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STRATEGIC RESEARCH AGENDA FOR RADIOECOLOGY

A second version with stakeholder input

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www.star-radioecology.org



STAR WORKING GROUP on Developing a Strategic Research Agenda

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Preface and Executive Summary

To address emerging issues in radioecology within Europe, eight organisations¹ signed a Memorandum of Understanding (MoU) in 2009 that formed the European Radioecology Alliance². The MoU states the intentions of Radioecology Alliance members to integrate a portion of their respective R&D efforts into a trans-national programme that will enhance and sustain European radioecological competences and experimental infrastructures. The Radioecology Alliance members, at present incorporating an expanding number of organisations³, recognise that their shared radioecological research can be enhanced by efficiently pooling resources among its partner organizations and prioritising group efforts along common themes of mutual interest.

A major step in this prioritisation process was to develop a Strategic Research Agenda (SRA). An EC-funded Network of Excellence in Radioecology, called STAR (Strategy for Allied Radioecology⁴), was formed to, among other tasks, develop the SRA. STAR published the first draft Strategic Research Agenda (SRA) in radioecology (Hinton *et al.*, 2013) as a vision of what can be achieved in the future through a directed effort and collaboration by many organisations. The SRA outlined a suggested prioritisation of research topics in radioecology, with the goal of improving research efficiency and more rapidly advancing the science. It responded to the question: “*What topics, if critically addressed over the next 20 years, would significantly advance radioecology?*”

The Radioecology Alliance has become an Association open to other organisations with similar interests in promoting radioecology, both within and outside of Europe. Thus, although the development of the SRA was largely a European effort, the hope is that it will stimulate an open dialogue within the international radioecology community.

In developing the draft SRA, STAR was strengthened by the recommendations from its External Advisory Board and also sought input from the larger radioecology research community:

- other pan-European platforms with research topics that require radioecology [Multidisciplinary European Low Dose Initiative (MELODI); European Platform on Preparedness for Nuclear and Radiological Emergency Response and Recovery (NERIS); Implementing Geological Disposal of Radioactive Waste Technology Platform (IGD-TP)];
- other radioecology networks around the world [*e.g.*, National Center for Radioecology (NCoRE), within the United States];
- the International Union of Radioecology (IUR);
- international organisations [*e.g.*, World Health Organization; United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR); International Commission on Radiological Protection (ICRP), International Atomic Energy Agency (IAEA)];
- regulators;

¹ French Institute of Radiation Protection and Nuclear Safety (IRSN, France); Radiation and Nuclear Safety Authority (STUK, Finland); Belgian Nuclear Research Centre (SCK•CEN, Belgium); Natural Environment Research Council (NERC, United Kingdom); Research Centre in Energy, Environment and Technology (CIEMAT, Spain); German Federal Office for Radiation Protection (BfS, Germany); Swedish Radiation Safety Authority (SSM, Sweden); Norwegian Radiation Protection Authority (NRPA, Norway).

² European Radioecology Alliance <http://www.er-ALLIANCE.org/>, the association created by 8 organizations in Europe to integrate radioecological research in a sustainable way; also referred to as the ERA, and the Radioecology Alliance

³ During the last general assembly in June 2013, additional partners joined the Radioecology Alliance: Commissariat à l’Energie Atomique (CEA, France); University of Portsmouth (UK); National Nuclear Centre of the Republic of Kazakhstan (NNCRK, Kazakhstan); Radiological Protection Institute of Ireland (RPII, Ireland), Helmholtz-Dresden and Helmholtz Munchen (Germany).

⁴ www.star-radioecology.org ; and includes Stockholm University and the Norwegian University of Life Sciences.

- industry; and
- other interested stakeholders.

STAR actively requested a critique of the draft SRA and invited stakeholder input via a questionnaire on the STAR website (www.star-radioecology.org), and at an open workshop in Paris (12-13 November, 2012). The purpose of the workshop was to promote an exchange with the audience about the SRA; research needs in radioecology; prioritisation of future efforts; as well as to discuss how recommendations from the web-consultation and workshop should be incorporated [within a second version of the SRA](#). During the workshop, STAR welcomed recommendations from a variety of stakeholders, including NGOs, nuclear industry representatives, regulators, funding agencies and scientific non-profit societies from other environmental disciplines. Critique of the SRA was provided by several representatives of key organisations important to radioecology:

- Dr. Dick Roelofs, Chairman of STAR's External Advisory Board
- André Jouve, European Commission project officer
- Jean-René Jourdain, MELODI representative
- Raimo Mustonen, President of NERIS
- Sigurður Magnússon, President of HERCA
- Sergeï Fesenko, IAEA
- Jan Pentreath, ICRP Committee 5 Chair
- François Bréchignac, President of UIR
- Eduardo Gallego, IRPA representative
- Mike Thorne, BIOPROTA representative
- Dick Roelofs, SETAC representative
- Wendy Khune, NCoRE member, USA
- David Boilley, COR ENVI leader, France
- J. Houtmeyers, P-plant Tessengerlo Belgium
- Caroline Ferry, Electricité de France

The workshop better defined the context of the SRA relative to the goals of other existing platforms, such as NERIS, MELODI and IGD-TP. The stakeholders' comments, criticisms and suggestions have been itemized in a document available on the STAR website⁵ and also attached in the annex of this document. Stakeholder response to the SRA was overwhelmingly positive. The enthusiasm from stakeholders was as much for the general concept of a consolidated effort to address the difficult challenges in radioecology, as in the specifics of what STAR had suggested to be the key research priorities within the science.

[This second version of the SRA takes account of stakeholders' inputs](#). STAR's incorporation of each stakeholder's comment is identified within this second version of the SRA as [blue font](#), followed by the comment number (*i.e.* [\[C#n\]](#)).

This [version of the SRA](#) was distilled from several evaluations on the state of radioecology, including input from stakeholders ([during the above workshop and on-line consultation](#)), the interests of Radioecology Alliance member organisations, the International Union of Radioecology, lists of

⁵ https://wiki.ceh.ac.uk/display/star/Strategic+Research+Agenda?atl_token=7437cb7d61cbd37dfe5177db203fed6724e40e1

research needs, identification of data gaps and recommendations for the future of radioecology, and its sister science of ecotoxicology. Additionally, [this version of the SRA is also](#) formulated by considering several aspects related to (i) recent changes in policy; (ii) new scientific advancements; (iii) improving credibility with stakeholders; (iv) science deficiencies; (v) integration problems; and of course, (vi) early lessons from the Fukushima disaster.

The SRA prioritises three important **scientific challenges** that radioecology needs to address. Each of these scientific challenges is developed as a separate section of the SRA. Each includes a **vision statement** of what should be accomplished over the next 20 years in that area of radioecology, followed by a **Strategic Research Agenda** of key research lines required to accomplish the vision. Addressing these challenges is important to the future of radioecology to enable our science to provide adequate scientific knowledge to decision makers and the public.

The three scientific challenges presented below, with their 15 associated research lines, are a strategic vision of what radioecology can achieve in the future through a directed effort and collaboration by many organisations. It is a vision in which the participants were asked to think creatively and without boundaries as they imagine the results that could most shape the future of radioecology and benefit stakeholders. The reality is that the SRA will require considerable resources and time to bring to fruition. The “how”, “means” and practicality of accomplishing the research items presented in the SRA will be developed in a subsequent document that outlines the roadmap required to achieve the visions. The roadmap will link the SRA with the evolution of the science by providing the necessary action plans, resource allocation, and milestones required to achieve the SRA. [The first short-term \(5-y\) scientific roadmap for Radioecology, released in September 2013, is a transitional implementation plan to structure and enhance interactions between the Radioecology Alliance and two existing European research platforms, namely NERIS and MELODI.](#)

Challenge one: To Predict Human and Wildlife Exposure in a Robust Way by Quantifying Key Processes that Influence Radionuclide Transfers and Exposure

Our strategic vision is that over the next 20 years radioecology will have achieved a thorough mechanistic conceptualisation of radionuclide transfer processes within major ecosystems (terrestrial, aquatic, urban), and be able to accurately predict exposure to humans and wildlife by incorporating a more profound understanding of environmental processes.

Strategic Research Agenda

1. Identify and mathematically represent key processes that make significant contributions to the environmental transfers of radionuclides and resultant exposures of humans and wildlife.
2. Acquire the data necessary for parameterisation of the key processes controlling the transfer of radionuclides.
3. Develop transfer and exposure models that incorporate physical, chemical and biological interactions, and enable predictions to be made spatially and temporally.
4. Represent radionuclide transfer and exposure at a landscape or global environmental level with an indication of the associated uncertainty.

Challenge two: To Determine Ecological Consequences under Realistic Exposure Conditions

Our strategic vision is that over the next 20 years radioecology will have gained a thorough mechanistic understanding of the processes inducing radiation effects at different levels of biological

organisation, including the consequences on ecosystem integrity, and be able to accurately predict effects under realistic conditions.

Strategic Research Agenda

1. Establish processes link radiation induced effects in wildlife from molecular to individual levels of biological complexity.
2. Determine what causes intra-species and inter-species differences in radiosensitivity (*i.e.* among cell types, tissues, life stages, among contrasted life histories, influence of ecological characteristics including habitats, behaviour, feeding regime...).
3. Understand the interactions between ionising radiation effects and other co-stressors.
4. Identify the mechanisms underlying multi-generational responses to long-term ecologically relevant exposures: maternal effects, hereditary effects, adaptive responses, genomic instability, and epigenetic changes/transformations/processes.
5. Understand how radiation effects combine in a broader ecological context at higher levels of biological organisation (population dynamics, trophic interactions, indirect effects at the community level, and consequences for ecosystem functioning).

Challenge three: To Improve Human and Environmental Protection by Integrating Radioecology

Our strategic vision is that over the next 20 years radioecology will develop the scientific foundation for the holistic integration of human and environmental protection, as well as their associated management systems.

Strategic Research Agenda

1. Integrate uncertainty and variability from transfer modelling, exposure assessment, and effects characterisation into risk characterisation.
2. Integrate human and environmental protection frameworks.
3. Integrate the risk assessment frameworks for ionising radiation and chemicals.
4. Provide a multi-criteria perspective in support of optimised decision-making.
5. Integrate ecosystem approaches, such as ecosystem services and ecological economics, within radioecology.
6. Integrate Decision Support Systems.

The vision statements and strategic agenda presented above concentrate on the research aspects of radioecology. The final Strategic Agenda will also include plans for other equally important aspects of our science (*i.e.* maintaining crucial radioecological infrastructures; education; and knowledge management). The other phases will be developed over the next two years with input from stakeholders and the larger radioecology community.

For society to obtain a significant contribution from the radioecology of the future, a long-term, multidisciplinary approach is needed that goes beyond national boundaries. It is our hope that a Strategic Research Agenda for radioecology will focus and prioritise our collective efforts, resulting in increased value and more rapid advancement in our understanding of environmental radioactivity.

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1 INTRODUCTION TO SECOND VERSION

The STAR Network of Excellence⁶ (Strategy for Allied Radioecology) was funded in February 2011, under the 7th Framework programme of the European Commission, to assist in the development of a sustainable, integrated radioecology programme within Europe. STAR developed and published the first Strategic Research Agenda (SRA) in radioecology (Hinton *et al.*, 2013) as a vision of what can be achieved in the future through a directed effort and collaboration by many organisations. STAR actively requested a critique of the SRA and invited stakeholder input via a questionnaire on the STAR website and a stakeholders' workshop in November 2012. The stakeholders' comments, criticisms and suggestions have been itemized in a document available on the STAR website⁷ (also attached in the annex of this document). Stakeholder response to the SRA was overwhelmingly positive. The enthusiasm from stakeholders was as much for the general concept of a consolidated effort to address the difficult challenges in radioecology, as in the specifics of what STAR had suggested to be the key research priorities within the science.

This document constitutes the second version of the SRA and incorporates the many excellent ideas expressed by stakeholders via the questionnaire and the stakeholders' meeting. STAR's incorporation of each stakeholder's comment is identified within this version of the SRA as **blue font**, followed by the stakeholder's comment number from the annex (*i.e.* [C#n]). This method allows a stakeholder to determine how a specific suggestion was incorporated within this second draft of the SRA. Note that the annex also contains the action taken by the STAR consortium in addressing the comment. When a stakeholder requested an action, but that action was already addressed in the first version of the SRA, then the comment number was placed after the appropriate sentence/paragraph of the original text of the SRA.

Additionally, this version of the SRA, when submitted to the EC as a STAR Deliverable in January 2014, will contain a new section on education and training, which are critically important components in developing a sustainable science.

