EUROPEAN RADIOECOLOGY ALLIANCE

Strategic Research Agenda for Radioecology

3rd version

[DRAFT]

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European Radioecology Alliance
http://www.er-alliance.eu/

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The European Radioecology Alliance

The member organisations of the European Radioecology Alliance (ALLIANCE)[1] bring together parts of their respective research and development programmes into an integrated programme that addresses scientific and educational challenges in assessing the impact of radioactive substances on humans and the environment and that maintains and enhances radioecological competences and experimental infrastructures. This integration is important and required to enable tackle complex radioecological challenges that could not be dealt with by one organisation alone.

To address emerging issues in radioecology within Europe, eight founding organisations signed a Memorandum of Understanding (MoU) in 2009 that formed the ALLIANCE. 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, at present incorporating an expanding number of organisations, recognise that their shared radioecological research can be enhanced by efficiently pooling resources among its partner organizations and prioritising group efforts along common themes of mutual interest. A major step in this prioritisation process was to develop a Strategic Research Agenda (SRA). This is one of the tasks of the SRA Working Group of the ALLIANCE.

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

The list of the ALLIANCE members at the date of the 2019 General Assembly is given below.

[1] European Radioecology Alliance http://www.er-ALLIANCE.org/, the association created by 8 founding organizations in Europe to integrate radioecological research in a sustainable way; also referred to the Radioecology Alliance.

Table 1 – List of the ALLIANCE member organisations and representative persons in Working Groups

ALLIANCE members *year subscription and representative persons (**ALLIANCE contact** in bold)*	**EJP CONCERT Working Groups**				**Topical Roadmaps Working Groups**				
	SRA & Roadmap	**Education & Training**	**Infrastructures & Sustainability**	**Stakeholders**	**Human food chain modelling**	**NORMs**	**Marine radioecology**	**Atmospheric transfer**	**Transgeneration. & radioSensitivity**
SCK.CEN - Nuclear Research Center - Belgium (founding member - 2012)									
Hildegarde Vandenhove	x		x			x			
Nele Horemans	x		x						x lead
Jordi Vives i Batlle	x	x					x lead		
Lieve Sweeck	x				x	x			
Nathalie Vanhoudt					x	x			
Talal Al Mahaini					x	x			
DSA - Radiation and Nuclear Safety Authority - Norway (formerly NRPA - founding member, 2012)									
Jelena Mrdakovic Popic	x			x		x			
Anne Liv Rudjord			x						
Justin Brown					x				
Mikhail Iosjpe							x		
Bredo Moller								x	
Dag Brede									x
IRSN - Institute for Radiological Protection and Nuclear Safety - France (founding member, 2012)									
Rodolphe Gilbin	x lead	x							x
Celine Duffa	x						x lead		
Olivier Masson	x							x lead	
Laureline Fevrier			x			x			
Marie Simon-Cornu					x				
Sylvain Bassot						x			
Chartlotte Cazala						x			
Rodolfo Gurriaran								x	
NERC-CEH - Centre for Ecology & Hydrology - UK (founding member, 2012)									
Nick Beresford	x	x lead			x lead	x	x		x
Catherine Barnett		-			x lead				
Dave Spurgeon		-			-				x
STUK - Radiation and Nuclear Safety Authority - Finland (founding member, 2012)									
Sisko Salomaa				-	-	-	-	-	-
Maarit Muikku	x		x						
Pia Vesterbacka			x			x			
Tuomas Peltonen					X				
Juhani Lahtinen					X				
Antti Kallio						x			
SSM - Radiation Safety Authority - Sweden (founding member, 2012)									
Karolina Stark	x				x				x
CIEMAT - Center for Energy, Environmental and Technological Research - Spain (founding member, 2012)									
Almudena Real	x	x	x lead			x		x	
Danyl Perez-Sanchez			-		x				
Juan Carlos Mora			-			x	x		
Catalina Gascó			-					x	
MªAntonia Simón			-					x	

Table 1 *(cont'd.)*

ALLIANCE members **Table 1** *(cont'd.)*	**EJP CONCERT Working Groups**				**Topical Roadmaps Working Groups**				
	SRA	**E&T**	**Infra**	**Stkhlds**	**Food Chain**	**NORM**	**Marine**	**Atmo**	**TESS**
BfS - Federal Office For Radiation Protection - Germany (founding member, 2012)									
Martin Steiner	x		x	**x lead**	x	x	x		
Bernd Hoffmann				-	x	x			
Jacqueline Bieringer				-				x	
Christopher Strobl				-				x	
CEA - Alternative Energies and Atomic Energy Commission - France (2014)									
Laure Sabatier									
Catherine Berthomieu	x				x	x			
Virginie Chapon						x			
Jacques Bourguignon					x	x			
Olivier Evrard							x		
Dominique Calmet								x	
NNCRK - National Nuclear Centre of the Republic of Kazakhstan (2014)									
Sergey Lukashenko									
Zhanat Baigazinov					x				
HMGU - Helmholtz Zentrum München - Germany (2014)									
Jochen Tschiersch	x							**x lead**	
Jan Christian Kaiser									
HZDR - Helmholtz-Zentrum Dresden-Rossendorf - Germany (2014)									
Thuro Arnold	x					**x lead**			
Susanne Sachs	x					**x lead**			
Karim Fahmy									x
Vinzenz Brendler									
Gerhard Geipel									
EPA - Environmental Protection Agency - Ireland (2014)									
Simon O'Toole	x						x		
GIG - Central Mining Institute - Poland(2015)									
Boguslaw Michalik	x	x	x		x	x			x
Malgorzata Wysocka									
Krystian Skubacz								x	
Izabela Chmielewska									x
IST - Technical University of Lisbon - Portugal (2015)									
Maria José Madruga	x				x	x			
Isabel Paiva		x				x			
José Corisco			x		x	x			
Mário Reis				x	x	x			
Fernando Carvalho								x	
NMBU-CERAD - Center for Environmental Radioactivity - Norway (2015)									
Brit Salbu	x							x	x
Lindis Skipperud		x				x			
Ole Christian Lind			x					x	
Hans Christian Teien			x				x		
Deborah Oughton				x	X				

Table 1 *(cont'd.)*

ALLIANCE members	**EJP CONCERT Working Groups**				**Topical Roadmaps Working Groups**				
Table 1 *(cont'd.)*	**SRA**	**E&T**	**Infra**	**Stkhlds**	**Food Chain**	**NORM**	**Marine**	**Atmo**	**TESS**
Yevgenia Tomkiv				x					
IMROH - Institute for Medical Research and Occupational Health - Croatia (2015)									
Ivica Prlić						x			
Marin Mladinic						x			
NCSR Demokritos - Institute of Nuclear and Particle Physics - Greece (2016)									
Kostas Eleftheriadis								x	
Eleni Florou					x				
CLOR - Central Laboratory for Radiological Protection - Poland (2016)									
Paweł Krajewski	x		x			x			
Krzysztof Ciupek		x							
UB - University of Barcelona - Spain (2016)									
Miquel Vidal	x	x	x		x	x			
Anna Rigol					x				
LARUEX - Environmental Radioactivity Laboratory of the University of Extremadura - Spain (2017)									
Francisco Jav. Guillén Gerada		x	x		x	x	x	x	
UPV-EHU - University of the Basque Country - Spain (2017)									
Fernando Legarda	x				X				
Margarita Herranz		x				x			
Raquel Idoeta			x			x			
Saroa Rozas					X				
UGR - University of Granada - Spain (2017)									
Mohamed L. Merroun	x	x				x			
Thünen Institute (2017)									
Marc-Oliver Aust									
Pedro Nogueira	x				x		x		x
University of Porto - Portugal (2018)									
Ruth Pereira						x			x
University of Aveiro - Portuga (2018)									
Sonia Mendo						x			x
Joana Lourenço						x			x
Leibniz Universität Hannover - Germany (2019)									
Georg Steinhauser		x			x			x	
Clemens Walther		x			x				
NRG – Consultancy & Services - Netherlands (2019)									
Govert de With	x				x	x	x		
CNRS-IN2P3 - National Institute of Nuclear Physics and Particle Physics - France (2019)									
Gilles Montavon						x			
IER - Institute of Environmental Radioactivity at Fukushima University - Japan (2019)									
Hirofumi Tsukada									

Preface and Executive Summary

The ALLIANCE Strategic Research Agenda (SRA) devoted to radioecology is a living document that defines a long-term vision (20 years) of the needs for, and implementation of, research in radioecology in Europe. Initiated by the STAR[2] Network of Excellence (Hinton et al., 2013), the current reference document is the third version of our SRA. It integrates the update of the research strategy implemented under the EU funded COMET[3] project (Garnier-Laplace et al., 2018). The CONCERT European Joint Program (EJP) extended the opportunity for **integration at the European level in a synchronised manner for all the platforms for research in radiation protection** by coordinating the release of a joint research roadmap for all platforms, planned in December 2019. This reference document, shared by stakeholders and researchers, will serve as an input to those responsible for defining EU research call topics.

This updated version of the SRA constitutes the ALLIANCE contribution to the CONCERT WP2 task for the development of SRA, roadmap and priorities for research on radioecology. A first activity was to make sure that recent scientific knowledge from radioecology (research outputs from the EC-funded projects (STAR, COMET and CONCERT funded projects: CONFIDENCE, TERRITORIES), main research advances from the ALLIANCE members and relevant international research outputs was integrated. Thus, it considers the state of radioecology and the stakeholders views, the interests of ALLIANCE member organisations, the research needs, data gaps and recommendations for the future of radioecology, and its sister science of ecotoxicology.

Research in radioecology and related sciences is justified by **drivers of various types**, such as policy changes, scientific advances and knowledge gaps, radiological risk perception by the public, integration of research infrastructures, education and training to serve recruitment, lessons learned from the Fukushima disaster and a growing awareness of interconnections between human and ecosystem health. This version of the SRA is formulated by considering several aspects related to these drivers.

Furthermore, it explores how **social and human sciences**, including ethical developments and communication issues, could contribute to the consolidation of European radiation protection culture, bringing together human perceptions and behaviour with science and technology. Research and innovation supporting the implementation of the revised European Basic Safety Standards is also considered.

The strategy underlying the SRA development and its implementation within a roadmap is driven by the need for **improvement of mechanistic understanding across radioecology, such that we can provide fit-for-purpose human and environmental impact/risk assessments in support of protection of man and the environment, in interaction with society and for the three exposure situations defined by the International Commission on Radiological Protection**, ICRP (i.e., planned, existing and emergency).

[2] https://radioecology-exchange.org/content/star
[3] https://radioecology-exchange.org/content/comet

Adequate research **infrastructures and capabilities** (facilities, equipment, methods, databases and models) are a necessary resource for state-of-the-art radioecological research. Ideas about how to study and evaluate the behaviour and impacts of radiation and radionuclides on the living world are changing. Consequently the required infrastructure and capabilities are also changing. Therefore, the updated version of the SRA specifically addresses the research infrastructures and capabilities needs in this SRA.

Implementation of the SRA and the future of radioecology will depend on scientists and professionals being trained with skills relevant to industry and the needs of other stakeholders. It is critical for a vibrant science to continually attract and recruit bright, young talents into the discipline. Thus, the updated version of the SRA also includes a section on **education and training challenges in radioecology**, the associated vision and key action lines.

The SRA prioritises **three important scientific challenges** that radioecology needs to address. Each of these scientific challenges includes a vision statement of what should be accomplished over the next 20 years, followed by key research lines required to accomplish the vision. Addressing these challenges is important to the future of radioecology to enable the science to provide adequate scientific knowledge and tools to decision makers and the public. Other European platforms, among MELODI (Low-dose health effects), NERIS (Emergency preparedness and post-emergency management), EURADOS (Dosimetry of ionising radiation), have expressed common interests for some of the research lines.

The three scientific challenges presented below, with their **14 associated research lines**, are a strategic vision of what radioecology could achieve in the future through a directed effort and collaboration by many organisations. It is a vision in which the participants were asked to think creatively and without boundaries as they imagine the results that could most shape the future of radioecology and benefit stakeholders.

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.

Research Lines:

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 process-based transfer and exposure models that incorporate physical, chemical and biological interactions and associated kinetics, and enable predictions to be made *spatially and temporally*
4. Represent radionuclide transfer and exposure at a landscape or large geographic scale with an indication of the associated uncertainty

Challenge two: **To Determine Ecological Consequences under Realistic Exposure Conditions**

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

Research Lines:

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 (e.g., maternal effects, hereditary effects, adaptive responses, genomic instability, and epigenetic 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.

