamination are not expressly covered by these systems.

The increasingly cited concept of “ecosystem services” may aid in highlighting humans’ dependence on the environment. This notion stemming from an anthropocentric vision may prove to be an important communication tool. However, work needs to be carried out to determine how it can or should be implemented in radiological protection of the environment (Morelli and Møller, 2015).

3.1.1. Recommendations

- Ecosystem approaches need to be supported by systems-level research emphasizing interactive responses to radiation exposure, propagation of effects, delayed effects, indirect effects, and resistance and resilience of ecological systems (e.g. Bréchignac et al., 2011).
- Environmental protection criteria to be developed should consider population and ecosystem attributes involving more integrated and functional endpoints such as population

dynamics, biodiversity, decomposition, primary productivity, energy transfer or nutrient flow.

3.2. Linking field and laboratory studies and modeling

Both field and laboratory studies are needed to form the scientific basis for environmental assessments. These should be complementary and largely co-constructed to improve the overall analytical power, but need not have the same objectives, methods or endpoints.

Statement 3: Field studies and experiments, especially those focusing on populations, make a vital contribution to the scientific background necessary to achieve the environmental protection goals. Field data are essential to account for realistic exposure scenarios, as well as to investigate how exposure to radionuclides interacts with other environmental factors to determine the effects on natural populations.

Field studies focusing on species assemblages are essential to account for variation across species and higher-level taxa in exposure, sensitivity, and response to radioactive contaminants in combination with other stressors. Although entangled in various functional groups of ecosystems, natural populations and their individuals in their ecological settings are the fundamental units for investigating expected consequences of radiological contamination. These include both direct and indirect consequences mediated by effects on other interacting species and/or trophic levels. Field studies are usually characterized by lower statistical power, therefore delivering less certainty about causes and effects, but they benefit from higher ecological relevance.

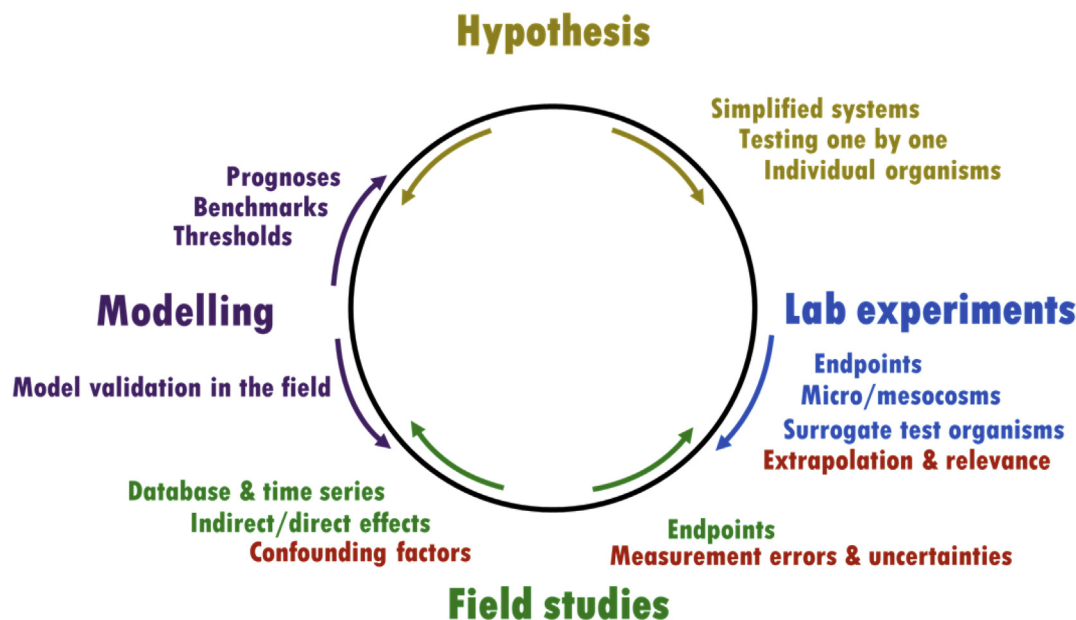


Fig. 3. Hypothesis-driven inference strategy linking laboratory experiments, field studies and modeling. Potential contributions of each approach to advancing protection of the environment are shown, as well as links between the different stages of the proposed iterative strategy. The circular shape is used to represent interconnectedness and reciprocal (two-way) feedback between the different stages and approaches. Shortcomings of each approach that can be resolved by resorting to a different methodology are indicated in red.