This version of the SRA contains additional text that strongly supports collaborative research among the three important 'pillars' of radiological protection:

- radioecology (Radioecology Alliance platform);
- emergency response and management of post accident situations (NERIS⁸ platform); and
- low dose risk research (MELODI⁹ platform).

As a result, the SRA will better position radioecology within the broader European radiation protection programmes as they evolve towards the HORIZON2020 framework. The SRA has been used to help define the COMET¹⁰ project, and to produce the first short-term (5-y) Roadmap for Radioecology. The latter establishes a transitional implementation plan that structures and enhances interactions among the Radioecological Alliance, NERIS [C#19; C#20] and MELODI [C#25; C#26];

⁶ www.star-radioecology.org

⁷ https://wiki.ceb.ac.uk/display/star/Strategic+Research+Agenda?atl_token=7437cb7d61cbd37dfe5177db203fed6724e40e1

⁸ NERIS the European platform on nuclear and radiological emergency response <http://www.eu-neris.net>

⁹ MELODI Multidisciplinary European Low Dose Initiative <http://www.melodi-online.eu>

¹⁰ COMET Coordination and iMplementation of a pan-European instrument for radioecology – FP7 Euratom Fission-2013- project number: 604974, Start June 1, 2013, duration 48 months- WP2 is dedicated to “Joint programming and Implementation – Expanding the Radioecology Alliance”

2 INTRODUCTION TO THE STRATEGIC RESEARCH AGENDGA

Radioecology is a branch of environmental science devoted to a specific category of stressor: radioactive substances. The science includes key issues common with other groups of pollutants, particularly metals (*e.g.*, environmental transport, fate, speciation, bioavailability, and effects at various levels of biological organisation), as well as aspects specific to radionuclides (*e.g.*, specialised source terms, external irradiation pathway, radiation dosimetry, radioactive decay, and unique aspects of very low level measurements). **Radioecology emerged as a science in the late 1940s and 50s in response to concerns about releases from nuclear weapons production facilities and radioactive fallout from nuclear testing. Scientific studies of several subsequent accidents at nuclear facilities enhanced knowledge about radioecology; however, much of the early data was classified and not publicly available until the cold war ended in the late 1980s (Iiyin and Gubanov, 2004) [C#1].** Radioecological expertise is needed whenever radiation within the environment is of potential concern. A few examples include the nuclear fuel cycle (from uranium mining through deposition of radioactive wastes [C#6]); existing as well as new nuclear power plants; decommissioning of facilities; remediation of contaminated sites [C#93]; naturally occurring radionuclides; and nuclear accidents or terrorist events [C#4].

Following the Chernobyl accident, European research in radioecology excelled such that Europe's foremost expertise was widely recognised. However, radioecology has faced substantial decreases in funding over the last 15 years and now key elements of the expertise are declining. One major reason for the decline is that research efforts that were intensive during the years following the Chernobyl accident have substantially decreased. Most of the funding for radioecology during the last decade has focused on modelling efforts, mining existing data and data syntheses. Little funding has been available for the acquisition of new knowledge, especially through hypothesis-driven research. FUTURAE (2008), a Euratom Coordinated Action within the European Commission's 6th framework, surveyed the state of radioecology in Europe and found deficiencies in research, as well as in education, funding and infrastructure support. Although this situation has few visible consequences in the short term, with time, the declining competences and expertise in radioecology will have important implications, as is already evident in several countries where a decline has been more rapid. For example, a recent call for radiological expertise from various embassies in Japan, following the Fukushima disaster, alerted several government agencies to the scarcity of qualified personnel (*e.g.*, U.S. case¹¹).

To counter emerging problems and improve radioecology within Europe, eight organisations¹² signed a Memorandum of Understanding (MoU) that formed the European Radioecology Alliance¹³. The MoU states the intentions of Radioecology Alliance members to integrate a portion of their respective R&D efforts into a trans-national programme that will enhance and sustain European radioecological competences and experimental infrastructures. The MoU asserts that Radioecology Alliance members will jointly address scientific and educational challenges related to assessing the impacts of radioactive substances on humans and the environment. The Radioecology Alliance members are

¹¹ Information from presentation made by representatives of the U.S. Centers for Disease Control and Prevention during the annual meeting of the National Council on Radiation Protection (Washington, D.C.; 13 March 2012; see pages 13-14 of the 48th Annual Meeting Report): http://www.ncrponline.org/Annual_Mtgs/2012_Ann_Mtg/Electronic_NCRP_2012_Annual_Mtg_Program.pdf

¹² French Institute of Radiation Protection and Nuclear Safety (IRSN, France); Radiation and Nuclear Safety Authority (STUK, Finland); Belgian Nuclear Research Centre (SCK•CEN, Belgium); Natural Environment Research Council (NERC, United Kingdom); Research Centre in Energy, Environment and Technology (CIEMAT, Spain); German Federal Office for Radiation Protection (BfS, Germany); Swedish Radiation Safety Authority (SSM, Sweden); Norwegian Radiation Protection Authority (NRPA, Norway).

¹³ www.er-alliance.org

now expanding¹⁴ and they all recognise that their radioecological research can be enhanced by efficiently pooling resources and prioritising group efforts along common themes of mutual interest. A major step in this prioritisation process was to develop a Strategic Research Agenda (SRA). This is one of the tasks of the work programme of the STAR consortium¹⁵.

This Strategic Research Agenda is a suggested prioritisation of research topics in radioecology, with a goal of improving research efficiency and more rapidly advancing the science. It responds to the question: “*What topics, if critically addressed over the next 20 years, would significantly advance radioecology?*”

The Radioecology Alliance has become an Association open to other organisations with similar interests in promoting radioecology, both within and outside of Europe. Thus, although the development of the SRA has largely been a European effort, the hope is that it will stimulate an open dialogue within the international radioecology community. STAR, strengthened by the recommendations from its External Advisory Board, **has sought** input from the larger radioecology research community:

- other pan-European platforms with research topics that require radioecology [Multidisciplinary European Low Dose Initiative (MELODI); European Platform on Preparedness for Nuclear and Radiological Emergency Response and Recovery (NERIS); Implementing Geological Disposal of Radioactive Waste Technology Platform (IGD-TP)];
- other radioecology networks around the world [e.g., National Center for Radioecology (NCoRE), within the United States];
- the International Union of Radioecology (IUR);
- international organisations [e.g., World Health Organization; United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR); International Commission on Radiological Protection (ICRP), International Atomic Energy Agency (IAEA)];
- regulators;
- industry; and
- other interested stakeholders.

Comments and input for improving the SRA **were** welcomed via a link on the STAR website (www.star-radioecology.org). Additionally, STAR and the Radioecology Alliance **conducted** a stakeholders’ workshop in Paris (12-13 November, 2012). The purpose of the workshop **was to promote an exchange with the audience about the SRA and how to prioritise research lines. Additionally, discussions were held on how recommendations from the web-consultation and workshop should be incorporated into a second version of the SRA.** During the workshop, STAR **welcomed** recommendations from a variety of stakeholders, including NGOs, nuclear industry representatives, regulators, funding agencies and scientific non-profit societies from other environmental disciplines. The workshop **helped place** the STAR-Radioecology Alliance SRA **in context** to the goals of other existing platforms, such as NERIS, MELODI and IGD-TP. Details of the workshop **are** available on the STAR and Radioecology Alliance websites. **Beyond Europe, the close collaboration of the Radioecology Alliance with other radioecological organisations (e.g., IUR**

¹⁴ Since the last general assembly in June 2013, three additional partners have joined the Radioecology Alliance: CEA (FR), University of Portsmouth (UK), NNCRK (KZ)

¹⁵ STAR also includes Stockholm University and the Norwegian University of Life Sciences

and NCoRE) is critical to a cohesive, unified development and promotion of the science [C#36; C#37]. A Memorandum of Understanding for collaboration is under development between the Radioecology Alliance and both IUR and NCoRE. [C#36; C#37].

The SRA was distilled from several evaluations on the state of radioecology, including input from stakeholders (FUTURAE 2008), the interests of Radioecology Alliance member organisations, the International Union of Radioecology¹⁶, lists of research needs, identification of data gaps and recommendations for the future of radioecology, or its sister science of ecotoxicology (Whicker *et al.* 1999; Hinton 2000; Brechignac *et al.* 2003; Calow and Forbes 2003; Brown *et al.* 2004; Eggen *et al.* 2004; Garnier-Laplace *et al.* 2004; Shaw 2005; Alexakhin 2006; OECD-NEA 2007; Brechignac *et al.* 2008; Larsson 2009; Pentreath 2009; Salbu 2009a; Repussard 2011; Artigas *et al.* 2012).

Additionally, the SRA was formulated by considering several aspects related to (i) recent changes in policy; (ii) new scientific advancements; (iii) improving credibility with stakeholders; (iv) science deficiencies; (v) integration issues; (vi) potential risks, and of course, (vii) early lessons from the Fukushima disaster. Examples of these include the following:

- *Changing policy*: It is now recognised that the present framework of radiological protection should be changed to explicitly demonstrate protection of the environment. For example, an OCED/NEA report (2007), Scientific Issues and Emerging Challenges for Radiological Protection, specifically states that: “*The current system of radiological protection, not having been designed for this purpose, is a weak tool to demonstrate the level of radiological protection afforded to the environment.*” Note that radioecology has a critically important role in generating knowledge of how to demonstrate protection of the environment and providing well founded science such that benchmark dose rates can be defined. [C#53]. However, the actual actions triggered by exceeding an environmental limit is a policy-related response and not appropriate for this SRA [C#8].
- *New paradigms and scientific advancements*: Recent changes relevant to radiation effects on humans are also relevant to radioecology, and go beyond the previous dogma of single target theory for cell survival as the only mode of action for cell death. New ideas are being incorporated into the science, such as epigenetics, bystander effects, genomic instability and population consequences from multigenerational exposures. Radioecology will also capitalize on the rapid advances in the “-omic” sciences to help develop mechanistic explanations and early warning biomarkers.
- *Credibility concerns*: Uncertainties and lack of predictive power in risk assessments are major contributors to the public’s reduced credibility of radiological sciences, and thus a major driver for additional research to enhance knowledge [C#2]. Credibility of assessment models is particularly important because their predictions are often key constituents in decisions made about emergency response, waste management, environmental remediation, and litigation (Whicker *et al.* 1999). Some of these uncertainties originate from the exposure assessment, which is largely dependent on knowledge of the environmental behaviour of radionuclides. The acquisition of new scientific knowledge through research in radioecology is, therefore, a crucial element in improving human and environmental risk assessments, and thereby improving credibility with stakeholders.
- *Science deficiencies*: There are many examples of deficiencies in our science, but one example is the recognition that contaminants do not occur in isolation, as experimental

¹⁶ www.iur-uir.org/en/

protocols have historically implied, but instead occur as low concentrations of complex mixtures. Thus, changes are needed in our experimental approaches to address the important issue of whether radiation protection needs to be considered in the context of mixed contaminant scenarios? Radioecology can learn from other scientific disciplines (e.g., ecotoxicology) that are already addressing similar deficiencies in their studies of non-radioactive contaminants [C#3].

- *Integration issues:* Recognition that radioecology's future success, broadly defined as meeting stakeholder needs, will require integration in several ways and from several different perspectives. This applies particularly to radioecology's contribution to
 - applied radiation biology and low dose effects, emergency response, remediation, decontamination, and wastes disposal [C#5, C#6, C#, 7, C#52, C#58, C#90, C#91].
 - the use of radioactive tracers to study the dynamics of physical, biological and chemical processes has proved to be a valuable tool in many areas of science (e.g., oceanography, geomorphology, ecology, chemistry). Radioecologists have developed particular skills and tools relevant to tracer studies (i.e. specialized laboratories, legal permission to use radionuclides, knowledge and permits to deal with radioactive wastes). The contribution of this aspect of radioecology should be strengthened and used as a means of establishing bridges with other disciplines. Radioactive tracers are not included as a priority area for radioecology in the SRA because the use of radioactive tracers is a method and thus it is more appropriate for additional development within the roadmap [C#12, C#68].
 - a scientific foundation for integrating environmental protection and human protection under one generalised system, recognising that it would enhance efficiency and of much interest to regulators, industry and the public.
 - a more holistic ecosystems approach and integrating ecosystem services within environmental risk assessments
 - decision support systems and using multi-criteria decision analyses to improve post accident management
 - challenges associated within radiochemistry/nuclear chemistry
 - optimizing management options following exposure situations by integrating information generated by radioecology with data from other scientific disciplines [C#7].
- *Potential risks:* The accidents at Three Mile Island (USA, 1979), Chernobyl (Ukraine, 1986) and Fukushima (Japan, 2011) showed that human errors can override safety systems; that consequences can be more serious than expected; and that the extremely low probability of geohazards should not be underestimated. Future events may release radionuclides to the environment that are different from those for which we now have the most knowledge. Furthermore, the attack on the World Trade Centre (USA, 2001) demonstrated that terrorist groups have both the intention and capacity to attack urban centres. Thus, actions such as the misuse of nuclear weapons, attack on nuclear installations, or use of dirty bombs containing many poorly researched radionuclides may represent future challenges within radioecology.
- *Fukushima:* The Fukushima accident in Japan has highlighted the importance of radioecology and the need to understand environmental radioactivity. The accident in Japan led to major releases to both marine and terrestrial ecosystems. Since the Chernobyl accident,

considerable advances have been made in modelling atmospheric releases, as was evident by how well current models predicted the long distance transport and plume dynamics from Fukushima. However, the near-field atmospheric and terrestrial transfer models did not allow for the significant variation in interception, translocation and mobility of deposited caesium. Additionally, the dynamics of radionuclide distributions following the marine releases were not predicted well by the current equilibrium-based models, and considerable uncertainty exists as to what the marine impacts and recovery periods will be, especially within the near-shore environments. Radionuclide transfers within contaminated forests, erosion of contaminated soils, and the technical/social problems of disposing of huge amounts of materials, destroyed by the tsunami, but now contaminated with radionuclides, are still unresolved problems. These examples emphasise again the need for improved transfer and exposure models derived from a more profound understanding of environmental processes. Important field sites now exist at Fukushima to enhance scientific understanding. For example, studies conducted within the Chernobyl exclusion zone have produced contradictory findings, some of which could have considerable implications for human and environmental radiological protection (Beresford and Copplestone, 2011). Opportunities now exist at Fukushima to enhance our understanding of the ecological consequences and address problems that still remain unresolved, 25 years after the Chernobyl accident.