Research Lines:

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 including decision support systems for an optimised decision-making
5. Towards better interaction and integration of radioecology with other disciplines, including social sciences and humanities (SSH)

The reality is that the SRA will require considerable resources and time to bring to fruition. The "how", "means" and "practicality" of accomplishing the research items presented in the SRA are being developed in **topical roadmaps** that have been initiated by the COMET project, with the help and endorsement of the ALLIANCE Working Groups (WGs), on five priority subjects:

1. Marine Radioecology.
2. Human food chain.
3. Naturally Occurring Radioactive Materials (NORM).
4. Atmospheric Radionuclides in Transfer Processes.
5. Transgenerational Effects and Species Radiosensitivity.

The topical roadmap WGs regularly reviews the various roadmaps at a higher level to ensure that they are being consistent and complementary, without substantial overlaps, and without significant gaps. Their inputs were considered in this version of the SRA. Furthermore, a constant effort is to ensure that the roadmaps are translated effectively into adequately funded research programs, with funding at intra-national, national and international levels.

The vision statements of our strategic agenda concentrate on the research aspects of radioecology. The Strategic Agenda also includes plans for other equally important aspects of our science (i.e. maintaining crucial radioecological infrastructures and knowledge management).

Thanks to this work, the ALLIANCE has now the constituents to build a global roadmap with other research platforms in Radiation Protection. This will be the main output from the WP3 of the CONCERT EJP. This global roadmap will help in giving visibility to priority research to be implemented consistently with stakeholders' needs and request for associated funds. Based on building blocks constituted by topical roadmaps, the ALLIANCE roadmap will be established and viewed as a global picture of the main achievements planned for the next 15 to 20 years.

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 priorities our collective efforts, resulting in increased value and more rapid advancement in our understanding of environmental radioactivity.

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1. Introduction to the Strategic Research Agenda

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, speciation, bioavailability, and effects at various levels of biological organisation), as well as aspects specific to radionuclides (e.g., specialised source terms including radioactive particles, external irradiation pathway, radiation dosimetry, radioactive decay, and unique aspects of very low level measurements). Radioecology emerged as a science in the late 1940s and 50s in response to concerns about releases from nuclear weapons production facilities and radioactive fallout from nuclear weapons tests. Scientific studies of several subsequent accidents at nuclear facilities enhanced knowledge about radioecology; however, much of the early data was classified and not publicly available until the cold war ended in the late 1980s (Iiyin and Gubanov, 2004).

Radioecological expertise is needed whenever ionizing radiation within the environment is of potential concern. The CONCERT First Joint Roadmap Draft (Impens et al., 2017) grouped four contexts, from which three of them result from environmental release (or remobilisation) of radionuclides:

- **Human activities related to the nuclear energy cycle and other industrial applications** of ionising radiation not related to medical applications: Installations from the nuclear fuel cycle (from uranium mining through deposition of radioactive wastes); Industrial and scientific applications of ionising radiation; Military (former nuclear bomb testing sites, weapons fallout, nuclear-powered vessels.
- **Human activities related to the use of natural resources, containing naturally occurring radionuclides (NORM/ TENORM)**: Mining, processing, waste management of natural resources containing natural radionuclides (e.g. oil and gas extraction, NOR-rich ore mining); use, processing, recycling and waste management of technologically enhanced naturally-occurring radionuclides, including decommissioning of NORM affected industrial facilities; NORM contaminated legacy sites.
- **Natural radiation as source of ionising radiation**: terrestrial and cosmogenic radiation, natural events leading to radionuclide releases: High natural radiation background areas, potentially resulting in radon and thoron in indoor and outdoor air/ or in natural nuclides present in water/food; exposure to cosmic radiation at high-altitude or in space.

Seven exposure scenarios related those contexts have been identified and grouped according to the ICRP classification in planned, existing and emergency exposure situations. Five of these scenarios covers environmental exposure of the public and the ecosystems (two scenarios are not related to environmental exposures, i.e. patient exposure regarding medical applications and exposure of workers).

- Exposure of the general public, workers and the environment as a consequence of **industrial applications** of ionising radiation and the use of NORM in normal operation conditions.
- Exposure of the general public and the environment with regard to nuclear **legacy.**
- Exposure of the public and the environment to the **natural radiation** environment.
- Exposure of the general public, workers and the environment following a **major nuclear or radiological accident or incident** including long term consequences.

- Radiation protection of the public, workers and environment as a consequence of a **malevolent nuclear or radiological act** including long term consequences.

Following the Chernobyl accident, European research in radioecology excelled such that Europe's foremost expertise was widely recognised. Radioecology was faced with a substantial decrease in funding in the beginning of the 21st century leading to a decline of expertise. One major reason for the decline is that research efforts that were intensive during the years following the Chernobyl accident have substantially decreased. 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. Following FUTURAE but also following the Fukushima disaster, where a call for radiological expertise from various embassies in Japan, alerted several government agencies to the scarcity of qualified personnel (e.g., U.S. case[4]). Since then there has been a small but steady European funding but also the responsible authorities in the different European member states invested again in radiation protection research.

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

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

The original SRA was distilled from several evaluations on the state of radioecology, including input from stakeholders (FUTURAE 2008), the interests of ALLIANCE member organisations, the IUR[5], lists of research needs, identification of data gaps and recommendations for the future of radioecology, or its

[4] Information from presentation made by representatives of the U.S. Centers for Disease Control and Prevention during the annual meeting of the National Council on Radiation Protection (Washington, D.C.; 13 March 2012; see pages 13-14 of the 48th Annual MeetingReport): http://www.ncrponline.org/Annual Mtgs/2012 Ann Mtg/Electronic NCRP 2012 Annual Mtg Program.pdf

[5] www.iur-uir.org/en/

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; Garnier-Laplace et al. 2018).

The updated SRA was formulated by considering a number of different drivers (Garnier-Laplace et al., 2018):

- *Credibility concerns*: Uncertainties and lack of predictive power in risk assessments are major contributors to the public's reduced credibility of the radiological sciences, and thus a major driver for additional research to enhance knowledge. 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 mitigation (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.
- *Generating trust*: The general public needs to have the necessary confidence in decision makers to be able to trust their judgements, advice and recommendations. The increasing environmental awareness of the public reinforces the need for clarity and transparency within the scientific community relative to the long-term ecological consequences of any nuclear accident or chronic exposure situation. For example, the divergent scientific opinions on the effects on human health and wildlife in the Chernobyl exclusion zone do little for public confidence. This means that multidisciplinary opinions, either consensual or divergent, have to be shared and used to revisit evidence and related actions. Even more, as it has been demonstrated in the event of a nuclear accident, scientific consensus does not always translate into consensus of action by authorities (e.g., Oughton 2011; Hasegawa 2012; Beresford et al 2016).
- *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 also must capitalize on the rapid advances in the "-omic" and AOP sciences to help develop mechanistic explanations and early warning biomarkers.
- *Changing policy*: The present framework of radiological protection is moving towards the need to demonstrate the protection of the environment explicitly as opposed to an assumption of protection. For example, this is seen in the revised versions of the international Basic Safety Standards (BSS) (IAEA 2011) and to a lesser extent, in the Euratom BSS (European Commission 2013) in their interim or draft status at the time of the SRA inception.
- *Integration issues:* Recognition that radioecology's future success, such as for example, meeting stakeholder needs, will require integration into the whole system of radiological protection. The recent ICRP rearrangement of its Committees to address protection of people and the environment in an integrated manner is a further indication of the recognition of this need.
- *Potential risks:* The lessons learned following the accidents at Three Mile Island (USA, 1979), Chernobyl (Ukraine, 1986) and Fukushima (Japan, 2011) demonstrate a number of knowledge gaps, with excessively large uncertainties associated with a number of environmental

processes governing the fate and effect of radionuclides within ecosystems. Future events (e.g. misuse of nuclear weapons, attack on nuclear installations, or use of dirty bombs containing many poorly researched radionuclides) may release radionuclides to the environment that are different from those for which we now have the most knowledge. This situation results in uncertainties in human and wildlife dose assessments, making it difficult to robustly support the decision-making process.

- *Impact of controversial findings:* In the context of ecological consequences of nuclear accidents, the growing number of peer-reviewed publications alleging ecosystem damage from radiation doses at the level of natural background (and sometimes even below) undermine credibility in radioecology. If such findings evidencing the biological effects of ionising radiation at very low dose rates are correct, both the systems for environmental protection and protection of humans from ionising radiation will be questioned.
- *The growing awareness by the public* of the importance of the global quality of environmental resources and biodiversity, with many examples of national regulations directed to the protection of the environment as a whole (e.g., nature conservation, uses of environmental resources, air, soil, water quality). Even more significantly, human and ecosystem health are now recognised as strongly interconnected as evidenced, for example, by several principles and goals for sustainable development recently agreed upon in the 2030 development agenda of the United Nations (2015).
- *The need for an integrated approach in order to improve the degree of realism in dose assessments* (and therefore in evaluations of the associated impacts or risks) either for the public or wildlife for a wide range of exposure situations. Going towards more site specific, individual (for humans) dose assessments to enhance realism imply a need to improve risk communication among stakeholders as to the most significant uncertainties.
- The need to develop applied research activities in order to *solve several statements of the new Euratom BSS* that are related to radioecology. These needs are urgent since the BSS are already being translated into corresponding national laws.

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

The three scientific challenges presented below, with their 14 associated research lines, are a strategic vision of what radioecology can achieve in the future through a directed effort and collaboration by many organisations. It is a vision in which the participants were asked to think creatively and without bounds as they imagine the results that could most shape the future of radioecology and benefit stakeholders. Implementation of the SRA and the future of radioecology will depend both on (1) adequate research infrastructures and capabilities (facilities, equipment, methods, databases and models) and (2) scientists and professionals being trained with relevant skills for industry and the needs of other stakeholders. It is critical for a vibrant science to continually attract and recruit bright, young talent into the discipline. Thus, the updated version of the SRA also includes a section on Infrastructures and Capabilities and on Education and Training challenges in radioecology, the associated vision and key action lines. Those sections includes inputs from the CONCERT WP6 (access to infrastructures) and WP7 (Education and Training).

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

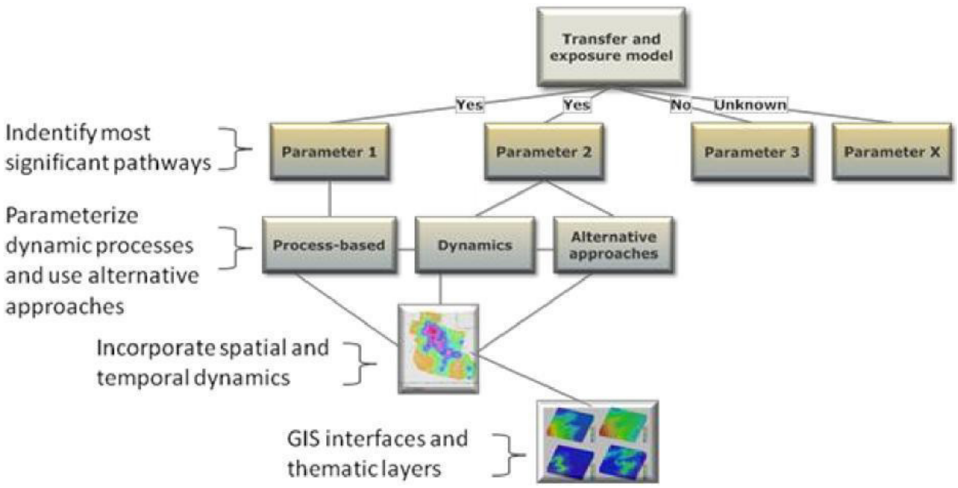

Figure 1. Scheme of key aspects to challenge one: To Predict Human and Wildlife Exposure More Robustly by Quantifying Key Processes that Influence Radionuclide Transfers, and Incorporate the Knowledge into New Dynamic process-based Models.