Laboratory experiments are fundamental tools that contribute to environmental protection. Thanks to their simplified and more controlled nature, laboratory experiments provide mechanistic insights into pathways of exposure and translation of exposure to biological effects at the genetic, cytogenetic and physiological levels. Laboratory experiments should help to clarify if such effects are purely physiological, meaning that they do not persist over generations, or if they arise from permanent mutational genome damage, that is harder to eliminate. Laboratory studies have allowed the development of methods of quantification of exposure to radiation, a database on dose-effect relationships in organisms (Coppstone et al., 2008), and a conceptual approach to risk assessment based on biological effects of radiation (similarly as for humans). They usually suffer from poorer ecological relevance, but benefit from clearer outcomes and higher statistical power.

It is to be stressed that field studies are generally based on chronic exposure, while laboratory studies usually use acute exposure. This creates a dichotomy that may be part of an explanation for the different conclusions drawn from field and laboratory studies.

Modeling is also an approach of high importance due to its capacity to support data testing and assimilation along an integrated ecosystem conceptual model. Microcosms and mesocosms play an integral role in linking laboratory and field studies in ecology (Odum, 1984). Such experimental systems provide an important middle-ground, allowing replication of experiments in semi-natural scenarios, but with fewer confounding variables. Recent combination of mechanistic modeling with model-guided experiments in a microcosm has proved very helpful in understanding the stressors' effects on this simplified ecosystem functioning (Lamonica et al., 2016).

In order to advance understanding of radiation ecological impacts on the environment, better links should be made between field, laboratory and modeling studies, using an iterative and hypothesis-driven process (Fig. 3).

Several examples of such linkages that recently proved successful in supporting better interpretation can be mentioned.

Garnier-Laplace et al. (2015) showed a high degree of consistency between dose measurements in the field and calculated dose estimates based on morphology, diet and ecology of birds at Fukushima. Otaki and coworkers (Hiyama et al., 2012; Taira et al., 2014) supported convincingly their hypothesis drawn from field observations that radiation induced mutations in the pale grass butterfly, when they obtained similar mutations in laboratory-based experiments under controlled conditions where the only variable was radiation.

Statement 4: Better continuity between laboratory and field studies should be developed to advance protection of the environment. Hypotheses should ideally be tested through an iterative strategy integrating field and laboratory studies, and modeling efforts.

3.2.1. Recommendations

- Contaminated sites have been subjected to long-term monitoring and observations but the extent and level of research is extremely limited compared to standard procedures in ecology. Surprisingly, there are few monitoring studies of the most common taxa at Chernobyl, Fukushima, Mayak and elsewhere. Long-term monitoring studies have been restricted to a few field studies at Chernobyl and Fukushima during the last decade. It is highly desirable to initiate and maintain annual monitoring studies of all common taxa at representative sites most contaminated by major accidental releases of radioactivity into the environment. The challenge here would be to carry out field experiments with a decent level of replication.
- The next step should be the development of ecosystem conceptual models, depicting networks of interactions and systems to generate hypotheses about nodes/pathways/sub-networks seen as important. This modeling effort could provide a comprehensive and integrated picture of observed radiation

biological/ecological effects, to be confronted with real data, and ultimately yielding an improved understanding.

- Such conceptual models could then be further supplemented by microcosm and mesocosm studies to help bridge the gap between field and laboratory studies. Overall, this would enable the use and integration of genetics and other biological tools/approaches in the more applied ecological investigations, informing ecology with genetics and physiology. Likewise, studies of epigenetics will provide information on patterns of methylation and other effects affecting the expression of genes.

3.3. Realism, multiple stressors and confounding factors

Multiple types of biological and ecological effects have been revealed by observational field studies at sites with elevated levels of radiation. Field experiments, however, are challenging to design and interpret, due to many potentially confounding variables such as diet, habitat, predator stress, biological stressors (parasites), presence or absence of competitors (including humans), abiotic factors (e.g. temperature, pH), hot spots of contamination, indirect and direct effects of exposure and exposure type (radionuclides, metals, chemicals, etc.).