Based on consideration of the items above, the SRA prioritises three major **scientific challenges** facing radioecology. Each of these scientific challenges is developed as a separate section of the SRA and includes a **vision statement** of what should be accomplished over the next 20 years in that area of radioecology. The **Strategic Research Agenda** includes key research lines deemed necessary to accomplish the vision.

The three scientific challenges presented below, with their 15 associated research lines, are a strategic vision of what radioecology can achieve in the future through a directed effort and collaboration by many organisations. It is a vision in which the participants were asked to think creatively and without bounds as they imagine the results that could most shape the future of radioecology and benefit stakeholders. The reality is that the SRA will require considerable resources and time to bring to fruition. The “how”, “means” and practicality of accomplishing the research items presented in the SRA will be developed in a subsequent document that outlines the roadmap required to achieve the visions. The roadmap will link the SRA with the evolution of the science by providing the necessary action plans, resource allocation, and milestones required to achieve the SRA. [Some prioritization of research lines \[C#51, C#71\], methods \[C#10\], appropriateness of laboratory versus field research \[C#70\], radionuclides to study \[C#11\], etc. will be suggested within the roadmap \[C#67\].](#) The first short-term (5-y) scientific roadmap for Radioecology is released in September 2013 with the main aim of establishing a transitional implementation plan to structure and enhance interactions between the Radioecology Alliance and two existing European research platforms in radiological sciences: NERIS and MELODI. Other expanded versions will follow under the lead of the COMET project and the Radioecology Alliance.

3 THREE SCIENTIFIC CHALLENGES IN RADIOECOLOGY

3.1 Challenge One: To Predict Human and Wildlife Exposure in a Robust Way by Quantifying Key Processes that Influence Radionuclide Transfers and Exposure

One of the fundamental goals of radioecology is to understand and predict the transfers of radionuclides and consequent exposure of humans and wildlife. This is needed for a wide range of

sources and release scenarios, exposure situations and assessment contexts in atmospheric, terrestrial (agricultural, semi-natural, natural, urban) and aquatic (marine, freshwater, estuaries) environments. The problem is that the key processes that govern radionuclide behaviour, associated transfers among environmental compartments and resulting exposures are not always well understood, leading to models that have an incomplete (or even inaccurate) representation of the processes. At the same time, scientific knowledge is gradually being accrued through on-going improvements in our understanding of these underlying processes. The challenge faced by radioecologists is to incorporate this knowledge into models capable of representing the behaviour of the radionuclides in a more realistic way, ideally considering the different levels of organisation present in the environment, from small to large scales (*i.e.*, from molecules to environmental compartments and global ecosystems). By making the models more realistic and process-based, we expect (i) a significant reduction in model uncertainty, (ii) a better quantification of environmental variability, (iii) identification of the most influential parameters, (iv) improved modelling tools capable of predicting radionuclide exposure to humans and wildlife under a variety of conditions, thereby enhancing the robustness of both human and wildlife assessments of exposure to ionising radiation, and, (v) to be able to provide scientifically justified safety assessments for hypothetical future situations that need to take into account biogeochemical cycling of radionuclides over large time scales, changing climate conditions, and changing landscapes [C#13; C#14; C#35; C#86; C#87; C#89] (Figure 1).

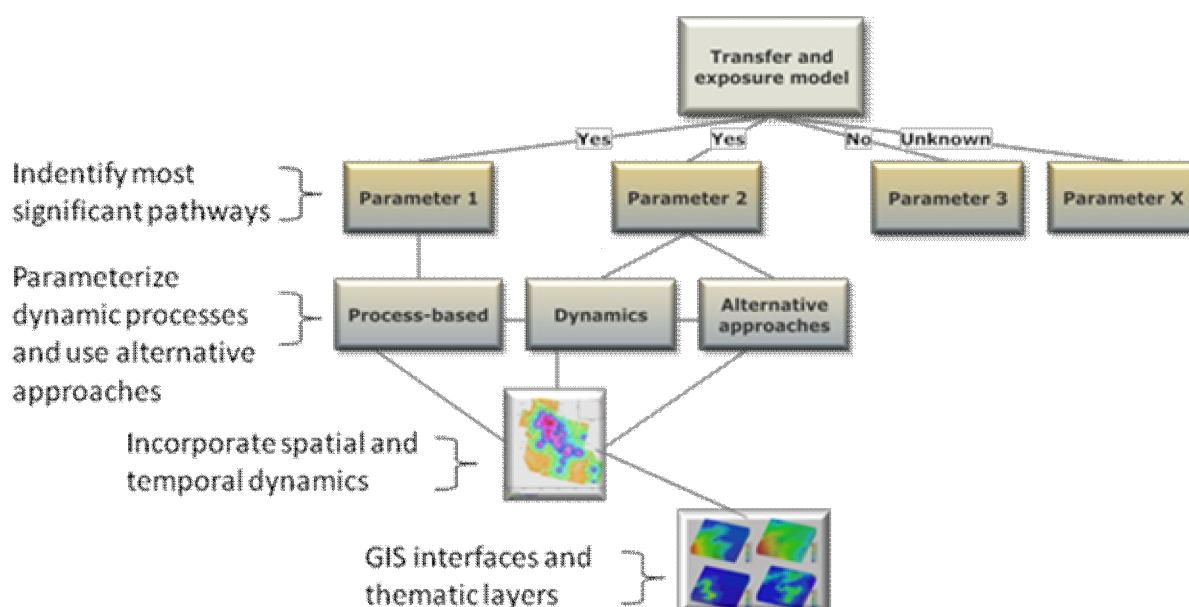


Figure 1. Scheme of key aspects to challenge one: To Predict Human and Wildlife Exposure More Robustly by Quantifying Key Processes that Influence Radionuclide Transfers, and Incorporate the Knowledge into New Dynamic Models.

The input data and models needed for assessing the environmental and human impacts following exposure to ionising radiation differ depending on the source term, release conditions (aquatic versus atmospheric, routine versus accidental), assessment endpoints and the type of space- and time-dependency (dynamics) of the problem. The simplest situation is one in which the radionuclides are released in a continuous and uniform way which is in balance with physical decay and dispersion into the wider environment. This leads to a static scenario in which radionuclide activity concentrations in the biota and surrounding medium are in a constant equilibrium, describable by empirical ratios. Such a description tends to dominate current radioecological assessment practices for the good reason that

it is a reasonable approximation for most routine release situations. However, the approach has difficulties when attempting to simulate releases occurring on very short time scales compared with the uptake and turnover processes in the ecosystem, such as a planned series of rapid pulsed releases or accidental situations. In such events, a simplistic, empirical ratio approach is no longer valid and a dynamic, process-oriented modelling approach is required, especially when the uncertainty due to simplistic nature of the empirical transfer parameters is not acceptable. Fundamental research is needed to better understand and model the key dynamic processes, [such that powerful dynamic process-based radioecological models can be parameterised and populated \[C#3\]](#).

Uncertainty and variability (the latter arising from 'true' heterogeneity) contribute to the lack of predictive accuracy and precision in radioecological assessment models (Kirchner and Steiner 2008). The need to conduct research to reduce uncertainty and capture variability in radioecological models is evident from model comparison exercises for human impact assessments (Sheppard *et al.*, 1997; IAEA, 2003); wildlife impact assessments (*e.g.*, Beresford *et al.*, 2008; Vives i Batlle *et al.*, 2011); the IAEA Coordinated Research Program on radioactive particles (IAEA, 2011) and from studies on the behaviour of long-lived radionuclides released from geological disposal facilities (*e.g.*, BIOPROTA, 2005). The description and assessment of the source term and its evolution typically have substantial uncertainty and variability. For example, a significant fraction of radionuclides released by nuclear events (such as testing of nuclear weapons or nuclear reactor accidents) are in the form of discrete particles and/or associated with aerosols, colloids or other complexes (Salbu *et al.*, 2009a). The inherent differences in the transport and bioavailability of particle-bound radionuclides compared with those existing as molecules, ions, or complexes have not been captured in radionuclide exposure assessment. As a result, there is a high degree of scientific uncertainty about the levels of risk to human health and the long-term ecological consequences of radioactive particles present in the environment.

Additionally, scarcity of data is one of the major sources of uncertainty, even for the simplest equilibrium models. Recently, the IAEA made a compilation of parameter values for estimating radionuclide transfers and found major data gaps (IAEA, 2009). For numerous elements (Cu, Eu, P, Nb, Ba, Na, Cr, Zr, Ca, Y, Ag, Fe, La, Cd, Sb, Pm, Tc, Ru and Po) soil-to-plant transfer factors were available for only 10 % of the plant and soil group combinations. For elements such as Nd, Pr, Rh and W, the soil-to-plant transfer factors were derived from only a single generic value estimated by expert judgment, or derived by analogy to a chemically similar element. The scarcity of data increases with trophic level and stages in the human food chain. For approximately 50 % of the listed radionuclide-animal product combinations, no transfer coefficient data were available. The wildlife empirical ratios compiled by IAEA (2012) also have substantial data gaps and many of the values are based on few data (345 of 946 values for the generic wildlife groups are derived from less than 3 observations). Such small data sets weaken the reliability of predictions and their true degree of variation; caution should therefore be used when applying such values in assessments.

The development of process-based models that rely less on empirical ratios would inevitably reduce the uncertainties associated with modelling the transfer of radionuclides in the environment. The result would be more realistic and accurate models for radiological impact assessments and an increased confidence in the assessment process when these models are applied. Empirical ratios typically dominate radiological assessment models (Ng, 1982; IAEA, 2009) and are valuable tools in that they have facilitated the modelling of radionuclide transfers and the resulting predictions of exposure to humans and wildlife. However, their use significantly increases the uncertainty of model predictions. Use of simple empirical ratios to represent the transfer between environmental media means aggregating many physical, chemical and biological processes into one parameter, which is an

implicit weakness of the approach when a detailed understanding of the processes operating and dynamics of the system is required.

For example, the mobility of radionuclides in soils and sediments is usually estimated using 'distribution coefficients' (K_d 's) defined as a simple solid/water activity concentration ratio assumed to be constant, despite considerable evidence that the K_d varies by orders of magnitude and that process-based rate constants can describe the situation more realistically (Børretzen and Salbu, 2002). Similarly, the uptake of radionuclides by animals and plants is often defined as a simple biota/medium (*e.g.*, soil or water) activity concentration ratio, equally assumed to be constant, and are not applicable for situations in which radioactivity levels in the medium are rapidly variable. For example, estimates using a dynamic biokinetic model of radionuclide concentrations in lobsters exposed to variable, pulsed discharges of ^{99}Tc released from Sellafield to the Cumbrian coast corresponded very well with measurements; however, predictions using an empirical factor-based equilibrium model differed by an order of magnitude (Vives i Batlle *et al.*, 2008). Additionally, the large variation in soil-to-plant transfer factors for Cs among agricultural crops (IAEA, 2009) is mainly because soil processes affecting radiocaesium fluxes are not adequately captured by empirical ratios, even when grouped by soil texture classes. Alternatively, the semi-mechanistic model of Absalom *et al.* (1999) explained 60 to 90 % of the observed variability in Cs uptake by plants by including soil contamination level, clay content of the soil and the soil exchangeable K status. Such [detailed understanding of the manner in which radionuclides interact with different soils is crucial to understand the transport of radionuclides through the environment and the manner in which humans and other organisms are exposed to radiation \[C#49\]](#).