The input data and models needed for assessing the environmental and human impacts following exposure to ionising radiation differ depending on the source term, release conditions (aquatic versus atmospheric, routine versus accidental), assessment endpoints and the type of space- and time-dependency (dynamics and speciation) 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, chemical and microbiologically influenced reactions and dispersion into the wider environment. This leads to a static scenario in which radionuclide activity concentrations in the biota and surrounding medium are assumed to be 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 (i.e. fit-for-purpose) approximation for most routine release and existing exposure situations. However, the approach has limitations when attempting to simulate releases occurring on short time scales compared with the uptake and turnover processes in the ecosystem, such as a planned series of rapid pulsed releases, accidental situations or simply when processes are influenced by diel and seasonal variations. In such events, a simplistic, empirical ratio approach is no longer valid and a dynamic, process-oriented modelling approach is required, especially when the uncertainty due to simplistic nature of the empirical transfer parameters is not acceptable. Fundamental research is needed to better understand and model the key dynamic processes, such that powerful dynamic process-based radioecological models can be parameterised and populated. However, recent consultation with industrial and regulatory end-users (Almahayni et al., 2019) demonstrated a need to more clearly communicate process-based models demonstrating the need for them, their benefits and (where relevant) showing that they are not overly complex/parameterised. To enable this there is also a need to ensure, where possible, that our models are validated (and that this validation is also effectively communicated); this presents an opportunity for the ALLIANCE (and other relevant platforms) to collaborate with the International Atomic Energy Agency within their model orientated programmes (e.g. EMRAS, MODARIA[6]).

In recent years, during EURATOM research programmes, the drive to improve radioecological models and make them less reliant on empirical ratio approaches has begun to lead to improved models and guidance.

The starting point was the STAR project, which contributed to Challenge 1 by improving wildlife dose assessment by initiating scientifically well founded alternative models to the concentration ratio (CR) approach for wildlife (Beresford et al. 2013, 2016), exploring the application of Bayesian approaches in radioecology (Hosseini *et al.,* 2013) and allometric models for wildlife (Beresford and Vives i Batlle, 2013). As well as potentially providing a more robust model than the CR approach, this work also began to establish scientifically robust extrapolation approaches. These are required, as reliable parameters will never be fully available for all radionuclide, wildlife species or human foodstuff combinations (our lack of ability to assess many radionuclides was raised by end-users in a recent consultation (Beresford et al. 2019)). STAR also considered the feasibility of process-based models supporting the priority this activity was given within the SRA (Urso et al. 2015) and identified priorities for improving 'environmental dosimetry' for biota assessments (Stark et al. 2017). Progress has been made (including under the auspices of the STAR and COMET projects) on some of the priorities identified by Stark et al. (2017); of relevance to Challenge 1 are assessments of animal-environment interactions with the view of determining if current assessment models are fit for purpose (Aramrun et al., 2019; Hinton et al.,

[6]https://www-ns.iaea.org/projects/modaria/modaria2.asp?s=8&l=129

2015, 2019) and recommendations for improved field dose assessments (Beaugelin-Seiller et al. in-press, on-line).

The EU project COMET, the follow–on project to STAR, had a specific focus to initiate studies to address Challenge 1 of the original SRA through five 'initial research activities' (IRAs). These studies strengthened collaboration between the experimentalists and modellers, invested in field research and initiated studies at the Observatory Sites to support the research (e.g. Beresford et al. online, in-press; Muikku et al. 2018).

The human food chain IRA of COMET, together with activities in the OPERRA-HARMONE project, began to consider regionalisation of radioecological models within Europe with a focus on non-radiological parameters (see Brown et al. 2018 for an overview of COMET-OPERRA-HARMONE activities). An approach, adapted from plant sciences, using Residual Maximum Likelihood (REML) modelling to develop models based on taxonomy was successfully used to derive an alternative model to the CR approach, which accounts for the effect of site, for freshwater (Cs) and terrestrial wildlife species (Cs, Pb, Se, Sr and U) (Beresford et al. 2013; Beresford & Willey 2019; Søvik et al. 2017). A REML model was also successfully fitted to Cs data for marine species but its predictive power was poor (Brown et al. 2019). For around 20 years there have been recommendations that REML models (often referred to a 'phylogeny') could be used to make predictions of radionuclide concentrations in plants (e.g. Willey 2010). However, the suggested models have never been validated. The CONCERT-CONFIDENCE project (which had a work package specifically addressing priorities in human food chain modelling as identified by the working group associated with this SRA) has begun to assess how well such models predict plant concentrations of Cs and Sr making the recommendations that the models appear to have merit but that they need to be parametrised for the edible portions of plants (currently the models are parameterised using green shoots only) (Beresford et al. 2019).

The CONCERT-CONFIDENCE project additionally assessed and developed process-based soil-plant transfer models (Almahayni et al., 2019). Models have been developed for Sr using soil properties (e.g. Ca, Mg, organic matter and clay contents) and plant Ca, though these need to be more fully validated. The previously published model for Cs (Absalom et al 2001) was re-evaluated and recommendations made to expand the number of crops and soils included in its parameterisation. Other projects, e.g. the Radioactivity and the Environment (RATE) programme in U.K., have explored the development of process based soil models for radionuclides of concern for long-term assessments of geological disposal facilities (e.g. Shaw et al. 2019). The CONCERT-CONFIDENCE project has also demonstrated how it is possible to add a process-based sub-model in to an existing human food chain model (in this case the Terrestrial Food Chain and Dose Module of the JRodos decision support system) (Almahayni et al., 2019).

The NORM IRA of COMET identified the key processes for safety assessment studies using an FEP approach (Features, Events and Processes) to highlight future research priorities.

Within the marine IRA and the associated COMET-FRAME project, dynamic transfer models for marine biota were applied to the Fukushima scenario (e.g. Vives i Batlle et al., 2016). Specific activities have included the development within the marine topical working group of process-driven dispersion, biokinetic and trophic transfer models with the marine roadmap group. A position paper was published to expand the role of mechanistic investigations and models in the marine environment, and to formulate future priorities in this direction (Vives i Batlle, 2017).

Then, the OPERRA-HARMONE project developed the integration of marine dynamic transfer modelling with emergency methodologies, whereas in CONCERT-TERRITORIES different levels of complexity of marine models were compared to simulate the West Cumbrian beaches, contaminated by releases from the Sellafield reprocessing facility.

The COMET project, as part of the work of the forest modelling IRA, generated a handbook giving practical guidance on the need and applicability of process-based modelling in conjunction with other approaches from simple to complex, for modelling contamination in forests (Diener et al., 2017). CONCERT-TERRITORIES built upon these previous activities to produce guidance in forest modelling.

Process-based models now take into account incorporation as one of the key processes in cycling models (Gonze & Calmon, 2017). Indeed, in the area affected by the Daiichi nuclear accident in Japan, early stage dynamics of radiocesium in forest ecosystems, mainly driven by the rates of canopies depuration (returns to forest floor processes/fluxes) were investigated within several Japan-funded and a French-funded projects (AMORAD) for various species (Loffredo et al., 2015 ; Kato et al., 2019). A significant sapwood-to-heartwood translocation of radiocesium was measured, which led to its accumulation in heartwood of the Japanese cedar, the dominating tree species (Kuroda et al., 2013; Coppin et al., 2016; Ohashi et al., 2017). This surprising phenomenon was unexpected from the Chernobyl experience.

CONCERT-TERRITORIES has compared 5 models applicable to cycling of radionuclides in soil-tree systems. One of this model, ECOFOR SVAT (a soil vegetation atmosphere transfer model), was fully developed and parametrized under controlled conditions at the Belgian NORM-contaminated forest Observatory (ECOFOR, Vives i Batlle et al., 2019), whereas another one was based on meta-analysis of Japanese data (Gonze & Calmon, 2017).

These models have been applied in the Norwegian Fen site (NORM), in the Belgian NORM site, in the Fukushima forests contaminated by the FDNPP 2011 accident, and compared according different criteria, including quantitative criteria based on validation against monitoring data (Brown et al., 2019). Surprisingly, in some cases, the most detailed (most process-based) model was performing least well than empirical models. Possible reasons for this have been discussed and it can be concluded that a model should not be treated as a black box, but knowledge of the calculation methods used is necessary if a more fundamental understanding of model performance is to be achieved. Qualitative criteria were also considered

The ongoing translocation of forest contamination to other environmental compartments has to be considered for the entry into the food chain. Our Japanese colleagues quantified soil erosion and assessed ^{137}Cs inventory in agricultural and forested areas within 10 km from the Fukushima Daiichi nuclear power plant was quantified and ^{137}Cs accumulation (direct litter fall into rivers, lateral inflow from the forest litter layer, and lateral transfer from forest or agricultural soil) and fractionation in ponds and river systems and subsequent accumulation in freshwater (Laceby et al., 2016; Naulier et al., 2017).

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). Quantification of parametric uncertainty (is more and more developed in radioecological modelling as discussed by the Working Group 5 of IAEA MODARIA and reviewed by Urso et al. (2019) in the frame of CONCERT-TERRITORIES. Quantification of scenario and conceptual uncertainties is more limited but approaches haven been proposed by Working Group 5 of IAEA MODARIA and by Urso et al. (2019). These uncertainties can be propagated in uncertainty analysis, possibly separately from parametric variability in the case of two-dimensional (or second-order) approaches (Simon-Cornu et al., 2015; Ciecior *et al*., 2018; Urso et al., 2019). Various sensitivity analysis methods can be used to approach the influence of these uncertainties (Sy et al., 2016; Urso et al., 2019).

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 the COMET IRA on particles (Salbu et al, 2018) 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. Proper source term input (e.g. volatiles, low molecular mass species, colloids, particles, fragments) will impact uncertainty and variability in the outcome of transport, transfer, dose and impact models. 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 COMET-RATE project was devoted to improving the ability to quantify the processes of radioactive particle transformation in the environment and associated radionuclide leaching and to improve the assessment of ecosystem transfer in environments impacted by radioactive particles (Salbu et al., 2018). 2018). Following the Chernobyl accident, a large fraction of radionuclides, including radioactive Cs and Sr were associated with fuel particles, while radioactive Cs also was associated with silicate particles in release from unit 2 and 3 in Fukushima. Thus, these entities would influence on the ecosystem transfer). The CONFIDENCE project has for the first time begun to assess the relevance of particles when modelling human food chain transfer (Lind et al., 2019).

Scarcity of data is one of the major sources of uncertainty, even for the simplest equilibrium models. The IAEA made a compilation of parameter values for estimating radionuclide transfers and found major data gaps (IAEA, 2009). For numerous elements (Cu, Eu, P, Nb, Ba, Na, Cr, Zr, Ca, Y, Ag, Fe, La, Cd, Sb, Pm, Tc, Ru and Po) soil-to-plant transfer factors were available for only 10 % of the plant and soil group combinations. For elements such as Nd, Pr, Rh and W, the soil-to-plant transfer factors were derived from only a single generic value estimated by expert judgment, or derived by analogy to a chemically similar element. The scarcity of data increases with trophic level and stages in the human food chain. For approximately 50 % of the listed radionuclide-animal product combinations, no transfer coefficient data were available. The wildlife empirical ratios compiled by IAEA (2014) 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 is not clear; caution should therefore be used when applying such values in assessments. In order to help overcome these limitations, the STAR-COMET-CONCERT-CONFIDENCE EURATOM funded projects and the UK sponsored TREE project[7] have advance extrapolation approaches (e.g. Beresford et al, 2016). However, whilst data compilations such as IAEA (2009; 2014) demonstrate some limitations in existing data, the situation is actually worse as these compilations have only compiled what is available or have focused on radionuclides include in

[7]https://tree.ceh.ac.uk/

commonly used models. End-users have highlighted the lack of data for a range of radionuclides which they need to conduct assessments for (Beresford et al. 2019x)). These include radionuclides: released by medical facilities (e.g. radioisotopes of Cr, F, Fe, Ga, Ho, In, La, P, Re, Sm, Tc, etc.); associated with the decommissioning of nuclear licenced sites (including, ^{108,108m}Ag, ^{243}Am, ^{10}Be, ^{41}Ca, ^{152,154,155}Eu, ^{55,59}Fe, ^{203}Hg, ^{93}Mo, ^{22}Na, ^{93m}Nb, ^{147}Nd, ^{93m}Nb, ^{193}Pt, ^{46}Sc, ^{151}Sm and ^{182}Ta); relevant to fusion reactors (including activation products such as Fe, Ni, Mn); long-lived radionuclides associated with geological disposal facility assessments. For some of these radionuclides there are no existing data for either human or wildlife assessment, and no guidance on how to conduct an assessment given this lack of data.