Statement 5: Strategies need to be developed to disentangle the direct and indirect effects of radiation on (populations of) biota in natural ecosystems, as well as the confounding factors that prevent clear interpretation of the results.

Significant work remains to link field studies and ecosystem properties with updated and improved datasets on radiation effects. Whereas recent laboratory-based experiments by the radioecology community have assembled a database of radiation effects on organisms of various species, its robustness suffers from lack of replication and inclusion criteria that are still sometimes subject to criticism. Commensurable effort should be invested in developing a database of radiation impact observations from field studies, especially for population- and ecosystem-related endpoints.

When disagreements, however, remain on the degree to which field observations can be attributed to radiation effects, the iterative hypothesis-driven inference strategy recommended above (Statement 4) together with efforts of independent replication should help resolve confounding factors. Basically, this is a question of setting up an appropriate experimental design (Møller and Mousseau, 2016).

3.3.1. Recommendations

- It is important to consider the interconnectedness of species, investigating interspecific interactions, as well as designing field studies that integrate different trophic levels and look at higher ecosystem levels.
- The design of future field experiments should also consider testing and replication of published information on chemical or metal exposure and effects on species in ecosystems of interest.
- Attention should be dedicated to making use of experimental designs and statistical methods that are most appropriate to resolving confounding factors.

3.4. Dose and exposure characterization

There is an ongoing need to improve the measurement of environmentally relevant exposures, particularly under multiple sources of exposure from different types of radionuclides and other stressors. The quantification of exposure to radiation still accounts for a large portion of the uncertainty affecting risk assessment. Both

dose rate and total accumulated dose (over the whole life span, and especially at low dose rates) need to be addressed, with a further focus on sensitive life stages (e.g. developmental and reproductive life stages, looking in particular at gametes and embryos).

Assessment of dose to tissues and organs is still poorly developed for non-human biota. This limits the analytic power of both laboratory and field studies, due to the fact that such tissues and organs may have widely different radiosensitivities, and/or could accumulate radionuclides to differing degrees.

Dose and exposure characterization are essential for reference organism approaches which relate dose to biological effects at the genetic, cytogenetic, physiological, cellular and individual levels. Such approaches based upon biology can help at early stages and mesh with existing systems focused on humans. However, protection of ecosystems clearly requires a system-level inference strategy and associated methodology.

Statement 6: Reference organism approaches represent an important first step to characterize doses to biota, but they have significant limitations. More effort should be placed on understanding mechanisms and processes of how radiation effects are manifested in natural ecosystems, and on quantifying dose in the field.

Considering high level emergent properties of ecosystems such as resilience, it is doubtful that a universal standard (dose or dose rate) suitable for protection of any ecosystem can be established. Each ecosystem has its particular level of resilience at any time and experiences a variety of concomitant stressors. Due to the very multi-dimensional character of ecosystems in which combined and indirect effects produce a cascade of outcomes, the most serious effects may not result from ionizing radiation alone but from its combination with other factors. In such a case, ionizing radiation would then only act as a trigger promoting ecological disruption. Accounting for such a disruption mechanism at the system level requires consideration of endpoints operating at the ecosystem level (ecosystem structure, ecosystem functioning).

3.4.1. Recommendations

- A better knowledge of the relative radiosensitivities of different species and endpoints will allow us to understand and predict the mechanisms underlying interspecies interactions in an irradiated ecosystem. The time is now ripe to revisit the chart of radiosensitivity across the kingdom of life (Whicker and Schultz, 1982). It has often been cited as a demonstration that radiosensitivity increases together with complexity of life (from unicellular bacteria up to higher levels of organization such as mammals). However, radiosensitivity also varies according to the endpoint through which it is measured (Copplestone et al., 2008). There are today sufficient data collected for many species both on organism-related endpoints (laboratory experiments) and individual or population endpoints, to enable the construction of (different) scales of radiosensitivity for each individual endpoint (or category of related endpoints with similar responses) (e.g. literature reviewed to assemble the ERICA (Real et al., 2004) and EPIC (Sazykina and Kryshev, 2003, 2006) data bases, as well as unpublished grey literature assembled in nuclear industrial/research sites).
- Improved efforts of quantifying dose (dose rate and accumulated dose) are warranted, especially for field experiments where exposure is usually complex (different radiation types, different routes of internal/external exposure, different radiosensitivities across the life cycle of organisms).