The environmental behaviour of radionuclides is controlled by complex biological, chemical and physical processes which may vary (1) spatially - due to differences in water chemistry, sedimentary dynamics, soil type, land use management, and diversity of biological assemblages and communities; (2) temporally - due to time after release, organism's life stage, climatic stressors such as floods, storms, water cascading, biologically-driven processes, [landscape evolution \[C#86\]](#) and scenarios of global change; and (3) with source term - due to history of the releases, physico-chemical forms, and presence of co-contaminants. Unfortunately, although the spatial and temporal components of processes are acknowledged to be important and have been the focus of considerable research (*e.g.*, Salbu, 2009b; Vandenhove *et al.*, 2007; Eyrolle *et al.*, 2009), they are still poorly developed in radionuclide transfer and exposure models. In addition, a gap generally exists between the measurement scale typically used in research studies and the scale needed in management decisions and regulatory measures. One of the reasons for this gap is that the understanding of radionuclide interactions in the environment is often based on small-scale observations or experiments, and it is not known how such processes or changes may affect key processes and functioning of environmental systems at larger scales. Therefore, understanding of spatial scales between and within environmental compartments and the impact from global circulation patterns needs to be expanded to provide improved assessment and management strategies for radionuclides released into the environment.

3.1.1 Strategic vision for research

Our strategic vision is that over the next 20 years radioecology will have achieved a thorough mechanistic conceptualisation of radionuclide transfer processes within major ecosystems (terrestrial, aquatic, urban) for a wide range of source terms, release scenarios and exposure situations [C#4; C#6; C#46; C#93], and be able to accurately predict exposure to humans and wildlife by incorporating a more profound understanding of environmental processes.

3.1.2 Strategic agenda

The major aim of challenge one is to develop process based models of environmental transfer and exposure to substantially improve human and environmental dose and impact assessment [C#74].

The approach can, and will, be applied to a wide range of sources encompassing existing (e.g. uranium mining and milling sites, NORM sites, post accident situations), planned (e.g., new build, (geological) waste disposal) and emergency exposure situations. Emergency situations are the focus of the SRA of NERIS so the radioecological related aspects will be researched and developed in close collaboration with NERIS. Related to (high-level) waste disposal our SRA will concentrate on the biosphere and geosphere/biosphere interaction zone, linking to networks such as BIOPROTA¹⁷ and IGD-TP¹⁸ [C#4; C#6; C#46]. Environments other than temperate ecosystems will be considered [C#5; C#35].

The mechanistic, process-based, approach should

- enable long-term forecasts and the influence of climate and landscape changes on the environmental transfers of radionuclides [C#14; C#35; C#82; C#86; C#87; C#89];
- assist in the development of tools for response, remediation, and restoration [C#52]; and
- support decision making [C#28; C#53].

Validation of all models will be performed using independent data not used in model parameterisation [C#50].

The following four research lines will need to be addressed to achieve this vision.

3.1.2.1 **Identify and mathematically represent key processes that make significant contributions to the environmental transfers of radionuclides and resultant exposures of humans and wildlife**

A challenge for radioecologists over the next two decades is to develop a sufficient understanding of environmental transfers and exposure processes that permit observations to be explained and robust predictions made. The main aspects will be (i) identifying where the most advantage can be gained in reducing uncertainty and understanding variability, (ii) justifying the additional research required to parameterise dynamic-mechanistic models, and (iii) identifying the level of model complexity needed for specific exposure scenarios.

Criteria will be developed to identify key processes that have a significant impact on radionuclide transfers in atmospheric, terrestrial and aquatic environments. Amongst the features considered will be source-term-specific release scenarios (including physico-chemical forms), spatial and temporal dynamics in source term–environment interfaces (dispersion and dilution, changes in radionuclide speciation due to physical, chemical and biological interactions), migration and cycling pathways in specific ecosystems, and radionuclide uptake, accumulation, redistribution and depuration by organisms. Once the key processes have been identified, equations will be derived that capture their temporal and spatial kinetics. Criteria to identify the relevant factors and processes could be inferred from the variability observed in aggregated parameters and the associated uncertainties in transfers, as shown by scatter plots of empirical transfer factor values and associated cumulative distribution functions. A classification based on key environmental characteristics, taxonomy, source term, etc.

¹⁷ <http://www.bioprota.org/>

¹⁸ <http://www.igdtp.eu/>

along with a scientific understanding of radioecological mechanisms, should help unravel and classify the processes underlying the aggregated parameters.

One of the goals of this research line is to identify the key processes, based on fundamental biogeochemical and ecological principles that govern the transfer of radionuclides within major ecosystems types (e.g., agricultural, grasslands, coniferous forests, freshwater lakes and rivers, marine systems, urban environments). This goal can be realised by the development of conceptual and mathematical test models allowing the identification and ranking of key processes in a qualitative manner using expert judgement. Parameter sensitivity analysis can also be used to rank parameters and processes in radionuclide transfer models with respect to their relative influence on both the magnitude and the uncertainty of the model predictions (e.g., Breshears *et al.*, 1992).

Additionally, within this research line, we intend to progress towards process-based dynamic models. [Process-based modelling is essential to demonstrate that scientifically justified impact and safety assessments can be made for future situations \[C#13\]](#). The various empirically-based model parameters will be replaced by mathematical equations that describe the key physical, chemical and biological processes that govern radionuclide transfers. Properties specific to radionuclides and the biotic and abiotic components of each environment will be incorporated. Examples include:

- using Fick's, Darcy's and Richard's laws for simulating rates of water movement in porous media;
- advection-dispersion equations for describing flow kinetics in aquatic environments;
- relating the environmental mobility of radionuclides to the oxidising/reducing properties in which they reside via pH, redox potentials, salinity, mineralogy or general chemical composition; and
- metabolic theory for describing the biokinetics/toxicokinetics of contaminants in living organisms.

In all cases, the objective will be to produce a set of physically and dimensionally consistent primary differential equations that represent the temporal dynamics of processes governing radionuclide transfers. The equations will, to the extent possible, incorporate the material properties of the radionuclides and environments and, ultimately, the basic laws of nature. For some radionuclides, especially those associated with previous accidents such as I, Sr and Cs, but also for a number of radionuclides such as U, Pu, Am, data exist to describe time dependency in transfer of many important processes.

[It is important that the knowledge gained from the various research activities is rapidly assimilated and made available to the wider community. This is likely to require the development of flexible and open databases that do not 'force' the information into an over-constrained conceptual model framework, together with a platform \(or platforms\) for the modular development of mathematical models \[C#23\]](#).

3.1.2.2 **Acquire the data necessary for parameterisation of the key processes controlling the transfer of radionuclides**

Recent data collection activities (such as compilation of the IAEA handbook of radioecological transfer parameters) have identified significant data gaps and limitations for many of the empirical parameters which underpin dose assessment models for humans and wildlife. The wide range of radionuclides, human foodstuffs and species of wildlife means that, pragmatically, we may never be in the position of having empirical data for everything. There is a need to consider alternative

approaches to address this problem in the most robust manner possible (rather than relying on highly conservative judgment to avoid analysing the problem in more depth, as is often the case). Extrapolating across the periodic table using chemical analogues is such an approach. For example, in the context of the Fukushima accident, it was proposed that estuarine reactivity of short-lived radioactive tellurium could be assessed based on the behaviour of its stable analogue. Other approaches, such as Bayesian statistics, allow a low number of empirical observations to be supported by inferences from more comprehensive, larger datasets. [Some approaches to extrapolate data have been suggested for application across species \(wildlife species or human food chain species\) such as phylogeny \(i.e. using ‘common ancestry’ to categorise transfer\) and allometric \(mass dependent\) relationships \[C#74\].](#)

The data for model parameterization will require focused laboratory-based work and field studies, as well as on-going reviews of published information from the wider scientific community, (both at suitably-designated "observatory sites" and more generally from environmental monitoring). For example, a preliminary inventory of databases acquired from observatories and monitoring sites at the European scale by the various STAR partners highlighted the richness of environmental data, especially their temporal and spatial distributions, even though heterogeneity and data gaps were identified. Some of these data gaps are expected to be filled by innovative analytical tool developments in both radioactive and non-radioactive metrology. For example, difficulties persist in quantifying the various radioactive decay products from the natural U-Th decay chains within the same sample at a given time. In this context, ICP-MS and AMS analyses offer potentially exciting solutions. [To maximise opportunities for data acquisition whilst minimising the environmental impacts of our science, a strategic focus should be placed on the development and adoption of non-lethal methodologies \(which do not require animals to be killed\) for use in radioecological research \[C#66\].](#)

3.1.2.3 **Develop transfer and exposure models that incorporate physical, chemical and biological interactions, and enable predictions to be made spatially and temporally**

Accurate, process-based radioecological modelling can reduce the uncertainty of model predictions and consequently lead to a greater confidence in the results. For example, the consideration of chemical and physical speciation of radionuclides and their effect on subsequent environmental transfer (*e.g.*, Salbu, 2009b; Mitchell *et al.*, 1995) reduces the 1-order of magnitude discrepancy between the near-field and far-field K_d 's in the assessment of plutonium releases from Sellafield. Likewise, assessments of the globally-circulating radionuclides ^{14}C and ^3H have been greatly improved by including the influence of stable carbon, nitrogen and hydrogen cycles in radionuclide transfers (*e.g.*, Schell *et al.*, 1974). It is expected that the early dynamics of radionuclide distributions following atmospheric deposition and marine releases will play a major part in assessing the consequences of the nuclear accident at Fukushima. Other examples of areas where our process

The transfer models developed should be able to integrate radioactive contaminants into the general dynamics of ecological systems. An example is using pollutant-coupled soil-vegetation-atmosphere transport models to investigate the wider, long-term circulation patterns of [radionuclides in the geosphere-biosphere interface, and taking into account the biogeochemical \(re\)cycling of radionuclides over very long time-scales, changing climate conditions and evolving ecosystems \[C#46\].](#) Other examples are the coupling of short-range, coastal dispersion with long-range movement of water and sediment dynamics to identify the ultimate fate of radionuclides in the marine environment, as part of the climate-induced ocean global circulation patterns understanding should be improved are the behaviour of radionuclides at interfaces (*e.g.*, atmosphere-water surfaces,

land-coastal, watershed-freshwater courses, saline-freshwater, geosphere-biosphere, oxic-anoxic) and the influence of co-contaminants on radionuclide behaviour. and representing the redox behaviour in soil and uptake by plants in an integrated way. In addition, drivers of global change, such as climate variation and evolving hydrological and land use changes, will influence the transport, fate and effects of radionuclides in the environment, and therefore need to be considered. Ultimately, by using transport equations and well-defined boundary conditions, a dynamic, process-based understanding can be incorporated into our models, especially for systems which are outside their biogeochemical equilibrium. An analysis that relates to fundamental processes becomes conceptually simpler. Moreover, it facilitates performing the necessary abstractions and simplifications *a posteriori* (by way of a simplified description of less important sub-processes) rather than *a priori* (by way of insufficiently justified transfer parameters).

[This more process-based mechanistic modelling is expected to more accurately assess radionuclide transfer between and within environmental compartments and as such assure more robust human and ecological impact assessments \[C#74\].](#)

Radioecology is particularly under-developed in analysing the interactions of substances with living organisms at the membrane level, as well as in considering the biokinetics of internally incorporated substances leading to their time-dependent distribution, assimilation and elimination. An expectation is that it will be possible to combine circulation, metabolism and elimination processes with toxicokinetics and consequently gain an understanding of the effects of radioactive pollutants that follow the same distribution routes as their non-radioactive counterparts. In this way, we can properly test the hypothesis that chronic irradiation of individuals by internally deposited radionuclides leads to similar physiological/metabolic mode(s) of action as external irradiation.

There is a need to assess wildlife exposure more realistically by considering spatial as well as temporal variability in habitat utilisation, contaminant densities, interactions between organisms (*e.g.*, predation) and interactions of organisms with their environment (*e.g.*, movement). During various life stages, dynamic processes may change many characteristics of an individual organism, such as weight, food intake, metabolism, and internal contaminant concentration. Additionally, the food sources and habitat will also vary. These changes influence the amount of contaminant intake and/or external irradiation levels. By modelling exposure dynamically and mechanistically, these changes can be taken into account. By introducing spatial heterogeneity models, it will be possible to take into account the organism's movements (*e.g.*, foraging behaviour, migration, burrowing or nesting in function of life history stages).