The outcome will be more realistic and accurate models for radiological impact assessments and an increased confidence in the assessment process when these models are applied (however, as noted above the benefits of such models need communicating to stakeholder and the models must be sufficiently validated, i.e. on observatory sites.).). 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, the use of simple empirical ratios to represent the transfer between environmental media means aggregating many physical, chemical and biological processes into one parameter, and this is an implicit weakness of the approach leading to the observed variability and uncertainty in model predictions.

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, assuming equilibrium conditions. However, there is considerable evidence that the K_d varies by orders of magnitude under changing geochemical conditions and that process-based dynamic models can describe the situation more realistically (Børretzen and Salbu, 2002). A major improvement here is to further develop the "smart Kd" concept (Stockmann et al., 2017) that relies on data bases of surface complexation constants which are combined with information from the respective field sample. Similarly, the uptake of radionuclides by wild animals and plants (including crops) is often defined as a simple animals or plant to medium (*e.g.,* soil or water) activity concentration ratio, equally assumed to be constant. 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 e.g., 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 understanding of the chemical speciation of radionuclides in different soils, as well as microbiological processes, is crucial to understand the transport of radionuclides through the environment and the manner in which humans and other organisms are exposed to radiation. Improving our understanding and developing process-based approach should result in models which are globally applicable and potentially able to model the impact of soil-based countermeasures (e.g. Cox et al., 2005). Recent studies with respect to process-based models have been discussed briefly above.

The environmental behaviour of radionuclides is controlled by complex biological, chemical and physical processes which may vary (1) spatially - due to differences in water chemistry, sedimentary dynamics, soil type, land use management, and diversity of biological assemblages and communities; (2) temporally - due to time after release, organism's life stage, climatic stressors such as floods, storms, water cascading, biologically-driven processes, landscape evolution and scenarios of global change; and (3) with source term - due to history of the releases, physico-chemical forms (speciation),, and presence of co-contaminants. Unfortunately, although these factors 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. Spatially implemented process-based soil-crop models have previously been developed and incorporated into decision support systems (Gillett et al., 2001; Cox et al., 2005). However, such models have not been widely adopted likely because of poor communication of their benefits and lack of confidence by end-users as they are perceived to be too complicated (Almahayni et al., 2019). Recent activities in the CONCERT-CONFIDENCE project with respect to process-based models and also the incorporation of source-term (different radioactive particle types as a continuation of particle work under COMET-RATE) has been discussed above. When the source term is very uncertain, it has also been proposed to back-reconstruct it based on environmental data as intensively studied in NERIS for accidental situations and also proposed for routine situations, e.g. with an empirical calibration of uranium releases of nuclear fuel cycle facilities (Pourcelot et al., 2017).

With respect to predicting the exposure of wildlife the potential importance of considering the extent to which spatial variability may need to be considered has been highlighted in study which have attached dosimeters and GPS collars to animals in contaminated environments (Aramrun et al., 2019; Hinton et al., 2019). CONCERT-TERRITORIES has also demonstrated that no relevant dose assessment can be obtained without taking into account the actual location of the animals via their GPS tracks (Jones et al., 2019). The COMET and OPERRA-HARMONE projects considered spatial variation at the scale of regionalisation though largely considering element independent because of the lack of regional radionuclide transfer parameter data. Work in CONCERT-CONFIDENCE has begun to address the lack of data for Mediterranean food production systems (Guillén et al. 2019); similarly data have recently been provided for Mediterranean wildlife in collaboration with the COMET project (Guillén et al. 2018).

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. This is particularly important in atmospheric and marine modelling as highlighted by the findings of COMET project FRAME regarding radionuclide transport processes in marine ecosystem near Fukushima (such as, for example, groundwater infiltration to sea) and of the IAEA MODARIA working group on marine dispersion modelling, also in Fukushima.

Process based models have varying degrees of complexity that depend on the situation modelled. Yet a process based model is not necessarily always too complex and may be easier to explain to the public than a 'black-box' model based on ratios and rate constants. The observation that the model complexity may change depending upon need has led to the suggestion that it would be useful to have one modelling package where different components are modularly assembled. The implementation of the FDMT food chain model, the 'Absalom' model and a sub-model for particle source terms into the EGOLEGO package within CONCERT-CONFIDENCE (Brown et al., 2018; Lind et al., 2019) are a good demonstration of how we could develop models in the future.

In summary, the priority given in this SRA to process-based modelling is based on sound science, the ability of such models to reduce modelling uncertainty, increased predictive power, their ability to treat dynamic situations, potential to model soil-based countermeasures and their higher transferability (i.e. if successfully parameterised such models should be applicable anywhere) compared with empirical models. There is however, as already noted, a lack of uptake of the previously developed process-based models by end-users and we need good communication, training and the ability to demonstrate validation to improve this in the future. An example of progress in accepted application of more complex models was the utilisation of the advances in marine biota transfer modelling made after Fukushima, by the UNSCEAR assessment of the impact of the accident on the marine environment (Vives i Batlle et al., 2014; Strand et al..,., 2014).

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) for a wide range of source terms, release and migration scenarios and exposure situations, where relevant and needed, and be able to accurately predict exposure to humans and wildlife by incorporating a more profound understanding of environmental processes and assure that fit-for-purpose process-based models based on scientific modelling of the radioecological mechanisms will have found a way into future assessment tools.

2.1.2. Strategic agenda

The major aim of challenge one is to develop process based models of environmental transfer and exposure to substantially improve human and environmental dose and impact assessment. Research should be focussed on those factors contributing the most to uncertainties in exposure assessments. The developed process-based models will begin to form part of the next generation of assessment tools. They should also contribute to addressing the need for an integrated approach to human and wildlife exposure assessment.

The approach can be applied (with an appropriate level of complexity) to a wide range of sources encompassing existing (e.g. uranium mining and milling sites, NORM sites, post-accident situations), planned (*e.g.,* new build, (geological) waste disposal, NORM involving industries, medical radio-isotope and radiopharmaceuticals production facilities) and emergency (accident, incident, malevolent acts) exposure situations. Emergency situations are the focus of the SRA of NERIS so the radioecological related aspects will be researched and developed in close collaboration with NERIS); aspects of source-term characterisation, distribution and migration through food chains, development of countermeasures and remediation strategies are within the remit of Challenge 1 of the ALLIANCE's SRA. Related to (high-level) waste disposal our SRA will concentrate on the biosphere and geosphere/biosphere interaction zone, linking to networks such as BIOPROTA[8] , IGD-TP[9] and EURADScience[10] as well as the IAEA MODARIA successor projects. Environments other than temperate ecosystems will be considered.

The mechanistic, process-based, approach should

- Enhance scientific knowledge about environmental processes and their mutual interactions. Radionuclides then become tracers to understand local and large scale processes, which in turn can help inform other disciplines (such as ecology, geochemistry and toxicology);
- Enable long-term forecasts and the influence of climate and landscape changes on the environmental transfers of radionuclides;
- Assist in the development of tools for response, remediation, and restoration; and
- Support multi-criteria analysis and hence decision making.

Validation of developed models will be important to ensure end-user uptake; there is potential for a strong collaboration with IAEA programmes in model validation.

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 profound understanding of environmental transfers and exposure processes that permit observations to be explained and robust predictions to be made. The main aspects will be (i) identifying processes, parameters or factors that contributes the most to the overall uncertainties, (ii) determine the level of model complexity needed for specific exposure scenarios and (iii) justifying the additional research required for data generation and to parameterise dynamic-mechanistic models.

Criteria will be developed to identify key processes that have a significant impact on radionuclide transfers in atmospheric, terrestrial, aquatic and built-up (e.g. urban) environments. One tool at our disposal to implement this is the concept of process sensitivity analysis developed in geological disposal safety assessment (Features, Events and Processes - FEP) where processes rather than parameters are varied/added/removed to test the optimum process representation in a radioecological model; this approach was applied by the COMET project and further refined by CONCERT-TERRITORIES. Amongst the model features considered will be source-term-specific release scenarios (including physico-chemical forms), spatial and temporal dynamics in source term–environment interfaces (dispersion and dilution, changes in radionuclide speciation due to physical, chemical and biological interactions), migration and cycling pathways in specific ecosystems, and radionuclide uptake, accumulation, redistribution and depuration by organisms. Once the key

[8] http://www.bioprota.org/
[9] http://www.igdtp.eu/
[10] http://hal.in2p3.fr/in2p3-02169313

processes have been identified, equations will be derived that capture their temporal and spatial kinetics. Criteria to identify the relevant factors and processes could be inferred from the variability observed in aggregated parameters and the associated uncertainties in transfers, as shown by scatter plots of empirical transfer factor values and associated cumulative distribution functions. A classification based on key environmental characteristics, taxonomy, source term, etc. 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 physical, 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) or contexts (e.g. nuclear or NORM related industrial environments, waste disposal environments). Some elements of this knowledge may exist in other fields (e.g. soil scientists). This goal can be realised by the development of conceptual and mathematical test models allowing the identification and ranking of key processes in a quantitative, but also in a qualitative manner using expert judgement. Process and parameter sensitivity analysis can 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). Systematic model reduction can be applied to test the utility of the model components (e.g. Tarsitano et al., 2011). For the future, the verification of model predictions could better benefit from a comparison with observatory data.

Within this research line, we intend to progress further towards process-based dynamic models. Process-based modelling is essential to demonstrate that scientifically justified impact and safety assessments can be made for future situations. 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. A key issue is then to validate the model outcome in the field. Examples include:

- relating the environmental mobility of radionuclides to their speciation resulting from the oxidising/reducing properties, pH, redox potentials, salinity, DOC, mineralogy, general chemical composition of environmental media or biological actors (e.g. microbial activity, presence of mycorrhiza);
- advection-dispersion equations for describing flow kinetics in aquatic environments;
- simulating rates of water movement in porous media; and
- metabolic theory for describing the biokinetics/toxicokinetics of contaminants in living organisms.

In all cases, the objective will be to produce a set of physically and dimensionally consistent primary differential equations that represent the temporal and spatial 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, data exist to describe time dependency in transfer to some extent. Knowledge on associated processes has advanced for post-accident situations (Cs, Sr, I) but is generally deficient for other exposure situations and contexts (unforeseen events, decommissioning of nuclear facilities, urban context, industrial environment) and the majority of other radionuclides. For some recently emerging radionuclides such as medical radioisotopes, data are missing but scoping calculations related to potential dose contribution are required before setting of too complex modelling.

It is important that the knowledge gained from the various research activities is rapidly assimilated and made available to the wider community. This is likely to require the development of flexible and open databases that do not 'force' the information into an over-constrained conceptual model framework, together with a platform (or platforms) for the modular development of mathematical models (as exemplified by recent work in the CONCERT-CONFIDENCE project (Brown et al., 2018; Lind et al., 2019).

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

Major data collection activities (such the IAEA handbooks of radioecological transfer parameters) have identified significant data gaps and limitations for many of the empirical parameters which underpin dose assessment models for humans and wildlife. The wide range of radionuclides, human foodstuffs and species of wildlife means that, pragmatically, we may never be in the position of having empirical data for everything.

There is a need to consider alternative approaches to address this lack of data for model parameterisation in the most robust manner possible (rather than relying on highly conservative judgment to avoid analysing the problem in more depth, as is often the case currently). Extrapolating across the periodic table using chemical analogues is such an approach. For example, in the context of the Fukushima accident, it was proposed that estuarine reactivity of short-lived radioactive tellurium could be assessed based on the behaviour of its stable analogue. Other approaches, such as Bayesian statistics, allow a low number of empirical observations to be supported by inferences from more comprehensive, larger datasets (this approach was been used in the parameterisation of the ERICA Tool (Brown et al., 2016)). Some approaches to extrapolate data have been suggested for application across species (wildlife species or human food chain species) such as phylogeny (*i.e.* using 'common ancestry' to categorise transfer) and allometric (mass dependent) relationships. These approaches have started to be advanced by activities in the STAR, COMET, CONCERT-CONFIDENCE and TREE projects (see above).

