EUROPEAN COMMISSION
Community research

STAR

(Contract Number: Fission-2010-3.5.1-269672)

DELIVERABLE (D-N°2.1)

DRAFT STRATEGIC RESEARCH AGENDA

Author(s): T. G. Hinton[1], J. Garnier-Laplace[1], H. Vandenhove[2], M. Dowdall[3], C. Adam-Guillermin[1], F. Alonzo[1], C. Barnett[5], K. Beaugelin-Seiller[1], N.A. Beresford[5], C. Bradshaw[7], J. Brown[3], F. Eyrolle[1], L. Fevrier[1], J-C. Gariel[1], R. Gilbin[1], T. Hertel-Aas[9], N. Horemans[2], B. J. Howard[5], T. Ikäheimonen[4], J. C. Mora[6], D. Oughton[9], A. Real[6], B. Salbu[9], M. Simon-Cornu[1], M. Steiner[8], L. Sweeck[2], J. Vives i Battle[2]

[1]IRSN, [2]SCK-CEN, [3]NRPA, [4]STUK, [5]CEH, [6]CIEMAT, [7]SU, [8]BfS, [9]UMB

……………………………………………

Reporting period: February 2011 – April 2012

Date of issue of this report: April 2012

Start date of project: 01/February/2011 Duration: 54 Months

EURATOM

DISTRIBUTION LIST

Name	Number of copies	Comments
A. Jouve, STAR EC Project Officer	1	(all copies provided electronically)
T. Hinton, STAR Co-ordinator (WP-1), IRSN	1	
L. Février, IRSN	1	
STAR Management Team members: WP-2; T. Ikaheimonen, STUK WP-3; M. Dowdall, NRPA WP-4; H. Vandenhove, SCK-CEN WP-5; J. Garnier-Laplace, IRSN WP-6; D. Oughton, UMB WP-7; B. Howard, NERC	1 per member	
STAR Steering Committee G. Kirchner, BfS A. Real, CIEMAT J-C. Gariel, IRSN T. Ikaheimonen, STUK H. Vandenhove, SCK-CEN C. Bradshaw, SU A. Liland, NRPA B. Howard, NERC B. Salbu, UMB	1 per member	
STAR Wiki site		
STAR's External Advisory Board	1 per member	
ALLIANCE members	1 per member	

Project co-funded by the European Commission under the Seventh Euratom Framework Programme for Nuclear Research &Training Activities (2007-2011)		
Dissemination Level		
PU	Public	
RE	Restricted to a group specified by the partners of the [STAR] project	RE
CO	Confidential, only for partners of the [STAR] project	

EXECUTIVE SUMMARY

To address emerging issues in radioecology within Europe, eight organisations[1] signed a Memorandum of Understanding (MoU) that formed the European Radioecology ALLIANCE[2]. The MoU states the intentions of 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 ALLIANCE members 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 is to develop a Strategic Research Agenda (SRA). An EC-funded Network of Excellence in Radioecology, called STAR (Strategy for Allied Radioecology[3]), was formed to, among other tasks, develop the SRA. This manuscript is the first published draft of the SRA.

This Strategic Research Agenda outlines a suggested prioritisation of research topics in radioecology, with the 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 SRA was distilled from several evaluations on the state of radioecology, including input from stakeholders, the interests of ALLIANCE member organisations, the International Union of Radioecology, lists of research needs, identification of data gaps and recommendations for the future of radioecology, or its sister science of ecotoxicology. 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.

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 and in providing adequate scientific knowledge to decision makers and the public.

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] 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] www.er-alliance.org

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

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 the realistic conditions in which organisms are actually exposed.

Strategic Research Agenda

1. Mechanistically understand how processes link radiation induced effects in wildlife from molecular to individual levels of biological complexity.
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…).
3. In a broader exposure context, understand the interactions between ionising radiation effects and other co-stressors.
4. In a broader ecological context, understand 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 services, ecological economics and ecosystem approaches within radioecology.
6. Integrate Decision Support Systems.

The three Scientific Challenges presented above, with their 15 associated research lines, have been 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.

The SRA will require considerable resources and time to bring to fruition. 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 (e.g. 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.

Developing an SRA is not a linear process, but one that must have feedback loops designed for continued input and innovation. STAR will publish this draft SRA *via* various routes and seek input from the larger radioecology research community, industry, STAR's External Advisory Board, international organisations (WHO, UNSCEAR, ICRP, IAEA), the International Union of Radioecology, other Networks of Excellence (DoReMi, NERIS, NCoRE) and interested stakeholders. Critique and input for improving the SRA are welcomed *via* a link on the STAR website (www.star-radioecology.org), or a discussion forum on a radioecology group page of LinkedIn (http://www.linkedin.com/groups/STAR-Network-Excellence-in-Radioecology-4244536?trk=myg_ugrp_ovr). Additionally, STAR will conduct several open workshops to further develop the SRA.