3.5. Field study methods

Much of the recent field work tends to focus on single accidental releases. The historical reasons for this are understandable, and it must also be acknowledged that methodological approaches in field ecology and other disciplines may differ. An approach that integrates field and laboratory studies would increase comprehension between the disciplines, and probably also help more scientific confidence and more funding for important field studies. For example, screening of biological communities for the collection of measurements and samples should integrate with developments in dose reconstruction and characterization, in order to clarify variation across species in exposure or sensitivity.

Statement 7: Research programs and studies should encourage a multidisciplinary approach among radioecologists, radiobiologists, ecologists, evolutionary biologists, statisticians, modelers and geneticists. Field study design should encompass methods and approaches established in ecology and address a diverse range of sites and cases with preferably experimental approaches.

It is possible to conduct experimental field studies capable of establishing a sufficient level of confidence and consensus in the likely cause-effect relationship of radiation effects in ecosystems. This requires increasing collaboration between different disciplines, with regard also to identifying the endpoints to be analyzed and the number and types of sites to be investigated.

Field studies are most generally conducted by ecologists who rely on observations, experiments and associated measurements in the real environment. There is a wide array of possible and necessary methods (contamination conditions, endpoints, etc.) that allow field studies to yield correlations but also causality between radiation and potential effects. Ecosystem level endpoints could include keystone species/groups (nodes) and key ecosystem processes (links) appropriate to the ecosystem in question (e.g. structural and functional endpoints). Though this appears conceptually attractive, there are practical aspects to consider and resolve before application.

Substantial environmental monitoring of radiation is conducted by operators in the vicinity of nuclear power plants. Currently, the data generated are insufficient to support complex ecosystem studies and protection, largely because environmental levels tend not to be recorded if they lie below the set detection level, or if the instruments in use are limited (e.g. detecting external gamma radiation only). End of pipe or close to stack releases can be measured and used to model environmental levels but cannot function for legacy sites or post-accidental situations. However, provided there is improved cooperation between researchers and operators, such environmental monitoring could be expanded to deliver additional useful observations (ecosystem structure and functions), to establish the normal range of criteria of interest, and enable development of a list of reference ecosystems.

3.5.1. Recommendations

- A wider variety of sites, presenting different ecosystem situations with complex variables, should be exploited to advance our understanding of radiation effects at population and ecosystem levels and how these are mediated through biological effects at the organismal level. The sites of particular relevance are:
 - Accidentally contaminated sites (Kyshtim, Chernobyl, Fukushima, etc.).

- Legacy sites (Mayak, Kola Peninsula, Semipalatinsk, Pacific atolls, etc.).
- Sites with a high level of natural radioactivity (Kerala, Poças de Caldas, Komi).
- Well characterized sites, which may include: uranium mining sites; US DOE sites; gas and oil sites; marine sites receiving exhaust pipes; former test sites; waste management/waste disposal sites.
- Sites with already existing monitoring programs and other historical databases that could complement the gathering of new information; pertinent existing observatories and non-contaminated sites.
- In addition to widening the scope of sites of interest, a renewed effort of historical data assembly and mining should be carried out, accessing the Russian, Ukrainian and Belarussian literature, the grey literature and other unpublished government and industry reports.