The data for model parameterisation will require focused laboratory-based work and field studies, as well as on-going reviews of published information from the wider scientific community (both at suitably-designated "observatory sites" and more generally from environmental monitoring). For example, a preliminary inventory of databases acquired from observatories and monitoring sites at the European scale by the various STAR partners highlighted the richness of environmental data, especially their temporal and spatial distributions, even though heterogeneity and data gaps were identified. The Belgian NORM site (Alliance observatory intensely investigated in CONCERT- TERRITORIES) proved the benefit of establishing mechanistic investigations in controlled conditions to scientifically explore process-based models (Vives I Battle, 2019). The Upper Silesia Coal Basin (another European radioecological observatory) was also investigated in CONCERT-TERRITORIES in order to explore the conceptual scheme of processes occurring in a Polish lake displaying NORM, including the occurrence of early diagenesis process (Mora et al., 2019). Even if less exhaustively informative, long-term data series obtained along routine surveillance programs can also provide information for transfer modelling (Brimo *et al*., 2019).

Some of the data gaps are expected to be filled by innovative analytical tool developments in both radioactive and non-radioactive metrology. For example, difficulties persist in quantifying the various radioactive decay products from the natural U-Th decay chains within the same sample at a given time. In this context, ICP-MS and AMS analyses offer potentially exciting solutions.

To maximise opportunities for data acquisition whilst minimising the environmental impacts of our science, a strategic focus should be placed on the development and adoption of non-lethal methodologies (which do not require animals to be killed) for use in radioecological research.

The ALLIANCE have highlighted the need for experimentalists and modellers to work together from project outset, in order to obtain the correct match and compatibility of models and the data necessary to parameterise them.

2.1.2.3. Develop process-based transfer and exposure models that incorporate physical, chemical and biological interactions and associated kinetics, and enable predictions to be made spatially and temporally

Accurate, process-based radioecological modelling reduces model conceptual uncertainty and can reduce the uncertainty of model predictions, leading 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; Salbu et al., 2018; 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). Knowing the early dynamics of radionuclide distributions following atmospheric deposition and marine releases has already played a major part in understanding the consequences of the nuclear accident at Fukushima. These developments are also crucial in context of site and environmental remediation.

The transfer models developed should be able to integrate radioactive contaminants into the general dynamics of ecological systems. An example is using pollutant-coupled soil-vegetation-atmosphere transport (SVAT) models to investigate the wider, long-term circulation patterns of radionuclides in the geosphere-biosphere interface (e.g. ECOFOR forest modelling as used in CONCERT-TERRITORIES), and taking into account the biogeochemical (re)cycling of radionuclides over very long time-scales, changing climate conditions and evolving ecosystems. Other examples are the coupling of radionuclide transfer biokinetic modelling with 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 performed by the D-DAT model in COMET-FRAME. Ahead in the future lies the further coupling of such modelling with the climate-induced ocean global circulation patterns but also to include speciation in these dynamic models. Other understanding that should be improved includes the behaviour of radionuclides at interfaces (*e.g.*, atmosphere-water surfaces, land-coastal, watershed-freshwater courses, saline-freshwater, geosphere-biosphere, oxic-anoxic, air and water and built environment) and the influence of co-contaminants on radionuclide behaviour. Furthermore, progress is awaited on representing the redox behaviour in soil, influence of soil organisms on mobility and uptake by plants and other organisms in an integrated way, improving semi-mechanistic models such as the Absalom model. 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 dispersion, transport and kinetic exchange 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, fundamental for the understanding of accidental situations and incidents but also in the context of NORM (decay chains seldom in 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). In addition, as stated previously, it should be more feasible to communicate, to the public, a process-based model than an empirical model based on aggregated parameters which contain a lot of implicit assumptions.

This more process-based mechanistic modelling is expected to more accurately assess radionuclide transfer between and within environmental compartments and as such assure more robust human and ecological impact assessments. Process-based and mechanistic models are also expected to advance countermeasure strategies and optimize site remediation and restoration.

Radioecology is particularly under-developed in analysing the interactions of substances with living organisms at the cell 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 internally deposited radionuclides (links with Challenge 2).

There is a need to assess wildlife exposure more realistically by considering spatial as well as temporal variability in for instance, habitat utilisation, contaminant densities and interactions between organisms, all of which impact animal movement and hence exposure in heterogeneously contaminated environments. During various life stages, dynamic processes may change many characteristics of an individual organism, such as weight, food intake, metabolism, internal contaminant concentration and the habitat in which they reside. These factors all 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. Recent studies in which GPS units and dosimeters were attached to free ranging animals show the potential impact of not taking these factors into account in assessments (Aramrun et al., 2019; Hinton et al., 2019). Advances in this area would have synergies with population modelling (Alonzo et al., 2016; Vives i Batlle et al., 2012) approaches being developed to better predict ecosystem level effects (links with Challenge 2). Animal mobility can be predicted using 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 though the use of agent based random walk models and mass-balance food-web approaches is currently being assessed[11].

Wildlife dosimetry is also in need of some advancements (e.g. Stark et al., 2017). 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 and microdosimetry measurement to be able to account for differences in sensitivity among various organs and to better assess the dose-response relationships in particular situations for improved future predictions. Initial simplistic investigations on this topic were carried out during the FASSET and ERICA EURATOM projects whilst other work has explored the use of voxel phantoms (e.g. Ruedig et al., 2015). Comparison of voxel phantoms (detailed three dimensional models which represent individual organs/tissues and can cope with heterogeneous distribution) with the simplistic ellipsoid used in assessment models have tended to demonstrate that for regulatory assessment the ellipsoid approach is generally sufficient (Ruedig et al., 2015). Where voxel phantoms will be of value is in the analyses of effects data, perhaps most especially from contaminated field sites with a mixed radionuclide profile (e.g. the Chernobyl Exclusion Zone). Skewed dose distributions from internally incorporated radionuclides (macro-distribution of radionuclides within organisms, but also the micro-distribution within specific organs and tissues, especially for alpha or beta emitters and for radioactive particles) also represent a challenge as it can significantly influence radiotoxicity. Studies in this field should involve collaboration with EURADOS on advanced dose assessment techniques and dose monitoring tools (e.g. the notable developments in microdosimetry). However, more basic improvement is also needed to reduce the uncertainties in environmental dosimetry, notably geometries used for plant are currently poor and do not necessarily consider the most exposed or sensitive plant parts (e.g. the geometry for a tree is represented by a section of trunk).

The Observatory Sites initiated under COMET and continued to be assessed under CONCERT-TERRITORIES (cf. 2.1.2.2) and with continued support of the ALLIANCE are excellent large-scale field laboratories with spatial variability. These site allow for multidisciplinary studies (radioecology, dosimetry, toxicology, hydrogeology, ecosystem approaches, etc.), long-term investigation of environmental processes, parameter value generation, modelling tool testing and validation within real systems. Observatory sites are established in Chernobyl and Fukushima but also NORM contaminated sites are established. The Observatory Sites will be receiving due attention and further development as an essential radioecological 'infrastructure' (see also section §0 -

[11] https://gnssn.iaea.org/RTWS/modaria/Shared%20Documents/MODARIA%20II/3rd%20MODARIA%20II%20Technical%20Meeting/25th%20October%202018%20-%20TM%20Closing%20Plenary%20Presentations/06%20-%20WG5%20TM3%20Closing%20Presentation%20(Beresford+Vives).pdf

Strategic Agenda for Infrastructures).

2.1.2.4. *Represent radionuclide transfer and exposure at a landscape or large geographic scale with an indication of the associated uncertainty*

The objective of this research line is to improve the current status by mapping radionuclide transfer and exposure at the European or global scale based on thematic maps, including spatial and temporal variability, using the newly developed process-based models. Since geographical distributions of radionuclides tend to be highly heterogeneous (Van der Perk *et al.*, 1998), a detailed understanding is needed of radionuclide transfer processes at multiple scales, such that transfer can be mapped using GIS systems at the landscape level. Within this research line we intend to design and implement a user-friendly, state-of-the-art GIS interface with the developed models, facilitating mapping of radionuclide transfer and exposure at a landscape level to identify sensitive environmental compartments/areas. An added benefit of such development could be the integration of knowledge at the European level (interaction with challenge 3). Spatial dimensioning on the European scale has occurred in a number of systems with GIS capabilities, such as SAVE (Spatial Analysis of Vulnerable Ecosystems in Europe), RESTORE (Restoration Strategies for Radioactive contaminated Ecosystems), CESER (Countermeasures: Environmental and Socio-Economic responses) and RODOS (Real-time On-line Decision Support system for off-site emergency management in Europe) (Howard *et al.*, 1999; Voigt *et al.,* 1999; Salt *et al.*, 2000; Ehrhard *et al.*, 1997). However, improvements in spatial dimensioning are needed by incorporating better process-based approaches. Such an approach was proposed by Gonze et al. (2016) who modelled at the landscape level air dose rates with a process-based dynamic approach. This priority should be further developed in collaboration with NERIS), as they are of specific interest for post-accident situations.

An important task here will be to bridge the previously-mentioned difference between the small scales at which radionuclide behaviour and transport are often studied and the larger scales often relevant for management decisions, also in context of site and environmental remediation. 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. It would also enable the modelling (if appropriately parameterised) of countermeasures (as exemplified by Cox et al., 2005).

2.2. Challenge Two: To Determine Ecological Consequences under Realistic Exposure Conditions

There is a growing awareness by the public of the importance of the global quality of environmental resources and biodiversity, with many examples of national regulations directed to the protection of the environment as a whole (e.g., nature conservation, uses of environmental resources, air, soil, and water quality). Even more significantly, human and ecosystem health are now recognised as strongly interconnected as evidenced, for example, by several principles and goals for sustainable development recently agreed upon in the 2030 development agenda of the United Nations (2015).

This challenge is of high priority regarding new regulatory requirements for the radioprotection of the environment which has shifted during the last decade from an implicit to an explicit environmental protection. The IAEA's Fundamental Safety Principles (IAEA, 2006), revised ICRP Recommendations (ICRP, 2007), the revised versions of the international Basic Safety Standards (BSS) (IAEA, 2011) and to a lesser extent, the Euratom BSS (European Commission 2013) 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 can be based is key to answering social concerns about (eco)toxic effects from ionising radiation and its ecological consequences.

Over the last 20 years, international efforts have focused on new strategies for protecting the environment from radioactive substances e.g. by setting up an effects database for non-human species (FREDERICA) (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)]. Whilst the ERA-type approach is a substantial advancement in radioecology, a lack of sufficient data prevents current ERA analyses from fully accounting for the realistic environmental conditions that organisms are actually exposed and ecological processes that are actually affected.

Data are still insufficient to take into account low dose effects, variable dose rate regime, dose deposit heterogeneity (from molecular targets up to individuals and ecosystems), multi-contaminant scenarios (including the different exposures from external irradiation and internal contamination), species variation in radiation sensitivity due to life-history traits, community 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 predictive risk assessments. The vision of this SRA is to address such deficiencies (Figure 2).

There exists still considerable scientific disagreement on the actual extent of the radiation effects on wildlife in contaminated areas. Many studies have reported no significant effects of radiation on wildlife (e.g. in the Chernobyl and Fukushima exclusion zones), whereas others reported significant radiation effects on different wildlife groups at very low dose rates (below natural background exposure) (Beresford et al., 2016; Chesser and Baker, 2006; Moller and Mousseau, 2009, 2016; Beresford et al., 2019; Fuller et al., 2019). This controversy challenges the ecological protection criteria published by research groups, as well as international organisations that issue guidance for radiological exposures. Several protection criteria with different ways of derivation and different protection purposes are established (UNSCEAR, 2008; ICRP, 2008; Anderson et al., 2009; Garnier-Laplace et al., 2010); ICRP, 2014).