An organism's mobility in a heterogeneously contaminated area will contribute significantly to the variation in exposure observed between individuals. This mobility can be captured in random or quasi-random walk models (Loos *et al.*, 2006). A particular potential of this approach is its ability to determine what individuals or populations of a particular species are more at risk, rather than treating all the individuals of a species in a given ecosystem as having received the same exposure. In present exposure models, these aspects are not yet considered.

Wildlife dosimetry is also in need of major advancements. Current wildlife dosimetry models are simplistic and generally describe organisms as single ellipsoid forms that are homogeneous in composition and contamination. We should evaluate, in connection with challenge 2 on effects assessment, how important it is to incorporate radionuclide-specific heterogeneous distributions within the body, to account for differences in sensitivity among various organs, and apply weighting factors based on the relative biological effectiveness of different types of emissions (*i.e.*, alpha, low- and high-energy beta and gamma-rays). Skewed dose distributions [from internally incorporated](#)

radionuclides (macro-distribution of radionuclides within organisms, but also the micro-distribution within specific organs and tissues, especially for alpha or beta emitters and for radioactive particles) also represent a challenge as it can significantly influence radiotoxicity [C#22]. Improvement is needed to reduce the dominant uncertainties in environmental dosimetry.

3.1.2.4 **Represent radionuclide transfer and exposure at a landscape or global environmental level with an indication of the associated uncertainty**

The objective of this research line is to improve the current status by mapping radionuclide transfer and exposure at the European or global scale based on thematic maps, including spatial and temporal variability, using the newly developed process-based models. Since geographical distributions of radionuclides tend to be highly heterogeneous (Van der Perk *et al.*, 1998), a detailed understanding is needed of radionuclide transfer processes at multiple scales, such that transfer can be mapped using GIS systems at the landscape level. Within this research line we intend to design and implement a user-friendly, state-of-the-art GIS interface with the developed models, facilitating mapping of radionuclide transfer and exposure at a landscape level to identify sensitive environmental compartments/areas. An added benefit of such development could be the integration of knowledge at the European level (interaction with challenge 3). Spatial dimensioning on the European scale has occurred in a number of systems with GIS capabilities, such as SAVE (Spatial Analysis of Vulnerable Ecosystems in Europe), RESTORE (Restoration Strategies for Radioactive contaminated Ecosystems), CESER (Countermeasures: Environmental and Socio-Economic responses) and RODOS (Real-time On-line Decision Support system for off-site emergency management in Europe) (Howard *et al.*, 1999; Voigt *et al.*, 1999; Salt *et al.*, 2000; Ehrhard *et al.*, 1997). However, improvements in spatial dimensioning are needed by incorporating better process-based approaches.

An important task here will be to bridge the previously-mentioned difference between the small scales at which radionuclide behaviour and transport are often studied and the larger scales often relevant for management decisions. A GIS interface could include reference values (geochemical or anthropogenic backgrounds) and thus provide useful means to evaluate the level of exposure. The changing exposure conditions experienced by wildlife animals as they traverse and utilise various habitats with heterogeneous contamination could also be incorporated and visualised to improve our understanding of the exposure conditions and, as result, reduce uncertainties in the environmental assessment. Thematic maps of different terrestrial variables such as land use, soil type, leaf area index and crop coefficient, local climate, etc. will be linked to the radionuclide transport datasets. Such a system will enable robust environmental exposure predictions at various scales, allowing advanced visualisation of the complex interactions between radionuclides and the various environmental properties and processes. The system would also facilitate communication with stakeholders.

To identify and evaluate the importance of data, knowledge gaps and detailed requirements for process based modelling; an international platform where modellers, experimentalists and end-users can exchange information, ideas and experience needs to be established. Thus, a success criterion for the Radioecology Alliance will be a close collaboration between these different communities. This has not always been the case in the past, reducing the exchange of new radioecological knowledge and improved models.

3.2 Challenge Two: To Determine Ecological Consequences under Realistic Exposure Conditions

New approaches to understand and assess the effects of radiation on wildlife are emerging; mainly due to the similarities that radioecology has with ecotoxicology of chemical substances, stress ecology (Van Straalen 2003) and human radiation biology. There is opportunity to collaborate more efficiently with researchers from environmental sciences including ecology and ecotoxicology, due to shared challenges (e.g., for extrapolating from acute to chronic ecotoxicity, laboratory to field, one species to another, individual to populations), methods, concepts, models, and tools. Whilst taking benefits of these similarities through collaboration, from the radioecological perspective this challenge should be focused on solving priority issues specific to radioactive substances [C#3; C#69]. The development of common research activities between the Radioecology Alliance and the European research platform dedicated to low dose human health effects (namely MELODI) will be implemented rapidly. The planned research under the framework of COMET about epigenetic processes is also proposed as a field of common interest to further develop interactions between the two platforms in the first 5-y roadmap to be released by STAR/Radioecology Alliance [C#25; C#26]. The new approaches adopted by environmental sciences in general, and ecotoxicology and ecology in particular [C#69], emphasize that to properly determine the effects from any contaminant we must address the realistic environmental conditions in which organisms are actually exposed, including the consequences to ecosystem integrity (i.e. structure, composition, function). We must link exposure to effects under realistic conditions that incorporate natural abiotic factors (e.g., climate change, temperature, flooding events, snow and ice) as well as biotic factors (e.g., physiological and life-history status of organisms; ecological processes such as competition, predation, and food availability). Adding realism in the quantification of wildlife exposure should be aimed at developing an integrated exposure assessment approach that encompasses the dynamics over time and space during the entire life cycle and includes the influence of other environmental factors (e.g., contaminants, habitats changes, life style) [C#57]. One operational outcome from this challenge directly relevant to radioprotection of flora and fauna is to establish sound-science protection criteria for ecosystems and their sub-organisational levels following exposure to radioactive substances (whatever the source term (e.g., artificial radionuclides, NORMs, high-level radioactive wastes) and the environmental situations of interest (e.g., emergency, planned or existing exposure situations) [C#4; C#6; C#94]).

This challenge is of high priority regarding new regulatory requirements for the radioprotection of the environment. The latter has now shifted from an implicit environmental protection to an explicit one. For several decades, control of radioactive substances released into the environment was exclusively viewed through a human radioprotection paradigm that followed the guidance of the International Commission on Radiological Protection (ICRP, 1991) which ...”believes that the standard of environmental control needed to protect man to the degree currently thought desirable will ensure that other species are not put at risk”. The IAEA’s Fundamental Safety Principles (IAEA, 2006), revised ICRP Recommendations (ICRP, 2007), and the new interim version of the international Basic Safety Standards (IAEA, 2011) promote developing guidance on wildlife radiological risk assessments and, as a consequence, espouse the need for ecological protection criteria of radioactively contaminated environments.

Acquiring new scientific results on which decisions are based is key to answering social concerns about (eco)toxic effects from ionising radiation. Management decisions should be, in part, scientifically based. The general public needs to trust decision makers. The enhanced environmental awareness of the public highlights the need for clarity, transparency and consensus within the

scientific community relative to the long-term ecological consequences of any nuclear accident or chronic exposure situation. For example, the divergent opinions on the effects of the Chernobyl accident on human health and wildlife in the Chernobyl exclusion zone do little for public confidence and understanding. Effects to wildlife within the Chernobyl Exclusion Zone have recently been reported at exceptionally low dose rates (from 0.01 to 1 $\mu\text{Gy/h}$; Møller and Mousseau, 2009). The research has been criticised because of confounding factors, poor dosimetry and inappropriate data interpretation (Smith, 2008; Wickliffe, 2011). Nonetheless, the findings, if independently substantiated by other scientists, challenge the ecological protection criteria published by several other research groups, as well as international organisations that issue guidance for radiological exposures [e.g., 10 $\mu\text{Gy/h}$ for protecting ecosystems (Anderson *et al.*, 2009; Garnier-Laplace *et al.*, 2010); 40 $\mu\text{Gy/h}$ for protecting terrestrial animals, 400 $\mu\text{Gy/h}$ for plants and aquatic wildlife (UNSCEAR, 2008; ICRP, 2008). The findings also indicate that human radiological protection criteria may need to be questioned. The need to resolve this important low dose rate controversy at Chernobyl (to understand the phenomenon, and in doing so enhance public confidence) was an important consideration in developing this SRA.

Over the last 15 years, international efforts have focused on new strategies for protecting the environment from radioactive substances. For example, in Europe considerable work has been focused on collating relevant information on effects of ionising radiation in non-human species compiled into the FREDERICA database (Coppelstone *et al.*, 2008) and producing screening ecological benchmarks needed to implement a tiered Ecological Risk Assessment approach (ERA) [(FASSET (Williams, 2004), ERICA (Larsson, 2008), PROTECT (Howard *et al.*, 2010)]. Whilst the ERA-type approach is a substantial advancement in radioecology, a lack of sufficient data prevents current ERA analyses from fully accounting for the realistic environmental conditions that organisms are actually exposed. For example, data are still insufficient to take into account low dose effects, variable dose rate regime, multi-contaminant scenarios, species variation in radiation sensitivity due to life-history traits, or ecosystem level effects. Such knowledge gaps are accounted for *via* extrapolation and the use of assessment factors (or safety factors) that add conservatism and increase uncertainties in risk assessments. The vision of this SRA is to address such deficiencies (**Figure 2**).

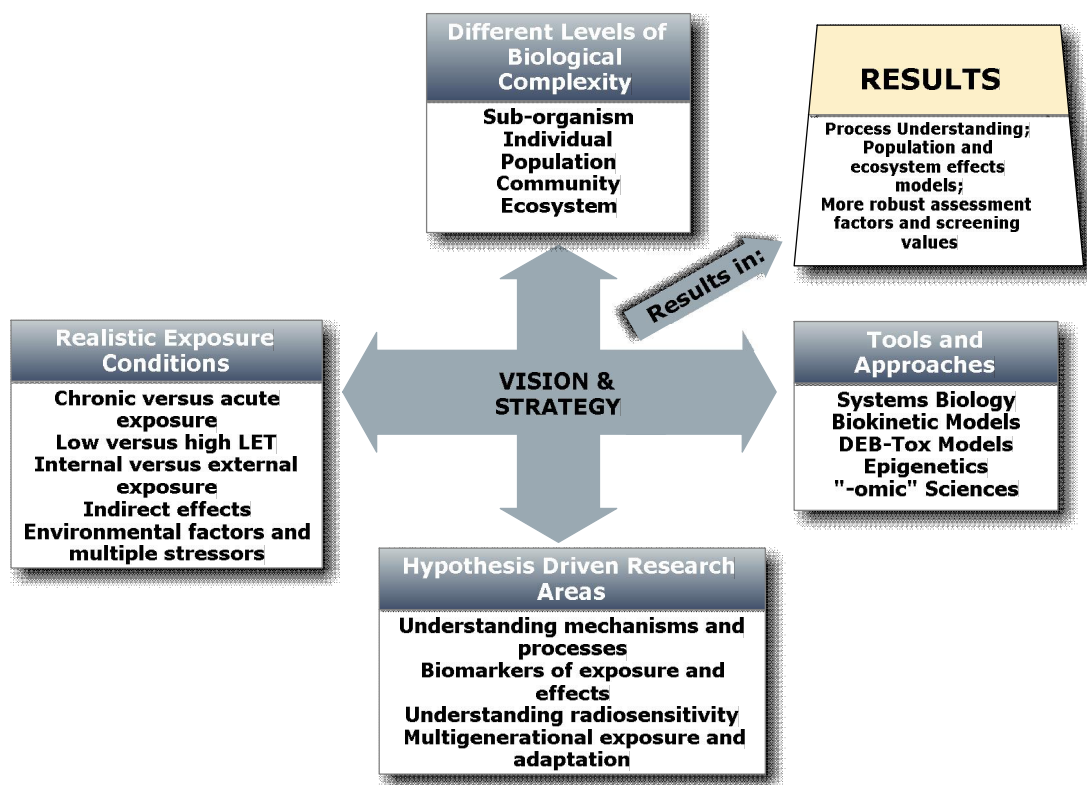


Figure 2. Schematic of the components and anticipated results of the Strategic Research Agenda concerned with challenge two: To Determine Ecological Consequences under the Realistic Conditions that Organisms are Actually Exposed.

3.2.1 Strategic vision for research

Our strategic vision is that over the next 20 years radioecology will have gained a thorough mechanistic understanding of the processes inducing radiation effects at different levels of biological organisation, including the consequences on ecosystem integrity, and be able to accurately predict effects under the realistic conditions in which organisms are actually exposed.