4. Conclusions

To assess (and manage) radiological risk at the ecological level responds to ethical imperatives from several perspectives, and can be regarded as a duty both to human society and to the ecosystems of which we are a part (IAEA, 2002; Oughton, 2003; IUR, 2012). Proper risk assessment, and subsequent management, requires both an appropriate understanding and a convincing and appropriate system of environmental protection. In this context, promoting shared understanding within the scientific community regarding the occurrence of ecological impacts of radiation is of high strategic importance. In particular, the still on-going debate on whether or not the Chernobyl and Fukushima accidents are having ecological consequences needs to be resolved (Beresford and Copplestone, 2011; Hiyama et al., 2012; Geras'kin et al., 2013; Møller and Mousseau, 2015, 2016; Taira et al., 2014). Suspicion by scientists as to results obtained outside their own chapel, and lack of consensus about assessing and interpreting risk, may jeopardize the radioecology community's credibility in the eyes of decision makers and funding agencies, and ultimately the public. Further to the early consensus statement elaborated 15 years ago (IUR, 2002a), the Miami Consensus Symposium has constructed a new set of collectively agreed statements about means to assess the ecological impact of radiation and their conceptual implications for designing environmental protection.

The Miami statements urge in particular a better effort to create linkage between controlled experimentation in the laboratory and *in situ* studies. At present these are often carried out by different scientists, or groups of scientists, educated in separate disciplines (see Hinton and Bréchnignac, 2005). All apply their respective conceptual and methodological approaches which do not look, for example, at the same endpoints. Generally speaking, laboratory scientists look at biological effects (interaction of radiation with molecules, cells, tissues, and individual organisms) while field scientists look at ecological impact of radiation on individuals and populations of species interacting with populations of other taxa and hence constituting ecosystems. This cultural gap largely explains why respective scientific communities have so far largely operated in isolation from one another. Collective consensus is now being expressed that further research should no longer suffer from this historical weakness, and a strategy for broader collaboration and coordinated work is strongly encouraged.

The Miami discussion also emphasized that ecosystem approaches provide a unifying conceptual basis: for linking laboratory and field studies, for assembling human and environmental radiological protection in a justified and coherent manner, and for integrating scientific understanding gained at various levels,

analytic as well as systemic, toward the goal of assessing ecological risk *in situ* while ultimately providing better protection.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.jenvrad.2016.03.021>.