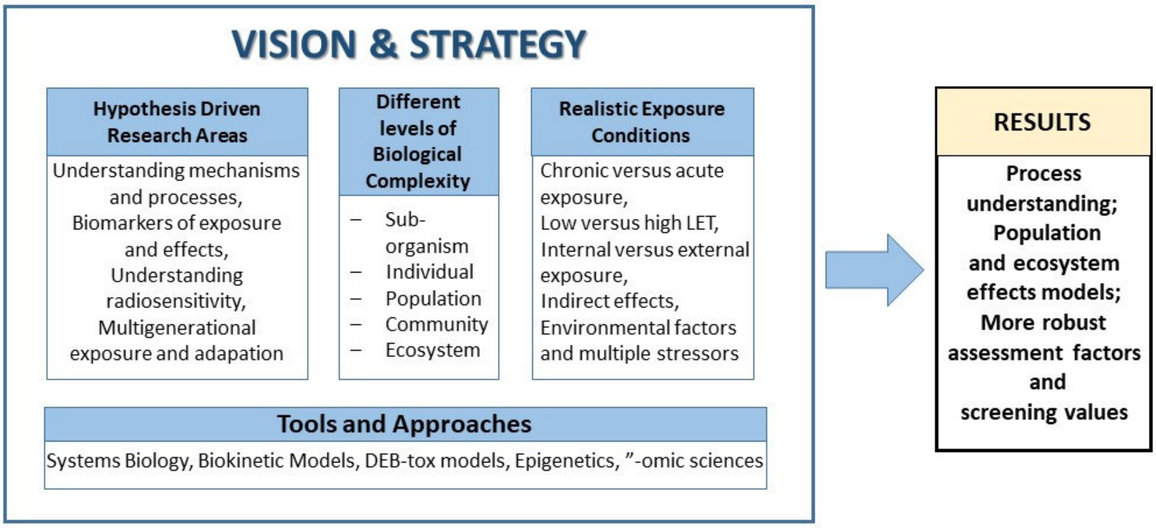

Figure 2. Schematic of the components and anticipated results of the Strategic Research Agenda concerned with challenge two: To Determine Ecological Consequences under the Realistic Conditions that Organisms are Actually Exposed.

In the last decade the STAR, COMET and TREE programmes were large multi-institute programmes, in part designed to address these identified priorities. Whereas STAR initiated research on multiple stressors, the COMET project focussed on understanding the role of epigenetic processes in the trans-generational effects of radiation (Saenen et al., 2017; Horemans et al., 2019; Beresford et al., 2019). The need to further 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.

In order to build new environmental radiation protection approaches and to understand and assess the effects of radiation on wildlife, radioecology will need to benefit and collaborate across different disciplines such as environmental sciences including ecology and ecotoxicology of chemical substances, stress ecology (Van Straalen, 2003) and other European research platforms such as MELODI with which it shares a number of challenges (e.g., for extrapolating from acute to chronic ecotoxicity, laboratory to field, one species to another, individual to populations) as well as methods, concepts, models, and tools. New approaches adopted by environmental sciences in general, and ecotoxicology and ecology in particular, 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). Realistic environmental conditions incorporate natural abiotic factors (e.g., climate change, temperature, flooding events, snow and ice) as well as biotic factors (e.g., physiological and life-history status of organisms; ecological processes such as competition, predation, and food availability). Adding this realism will aid at developing integrated exposure assessment approaches (including the development of proper tools for the dose calculation for wildlife species) that encompass the dynamics over time and space during the entire life cycle of organisms (links with Challenge 1). One operational outcome from this challenge, directly relevant to radioprotection of flora and fauna, is to establish sound-science protection criteria for ecosystems and their sub-organisational levels following exposure to radioactive substances, whatever the source term and the environmental situation.

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 describe and predict effects under the realistic conditions in which organisms are actually exposed.

2.2.2. Strategic agenda

Similarly to Challenge one, the key research lines developed below are intended to be applied for all exposure situations, as described by the CONCERT Joint Roadmap scenarios: planned exposures situations under normal operation conditions (scenarios 2), existing environmental exposure scenarios with regard to legacy (scenario 4) and natural radiation (scenario 5), as well as long term exposures after accidents (scenario 6) and malevolent acts (scenario 7). To address these, studies will have to include an appropriate combination of laboratory studies conducted under controlled conditions and field studies and statistical data treatment and/or mathematical modelling. In connection with challenge one, common to all five research lines outlined below, is a crucial need for an improved dosimetric assessment to reduce uncertainty and enhance robustness of dose estimates and for the establishment of dose-response relationships, whatever the model used (e.g., logistic, hormetic, linear non threshold). Such response relationships constitute the basis for any predictive risk assessment. Specifically, the following five research lines will need to be addressed to achieve the 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 aims at identifying key molecular/cellular and individual characteristics driving radiation induced effects at the individual level. The use of advanced analytical methods from molecular biology including high-throughput screening technologies and computational models to extrapolate data at different levels of biological complexity, holds great promise for enhancing our mechanistic understanding of radiation induced responses at the sub-cellular levels and their consequences to individuals and is shared between human and other organisms (Mothersill et al., 2018). One way of describing the links between molecular initiation of the response and the observed adverse effects is through the formulation of an Adverse Outcome Pathway (AOP) (Ankley et al., 2010; Groh et al.,., 2015). The formulation of a radiation specific AOP will form a framework within which data and knowledge coming from different organisms, different levels of biological complexity and even multiple stressors are synthesised in a way that is useful for risk assessment. The key molecular events (which may include epigenetic change) of an AOP might serve as a potential biomarker, once their response sensitivity and natural variability in populations are characterised. With validated biomarkers under field conditions and populations of native or non-native species (e.g., using caged animals in the environment), innovative biomonitoring in the field should be developed, with a preference to non-lethal methods and tools where possible. Field studies will be required to test the detectability of radiation induced changes used as biomarkers within complex realistic exposure situations (e.g., confounding factors such as seasonal variations, other contaminants, changes in habitats). A radiation-related AOP for different organisms together with specific biomarkers could potentially be used in a regulatory setting to verify the results of impact assessments for operational facilities.

In addition, coupled Biokinetics/Dynamic Energy Budget (DEB) approaches can aid in understanding 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 responses?
- How may those elementary mechanisms result in adverse outcomes at the cellular and individual levels (immune and neurological systems integrity, general metabolism, reproduction, growth, survival, behaviour, susceptibility to diseases)?
- How do radiation type (α, β, γ), exposure duration (acute, chronic), pathways (external vs. internal irradiation) and cellular/biological characteristics modulate the quality and quantity of damages? Are those damages reversible?
- Do specific modes of action or master genes exist for different types of radiation, and can they be used to develop specific biomarkers or biosensors or AOPs?

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 recent research suggests that current international protection benchmarks may not be protective of all organism groups (Raines, 2018). 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 and Adam-Guillermin et al.,., 2017).Differences in sensitivity between species also lie behind overall effects at higher levels (community, ecosystem). Understanding the mechanisms of inter-species radiation sensitivity may also help us understand mechanisms behind intra-species variation (Beresford et al., 2019).

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

- How do differences in DNA damage between different species, or the potential for DNA repair, explain the inter- intra-species differences in radiosensitivity?

- For internal contamination, how does uneven internal distribution of radionuclides and the subsequent 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. The environment is contaminated with low concentrations of complex mixtures (e.g., radionuclides, metals, pesticides, fire retardants and endocrine disruptors) and non-optimal or adverse environmental conditions (e.g. heat, drought) (Vanhoudt et al., 2012; Vandenhove et al., 2012; Mothersill et al., 2019). Studying a contaminant in isolation is necessary and provides critical information on the underlying mechanism resulting in detectable effects and can be used to test the specificity of biomarkers but cannot predict possible interactions among the many stressors to which organisms are exposed. Interactions can provide protective effects and reduce overall damage, or augment effects in negative, synergistic ways (SCHER, SCCS, SCENIHR, 2012).

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. 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.

Some research projects, including the EU funded STAR project, have been trying to answer the question of multi-contaminant/stressors (Gilbin et al., 2015; Gagnaire et al., 2017). While studies of stressor interactions are common in ecotoxicology, it has been difficult to derive general rules by which to predict how different species may be effected by a given combined stressor exposure (additive, greater than additive, less than additive) (Holmstrup et al., 2010; Vanhoudt et al., 2012). For many species, the limits of tolerance for some types of stressors (e.g. soil pH, temperature ranges) are known. Measurements of potential stressors along with radioecological measurements may identify those cases in which radionuclide exposures coincide with other stressful conditions helping to identify when multiple stressor effects may need to be taken in to account (Beresford et al., 2019.).).

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 (Escher et al., 2017).

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. This is true whatever the radiation type and exposure pathways.

The mechanisms involved in organism responses to chronic radiation exposure, both within and between generations, are the subject of an active debate in the scientific literature (e.g. Boubriak et al., 2016; Carroll et al., 2007; Goodman et al., 2019; Horemans et al., 2019). Whilst adaptation of organisms to radiation within the Chernobyl Exclusion Zone (CEZ) has been suggested (Møller and Mousseau, 2016; Boubriak et al., 2008), it has not yet been the focus of any comprehensive research programme. If it does occur, adaptation of specific populations could lead to adaptation of the ecosystem over time (e.g. the plant biome is thought to help plants cope with abiotic stress such as drought or salinity (Dodd and Pérez-Alfocea, 2012; Liu and Zhang, 2015)). If adaptation to chronic radiation exposure exists in the CEZ, it will have implications for the interpretation of studies comparing current effect and exposure levels.

Radiation can directly affect DNA by ionisation of the molecules that form the double helix indirectly through formation of Reactive Oxygen Species (ROS) leading to molecular lesions (e.g., base degradation or deletion, single- or double-strand breaks, protein-DNA cross link). Indirect effects of oxidative stress can also 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 changes in epigenetic mechanisms that cause changes in cell signalling processes [e.g., genomic instability (genomic damage expressed post-irradiation, after many cell cycles), bystander effects (where non-irradiated cells in proximity to irradiated cells exhibit effects similar to those that received the radiation), and reduced repair efficiency (e.g., Morgan, 2003; Mothersill et al., 2009].

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 (Horemans et al,., 2019). 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? What is the impact of previous 'acute' radiation exposure on organisms in contaminated environments now?

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)

Regardless of the stressor or type of contaminant, the vast majority of ecotoxicological data describe effects on individual traits of organisms 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). 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 radioecology, the importance of an ecosystem approach has been emphasised many times over the last decade. Several publications and international workshops have led to a number of recommendations and consensus statements (Bradshaw et al., 2014; Bréchignac et al., 2016; Mothersill et al., 2018, 2019).

In the wild, species within the same environment are differentially exposed to radioactivity due to their specific habitat, behaviour, and feeding regime. Species also have different sensitivities to radiation. In an ecosystem, this means that the various responses of species to radiation will also alter the interactions between species and may affect aspects such as competition, predator-prey or parasite-host interactions. This may lead to secondary effects that change community structure, composition and function. These secondary, indirect effects may impact a population to a larger extent than the direct effects of radiation. Such issues have been poorly addressed in radioecology and, for that matter in ecotoxicology, partly due to the complexity of studying multi-species assemblages in the laboratory or unravelling complexity in field situations. Recently, a literature review assessing the design and properties of multispecies effect-study experiments and their suitability for radioecology is currently in review (Haanes et al, submitted). A few experiments using microcosms (multispecies experiments) have clearly demonstrated such indirect effects (e.g., Doi et al., 2005; Fuma et al., 2010) at quite high doses. A recent microcosm study performed at dose rates similar to those at contaminated field sites (Hevrøy et al., 2019) allowed to isolate specific relationships between interacting species in an ecosystem and test the direct and indirect effects. Studies have investigated the effects of ionising radiation on wildlife from subcellular to community levels in the CEZ (e.g. Beresford et al., 2019) and increasingly in the Fukushima region. However, the consequences of increased ionising radiation levels on key ecosystem processes such as plant production, the degradation of dead organic matter, and elemental cycling have received little attention.

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. Modelling 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 invertebrates with different life cycles (Alonzo et al., 2008). Such models are a valuable, under-utilised method for predicting effects from environmental stressors, and thus are included within this SRA as they need to be further explored in radioecology. However, all models need to be tested in realistic systems (e.g., complex laboratory studies or in the natural environment) before accepting them as predictive tools.

The propagation of effects from individuals to population depends on the characteristics of specific life histories. 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? 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. For example, recent studies (ALLIANCE, 2018) demonstrate shifts in developmental and reproductive endpoints (e.g. flowering time or sexual maturity) due to radiation exposure, that may be significant for ecological functioning (e.g., delayed production of pollinators and earlier flowering may mean no floral resources are available for pollinators). 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) key ecosystem processes (function)?
- How does ionising radiation affect the provision of goods and services provided by the environment of importance to humans (e.g. how species lifecycle dynamics may become uncoupled from the resources (e.g. food supply, nest sites, pollinators) on which they rely)?