To our knowledge, this is the first Strategic Research Agenda for radioecology. 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.

TABLE OF CONTENTS

EXECUTIVE SUMMARY 3

1 INTRODUCTION 8

2 THREE SCIENTIFIC CHALLENGES IN RADIOECOLOGY 11

2.1 CHALLENGE ONE: To Predict Human and Wildlife Exposure in a Robust Way by Quantifying Key Processes that Influence Radionuclide Transfers and Exposure 11

2.1.1 Strategic Vision for Research 13

2.1.2 Strategic Agenda 13

2.1.2.1 Identify and mathematically represent key processes that make significant contributions to the environmental transfers of radionuclides and resultant exposures of humans and wildlife 13

2.1.2.2 Acquire the data necessary for parameterisation of the key processes controlling the transfer of radionuclides 15

2.1.2.3 Develop transfer and exposure models that incorporate physical, chemical and biological interactions, and enable predictions to be made spatially and temporally 15

2.1.2.4 Represent radionuclide transfer and exposure at a landscape or global environmental level with an indication of the associated uncertainty 17

2.2 *CHALLENGE TWO*: To Determine Ecological Consequences under Realistic Exposure Conditions 18

2.2.1 Strategic Vision for Research 19

2.2.2 Strategic Agenda 19

2.2.2.1 Mechanistically understand how processes link radiation induced effects in wildlife from molecular to individual levels of biological complexity 19

2.2.2.2 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…) 20

2.2.2.3 In a broader exposure context, understand the interactions between ionising radiation effects and other co-stressors 20

2.2.2.4 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). 21

2.2.2.5 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) 22

2.3 *CHALLENGE THREE*: To Improve Human and Environmental Protection by Integrating Radioecology 24
2.3.1 Strategic Vision for Research 25
2.3.2 Strategic Agenda 25
2.3.2.1 Integrate uncertainty and variability from transfer modelling, exposure assessment, and effects characterisation into risk characterisation 25
2.3.2.2 Integrate human and environmental protection frameworks 26
2.3.2.3 Integrate the risk assessment frameworks for ionising radiation and chemicals 27
2.3.2.4 Provide a multi-criteria perspective in support of optimised decision-making 27
2.3.2.5 Integrate ecosystem services, ecological economics and ecosystem approaches within radioecology 28
2.3.2.6 Integrate Decision Support Systems 29
3 NEXT STEPS: BUILDING CONSENSUS 30
4 REFERENCES 31

1 INTRODUCTION

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 measurement). 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); existing, as well as new nuclear power plants; decommissioning of facilities; remediation of contaminated sites; naturally occurring radionuclides; and nuclear accidents.

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. case[4]).

To counter emerging problems and improve radioecology within Europe, eight organisations[5] signed a Memorandum of Understanding (MoU) that formed the European Radioecology ALLIANCE[6]. The MoU states the intentions of 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 ALLIANCE members will jointly address scientific and educational challenges related to assessing the impacts of radioactive substances on humans and the environment. The ALLIANCE members 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). An EC-funded Network of Excellence in Radioecology, called STAR

[4] Information from presentations made by representatives of the U.S. Centers for Disease Control and Prevention, and U.S. Department of Energy during the annual meeting of the National Council on Radiation Protection (Washington, D.C.; 13 March 2012).

[5] 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).

[6] www.er-alliance.org

(Strategy for Allied Radioecology[7]), was formed to, among other tasks, assist in developing the SRA. This document is the first published draft of the SRA.

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 SRA was distilled from several evaluations on the state of radioecology, including input from stakeholders (FUTURAE 2008), the interests of ALLIANCE member organisations, the International Union of Radioecology[8], 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 demonstrate specific 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.*"

- *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. 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 protocols have historically implied, but instead occur as low concentrations of complex mixtures. Thus,

[7] www.star-radioecology.org; also includes Stockholm University and the Norwegian University of Life Sciences
[8] www.iur-uir.org/en/

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?

- *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. Examples include:
    - providing 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.
    - taking a more holistic ecosystems approach and integrating ecosystem services within environmental risk assessments
    - integrating decision support systems and using multi-criteria decision analyses to improve post accident management
    - optimizing management options following exposure situations by integrating information generated by radioecology with data from other scientific disciplines
- *Potential risks*: The accidents at Three Mile Island (USA, 1979), Chernobyl (Ukraine, 1986) and Fukushima (Japan, 2012) showed that human errors can override safety systems; that consequences can be more serious than expected; and that the extremely low probability of geological hazards should not be underestimated. Future events may release radionuclides to the environment that are different from those in 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 radionuclides more exotic than caesium 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 at Fukushima exist to enhance our understanding of the ecological consequences of radioactive contamination 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. 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 and in providing adequate scientific knowledge to decision makers and the public.