3.2.2 Strategic agenda

The following five research lines will need to be addressed to achieve this vision. In a similar way to that for challenge one, the key research lines developed below are intended to be applied for existing (e.g., uranium mining and milling sites, NORM sites, post accident situations), planned (e.g., new build, geological waste disposal) and emergency exposure situations [C#4; C#6; C#15]. To address these research lines, studies will have to include an appropriate combination of laboratory bioassays under conducted controlled conditions, field studies and statistical data treatment and/or mathematical modelling [C#70; C#92]. In connection with challenge one, common to the five research lines, there is a crucial need for improved dosimetric assessment for wildlife to reduce uncertainty and enhance robustness of dose estimate. Establishment of dose-response relationships, whatever the model used (e.g., logistic, hormetic [C#95], linear non threshold) is also common to all research lines since such response relationships constitute the basis for any predictive risk assessment [C#22].

3.2.2.1 Mechanistically understand how processes link radiation induced effects in wildlife from molecular to individual levels of biological complexity

This research line, comprising to some extent, shared issues between human and other organisms, will identify key molecular/cellular and individual characteristics driving radiation induced effects at the individual level, which is a priority shared with MELODI [C#25; C#26; C#66]. The use of advanced analytical methods from molecular biology is a pioneering application in radioecology (e.g., Mothersill *et al.*, 2009), and when added to a systems biology approach (Handy, 2008), holds great promise for enhancing our mechanistic understanding of radiation induced responses at the sub-cellular levels and their consequences to individuals. Several approaches would be implemented such as “omics” and system-specific biomarkers (e.g., genotoxicity including damage and repair dynamics, immunotoxicity, neurotoxicity). This will potentially result in identification of new biomarkers, once their response sensitivity and natural variability in populations are characterised [C#16; C#60; C#75]. With validated biomarkers under field conditions and populations of native or non-native species (e.g., using caged animals in the environment), innovative biomonitoring in the field should be developed, with a preference to non-lethal methods and tools where possible [C#50; C#66; C#75]. Field studies will be required to test the detectability of radiation induced changes used as biomarkers within complex realistic exposure situations (e.g., confounding factors such as seasonal variations, other contaminants, changes in habitats) [C#9].

In addition, coupled Biokinetics/Dynamic Energy Budget (DEB) approaches will be developed to understand the metabolic mode of actions at the individual level following radiological exposures. DEB theory (Kooijman, 2000) offers a single consistent framework to understand effects of stressors on growth, reproduction and survival in an integrated way.

Examples of key issues are given to illustrate this research line:

- How does the oxidative status of the cells (or tissue/organisms) modulate the mechanisms?
- How may those elementary mechanisms result in adverse outcomes at the cellular and individual levels (immune and neurological systems integrity, general metabolism, reproduction, growth, survival, behaviour, susceptibility to diseases)?
- How do radiation type (α , β , γ), exposure duration (acute, chronic), pathways (external vs. internal irradiation) [C#65] and cellular/biological characteristics modulate the quality and quantity of DNA damage and repair? Are those damages reversible?
- Do specific modes of action or master genes exist for different types of radiation, and can they be use to develop specific biomarkers or biosensors?

3.2.2.2 Understand what causes intra-species and inter-species differences in radiosensitivity (i.e. among cell types, tissues, life stages, among contrasted life histories, influence of ecological characteristics including habitats, behaviour, feeding regime...)

Even though the fundamental mechanisms that cause radiation damage seem universal, individual responses to radiation exposure vary tremendously, depending on factors such as type of radiation (variation up to *ca.* x50); acute versus chronic exposure (variation *ca.* 1-2 orders of magnitude); cell type; biological endpoint (e.g., reproduction versus mortality); life stage (embryos, larvae, and juveniles stages are the most sensitive); species (variation *ca.* 6 orders of magnitude); and level of biological organisation; simple laboratory experiments versus complex ecosystems (UNSCEAR, 2008). Some general parameters known to determine the sensitivity of an organism to radiation are: the DNA content (i.e. mean chromosome volume) of the cell; the efficiency and types of DNA repair/pathways; the cell repopulation capacity; and the ability of tissue and organs to regenerate (reviewed in Harrison and Anderson, 1996). Most recently, Fuma *et al.* (2012) combined nuclear

DNA mass and species sensitivity distributions to derive hazardous doses for amphibians acutely exposed to radiation and to establish effect benchmark values.

This research line will be strongly combined with the first one. It will highlight the key drivers for intra- and inter-species radiosensitivity difference. A combination with phylogeny/homology concepts as it exists in comparative toxicology could help to support inter-species extrapolation. This research line requires a long-term commitment and comprises fundamental key issues such as:

- How do differences in DNA damage between different species, or the potential for DNA repair, explain the inter- intra-species differences in radiosensitivity?
- For internal contamination, how does dose heterogeneity in the cell/tissue/organ influence the biological response? [C#65]
- What is the variability in sensitivity / response between life stages and between species?
- How do those findings, combined with a phylogeny/homology-type approach, support inter-species extrapolation?
- How do occupied habitats, organism behaviour and feeding regimes contribute to determining potentially exposed/critically sensitive life stages and species?

3.2.2.3 In a broader exposure context, understand the interactions between ionising radiation effects and other co-stressors

Exposure to multiple stressors may directly or indirectly modulate radiation effects. Multiple stressors provide one example of the disparity between biological effects research protocols and the reality of actual exposure conditions. The environment is contaminated with low concentrations of complex mixtures (*e.g.*, radionuclides, metals, pesticides, fire retardants and endocrine disruptors). Exposure to multiple contaminants is the rule, not the exception (Hinton and Aizawa, 2007). Studying a contaminant in isolation is necessary and provides critical information on the underlying mechanism resulting in detectable effects. [Additionally, an understanding of the mechanisms of individual contaminants could eventually lead to the development of biomarkers specific to non-radioactive contaminants versus radiation-specific ones \[C#44\].](#) However, the danger and lack of realism in studying contaminants in isolation is that it cannot predict possible interactions among the many stressors to which organisms are exposed. Interactions can provide protective effects and reduce overall damage, or augment effects in negative, synergistic ways.

The effects of radiation may be altered when in the presence of other contaminants or stressors. For radioactive elements such as uranium, chemotoxicity due to the action of a metal and radiotoxicity due to alpha radiation can be regarded as a mixture of stressors coming from a single element (Mathew *et al.*, 2009; Miller *et al.*, 2002). Modifying effects of multiple stressors can be the consequence of altering the bioaccumulation characteristics of radionuclides, or influencing the radiosensitivity of the species (*e.g.*, Au *et al.*, 1994; Sugg *et al.*, 1996). Radiosensitivity is affected by exposure to other contaminants and a combination of stressors reduces the physiological fitness of organisms. For example, interaction of heavy metals and radionuclides, and the resulting modification of radiosensitivity, may occur by altering the capability of an organism's antioxidant defence system. Some studies from human radiobiology, reviewed by Cai *et al.* (1999) focused on the protective role of metallothioneins (MTs) against DNA damage caused by chemical stressors, such as cadmium for example, and radiation. MTs can also act as an antioxidant and a free radical scavenger (Sato and Bremner, 1993; Viarengo *et al.*, 2000). Therefore, the presence of MTs, up-regulated due to the presence of a metal contaminant, may provide protective effects from radiation-induced genotoxicity and/or cytotoxicity. Moreover, the induction of MTs has been suggested as one of the

mechanisms for the adaptive response in low-dose ionising radiation exposure, where it may act as a free radical scavenger (Cai and Cherian, 1996). Alternatively, some metals reduce DNA repair capabilities, thus potentially causing synergistic effects when combined with radioactive contaminants. Multiple stressors are included within our SRA because of the need to understand the potential for mixtures to cause antagonistic or synergistic interactions with radiation.

Research should be developed to understand radiation effects in the context of contaminant mixtures and multiple stressors. Emphasis will be placed on identifying combinations of mixtures and stressors that interact such that super-additive and sub-additive effects are likely to occur with radiation. The potential for interactions among stressors will be based on their modes of action and their cellular targets at the molecular level (*e.g.*, oxidative stress, genotoxicity). This will also contribute to the understanding of radiotoxicity and chemotoxicity, and their delineation when it is relevant [C#44]. Because of the multitude of potential stressors that exists in real exposure conditions, early research efforts will develop a scheme to prioritise hypotheses and maximise research efficacy.

Examples of key questions addressed in this research line are:

- What are the combinations of mixtures situations or co-contaminants that are likely to show interacting effects with radiation?
- What are the mechanisms underlying interacting effects of different co-contaminants and radiation or radionuclides?
- At what level does interaction take place: for example at the exposure, uptake, internal redistribution of the radionuclides, at the site of damage or in regulation and signal transduction of the response of the organism towards radiation effects?

3.2.2.4 **In a broader ecological context, understand the mechanisms underlying multi-generational responses to long-term ecologically relevant exposures (*e.g.*, maternal effects, hereditary effects, adaptive responses, genomic instability, and epigenetic processes).**

A strong connection with evolutionary ecology [C#69] is needed to study adaptive responses and modulation of effects at a multi-generation scale following exposures to radiation. Understanding long-term effects of radiation on the phenotypic and genetic characteristics of the population is crucial to assess the risk of population extinction and its consequence for the maintenance of both genetic biodiversity and species biodiversity. **This is true whatever the radiation type and exposure pathways [C#65].**

Radiation can directly affect DNA by ionisation of the molecules that form the double helix. However, ionising radiation, like a great number of other stressors, also forms Reactive Oxygen Species (ROS) that indirectly cause molecular lesions (*e.g.*, base degradation or deletion, single- or double-strand breaks, protein-DNA cross link). Indirect effects of oxidative stress can alter protein, enzyme and lipid structure or function, resulting in disruption of general metabolism. Other alterations of the cellular genome can be induced by ionising radiation through epigenetic mechanisms that cause changes in cell signalling processes [*e.g.*, genomic instability (genomic damage expressed post-irradiation, after many cell cycles), bystander effects (where non-irradiated cells in proximity to irradiated cells exhibit effects similar to those that received the radiation), and reduced repair efficiency (*e.g.*, Morgan, 2003; Mothersill *et al.*, 2009) [C#59].

Knowledge about genomic instability incorporating changes in the epigenetics and in the DNA sequence due to mutations and repaired double strand breaks should be improved to support the understanding and prediction of the evolutionary response of populations chronically exposed to

ionising radiation. One novelty could be to associate an experimental approach (lab and field) with quantitative genetic methods to study the evolutionary response of a natural population to a rapid change in its environment [C#70; C#92].

Some of the major elementary key questions are:

- What are the biological and evolutionary significance of genomic and epigenetic changes due to exposure to ionising radiation? How much do they contribute to transmission of genomic damage to offspring, through successive generations?
- What is the influence of ionising radiation exposure on epigenetic changes in comparison with other environmental factors?
- To what extent does multigenerational exposure make the consequences worse (or better)? Are populations that are exposed for several generations to ionising radiation more (or less) resistant to new environmental changes? What is the molecular basis of resistance (or vulnerability) in comparison to non-exposed populations?

3.2.2.5 **Understand how radiation effects combine in a broader ecological context at higher levels of biological organisation (population dynamics, trophic interactions, indirect effects at the community level, and consequences for ecosystem functioning)**

Our knowledge of radiation effects (and radiation protection) is based almost entirely on single species experiments, while in reality species are exposed as part of a multi-species assemblage. In the wild, species within the same environment are differentially exposed to radioactivity due to their specific habitat, behaviour, and feeding regime. Species also have different sensitivities to radiation. In an ecosystem, this means that the various responses of species to radiation will also alter the interactions between species and may affect aspects such as competition, predator-prey or parasite-host interactions. This may lead to secondary effects that change community structure, composition and function. These secondary, indirect effects may impact a population to a larger extent than the direct effects of radiation. Such issues have been poorly addressed in radioecology and, for that matter in ecotoxicology, partly due to the complexity of studying multi-species assemblages in the laboratory or unravelling complexity in field situations. However, a series of experiments using microcosms have clearly demonstrated such indirect effects (*e.g.*, Doi *et al.*, 2005; Fuma *et al.*, 2010), and some field studies from Chernobyl also point in that direction (Geras'kin *et al.*, 2008).

Moreover, many effects require long periods of time before they are detectable, thus often making it difficult to correlate cause with effect. Substantiation of effects at the population level is difficult because of compensating mechanisms and indirect effects that become more abundant as examination progresses from molecules to ecosystem.