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 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, including social sciences and humanities (SSH) to provide necessary scientific basis for system and practice of radiation protection and to ensure proper answers on societal questions and challenges in different exposure situations. Thus, radioecology's future success, broadly defined as meeting stakeholder needs, will require integration in several ways and from several different perspectives. This portion of the SRA identifies several integration challenges (Figure 3), as well as highlights the advantages gained by the science of radioecology in meeting the integration challenges:

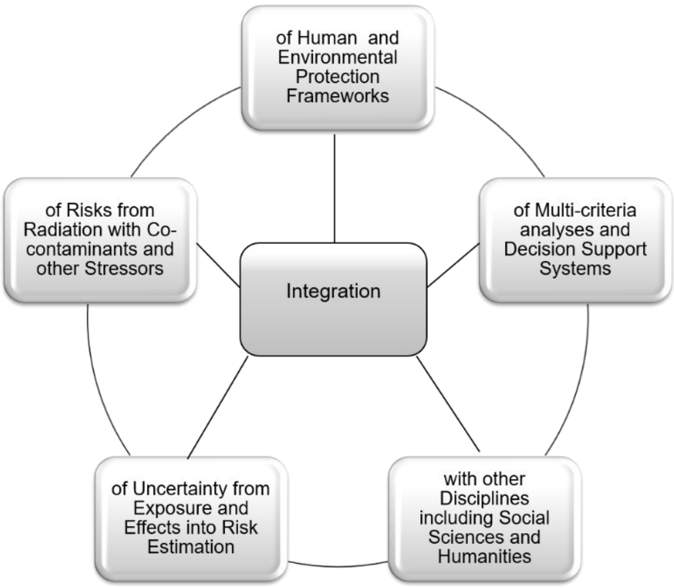

Figure 3. Five areas in challenge 3: To Improve Human and Environmental Protection by Integrating Radioecology.

During the last decades, the need was recognised for explicit demonstration of the protection of the environment from the effects of radioactive contaminants, which also resulted in changes to international policy (ICRP, 2007; EU Directive 2013/59; ICRP, 2014). 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; Brechignac et al., 2016). In some important areas, however, the methodologies for human and environmental assessments still differ. This problem is exacerbated because human and environmental assessments are not complementary in terms of how they are conducted. The differences can 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 that may act as confounding variables, 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 whether 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 into account the disparities and specificities inherent in the exposure scenarios, as they play a significant role in the assessment of consequences – in terms of economic considerations and from a societal perspective. A continuum of effects includes societal concerns, varying degrees of economic impact or loss of societal benefit, administrative disruption, health impacts or loss of life and impact on ecosystem services. In addition to these impacts, the measures taken to address them may, in turn, incur societal and environmental side effects. This complex interplay has been well demonstrated in the aftermaths of both the Chernobyl and Fukushima accidents and has been taken into consideration when developing the Joint Roadmap of radiation research platforms in 2017.

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 based on multi-criteria decision analyses (MCDA) 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, graded 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 will be a primary driver for radioecological research in the coming decades. The recent events at Fukushima in Japan exemplify these problems and the existing challenges. 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 the 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 five research and integration 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 (including 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, and ecosystem). This means that any risk assessment at such integrated scales should simultaneously take into account: (i) variability of doses, depending on spatial variability of radionuclide transfers, as well as behavioural heterogeneity among exposed species, (ii) and variability in radiosensitivity among species, including gender- and life stage-dependencies. Improvements in risk assessments, and the increased confidence in their results, require challenge 3 to integrate all these sources of variability into a single calculation.

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

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

Some recent advances have been made in relation to characterising uncertainty and variability in transfer modelling and exposure assessment within EJP-CONCERT funded projects. From the CONCERT-TERRITORIES project, Urso et al. (2019) provide guidance for carrying out uncertainty analysis with experts' knowledge specifically in the field of radioecology. Structured information about parameter uncertainty, conceptual model uncertainty, scenario uncertainty as well as role of variability are presented together with analytical, probabilistic and Bayesian approaches and methodologies to quantify and (where possible) to reduce these uncertainties. From the CONCERT-CONFIDENCE project, Brown et al. (2018) explore how information on parameter uncertainty can be used in the agricultural food-chain models commonly implemented within European post radiological emergency decision support systems, the aforementioned ARGOS and RODOS systems. These new developments provide initial steps towards fulfilling the objectives of this research line. Integrating the mentioned uncertainties and variability into the overall risk assessment would contribute to better reliability of dose assessments in general (this being one of the ICRP's (2017) identified areas for which research is needed in order to support the system of radiological protection). Nonetheless, the requirement remains to reduce uncertainties so that risks to biota and humans can be better quantified, whatever the situation (low, as well as high risk situations; planned, existing and emergency situations). Most of the research lines described in Challenges 1 and 2, as well as research lines described in related SRAs from other platforms), identify research that could contribute to improved risk quantification. The strong links which are already being built between the ALLIANCE and existing radiation protection research platforms will help facilitate integration and reduce uncertainties

2.3.2.2. Integrate human and environmental protection frameworks

As with chemical pollutants, risk assessments for ionizing radiation has historically been exclusively focussed on human risk but have expanded to gradually include ecological risk. This shift is reflected in recent high-level policy changes. It is recognised that the present framework of radiological protection should be changed to explicitly demonstrate rather than assume the protection of the environment, as stated in the general recommendations of the International Commission on Radiological Protection (ICRP, 2007), international Atomic Energy Agency (IAEA, 2014) and in the EURATOM (EC, 2013) Basic Safety Standards.

Over the last decade, new drivers for integration of human and environmental protection frameworks have emerged, such as the increasing interest from society in environmental issues, requests to demonstrate the overall protection of the environment and aspirations to build public confidence through information and transparency. Human and ecosystem health are now recognized as strongly interconnected as evidenced, for example, by a number of principles and goals for sustainable development recently agreed in the 2030 development agenda of the United Nations (UN, 2015). Furthermore, according to the ICRP's recommendations about the integration issue in the ALLIANCE's SRA of Radioecology, more focus should be put on the development of an integrated view of all benefits and impacts that includes consideration of protection of people and ecosystems (Brechignac et al., 2016; Garnier-Laplace et al., 2017). Similarly, an integration concept that acknowledges the existing interactions between nonhuman species and man (i.e. the ecosystem concept), rather than methodologically driven concepts, has been recommended by the IUR (Brechignac et al., 2016; Garnier-Laplace et al., 2017).

Moreover, integrating environmental protection and human protection under one generalised system for radioprotection, would enhance efficiency and would be of great interest to regulators, industry and the public (Salomaa and Impens, 2016).),
Earlier, Pentreath (2009) in the context of ICRP's emerging approach noted that: "...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". Some initial steps with regards to exploring the issue of integration were taken in the radiological sciences through the application of case studies (Copplestone et al., 2010). A step forward has been made by the development of a combined screening model for both human and non-human biota in the form of the CROMERICA tool) (Mora et al., 2015).) Although, this integrated assessment

platform provides alignment with respect to the advection and dispersion models used in modelling the behaviour and fate of radionuclides, the tool falls short of providing a satisfactory amalgamation of all methodologies employed. More recently Copplestone et al. (2018) has explored how an integrated approach might be applied in planned, existing and emergency situations. This was achieved by, for example, showing how simplified numeric criteria may be used in planned exposure situations that are protective of both the public and non-human biota. Nonetheless, these deliberations still fall some way short of being considered a full framework for integration of human and ecological risk assessments for radionuclides. Further consideration of the acceptable or optimal level of integration for assessment approaches is still needed, and this might ideally involve the elicitation of stakeholder's views.

Further insights can be gained by recent developments that have occurred for the risk assessment of chemicals. The 'HEROIC' Consortium has promoted the concept of an integrated risk assessment in European regulatory frameworks for chemicals (Wilks et al., 2015). In this regard, Ciffroy et al. (2016) outlined several potential opportunities for the cross-fertilization of Environmental Exposure assessment (EEA) and Human Exposure assessment (HEA) data, as an input to develop an integrated system. Among other things, this might include the building of common exposure scenarios based on a tiered approach using cautious assumptions and simple deterministic models and developing tools to support the harmonization and sharing of EEA and HEA data and sampling designs.

The ALLIANCE is convinced that the scientific and pragmatic (application via appropriate tools) foundation for a holistic integration of human and environmental assessment should be addressed (Vandenhove et al., 2017). Further development, in the radiological sciences, of integrated methodologies for transfer, exposure and risk assessment, and the production of tools incorporating those methodologies for existing, emergency and planned exposure situations, remain a major step forward in ensuring efficient, adequate, demonstrable protection for both humans and the environment. Areas where active research towards integration is required include transfer/exposure and dosimetry. Currently, transfer/exposure studies for humans and biota are conducted separately using two dissimilar methodologies. For humans, biokinetic models employing a well-defined 'Reference person' to simulate intake/retention of a given radionuclide are combined with dosimetric models (e.g., Monte Carlo radiation transport codes) employing the elemental composition of the reference person, radiation weighting factors accounting for the quality of radiation (in causing biological damage) and the differential sensitivity of organs to convert an intake of activity into an effective committed dose (in Sv). For assessments of exposed plants and animals, using the ERICA Tool as an example, a simplified system involving concentration ratios (CRs) characterise the transfer, which is considered to be aggregated over all transfer pathways with no differentiation between organs or tissue types. Internal dose rates, assumed to be instantaneous, are then derived from an activity concentration in the whole body of the organism. It is evident that progress is still needed to gain fundamental knowledge (on underlying processes), validate tools and methods for performing realistic, integrated and graded impact and risk assessments for both humans and wildlife, across all ecosystems and exposure scenarios (Salomaa and Impens, 2017).

This challenge, incorporating the knowledge generated in other strands of activity within the SRA, will focus on the scientific and practical integration of human and environmental transfer and exposure methodologies. By determining where harmonisation of approaches for humans and environment is justifiable and beneficial, the challenge will focus on developing integrated methods for assessment in the areas of transfer, exposure, dosimetry and risk. Future research initiatives in this area need to continue good links with MELODI and the work being carried out by the ICRP.

2.3.2.3. *Integrate the risk assessment frameworks for ionising radiation and chemicals*

Both human populations and wildlife in polluted environments of radiological concern may be exposed to a complex mixture of radioactive and chemical substances and various confounding factors; such combined exposure may sometimes cause adverse effects. The need to account for multiple stressors in experimental set-ups, effect analysis and risk assessment has been recognized and addressed in the SRA through several research lines, among others, by integration of the risk assessment frameworks for ionizing radiation and chemicals.

Recently, new drivers that additionally implied the need for further development of integrated risk assessment frameworks emerged, such as the increased awareness by the public of the simultaneous presence of chemicals and ionizing radiation in the environment, their importance for ecological quality of environmental resources and for biodiversity. Integration of environmental exposure assessment for ionizing radiation and other stressors and optimization of radiological protection have recently been identified as a common challenge and knowledge gap in the Joint Roadmap of the international radiation research platforms (MELODI, NERIS, EURAMED, ALLIANCE) (Impens, 2017; Vanhavere, 2018).

Keeping and reinforcing the consistency between frameworks for chemicals and radiation, facilitates the mutual understanding between assessors and the exchange or mutualisation of methods and tools. In turn, this will help to facilitate stakeholders` understanding of risk from various sources, including radiation. Moreover, there is still a need to better characterise the relevant mixture exposure situations and a need for a validated integrated risk assessment approach simultaneously applicable to radionuclides and other contaminants.

The issue of multiple stressors in the risk assessment framework has recently been considered by studying the factors affecting the impact assessment of mixed waste disposal in the context of achieving an optimized waste management (BIOPROTA forum (2013, 2015;););); Thorne and Kautsky (2016;);); Thorne and Wilson (2015)). Although constraints such as missing data on stressors and endangered biota as well as the general complexity and diversity of existing mixed exposure scenarios, have been identified, steps for future alignment of the approaches by focussing on a relatively limited set of hazardous components (such as U, Pb, Cd, Cr and asbestos) have been proposed.

Furthermore, development of integrated multiple stressors risk assessment using species sensitivity distribution (SSD) in combination with mixture models (CA, RA, IA) allowed the derivation of an integrated proxy of ecological impact of radionuclide and stable stressors (msPAF, multisubstances potentially affected fraction of species) (Beaumelle et al., 2017; Beaugelin-Seiller et al., 2019).

One of the recommendations from the CONCERT-TERRITORIES project, aimed to regulatory authorities, focuses on establishing and implementing an integrative approach in decision making under exposure situations involving multiple stressors and including NORM.