2 THREE SCIENTIFIC CHALLENGES IN RADIOECOLOGY

2.1 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 consequential 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 ongoing improvements in our understanding of these underlying processes. The challenge faced by radioecologists is to incorporate this knowledge into conceptual 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, and (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.

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 radioactivity levels in the biota and the 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, certainly so 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, as well as to populate and parameterise the dynamic models.

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 largely been ignored 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 required 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 defined as a simple biota/medium (soil or water) activity concentration ratio, equally assumed to be constant, and known not to be 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.

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, and scenarios of global change); and (3) with source term (e.g. history of the releases, physico-chemical form, 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.

2.1.1 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), and be able to accurately predict exposure to humans and wildlife by incorporating a more profound understanding of environmental processes.

2.1.2 Strategic Agenda

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

2.1.2.1 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. One of the main aspects will be to identify where the most advantage can be gained in (i) 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. Among 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, as well as 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 transfer factor values and associated cumulative distribution functions. A classification based on key environmental characteristics, taxonomy, source term, etc. 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, heuristic way. 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. 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; metabolic theory for describing the biokinetics/toxicokinetics of contaminants in living organisms; and 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. 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.

2.1.2.2 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 (especially) 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 analyzing the problem in more depth, as is often the case). Some approaches to extrapolate data have been suggested for application across species such as phylogeny (i.e. using ‘common ancestry’ to categorise transfer) and allometric (mass dependent) relationships, as well as extrapolating across the periodic table using chemical analogues. 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.

The data for model parameterization will require focused laboratory-based work and field studies, as well as ongoing 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.

2.1.2.3 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 ^{3}H 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 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.

The transfer models developed should be able to integrate radioactive contaminants into the general dynamics of ecological systems. An example of this is using pollutant-coupled soil-vegetation-atmosphere transport (SVAT) models to investigate the wider, long-term circulation patterns of substances in the geosphere-biosphere interface. 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 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).

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 embedded particles also represent a challenge, as does the quantification of external exposure for some organisms (e.g. large plants like trees). Improvement is needed to reduce the dominant uncertainties in environmental dosimetry.

2.1.2.4 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 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 used in 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 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.

2.2 *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. The new approaches 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). One operational outcome from this challenge is to establish sound-science protection criteria for ecosystems and their sub-organisational levels following exposure to radioactive substances.

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 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 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 µGy/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 µGy/h for protecting ecosystems (Anderson *et al.*, 2009; Garnier-Laplace *et al.*, 2010); 40 µGy/h for protecting terrestrial animals, 400 µGy/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 on collating relevant information on effects of ionising radiation in non-human species compiled into the FREDERICA database (Copplestone 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)]. While 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.

2.2.1 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***.**

2.2.2 Strategic Agenda

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

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

This research line will identify key molecular/cellular and individual characteristics driving radiation induced effects at the individual level. 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.

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 (systems integrity -immune system, neurological system, general metabolism, reproduction, growth, survival, behaviour, susceptibility to diseases)?
- How do radiation type (α, β, γ), exposure duration (acute, chronic) 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 in order to develop specific biomarkers or biosensors?

2.2.2.2 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 elementary key issues such as those listed here:

- 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?
- 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?

2.2.2.3 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. 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 synergistic ways.

There are reasons to assume that 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 according to the capability of antioxidant defence systems of the organism. 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 are known to 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. 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?

2.2.2.4 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 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.

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 unirradiated 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; ECRR, 2010)].

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.

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?

2.2.2.5 **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 such things 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 degree 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 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 a need to be further explored in radioecology.

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; 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)?

2.3 *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 holistic, 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 needs, as well as highlights the advantages gained by the science of radioecology in meeting the integration challenges:

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 must take cognisance of the disparities and specificities inherent in the exposure scenarios, as they play a significant role in the costs – in terms of economic considerations and from the sociological/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 evidenced 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. Intrinsically bound to this need is the requirement for sound, fundamental and progressive science to underpin and derive maximum benefit from these efforts.

2.3.1 Strategic Vision for Research

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

2.3.2 Strategic Agenda

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

2.3.2.1 **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 a post-incidental or post-accidental 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.

2.3.2.2 **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 three or four decades. Risk assessments from radiation witnessed the same evolution, as is 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 (Copplestone 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 models) 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 map an intake of activity onto 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. Dose rates, assumed to be instantaneous, are then derived from the starting point of an activity concentration in the whole body plant or animal. 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.

2.3.2.3 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 for radiation facilitates mutual understanding between assessors, exchanges or mutualisation of methods and tools, and improve readability of risk assessment by stakeholders.

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 need to better characterise the relevant mixture exposure situations (analysis of more probable mixture exposure scenarios, occurrence of common mixtures), and for a validated integrated risk assessment approach simultaneously applicable to radionuclides and stable contaminants.