The propagation of effects from individuals to population [C#77] depends on the characteristics of specific life histories. Regardless of the stressor or type of contaminant, the vast majority of ecotoxicological data describe effects on individual traits of organisms. Most studies concerned with ionising radiation have examined effects at the cellular, tissue or individual levels. As demonstrated for chemicals, effects observed at these levels may propagate such that they have consequences at higher levels of biological organisation (population, community, ecosystem; *e.g.*, Forbes and Calow, 2002a; Forbes *et al.*, 2011). However, very few studies have actually measured effects at the higher levels. A few have attempted to extrapolate effects observed in individuals to what might occur in the population by using population dynamic models. Modeling the propagation of ionising radiation effects from individuals to populations has been addressed theoretically (Woodhead, 2003; Vives i Batlle *et al.*, 2010), and tested experimentally within the ERICA project by chronically exposing two invertebrates with different life cycles: earthworms and daphnids (Alonzo *et al.*, 2008). Such models

are a valuable, under-utilised method for predicting effects from environmental stressors, and thus are included within this SRA as they need to be further explored in radioecology. However, all models need to be tested in realistic systems (e.g., complex laboratory studies or in the natural environment) before accepting them as predictive tools [C#50].

Understanding and accounting for the differences in life history traits among species will likely reduce our current uncertainties in predicting effects to populations of wildlife exposed to radiation. Recognising the importance of life history strategies is not unique to radioecology [C#47]; Forbes and Calow (2002b) suggested that it was not feasible to identify *a priori* among growth, mortality and reproduction, the best predictors of population growth rate. This underlines the necessity for adequate experimental development to address the following questions for radioactive substances: (i) How sensitive is the population growth rate to changes in each of the life-history traits? or Which life-history stage(s) is sufficiently sensitive to influence the population growth; (ii) To what extent do effects on life-history traits influence population growth rate?

To extrapolate even further to communities or ecosystems, concerted collaborative effort is needed to carry out both controlled laboratory experiments on simple predator-prey relationships and more complex multi-species microcosms and field investigations/experiments, with a focus on ecosystem-relevant endpoints covering both ecosystem structure and function. In addition, development of population and ecosystem models capable of integrating radiation effects with population dynamics would substantially advance the field. Assessing the consequences of radioactive substances on ecological integrity (*i.e.*, structure, composition and function) is essential to optimize management of ecosystems resources (water, forest, agriculture...), as well as other natural goods and services provided to society. Key issues would include:

- How does radiation affect food availability and quality (taxonomic composition, nutritional value) for predatory species?
- How do radiation effects modulate under changing food conditions and varying environmental constraints such as predation, migration and natural mortality?
- How do radiation effects alter trophic interactions such as competition, parasite/host relationships?
- How do radiation effects ultimately lead to changes in taxonomic composition, biological diversity and complexity, including delayed effects after multiple generations particularly in populations already subjected to environmental stress?
- How does ionising radiation affect the ecological integrity (structure, composition and function)?

3.3 Challenge Three: To Improve Human and Environmental Protection by Integrating Radioecology

The risks posed by the presence of radionuclides in the environment require an efficient, balanced and adaptable assessment for protecting and managing exposed humans and environments. The individual contaminant-medium-pathway paradigm is changing towards a more integrated view of the environment as a whole. This shift not only concerns the direct effects of contaminants, but also how contaminated environments can be returned to a state of net benefit to society. Radioecology's position relative to this paradigm shift can be best maintained by embracing the concept of integration – integration of the underlying systems and methods of human and environmental protection, and integration of radioecology with other scientific disciplines. Thus, radioecology's future success, broadly defined as meeting stakeholder needs, will require integration in several ways

and from several different perspectives. This portion of the SRA identifies several integration challenges (**Figure 3**), as well as highlights the advantages gained by the science of radioecology in meeting the integration challenges:

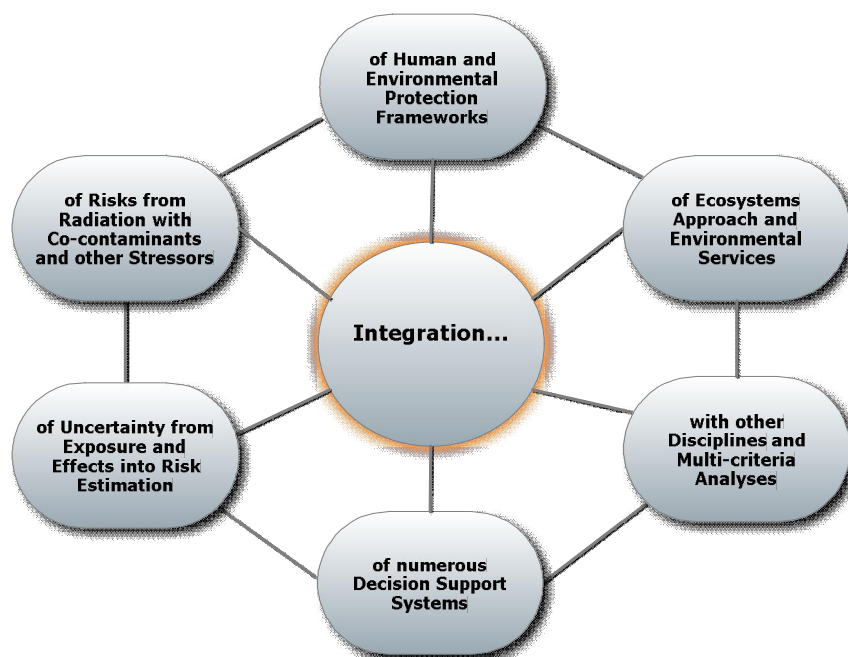


Figure 3. Six areas in challenge 3: To Improve Human and Environmental Protection by Integrating Radioecology.

During the last decade, the need was recognised for explicit demonstration of the protection of the environment from the effects of radioactive contaminants (ICRP, 2007). Significant effort has been expended in that regard and a system of environmental protection is emerging, along with the tools required to estimate exposure, evaluate risk and demonstrate protection (Larsson, 2008). In some important areas, however, the methodologies for human and environmental assessments differ. This problem is exacerbated because human and environmental assessments are not complementary in terms of how they are conducted. The differences cause difficulties for operators, stakeholders and regulators. An integration of the two radiation protection systems – both in terms of the underlying philosophy and the practical application via appropriate tools and systems - offers significant benefits on many levels.

Additionally, radionuclides and the risks posed by them to humans and the environment typically occur as part of a complex suite of co-contaminants and other stressors, as exemplified by waste streams from nuclear and non-nuclear industries, complex legacy contamination and releases as a result of accidents. There is a clear and long standing gap in our understanding of contaminant mixtures that include radioactive materials. Radioecological research integrated with other disciplines and directed towards better understanding of mixture effects, as well as adapted risk assessment methods aimed at predicting mixture effects, will make it possible to determine if radiation protection criteria are robust in a multiple contaminant context.

Radioactive contamination can occur as a result of a range of different scenarios, disparate in character and often specific in their actual or potential impacts. Routine operations of nuclear facilities, contamination from non-nuclear industries, and the potential contamination from new nuclear facilities are often of great concern to the public. Societal perception of the technical capacity

and resources required to prevent, mitigate or remediate impacts and ensure recovery of any contaminated area after a release (*routine, accidental or malevolent* [C#4; C#5; C#14; C#76]) must take into account the disparities and specificities inherent in the exposure scenarios, as they play a significant role in the *assessment of consequences* – in terms of economic considerations and from the societal perspective. A continuum of effects includes societal concerns, varying degrees of economic impact or loss of societal benefit, administrative disruption, health impacts or loss of life and impact on ecosystem services. In addition to these impacts, the measures taken to address them may, in turn, incur societal and environmental side effects. This complex interplay has been well demonstrated in the aftermaths of both the Chernobyl and Fukushima accidents.

Management approaches in planned, existing and emergency exposure situations can range from the minimal through ascending levels of complexity and detail. Although a significant amount of valuable knowledge exists for a wide range of exposure situations, it is fragmentary with respect to constituting an integrated strategy sufficient to deal with complex, dynamically changing conditions. In dealing with a range of actual or potential exposure situations, a gradient of integrated management approaches and the means of creatively implementing them are required. The development of such approaches necessitates the cost/benefit elaboration of management options in relation to, amongst others, societal needs, desires and expectations; economic costs; health; psychosocial and environmental costs; technical feasibility and potential costs to future generations. The development of appropriate tools – Decision Support Systems (DSSs) – for best implementing such approaches must occur in tandem with the development of management objectives to ensure that maximum benefit is derived. The need for integrated, graduated management approaches and the tools to implement them in handling the entire spectrum of possible effects of exposure, and ensuring the productivity and societal benefit of impacted areas is a primary driver for radioecological research in the coming decades. The recent events at Fukushima in Japan exemplify these problems and the existing deficiencies. Intrinsicly bound to this need is the requirement for sound, fundamental and progressive science to underpin and derive maximum benefit from these efforts.

3.3.1 Strategic vision for research

Our strategic vision is that over the next 20 years radioecological research will develop the scientific foundation for the holistic integration of human and environmental protection, as well as their associated management systems.

3.3.2 Strategic agenda

The following six research lines will need to be addressed to achieve the vision.

3.3.2.1 Integrate uncertainty and variability from transfer modelling, exposure assessment, and effects characterisation into risk characterisation

Risk assessment is usually organised in four steps: (i) formulation of the problem (or hazard identification), (ii) exposure assessment, (iii) effects characterisation, and finally (iv) risk characterization. Risk characterisation is thus the final step of risk assessment as it integrates information from the two previous steps: exposure assessment and effects characterization.

Challenge 1 of this SRA identified that transfers and exposure have to be assessed at multiple spatial scales, from an emitting source to the landscape or even global scale. Challenge 2 emphasised that effects have to be characterised not only at the individual level, but also at higher levels of biological organisation (population, community, ecosystem). This means that any risk assessment at such integrated scales should simultaneously take into account: (i) variability of doses, depending on spatial variability of radionuclide transfers, as well as behavioural heterogeneity among exposed

species, (ii) and variability in radiosensitivity among species, including gender- and life stage-dependencies. Improvements in risk assessments, and the increased confidence in their results, require challenge 3 to integrate all these sources of variability into a single calculation.

In parallel, the temporal variability characterising transfers and exposure (cf. challenge 1) as well as effects, from age-dependent differences to multi-generational responses (cf. challenge 2) need to be integrated over the period of interest for risk assessment, depending on the context, from weeks in an **emergency** situation to thousands of years for radioactive waste repositories.

Lastly, due to its inherent integrative power, risk characterisation is the *ad hoc* step to fully characterise the global uncertainty of a risk assessment, by incorporating uncertainty from exposure assessment and effects characterisation. Considering the multiple sources of uncertainty, including those mentioned in challenges 1 and 2, this final stage is the key to a real integrated ecological risk assessment.

There is an obvious need to reduce uncertainties so that risks to biota and humans can be better quantified, whatever the situation (low, as well as high risk situations; planned, existing and emergency situations). Most of the research lines described above in Challenges 1 and 2, as well as research lines described in related SRAs from other platforms (NERIS; MELODI), identify research that could contribute to improved risk quantification. The strong links which are already being built between the radioecology Alliance and the NERIS and MELODI platforms will help facilitate integration and reduce uncertainties [C#7; C#18; C#21; C#25; C#41; C#70; C#76].

3.3.2.2 Integrate human and environmental protection frameworks

The development of risk assessment frameworks for chemical pollutants initially focused on human health protection, and then expanded to include ecological risk assessments, undergoing considerable development during the last two or three decades. Risk assessments from radiation witnessed the same evolution, as reflected in the latest recommendations of the International Commission on Radiological Protection (ICRP, 2007). However, the development of a full framework for integration of human and ecological risk assessments for radionuclides for any specified exposure situation is still at an early stage (Coppstone *et al.*, 2010), and remains a significant challenge for radioecology, as suggested by Pentreath (2009) in the context of the existing ICRP approach: “...it will be essential to consider how protection of both people and the environment can be achieved within a broad philosophical framework, using complementary approaches, based on the same underlying scientific knowledge”.