In perspective, to meet the challenge of integration of risk assessment frameworks, the development process will require missing data collation, incorporation of overall uncertainty, sensitivity analysis, meta-analysis and integration of long time scales within the proposed tiered approach. There is a requirement to move away from a narrow focus on individual stressors either chemicals or radiation and from the exclusive consideration of single emission sources and exposure routes towards a broader, more holistic approach.

2.3.2.4. Provide a multi-criteria perspective including decision support systems for an 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 (including waste disposal options, remediation and decommissioning 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 will involve many stakeholders. There are significant needs in other sectors - economic, infrastructural, social services, production – that should be considered when selecting management options. Thus, there is a need to transparent communication to optimise management approaches for radioactive contamination that go beyond the simple consideration of radiation dose vs. economic cost. Optimisation requires expertise in areas such as radioecology, urban planning, social and economic sciences, information technology, waste handling, environmental and agricultural sciences, and risk perception and communication. From a practical viewpoint, the optimisation process could be based on the integration of decision support systems (DSSs) associated with radiological sciences with knowledge data-bases and other decision-aid tools from different disciplines (e.g., urban planning, economics, sociology) so that contaminated environments are managed in a holistic way to the maximum benefit for society. Concerning DSSs, the following aspects of how integration will be of benefit for decision making are apparent: (i) integration of available radioecological DSSs, (ii) development of 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 potential benefits of integrated DSSs have been evidenced by such systems as the RESRAD family of codes; and working towards tighter integration of European DSSs will serve to ensure compatibility, comparability and transparency on the European level, as well as serving to maintain Europe's position as world leader in the area of radioecology.

As discussed above, integration of human and environmental protection systems and methodologies is a challenge for radioecology (and MELODI) 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 and ensures an important feedback mechanism between radioecology research and stakeholders. 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 joint European research projects 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).

Multi-Criteria Decision Analysis is often employed for the analysis of complex problems involving non-commensurable, conflicting criteria that 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).

Proper site characterization, human and environmental exposure and impact assessments, safety assessments and evaluation of remediation and waste disposal options (in terms of technical performance, associated exposure reduction and social impact), constitute the basis for decision making and need to be underpinned by robust scientific and technological developments. At the same time, societal uncertainties and ethical implications must be seen as a constitutional part, of high importance, in every regulatory decision-making process.

The integrative and participatory process between the research community and relevant stakeholders has been recently established in EJP CONCERT to provide a range of benefits and optimized decision making based on (i) better definition of radiation protection objectives, (ii) improvement of existing knowledge and (iii) support in challenges of regulatory authorities and TSO to (IV) choice of relevant measures, proper risk and uncertainty communication.

2.3.2.5. Towards better interaction and integration of radioecology with other disciplines, including social sciences and humanities (SSH)

The system of radiological protection is underpinned by advanced research in numerous scientific disciplines including radioecology. At the European scale, efforts have been made in the last decade to establish and bring together European platforms for radiation protection research, namely MELODI, EURADOS, NERIS, ALLIANCE, EURAMED, as well as social sciences and humanities (SSH) researchers. A European Joint Programme for Radiation Protection Research CONCERT was organized (2015-2020) with the main objective being implementation of a joint activities in radiation protection research (ranging from organising open research calls to coordination and networking activities, including training, research infrastructure development and stakeholder involvement) (Impens et al., 2017).

Main results of joint activities targeted current system and practice of radiation protection by giving the contribution to questions of general importance. Furthermore, improved answers to societal needs and challenges have been provided, as well as sharing and better use of state-of-the art- research infrastructure.

Growing public awareness of the importance of the global quality of environmental resources and biodiversity nowadays covers various philosophical perspectives such as anthropocentrism (protection of resources), biocentrism (intrinsic value of organisms) and ecocentrism (intrinsic value on all living organisms and their natural environment). In these terms, integration of radioecology with other disciplines, especially SSH, would help in mutual understanding, generation of trust and improvement of credibility by better linking scientific findings with different stakeholders and general public needs.

Benefits from better integration of the fields of radioecology and SSH are numerous (Perko et al. 2019, CONCERT-TERRITORIES Deliverable 9.72) and can be of more general (1-3), but also of more specific nature (4-8). Some more prominent examples would be as following:

- bridging the gaps and/or improvement of the links and development of the tools for mediation between radioecology research and stakeholders, at more levels - from local, national to international;
- collaboration for research prioritization; getting the scrutiny into radioecology research and assessment methodologies;
- collaboration to develop the holistic approach for the governance of radiation risks;
- collaboration to develop integrated assessment framework for multiple hazards and integrated protection frameworks for man and biota;
- clarification of the stakeholders' viewpoints on various issues (e.g. integration of risk assessment approaches for chemicals and radioactive substances, different factors in multi-criteria decision making);
- improved social understanding of the uncertainties related to exposure characterization and risk assessments in different exposure situations;
- better risk communication on different levels (e.g., from better communication of modelled risk to better communication of knowledge-based intervention levels, remediation actions, etc. in relation to predicted but also perceived risk);
- identification of social constraints related to decision making based on impact and risk assessments (such as remediation and decommissioning).

3. Strategic Agenda for Education and Training

Scientific research in radioecology and application of that knowledge in the radiation protection of man and the environment requires scientists and workers with adequate competence, appropriate skills. Research-based education and training depends on access to relevant infrastructures and facilities. The EC EURAC project (2005) and the Radioecology Master Programme at the Norwegian University of Life Sciences (2007) have been important steps in promoting environmental radioactivity as an academic discipline under the Bologna Model. This work continued in the Network of Excellence STAR, with increased participation of STAR network scientists as teachers, international students and professionals taking course modules, an increase in the number of radioecology graduates as well as interaction and joint courses with DoReMi (low-dose research) and CINCH (radiochemistry). STAR also solicited stakeholder engagement (industry, regulators, academics, educators, etc) in the development of a strategic agenda through supply and demand workshops linked to education and training (STAR Deliverable 6.1 Oughton et al., 2012).

To secure the sustainability of education and training in radioecology internationally, potential funding mechanisms need to be discussed with the ALLIANCE, the Internal Union of Radioecology (IUR) and other relevant organizations, to maintain the Education and Training Platform developed in STAR and further developed under COMET/ OPERRA as well as under CONCERT-TERRITORIES.

3.1. Challenge: To maintain and develop a skilled workforce in Europe and world-wide, through university candidates and professionals trained within radioecology.

3.1.1. Strategic vision for Education and Training

The strategic vision is to secure and further develop a sustainable, integrated European training and education platform in radioecology that attracts top-level graduates and provides a workforce that has the necessary skills to meet future scientific, economic and societal needs within radioecology and other nuclear and environmental sciences.

3.1.2. Strategic agenda

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

- Increasing student and teacher/researcher mobility requires sustainable funding mechanisms within radioecology. Actions such as travel grants for students and guest lecturer fees have a relatively low cost, but need to be maintained. The ALLIANCE will foster attendance of students at international radioecology conferences by offering small supportive grants.
- Inclusion of bespoke E&T work packages in EU (and other large) funded projects with wide reaching outreach activities to deliver training across all levels from the public to researchers.

- Attachment of PhD, post doc or young researcher positions to EU (and other large) funded projects is encouraged.
- Exploring joint EU MSc opportunities through the Erasmus Mundus programme and other activities under Horizon 2020 and Horizon Europe. This would include mechanisms to increase the number of ECTS courses in radioecology that are given by European Universities as well as to stimulate integration within the ALLIANCE.
- Fostering links with other E&T programmes in nuclear and environmental sciences (e.g., radiation protection, emergency management, radiochemistry, ecology, environmental chemistry) to maximize use of infrastructure and human resources by ensuring courses are compatible between different disciplines. Links with environmental sciences (e.g. via lectures on courses) should be made at all educational levels, from schools to post graduate.
- Providing joint courses for students and professionals with both ECTS (academic credits) and ECVET (vocational credits) or equivalents. This will ensure student merits, efficient use of resources and offer important networking opportunities for students, both across countries and disciplines, as well as with potential employees.
- Increasing stakeholder and employer involvement in education and training through student placements, sponsored courses or university positions, and development of specialized intensive courses to meet stakeholder needs. For professional training courses, particular focus will be placed on access to state-of-the-art methods and models.
- Development of distance learning courses (including webinars) where applicable (e.g. modelling, impact and risk assessment), to increase the recruitment of students.
- Development of novel educational materials and approaches, and promoting participation in science festivals to bring radioecology to the wider public.
- Offering refresher courses and seminars at relevant regional and international conferences.
- Organising summer schools and field training courses.

4. Strategic Agenda for Infrastructures

Adequate infrastructures and capabilities are a necessary resource for state-of-the-art and excellence radioecological research, as well as for education and training activities in radioecology. Infrastructures and capabilities encompass the facilities, equipment, methods, databases and models, and also the expertise required to perform radioecological research.

In the recent past, several EURATOM funded projects have performed activities to drive the improvement of the knowledge and use of radioecology infrastructures in Europe. Thus, in the Network of Excellence on Radioecology STAR an inventory of infrastructure, including databases and sample archives, available in the member organizations was created (STAR Deliverable 2.2). Also during the STAR project, with the subsequent support of COMET and the ALLIANCE, a virtual laboratory was developed to contribute to the harmonization of practices and protocols between the different radioecological facilities.

The establishment of Radioecological Observatory sites[12] was proposed as a tool for innovative research, research integration and sustainability (Initiated in STAR and fostered in COMET and CONCERT-TERRITORIES[13] European projects, with the support of the ALLIANCE).

Within the EJP-CONCERT the work package 6 is devoted to increase visibility of radiation protection infrastructures. To do so, a database (AIR^{2}D^2) and a bulletin (AIR^2), on infrastructures have been created[14].

The approaches used to study and evaluate the behaviour and impacts of radiation and radionuclides on the living world are changing. Consequently the required infrastructures and capabilities are also changing. A robust long-term vision is essential to successfully and sustainably develop, construct and operate radioecological (and radiation protection) infrastructures and capabilities. Thus, a network of collaborations between organizations would allow advanced platforms to be utilized within the consortium, within Europe or internationally.

[12] Radioecological Observatory sites are contaminated field sites that provide a focus for long-term joint field investigations. The development of a pooled, consolidated effort maximises the sharing of data and resources. The Observatories also provide excellent training and educational sites.

[13] https://territories.eu/

[14] https://www.concert-h2020.eu/en/Concert_info/Access_Infrastructures

4.1. Challenge: To maintain and acquire the infrastructures and capabilities needed to accomplish the three scientific challenges, as well as to support the education and training challenge, of the SRA.

4.1.1. Strategic vision for Infrastructures

The strategic vision for the next 20 years is that radioecology will develop a sustainable, integrated network of infrastructures and capabilities, to best meet the needs of the radioecology community, both in research and in education and training activities.

4.1.2. Strategic agenda

The following four action lines will need to be addressed to achieve the vision.

- Identify the requirements for infrastructures and capabilities and create the partnerships of excellence that bring together these required infrastructure and tools.
- Maintain and keep up to date a web-based catalogue on physical infrastructures, e-infrastructures and capabilities to ensure an efficient and effective sustainable integration of resources and capacities at a European level and to show stakeholders the radioecology capabilities available.
- Further development of the Radioecological Observatory Sites (ROS). The ROS are considered as field laboratories where experiments are conducted that support greater understanding of radioecological processes, enables model development, validations and improvement and forecasting of future radioecological conditions. The data collected at the ROS and the models developed will be made available and may be combined with other datasets or data collected in other studies to support the three challenges of the SRA. ROS are a unique tool for integration among different disciplines through common studies, shared data, and E&T activities. Actually the ALLIANCE exploits ROS in the Chernobyl Exclusion Zone, the Fukushima Exclusion Zone and NORM-impacted sites in Belgium, Poland and France.
- Promote the visibility and joint use of existing infrastructures. Encourage wider collaboration, not only in the field of radioecology, but also in the broader area of radiation protection and with other related disciplines, leading to a better use and development of infrastructures.

5. Value of a Strategic Research Agenda

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

The three scientific challenges presented above, with their 14 associated research lines, are incompletely 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.

Additionally, this updated version of the SRA contains important sections on education and training of radioecology and infrastructure for our research. Sustaining knowledge and educating new scientists is critical to the viability of radioecology and was a concern expressed by several stakeholders.

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, as well as an improved ability to predict its effects on humans and the environment. It is expected that further integration within the global radiation protection community and consideration of stakeholders will push towards maximal efficiency, completeness and societal relevancy.

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