2.3.2.4 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 – 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. Optimisation requires expertise in areas such as radioecology, urban planning, social and economic sciences, information technology, waste handling, environmental and agricultural sciences, and communication. 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 (FARMING, EURANOS) that dealt, among others, with management options for the food chain, 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).

2.3.2.5 **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 and protection frameworks. The ecosystem approach is usually used 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 radiation 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.

2.3.2.6 **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/RODOS system. 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 code suite 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-TP 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.

3 NEXT STEPS: BUILDING CONSENSUS

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 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 that it will initiate an open dialogue within the international radioecology community. Developing an SRA is not a linear process, but one that must have feedback loops designed for continued input and innovation. STAR will publish this draft SRA *via* various routes and seek input from the larger radioecology research community, industry, STAR's External Advisory Board, international organisations (WHO, UNSCEAR, ICRP, IAEA), the International Union of Radioecology, other Networks of Excellence (DoReMi, NERIS, NCoRE) and interested stakeholders. Critique and input for improving the SRA are welcomed *via* a link on the STAR website (www.star-radioecology.org), or a discussion forum on a radioecology group page of LinkedIn (http://www.linkedin.com/groups/STAR-Network-Excellence-in-Radioecology-4244536?trk=myg_ugrp_ovr). Additionally, STAR will conduct several open workshops to further develop the SRA.

The vision statements and strategic agenda presented above concentrate on the research aspects of radioecology. The final Strategic Agenda will also plans for other equally important aspects of our science (e.g. 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.

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.

4 REFERENCES

Absalom J.P., Young S.D., Crout N.M.,, Nisbet A.F., Woodman R.F., Smolders E., Gillett A.G. 1999. Predicting soil to plant transfer of radiocesium using soil characteristics. *Environ Science & Technology* 33:1218-1223.

Alonzo F., Hertel-Aas T., Gilek M., Gilbin R., Oughthon D., Garnier-Laplace J. 2008. Modelling the propagation of effects of chronic exposure to ionizing radiation from individuals to populations. *Journ. Environ. Rad.*, 99:1464-1473.

Alexakhin R. 2006. Radioecology: History and state-of-the-art at the beginning of the 21st century. IN: *Radiation Risk Estimates i. Normal and Emergency Situations*. (Eds: A Cigna and M. Durante). Springer Publishing. pg 159-168.

Andersson P., Garnier-Laplace J., Beresford N.A., Copplestone D., Howard B.J., Howe P., Oughton D., Whitehouse P 2009. Protection of the environment from ionising radiation in a regulatory context (protect): proposed numerical benchmark values. *Journ. Environ. Rad.* 100:1100-1108.

Artigas J., et al. 2012. Towards a renewed research agenda in ecotoxicology. *Environ. Poll.* 16):201-206.

Au W.W., Heo M.-Y., and Chiewchanwit T. 1994. Toxicological interactions between nickel and radiation on chromosome damage and repair. *Environ. Health Perspect.* 102 (Suppl.9): 73-77.

Beresford NA, Balonov M, Beaugelin-Seiller K, Børretzen P, Brown J, Copplestone D, Hinston JL, Horyna J, Hosseini A, Howard B, Kamboj S, Nedveckaite T, Olyslaegers G, Sazykina T, Vives i Battle J, Yankovich T, Yu C. 2008. An international comparison of models and approaches for the estimation of radiological exposure to non-human biota. *Applied Rad. and Isotopes* 66:1745-1749.

Beresford N.A., and Copplestone D. 2011. Effects of ionising radiation on wildlife – what knowledge have we gained between the Chernobyl and Fukushima accidents? *Integrated Environ. Assess. & Manag*. 7:371-373.

BIOPROTA. 2005. Key issues in biosphere aspects of assessment of the long-term impact of contaminant releases associated with radioactive waste management. Report of a workshop to evaluate primary features, events and processes occurring in the geosphere-biosphere interface zone, and to identify methods for their resolution. SantCugat, 12-14 September 2005, 19 pp.

Børretzen P, and Salbu B. 2002. Fixation of Cs to marine sediments estimated by a stochastic modelling approach. *Journ. Environ. Rad.* 61:1–20.

Brechignac F. et al. 2003. Protection of the environment in the 21st century: radiation protection of the biosphere including human kind. Statement of the International Union of Radioecology. *Journ. Environ. Rad.* 70:155-159.

Brechignac, F. et al. 2008. Integrating environment protection, a new challenge: strategy of the International Union of Radioecology. *Radioprotection* 43: 339-356

Bréchignac F, Bradshaw C, Carroll S, Jaworska A, Kapustka L, Monte L, Oughton D. 2011. Recommendations from the International Union of Radioecology to Improve Guidance on Radiation Protection. *Integrated Environ. Assess. & Manag*. 7:411-413

Breshears D.D., Kirchner T.B., and Whicker F.W. 1992. Contaminant transport through agroecosystems: assessing relative importance of environmental, physiological and management factors. *Ecological Applications* 2:285-297.