Within the context of a coherent, holistic system of radiation protection for both humans and the environment, development of integrated methodologies for transfer, exposure and risk assessment, and the production of tools incorporating those methodologies for existing, emergency and planned exposure situations, will be a major step forward in ensuring efficient, adequate, demonstrable protection for both humans and the environment. Areas where active research towards integration is required include transfer/exposure and dosimetry. Currently, transfer/exposure studies for humans and biota are conducted separately using two dissimilar methodologies. For humans, biokinetic models employing a well-defined ‘Reference person’ to simulate intake/retention of a given radionuclide are combined with dosimetric models (*e.g.*, Monte Carlo radiation transport codes) employing the elemental composition of the reference person, radiation weighting factors accounting for the quality of radiation (in causing biological damage) and the differential sensitivity of organs to convert an intake of activity into an effective committed dose (in Sv). For assessments of exposed

plants and animals, using the ERICA Tool as an example, a simplified system involving concentration ratios (CRs) characterise the transfer, which is considered to be aggregated over all transfer pathways with no differentiation between organs or tissue types. Internal dose rates, assumed to be instantaneous, are then derived from an activity concentration in the whole body of the organism. This challenge, incorporating the knowledge generated in other strands of activity within the SRA, will focus on the scientific and practical integration of human and environmental transfer and exposure methodologies. By determining where harmonisation of approaches for humans and environment is justifiable and beneficial, the challenge will focus on developing integrated methods for assessment in the areas of transfer, exposure, dosimetry and risk. [Future research initiatives in this area need to establish good links with the work being carried out by the ICRP \[C#18\].](#)

3.3.2.3 **Integrate the risk assessment frameworks for ionising radiation and chemicals**

As mentioned above, the risk assessment framework was first proposed by the U.S. EPA for chemicals, before it was extended to radiation. Keeping and reinforcing the consistency between frameworks for chemicals and radiation, facilitates the mutual understanding between assessors and the exchange or mutualisation of methods and tools. [In turn, this will help to facilitate stakeholders' understanding of risk from various sources, including radiation \[C#19\].](#)

Moreover, this consistency is expected for risk assessment to be applied to a mixture of stressors, including *e.g.*, radionuclides, metals, pesticides, fire retardants and endocrine disruptors. Challenge 2 developed this issue from the point of view of effects characterisation. In addition to this, there is also a need to better characterise the relevant mixture exposure situations (analysis of more probable mixture exposure scenarios, occurrence of common mixtures), and a need for a validated integrated risk assessment approach simultaneously applicable to radionuclides and other contaminants.

3.3.2.4 **Provide a multi-criteria perspective in support of optimised decision-making**

In handling existing, planned and emergency exposures, a gradient of integrated management approaches is required as well as the means of creatively planning management strategies and assessing their effectiveness prior to implementing them. Although the primary driver in choosing management options for radiation exposure situations will always be the reduction or prevention of dose, the problem is inherently multi-factorial and multi-stakeholder. There are significant needs in other sectors - economic, infrastructural, social services, production – that should be considered when selecting management options. Thus, there is a need to optimise management approaches for radioactive contamination that go beyond simple consideration of radiation dose vs. economic cost. [Optimisation requires expertise in areas such as radioecology, urban planning, social and economic sciences, information technology, waste handling, environmental and agricultural sciences, and risk perception and communication \[C#28; C#42; C# 45; C#48; C#78; C#84; C#85\].](#) From a practical viewpoint, the optimisation process could be based on the integration of DSSs associated with radiological sciences with knowledge data-bases and decision-aid tools from other disciplines (*e.g.*, urban planning, economics, sociology) so that contaminated environments are managed in a holistic way to the maximum benefit of society.

In situations requiring decisions to be taken dealing with radioactive contamination, it is almost never the case that one criterion can be used in isolation when determining the actions to be taken. The previous paradigm in this regard has been the use of the single-criterion based tool by regulators, planners and other decision makers. However, the results of European research projects (*e.g.*, FARMING, STRATEGY, EURANOS) that dealt with management options for both internal and external exposure, clearly showed that apart from the radiological effectiveness and technical feasibility of the various management options, the acceptance of stakeholders and the public at large

is at least as important. Multi-criteria analysis (Linkov and Moberg, 2012) provides a suitable theoretical framework that can be used to combine quantitative and qualitative factors and to guide the decision process towards a satisfactory solution (since no global optimum exists in the presence of multiple, often conflicting criteria). By using decision tools based on a Multi-Criteria Decision Analysis, regional radioecological sensitivity factors can be ranked in a correspondence with all environmental and anthropocentric parameters which either exacerbate or mitigate the consequences of the contamination.

Multi-Criteria Decision Analysis is often employed for the analysis of complex problems involving non-commensurable, conflicting criteria which form the basis within which alternative decisions are assessed. This methodology promotes “a good decision-making process” (Keeney and Raiffa, 1972) by a clearer illustration of the different types of data and information items that go into decision-support, being able to deal in a structured and transparent way with multiple, conflicting objectives and value systems. At the same time, multi-criteria decision aid methods overcome the shortcomings of traditional decision support tools used in economy, such as Cost –Benefit Analysis, especially when dealing with values that cannot be easily quantified (*e.g.*, environmental issues), or translated in monetary terms due to their intangible nature (*e.g.*, social, cultural or psychological issues).

Risk communication, social acceptance and risk perception will be further developed in connection to the new FP7 EC-funded projects EAGLE¹⁹, which deals with risk communication and explores learning opportunities between generations, and OPERRA, which will develop a task on risk communication [C#27; C#28; C#29; C#42; C#45; C#48; C#78].

3.3.2.5 Integrate ecosystem services, ecological economics and ecosystem approaches within radioecology

A variety of approaches to environmental assessment and management are built on a more holistic approach to the sources and consequences of ecosystem change. All focus on the ecosystem, rather than single species, and have been linked to concepts of sustainability, environmental indicators and the sustainable use of resources. They stress the inherent dynamic interactions between system components (including humans), potential feedback loops, and indirect effects. The concepts of ecosystem services and ecological economics are aimed predominantly at the ultimate benefits of ecosystems for humans, either financially or otherwise, while the ecosystems approach is arguably less human-centred. Nevertheless, all approaches share a fundamental recognition of the integration and interdependency of humans and the environment. Ecosystem services are the benefits people obtain from ecosystems. These include *provisioning* services such as food and water; *regulating* services such as flood and disease control; *cultural* services such as spiritual, recreational and cultural benefits; and *supporting* services, such as nutrient cycling that maintain the conditions for life on Earth (Millennium Assessment, 2005). Within ecological economics, the concept has been used as a way of assigning a financial value to ecosystems, that otherwise do not have an explicit price (Costanza *et al.*, 1997). This enables a direct linkage between ecological outcomes and economic consequences so that scientists, economists and managers can use the same terms and units to describe ecological changes.

By starting to think in these terms, radioecology and radioecological protection could not only be more holistic and integrative, but also increase compatibility with other environmental assessment

¹⁹ EAGLE: Enhancing education, training and communication processes for informed behaviours and decision-making related to ionizing radiation risks.

and protection frameworks. The ecosystem approach is usually applied in the context of environmental assessment and environmental protection, but it is also a scientific approach. It is by its very nature integrative with respect to science and management, and considering all potential stressors and environmental factors that could affect ecosystem structure and function, while including humans as an integral part of the ecosystem. The concept is widely spread and being applied in, for example, the Convention on Biological Diversity, the European Union Habitat Directive, the Canadian Environment Protection Act, OSPAR Convention for the Protection of the Marine Environment of the North-East Atlantic, RAMSAR Convention on Coastal Wetlands, and holds promise as a unifying approach for radiation protection of the environment (Bréchignac *et al.*, 2011).

Despite the extent of application, specific protection goals and methods are often poorly defined and the drawing up of well-defined specific protection goals, with well-described and measurable assessment endpoints, based on solid ecosystem science will be a research focus for radioecology, both as a science and in support of management and assessment. In this context, priorities include: emphasising propagation of effects, delayed effects, and resistance and resilience of ecological systems; organism-level studies aimed at a more effective modelling of ecological system interactions; and interdisciplinary field studies of radiation-contaminated areas that bring together ecology and radioecology (Bréchignac *et al.*, 2011). Adopting more integrated and functional endpoints beyond the traditional organism level, as proposed in challenges 1 and 2, will serve to improve the relevance of information for decision-makers. The Ecosystem Services (ES) concept is increasing in prominence in environmental policy making and developments of new ERA methods, due to it being a coherent conceptual framework, its ability to integrate over environmental compartments or assessment methods, its applicability to a range of spatial and temporal scales, and its strength as a communication tool (Faber and van Wensem 2012, Nienstedt et al 2012). However, the science and valuation approaches needed to put policy into practice are still in their infancy, though developments are occurring in the fields of, for example, pollution (SETAC ES-AG 2012; Nienstedt *et al.* 2012), soil assessment (Faber and van Wensem, 2012; Thomsen *et al.*, 2012) and assessment of ecological quality (Paetzold *et al.*, 2010). Bearing in mind the huge economic and social impacts of radioactive contamination, the approach would have a great potential also within DSS and MCA, as well as stimulating a broader stakeholder engagement in radiological protection and radioecology.

3.3.2.6 Integrate decision support systems

Decision Support Systems (DSSs) - computerised systems facilitating the management of large amounts of data and providing assistance in data analysis, interpretation and presentation - have always represented to a large extent the visible “face” of radioecology and constitute an important interface between radioecological research and stakeholders. During the 4th and 5th research framework programs of the European Union, numerous radioecological DSSs (or models with significant DSS aspects) were developed, including CESER, SAVE, RESTORE, STRATEGY, ERICA and others, differing in terms of the environments or exposure situations to which they may be applied, the approaches used to estimate contaminant transfer, as well as in a range of other aspects. At the same time, a parallel strand of development has existed in the area of DSSs for emergency exposure situations as exemplified by the ARGOS and RODOS systems. Two major activities in the general area of radioecological DSSs have been conducted on the European level in recent years – EVANET-TERRA and EVANET-HYDRA – the former concerned with an evaluation of terrestrial DSSs and the latter with freshwater DSSs, the findings of these projects being useful in developing this SRA. In the area of DSSs, three aspects of how integration will be of benefit are

apparent: (i) integration of radioecological DSSs, (ii) DSSs for integrated assessment and (iii) integrating DSSs for existing and planned with those for emergency exposures. As evidenced by the findings of EVANET-TERRA and -HYDRA, the suite of currently available DSSs are disparate in terms of the exposure situations and environments they may be applied to, the nuclides involved and the technical platforms, reflecting the fragmented state of radioecology in Europe over the past 10 to 15 years. The benefits of integrated DSSs have been evidenced by such systems as the RESRAD family of codes and working towards tighter integration of European DSSs will serve to ensure compatibility, comparability and transparency on the European level, as well as serving to maintain Europe's position as world leader in the area of radioecology.

As discussed above, integration of human and environmental protection systems and methodologies is a challenge for radioecology with the potential for significant benefits which can only be fully realised if the means of efficiently implementing such systems are available to stakeholders, regulators and operators. The development of DSSs for integrated assessments of both man and environment is necessary in ensuring demonstrable protection in a manner accessible to stakeholders. Moving towards this goal serves to generate maximum benefit from the research of STAR and ensures an important feedback mechanism between radioecology research and stakeholders.

Development of DSSs for existing/planned exposures and emergency exposures has to a large extent followed two parallel trajectories. Emergency exposure DSSs tend to lack advanced radioecological components, while DSSs for planned and existing exposure situations often lack the means of handling the spatial scales that emergency exposure DSSs feature. The Fukushima accident has aptly demonstrated the problems inherent in a lack of convergence between these development strands and the lack of tools available for dynamic situations where the transition between emergency and existing exposure is not clear. The NERIS initiative has identified further development of emergency DSSs and engagement of stakeholders among its strategic activities. Integration of radioecology, as exemplified by the STAR initiative, its activities and research goals, with the NERIS platform will be a major step forward in the development of the next generation of DSSs.

4 EDUCATION AND TRAINING

[This section is currently being developed. It will be completed in late 2013 and will address several comments related to education and training \[C#32; C#40; C#64\].](#)

5 VALUE OF A STRATEGIC RESEARCH AGENDA

The acquisition of new scientific knowledge through research in radioecology is a crucial element in safeguarding humans and the environment against harmful consequences, as well as responding to stakeholders concerns regarding the presence of radionuclides in the environment. Such studies are important to society because over-estimation of exposures or effects could lead to unnecessary and costly restrictions; alternatively, under-estimation of the risks will result in injury to humans and the environment.

The three scientific challenges presented above, with their 15 associated research lines, are poorly studied because they are complex and complicated. Attempts to address them have been piecemeal. The only way to provide rapid and efficient solutions to these difficult problems is a focused, hypothesis-driven research program with clear common goals and resources shared among the international radioecology community. For society to obtain a significant contribution from the

radioecology of the future, a long-term, multidisciplinary approach is needed that goes beyond national boundaries.

The vision statements and strategic agenda presented above concentrate on the research aspects of radioecology. The final Strategic Agenda will also plan for other equally important aspects of our science (*i.e.* maintaining crucial radioecological infrastructures; development of advanced methods/technologies; education; recruitment; as well as knowledge management). The other phases will be developed over the next two years with input from stakeholders and the larger radioecology community.

To our knowledge, this is the first Strategic Research Agenda for radioecology. It is our hope that a science-based SRA for radioecology will focus and prioritise our collective efforts, resulting in increased value and more rapid advancement in our understanding of environmental radioactivity.

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