References

- Beresford, N.A., Copplestone, D., 2011. Effects of ionizing radiation on wildlife: what knowledge we have gained between the Chernobyl and Fukushima accidents? *Integr. Environ. Assess. Manag.* 3, 371–373.
- Beresford, N.A., Adam-Guillermin, C., Bonzom, J.-M., Garnier-Laplace, J., Hinton, T., Lecomte, C., Copplestone, D., Della-Vedova, C., Ritz, C., 2012. Response to authors' reply regarding "abundance of birds in Fukushima as judged from Chernobyl" by Möller et al. *Environ. Pollut.* 169, 139–140.
- Bradshaw, C., Kapustka, L., Barnhouse, L., Brown, J., Ciffroy, P., Forbes, V., Geras'kin, S., Kautsky, U., Bréchnignac, F., 2014. Using an ecosystem approach to complement protection schemes based on organism-level endpoints. *J. Environ. Radioact.* 136, 98–104.
- Bréchnignac, F., Bradshaw, C., Carroll, S., Jaworska, A., Kapustka, L., Monte, L., Oughton, D., 2011. Recommendations from the International Union of Radioecology to improve guidance on radiation protection. *Integr. Environ. Assess. Manag.* 7 (3), 411–413.
- Bréchnignac, F., 2016. Assessing ecological risk from radiation requires an ecosystem approach. In: Timofeeff-Ressovsky, N.W., Korogodina, V.L., Mothersill, C., Inge-Vechtomov, S.G., Seymour, C. (Eds.), *Biosphere and Humanity*. Springer, The Netherlands (in press).
- Cairns, J., Bidwell, J.R., Arnegard, M.E., 1996. Toxicity testing with communities: microcosms, mesocosms and whole-ecosystem manipulations. *Rev. Environ. Contam. Toxicol.* 147, 45–69.
- Carroll, S., 2009. Radiological protection of the environment from an NGO perspective. *Radioprotection* 44 (5), 439–443.
- Copplestone, D., Hingston, J.L., Real, A., 2008. The development and purpose of the FREDERICA radiation effects database. *J. Environ. Radioact.* 99, 1456–1463.
- Deryabina, T.G., Kuchmel, S.V., Nagorskaya, L.L., Hinton, T.G., Beasley, J.C., Lerebours, A., Smith, J.T., 2015. Long-term census data reveal abundant wildlife populations at Chernobyl. *Curr. Biol.* 2, R811–R826.
- ERICA, 2007. An Integrated Approach to the Assessment and Management of Environmental Risks from Ionizing Radiation. ERICA Project. European Commission, contract no. F16R-CT-2004–508847.
- FASSET, 2004. Framework for Assessment of Environmental Impact. Final Report of EC 5th Framework Programme, Contract FIGE-CT-2000–00102, p. 111.
- Garnier-Laplace, J., Geras'kin, S., Della-Vedova, C., Beaugelin-Seiller, K., Hinton, T.G., Real, A., Oudalova, A., 2013. Are radiosensitivity data derived from natural field conditions consistent with data from controlled exposures? A case study of Chernobyl wildlife chronically exposed to low dose rates. *J. Environ. Radioact.* 121, 12–21.
- Garnier-Laplace, J., Beaugelin-Seiller, K., Della-Vedova, C., Métivier, J.-M., Ritz, C., Mousseau, T.A., Möller, A.P., 2015. Radiological dose reconstruction for birds reconciles outcomes of Fukushima with knowledge of dose-effect relationships. *Sci. Rep.* 5, 16594.
- Geras'kin, S., Evseeva, T., Oudalova, A., 2013. Effects of long-term chronic exposure to radionuclides in plant populations. *J. Environ. Radioact.* 121, 22–32.
- Hinton, T.G., Bréchnignac, F., 2005. A case against biomarkers as they are currently used in radioecological risk analyses: a problem of linkage. In: Bréchnignac, F., Howard, B.J. (Eds.), *The Scientific Basis for Radiological Protection of the Environment*. Lavoisier Tec & Doc, Paris, France, pp. 123–135.
- Hiyama, A., Nohara, C., Kinjo, S., Taira, W., Gima, S., Tanahara, A., Otaki, J.M., 2012. The biological impacts of the Fukushima nuclear accident on the pale grass blue butterfly. *Sci. Rep.* 2, 570. <http://dx.doi.org/10.1038/srep00570>.
- IAEA [International Atomic Energy Agency], 2002. Ethical Considerations in Protection of the Environment from the Effects of Ionizing Radiation. IAEA-TECDOC-1270. IAEA, Vienna.
- ICRP [International Commission on Radiological Protection], 2003. *Annals of the ICRP*, Publication 91. A Framework for Assessing the Impact of Ionizing Radiation on Non-human Species, vol. 33. Pergamon Press, Oxford, UK, p. 266. no. 3.
- ICRP, 2008. *Annals of ICRP*, Publication 108. Environmental Protection: the Concept and Use of Reference Animals and Plants, vol. 38. Elsevier, Amsterdam, The Netherlands, p. 242. no. 4–6.
- IUR [International Union of Radioecology], 2000. Dose and Effects in Non-human Systems. IUR Report no. 1, p. 7. Osteras, Norway. www.iur-uir.org.