Brown J.E., Jones S., Saxen R., Thorring H., and Vives I Batlle J. 2004. Radiation doses to aquatic organisms from natural radionuclides. *J. Radiol. Prot*. 24:A63-A77.

Cai L., and Cherian M. G. 1996. Adaptive response to ionizing radiation-induced chromosome aberrations in rabbit lymphocytes: Effect of pre-exposure to zinc, and copper salts. *Mutation Research* 369:233-241.

Cai L., Satoh M., Tohyama C., and Cherian M. G. 1999. Metallothionein in radiation exposure: its induction and protective role. *Toxicology* 132:85-98.

Calow P., and V. Forbes. 2003. Does Ecotoxicology inform ecological risk assessment? *Env. Sci. & Tech.* 37:146A-151A.

Costanza R., d'Arge R., de Groot R., Farberk S., Grasso M, Hannon B, Limburg K, Naeem S, O'Neill RV, Paruelo J, Raskin RG, Sutton P, and van den Belt M. 1997. The value of the world's ecosystem services and natural capital. *Nature* 387:253-260

Copplestone D., Hingston J. and Real A., 2008. The development and purpose of the FREDERICA radiation effects database. *Journ. Environ. Rad.* 99:1456-1463.

Copplestone D.C., Brown J.E., and Beresford N.A. 2010. Considerations for the integration of human and wildlife radiological assessments. *Journ. Rad. Prot*. 30:283-297.

Doi M., Kawaguchi I., Tanaka N. 2005. Model ecosystem approach to estimate community level effects of radiation. *Radioprotection* 40 (Suppl. 1), s913-s919.

ECRR (2010) 2010 recommendations of the European Committee on radiation risk: the health effects of exposure to low doses of ionizing radiation. Regulators' Edition, Brussels, 2010, Chris Busby Ed., 248 pp.

Ehlken, S. and Kirchner, G. (2002). Environmental processes affecting plant root uptake of radioactive trace elements and variability of transfer factor data: a review. *Journal of Environmental Radioactivity* 58 (2): 97-112.

Eggen R., Behra R., Burkhardt-Holm P., Escher B., and Schweigert N. 2004. Challenges in Ecotoxicology. *Envion. Sci. & Tech.* 38:58A-64A

Ehrhardt J. 1997. The RODOS System: Decision Support for Off-Site Emergency Management in Europe, *Rad. Prot. Dosimetry*. 73:35-40

Eyrolle F., Masson O., Antonelli C., Arnaud M, and Charmasson S. 2009. The EXTREME project - Consequences of paroxystic meteo climatic events on the translocation of contaminants within the geosphere. *Radioprotection* 44:463-468.

Faber J., and van Wensem J 2012. Elaborations on the use of the ecosystem services concept for application in ecological risk assessment for soils. *Sci of the Total Environ.* 415: 3–8.

Forbes V.E., Calow P., Grimm V., Hayashi T.I., Jager T., Katholm A., Palmqvist A., Pastorok R., Salvito D., Sibly R., Spromberg J., Stark J., and Stillman R.A. 2011. Adding value to ecological risk assessment with population modelling. *Human and Ecological Risk Assessment.* 17: 287-299.

Forbes V .E., Calow P. 2002a. Population growth rate as a basis for ecological risk assessment of toxic chemicals. *Philosophical Transactions of the Royal Society of London Series B- Biological Sciences* 357:1299-1306.

Forbes V. E. and Calow P. 2002b. Extrapolation in ecological risk assessment: Balancing pragmatism and precaution in chemical controls legislation. *BioScience* 52:249-257.

Fuma S., Ishii N., Takeda H., Doi K., Kawaguchi I., Shikano S., Tanaka N., and Inamori Y. 2010. Effects of acute γ-irradiation on community structure of the aquatic microbial microcosm. *Journ. Environ. Rad.*101:915-922.

Fuma, S. Y. Watanabe, I. Kawaguchi, T. Takata, Y. Kubota, T. Ban-nai and S. Yoshida. (2012). Derivation of hazardous doses for amphibians acutely exposed to ionixing radiation. *Journ. Environ. Rad.* 103:15-19.

FUTURAE 2008. Deliverable 4: Networking–a way for maintaining and enhancing radioecological competences in Europe. (http://www.futurae.org/index.php?option=com_content&task=view&id=28&Itemid=1)

Garnier-Laplace J., Gilek M., Sundell-Bergman S., and Larsson C-M. 2004. Assessing ecological effects of radionuclides: data gaps and extrapolation issues. *J. Radiol. Prot.* A139-A155.

Garnier-Laplace J., Della-Vedova C., Gilbin R., Copplestone D., Hingston J., Ciffroy P. 2006. First derivation of predicted-no-effect values for freshwater and terrestrial ecosystems exposed to radioactive substances. *Environ. Sci. and Tech.* 40:6498-6505.

Garnier-Laplace, J., Beaugelin-Seiller, K., Hinton, T. (2011) Fukushima Wildlife Dose Reconstruction Signals Ecological Consequences. *Environ. Sci. and Tech.* 45: 5077-5078.

Garnier-Laplace J., Della-Vedova C., Andersson P., Copplestone D., Cailes C., Beresford N.A., Howard B. J., Howe P., and Whitehouse P. 2010. A multi-criteria weight of evidence approach to derive ecological benchmarks for radioactive substances. *Journ. Rad. Prot.* 30:215-233.

Geras'kin S.A., Fesenko S.V., and Alexakhin R.M. 2008. Effects of non-human species irradiation after the Chernobyl NPP accident. *Environ. International* 34:880-897.

Handy R.D. 2008. Systems toxicology: using the systems biology approach to assess chemical pollutants in the environment. *Advances in Experim. Bio.* 2:249-281.

Harrison F.L., and Anderson S.L. 1996. *Taxonomic and development aspects of radiosensitivity*, in: Amiro, B., Avadhanula, R., Johansson, G., Larsson, C.M., Luning, M. (Eds.), *Proceedings of the Symposium: Ionizing Radiation, the Swedish Radiation Protection Institute (SSI) and The Atomic Energy Control Board (AECB) of Canada*, 20–24 May, 1996, Stockholm, Sweden, pp. 65-88.

Hinton T. G. 2000. Strong inference, science fairs and radioecology. *J. Environ. Rad*. 51:277-279.

Hinton T. G., and Aizawa K. 2007. A layperson's primer on multiple stressors. In: *Multiple Stressors: A Challenge for the Future.* (Ed. C. Mothersill and I. Mossee). NATO Advance Research Workshop; Science for Peace Series. SpringerLink, Netherlands. ISBN 978-1-4020-6333-6; pg 57-69.

Howard B.J., Wright S.M. and Barnett C.L. (Eds). 1999. Spatial analysis of vulnerable ecosystems in Europe: Spatial and dynamic prediction of radiocaesium fluxes into European foods (SAVE). Final report. 65pp. Commission of the European Communities.

Howard B.J., Beresford N.A., Andersson P., Brown J.E., Copplestone D., Beaugelin-Seiller K., Garnier-Laplace J., Howe P.D., Oughton D., and Whitehouse P. 2010. Protection of the environment from ionising radiation in a regulatory context - an overview of the PROTECT coordinated action project. *Journ. Rad. Prot.* 30:195-214.

IAEA-BIOMASS-4. 2003. Testing of environmental transfer models using Chernobyl fallout data from the Iput River catchment area, Bryansk Region, Russian Federation Report of the Dose Reconstruction Working Group of BIOMASS Theme 2. Part of the IAEA Co-ordinated Research Project on Biosphere Modelling and Assessment (BIOMASS).

IAEA (International Atomic Energy Agency). 2006. Fundamental Safety Principles. IAEA Safety Standards for protecting people and the environment. *Safety Fundamentals SF-1.* International Atomic Energy Agency, Vienna.

IAEA (International Atomic Energy Agency). 2009. Quantification of Radionuclide Transfer in terrestrial and Freshwater Environments for Radiological Assessments. *IAEA TECDOC Series No. 1616.*

IAEA (International Atomic Energy Agency). 2011. Radiation Protection and safety of radiation sources: International basic safety standards Sources. Interim Edition. General Safety Requirements Part 3 - nGSR Part 3 (Interim). 96 pp. and annexes, IAEA,Vienna, Austria.

IAEA. (International Atomic Energy Agency). 2011. Radioactive Particles in the Environment: Sources, particle characteristics, and analytical techniques. *Technical Report Series*

IAEA (International Atomic Energy Agency). 2012. Handbook of Parameter Values for the Prediction of Radionuclide Transfer to Wildlife, *Technical Report Series*, under publication.

ICRP. 1991. Recommendations of the International Commission on Radiological Protections, ICRP Publication 60, *Annals ICRP* 21 (1-3) (Elsevier Science, New York).

ICRP. 2007. Recommendations of the International Commission on Radiological Protection. ICRP Publication 103. *Ann. ICRP* 37 (2-4).

ICRP. 2008. Environmental Protection - the Concept and Use of Reference Animals and Plants. ICRP Publication 108. *Ann. ICRP* 38 (4-6).

Keeney R.L. and Raiffa H. 1972. A critique of formal analysis in public sector decision making. In A.W.Drake, R.L.Keeney, P.M. Morse (Editors), *Analysis of Public Systems*, MIT Press, Cambridge, MA: 64-75.

Kirchner, G. and Steiner, M. (2008). Uncertainties in radioecological assessment models – Their nature and approaches to reduce them. *Applied Radiation and Isotopes* 66: 1750-1753.