- IUR, 2002a. Radiation protection in the 21st century: ethical, philosophical and environmental issues. In: Strand, Per, Oughton, Deborah (Eds.), *Consensus Conference on Protection of the Environment*. The Norwegian Academy of Sciences, Oslo, 22–25 October 2001. NRPA and Agricultural University of Norway, p. 79. ISBN 82-90362-16-1.
- IUR, 2002b. Protection of the Environment: Current Status and Future Work. IUR Report no. 3, p. 23. Osteras, Norway. www.iur-uir.org.
- IUR, 2012. Towards an Ecosystem Approach for Environment Protection with Emphasis on Radiological Hazards. IUR Report no. 7. International Union of Radioecology, p. 82, 978-0-9554994-4-9). www.iur-uir.org.
- IUR, 2016. In: Agreed Statements from the 2015 IUR Consensus Symposium on "Ecological Effects of Radiation on Populations and Ecosystems". International Union of Radioecology, IUR Statements, p. 4 (in press). www.iur-uir.org.
- Lamonica, D., Herbach, U., Orias, F., Clément, B., Charles, S., Lopes, C., 2016. Mechanistic modelling of daphnid-algae dynamics within a laboratory microcosm. *Ecol. Model.* 320, 213–230.
- Møller, A.P., Nishiumi, I., Mousseau, T.A., 2015. Cumulative effects of radioactivity from Fukushima on the abundance and biodiversity of birds. *J. Ornithol.* 156, S297–S305.
- Møller, A.P., Mousseau, T.A., 2015. Strong effects of ionizing radiation from Chernobyl on mutation rates. *Sci. Rep.* 5, 8363. <http://dx.doi.org/10.1038/srep08363>.
- Møller, A.P., Mousseau, T.A., 2016. Are organisms adapting to ionizing radiation at Chernobyl? *Trends Ecol. Evol.* 31 (4), 281–289.
- Morelli, F., Möller, A.P., 2015. Concerns about the use of ecosystem services as a tool for nature conservation: from misleading concepts to providing a "price" for nature, but not a "value". *Eur. J. Ecol.* 1 (1), 68–70. <http://dx.doi.org/10.1515/eje-2015-0009>.
- Mousseau, T.A., Möller, A.P., 2014. Genetic and ecological studies of animals in Chernobyl and Fukushima. *J. Hered.* 105, 704–709.
- Murphy, J.F., Nagorskaya, L.L., Smith, J.T., 2011. Abundance and diversity of aquatic macroinvertebrate communities in lakes exposed to Chernobyl-derived ionising radiation. *J. Environ. Radioact.* 102, 688–694.
- NEA [Nuclear Energy Agency], 2007. Scientific Issues and Emerging Challenges for Radiological Protection. Report of the Expert Group on the implications of radiological protection science. Report NEA-OECD no 6167. OECD Publications, Issy les Moulineaux, France, p. 119.
- Newman, M.C., 2001. *Population Ecotoxicology*. John Wiley & Sons, Ltd, Chichester, UK, p. 227.
- Odum, E.P., 1984. The mesocosm. *BioScience* 34, 558–562.
- Oughton, D.H., 2003. Ethical issues in protection of the environment from ionising radiation. *J. Environ. Radioact.* 66, 3–18.
- Pryakhin, E.A., Mokrov, YuG., Tryapitsina, G.A., Ivanov, I.A., Osipov, D.I., Atamanyuk, N.I., Deryabina, L.V., Shaposhnikova, I.A., Shishkina, E.A., Obvintseva, N.A., Egoreichenkov, E.A., Styazhkina, E.V., Osipova, O.F., Mogilnikova, N.I., Andreev, S.S., Tarasov, O.V., Geras'kin, S.A., Trapeznikov, A.V., Akleyev, A.V., 2016. *J. Environ. Radioact.* 151 (2), 449–460.
- Real, A., Sundell-Bergman, S., Knowles, F.J., Woodhead, D.S., Gize, I., 2004. Effects of ionising radiation on plants, fish and mammals: relevant data for environmental radiation protection. *J. Radiol. Prot.* 24, A123–A137.
- Sazykina, T.G., Kryshev, A.I., 2003. EPIC database on the effects of chronic radiation in fish: Russian/FSU data. *J. Environ. Radioact.* 68, 65–87.
- Sazykina, T.G., Kryshev, I.I., 2006. Radiation effects in wild terrestrial vertebrates – the EPIC collection. *J. Environ. Radioact.* 88, 11–48.
- Taira, W., Nohara, C., Hiyama, A., Otaki, J.M., 2014. Fukushima's biological impacts: the case of the pale grass blue butterfly. *J. Hered.* 105 (5), 710–722.
- Tannenbaum, L.V., 2005. A critical assessment of the ecological risk assessment process: a review of misapplied concepts. *Integr. Environ. Assess. Manag.* 1 (1), 66–72.
- UNSCEAR, 2015. Developments since the 2013 UNSCEAR Report on the Levels and Effects of Radiation Exposure due to the Nuclear Accident Following the Great East-Japan Earthquake and Tsunami. *A/AC.82/R.712*, p. 73.
- Whicker, F.W., Schultz, V., 1982. *Radioecology: Nuclear Energy and the Environment*, vol. I. CRC Press, Boca Raton, Florida, p. 212.