Kooijman S.A.L.M. 2000. *Dynamic Energy and Mass Budgets in Biological Systems*. 2nd ed. Cambridge University Press: Cambridge, U.K.
Larsson C-M. 2008. An overview of the ERICA integrated approach to the assessment and management of environmental risks from ionising contaminants. *Journ. Environ. Rad.* 99:1364-1370
Linkov I. and Moberg E. 2012. *Multi-Criteria Decision Analysis; Environmental Applications and Case Studies*. CRC Press. Boca Raton, FL. 186 pg.
Loos M., Ragas A.M., Schipper A.M., and Lopes J.P. 2006. D.4.2.1 A random-walk model that describes the accumulation of pollutants in selected ecological receptors in a floodplain area along the river Waal in the Netherlands. *EC-NoMiracle project report*, Project N°: 003956.
Mathews T., Beaugelin-Seiller K., Garnier-Laplace J., Gilbin R., Adam C., and Della-Vedova C. 2009. A probabilistic assessment of the chemical and radiological risks of chronic exposure to uranium in freshwater ecosystems. *Environ. Sci. and Tech.* 43:6684-6690.
Millennium Ecosystem Assessment, 2005. *Ecosystems and Human Well-being: Synthesis*. Island Press, Washington, DC. 160p. (http://www.maweb.org/en/index.aspx)
Miller A.C., Stewart M., Brooks K., Shi L., and Page N. 2002. Depleted uranium-catalyzed oxidative DNA damage: Absence of significant alpha particle decay. *Journ. Inorganic Biochem.* 91:246-252.
Mitchell P.I., Vives i Batlle J., Downes A.B., Condren O.M., León Vintró L. and Sánchez-Cabeza J.A. 1995. Recent observations on the physico-chemical speciation of plutonium in the Irish Sea and the Western Mediterranean. J*ourn. App. Rad. and Isotopes* 46:1175-1190.
Møller A.P., and Mousseau T.A. 2009. Reduced abundance of insects and spiders linked to radiation at Chernobyl 209 years after the accident. *Bio. Letters* 5:356-359.
Morgan W.F. 2003. Non-targeted and delayed effects of exposure to ionizing radiation: II. Radiation-induced genomic instability and bystander effects *in vivo*, clastogenic factors and transgenerational effects. *Rad. Research* 159:581–596.
Mothersill C.E., Smith R.W., and Seymour C.B. 2009. Molecular tools and the biology of low-dose effects. *BioScience* 59:649-655.
Nienstedt K., Brock T., van Wensem J., Montforts M., Hart A., Aagaard A., Alix A., Boesten J., Bopp S., Brown C., Capri E., Forbes V., Köpp H., Liess M., Luttik R., Maltby L., Sousa J., Streiss F., and Hardy A. 2012. Development of a framework based on an ecosystem services approach for deriving specific protection goals for environmental risk assessment of pesticides. *Sci. Total Environ.* 415: 31-38.
Ng YC.1982. A review of transfer factors for assessing the dose from radionuclides in agricultural products. *Nuclear Safety* 23:57-71.
OECD 2007. Organisation for Economic Cooperation and Development. Nuclear Energy Agency, Scientific Issues and Emerging Challenges for Radiological Protection. *Report of the Expert Group on the Implications of Radiological Protection Science.* NEA No. 6167; OECD Publishing; 2 rue André-Pascal, 75775 Paris .
Paetzold A., Warren P., Maltby L. 2010. A framework for assessing ecological quality based on ecosystem services. *Ecol. Complexity* 7:273–281
Pentreath R. J. 2009. Radioecology, radiobiology, and radiological protection: frameworks and fractures. *Journ. Environ. Rad.*, 100:1019-1026.
Real A., Sundell-Bergman S., Knowles J.F., Woodhead D.S., and Zinger I. 2004. Effects of ionising radiation exposure on plants, fish and mammals: Relevant data for environmental radiation protection. *Journ. Rad. Prot.*24:A123-A137.
Repussard J. 2011. Radioecology for tomorrow: An international challenge, both scientific and operational. Presented at the *International Conference on Radioecology and Environmental Radioactivity*. Hamilton, Ontario, Canada; 19 June 2011.
Salbu B. 2009a. Challenges in radioecology. *Journ. Environ. Rad.*,100:1086-1091.
Salbu B. 2009b. Speciation of Radionuclides in the Environment. *Journ. Environ. Rad.*, 100:281-282.
Salt C. and Culligan-Dunsmore M. 2000. Development of a spatial decision support system for post-emergency management of radioactively contaminated land. *Journ. Environ. Manag.*, 58:169-178.

Sato M., and Bremner I. 1993. Oxygen free radicals and metallothionein. *Free Radical Biology & Medicine* 14:325-37.

Schell W., Sauzay G., and Payne B. 1974. World distribution of environmental tritium. In: *Physical Behavior of Radioactive Contaminants in the Atmosphere*. IAEA, STI/PUB/354, Vienna, Austria, 1974, pp. 375-400.

SETAC Ecosystem Services Advisory Group (ES-AG) 2012. Summary of the 5th SETAC Europe Special Science Symposium: Ecosystem Services-From Policy to Practice. SETAC Globe 13(3).

Shaw G. 2005. Applying radioecology in a world of multiple contaminants. *Journ. Environ. Rad.*.81:117-130.

Sheppard M., Elrick D., and Peterson S. 1997. Review and performance of four models to assess the fate of radionuclides and heavy metals in surface soil. *Canad. Journ. Soil Sci.* 77:333-344.

Smith J.T. 2008. Is Chernobyl radiation really causing negative individual and population-level effects on barn swallows? *Biol. Lett*. 4:63-64.

Sugg W., Bickham J., Brooks J., Lomakin M., Jagoe C., Dallas C., Smith M., Baker R., Chesser R. 1996. DNA damage and radiocesium in channel catfish from Chernobyl. *Environ. Toxico.& Chem.* 15:1057-1063.

Thomsen M., Faber J., and Sorensen P. 2012. Soil ecosystem health and services – Evaluation of ecological indicators susceptible to chemical stressors. *Ecological Indicators* 16:67–75.

UNSCEAR. 2008. Vol. II. Sources of ionizing radiation *United Nations Scientific Committee on the Effects of Atomic Radiation*. Report to the General Assembly, with scientific annexe E. United Nations, New-York, 313 pp.

Vandenhove H., Van Hees M., Wouters K., and Wannijn J.. 2007. Can we predict uranium bioavailability based on soil parameters? Part 1: Effect of soil parameters on soil solution uranium concentration. *Environ. Poll.* 145:587-595.

Van der Perk M, Burrough PA, Voight G. 1998. GIS based modelling to identify regions of Ukraine, Belarus and Russia affected by residues of the Chernobyl nuclear power plant accident. Journal of Hazardous Materials 61:85-90.

Van Straalen N. 2003. Ecotoxicology becomes stress ecology. *Environ. Sci. & Tech.* 37:324A-330A.

Voigt G., Semioschkina N., Kiefer P., Howard B.J., Beresford N.A., Barnett C.L., Dodd B.A., Sanchez A.L., Singleton D.L. Wright S.M., Rauret G., Vidal M., Rigol A., Camps M., Sansone U., Belli M., Riccardi M., Strand P., Mehli H., Borghuis S., Van der Perk M., Burrough P., Crout N.M.J., Gillett A. & Absalom J. 1999. *Restoration Strategies for Radioactive Contaminated Ecosystems*. Final status Report. F14P-CT95-0021c, 33pp. European Commission, DGXII.

Viarengo A., Burlando B., Ceratto N., Panfoli I. 2000. Antioxidant role of metallothioneins: a comparative review. *Cellular & Mol. Bio.* 46:407-417.

Vives i Batlle J., Wilson R., Watts S., Jones S., McDonald P., and Vives-Lynch S. 2008. Dynamic model for the assessment of radiological exposure to marine biota. *Journ. Environ. Rad.* 99:1711-1730.

Vives i Batlle J., Wilson R.C., Watts S.J., McDonald P., Jones S.R., Vives-Lynch S.M., and Craze A. 2010. An approach to the assessment of risk from chronic radiation to populations of European lobster, *Homarus gammarus* (L.). *Rad. & Environ. Biophy.* 49:67-85.

Vives i Batlle J., Beaugelin-Seiller K., Beresford N.A., Copplestone D., Horyna J., Hosseini A., Johansen M., Kamboj S., Keum D-K., Kurosawa N., Newsome L., Olyslaegers G., Vandenhove H., Ryufuku S., Vives Lynch S., Wood M., and Yu C. 2011. The estimation of absorbed dose rate for non-human biota: An extended inter-comparison of data. *Rad. & Environ. Bio*phy. 50:231-251.

Wickliffe J. 2011. Clarification and explanation of experimental design and mechanistic dose-response effects for significant radioecological impacts. *Biol. Letters*, 3 Feb 2011, http://rsbl.royalsocietypublishing.org/content/5/3/356.abstract/reply#content-block

Williams C. (Ed) 2004 Framework for assessment of environmental impact (FASSET) of ionising radiation in European ecosystems. *Journ. Rad. Prot.* 24 (4A) (special issue).

Whicker F.W, Shaw G., Voigt G., and Holm E. 1999. Radioactive contamination: state of the science and its application to predictive models. *Env. Poll.* 100:133-149.

Woodhead D.S. 2003. A possible approach for the assessment of radiation effects on populations of wild organisms in radionuclide-contaminated environments? *J. Environ. Rad*.66:181-213.