An updated strategic research agenda for the integration of radioecology in the European radiation protection research

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Abstract

The ALLIANCE Strategic Research Agenda (SRA) for 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. The initial SRA, published in 2012, included consultation with a wide range of stakeholders (Hinton et al., 2013). This revised version is an update of the research strategy for identified research challenges, and includes a strategy to maintain and develop the associated required capacities for workforce (education and training) and research infrastructures and capabilities. Beyond radioecology, this SRA update constitutes a contribution to the implementation of a Joint Roadmap for radiation protection research in Europe (CONCERT, 2019a). This roadmap, established under the H2020 European Joint Programme CONCERT, provides a common and shared vision for radiation protection research, priority areas and strategic objectives for collaboration within a European radiation protection research programme to 2030 and beyond. Considering the advances made since the first SRA, this updated version presents research challenges and priorities including identified scientific issues that, when successfully resolved, have the potential to impact substantially and strengthen the system and/or practice of the overall radiation protection (game changers) in radioecology with regard to their integration into the global vision of European research in radiation protection. An additional aim of this paper is to encourage contribution from research communities, end users, decision makers and other stakeholders in the evaluation, further advancement and accomplishment of the identified priorities.

KEYWORDS

- **Strategic Research Agenda for radioecology**
- **Environmental exposure to radionuclides**
- **Radiation protection of the environment**
- **Integration of radiation protection research**
- **Education and Training**
- **Infrastructures**

Research in radioecology: societal and technological drivers

Radioecology is a branch of environmental science devoted to studying the fate of radioactive substances in the environment, the environmental exposure of humans and wildlife populations, and their consequences on ecosystems. Its field of research is broad and multidisciplinary in nature, and embraces basic science to form the foundation for environmental risk assessment and management. This includes the risks to human health, ecosystem health and protection of biodiversity, and the development of prevention and mitigation strategies to reduce exposure. 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 the use and testing of nuclear weapons. In subsequent decades radioecology further developed along with the increased use of nuclear power for civil purposes. Following the Chernobyl accident in 1986 European research in radioecology expanded, but was faced with a substantial decrease in funding at the start of the 21st century. The accident at the Fukushima Daïchi nuclear power plant, in 2011, highlighted the limitations in experimental data and in the robustness of models to predict the transfer of radionuclides in the environment and hence the human food chain (Raskob et al. 2018; Beresford et al. 2020a) as well as the scarcity of qualified personnel.

Technological developments in the nuclear and non-nuclear fields may impact on the exposure of ecosystems, wildlife and humans in particular. These include for example developments in decommissioning activities and long-term nuclear waste disposal, expansion of nuclear power in many countries (as part of the low-carbon transformation of economies worldwide). They also include hazards associated with naturally occurring radioactive materials (NORM) e.g. from mining and process industries, and the increasing use of medical radioisotopes. Simultaneously, there is a growing awareness among the public on the importance of global quality of the environment and its biodiversity. Furthermore, human and ecosystem health are increasingly recognised as strongly interconnected and need to be in balance with economic and social activities (United Nations, 2015). Research in radioecology is needed not only as a goal in itself, but also to maintain credibility in human health and ecological risk assessment and ensure public trust. The main drivers that demand for continued and innovative research in radioecology can be summarised in following three points.

1. *To provide independent scientific evidence and practical assessments to address public concerns about radiological hazards and the interconnection between human health and the environment.*

The need for scientific evidence stems from the fact that present models used in risk assessment are still subject to major uncertainties and sometimes even lack predictive power to demonstrate the (long-term) impact from major radiological events (Garnier-Laplace et al., 2018). The divergent scientific opinions on the effects on human health and wildlife in the Chernobyl exclusion zone are a typical example on this issue and do little good to public confidence (Beresford et al., 2020b). Further to this, recent scientific advancements in areas such as epigenetic changes, bystander effects, and genomic instability and population consequences from multigenerational exposures are also relevant in radioecology (Mothersill et al., 2018; Horemans et al., 2019). Radioecology must capitalise on the rapid advances in these scientific areas to help develop mechanistic explanations and early warning biomarkers. Finally, addressing public concerns requires more realistic, site-specific dose assessment tailored to the exposure conditions of the public or wildlife that is at risk. This implies further advancement of existing assessment models but also the need to improve risk communication among stakeholders on uncertainties.

2. To support evolution of policy making, international guidance and harmonisation.

A growing demand from the public for the protection and well-being of wildlife, ecosystems and the environment as a whole is resulting in regulations directed to the protection of the environment and everything within. This also includes the legislative framework for radiation protection, which is moving towards the need to demonstrate the protection of the environment explicitly as opposed to an assumption of protection (ICRP, 2007). For example, this is seen in the latest version of the international Basic Safety Standards (BSS) (IAEA, 2011). ICRP's rearrangement of its Committees in 2017 to address protection of people and the environment in an integrated manner is a further indication on the importance in environmental protection at the highest scientific level. Such developments must be complemented with methods and practices to demonstrate compliance with regulation and international guidelines. Radioecology research is needed to contribute to such a framework of methods and practices, to enable a mature regulatory framework where compliance can be demonstrated in an unambiguous manner.

3. To support new technological developments in the nuclear field, NORM and nuclear medicine.

For many of the developments involving radionuclide releases in the environment (e.g. decommissioning and nuclear waste, NORM disposal, legacy sites management, and medical uses of radioisotopes), shortcomings are prominently linked with the radionuclides concerned, some specific exposure conditions, transport and uptake routes. To address these shortcomings dedicated radioecology research is necessary.

Within this context, prioritisation of research efforts towards answers, methods and solutions that will be of greatest utility to society is required. Addressing and prioritising radioecological research challenges must be reinforced through a strong multidisciplinary coordination with scientific disciplines that address environmental hazards (ecotoxicology, ecology, climate sciences in the context of global change and environmental sciences in general), wider radiation protection issues (radiochemistry, radiobiology, radiotoxicology, dosimetry, nuclear and radiological emergency preparedness and response), and also with social and human sciences (sociology, philosophy, economics, ethics and communication).

Changing the game: research in radioecology to impact and strengthen radiation protection

The H2020 European Joint Programme CONCERT recently provided the opportunity to contribute to the integration of research across radiation protection, through the building of a joint European research roadmap (CONCERT, 2019a). Six European radiation protection research platforms contributed to this roadmap: MELODI[1] - health risks from low-dose ionising radiation exposure; ALLIANCE[2] - radioecology; NERIS[3] - nuclear and radiological emergency preparedness and response; EURADOS[4] - radiation dosimetry; EURAMED[5] - medical radiation protection; SHARE[6] - social sciences and humanities in ionising radiation research.

The Joint Roadmap defines priority areas and strategic objectives for collaboration and provides a vision for a European radiation protection research programme to 2030 and beyond (CONCERT, 2019a). It presents joint research challenges across the radiation protection platforms, which are relevant from both societal and radiation protection perspectives, in the context of existing and potential exposure scenarios.

The identified joint research challenges (CONCERT, 2019a) cover many disciplines, requiring collaboration of different research communities in addressing targeted **'Game Changers', defined as research issues that, when successfully resolved, have the potential to impact substantially and strengthen the system and/or practice of radiation protection for humans and/or the environment** through: 1) significantly improving the scientific evidence base, 2) developing principles and recommendations, 3) developing standards based on recommendations, and 4) improving practices.

Here we summarise how the updated ALLIANCE SRA for radioecology links with the joint research Challenges and 'Game Changers' for overall radiation protection in Europe, as illustrated in **Figure 1**. The SRA responds to the question: 'What topics, if critically addressed over the next 20 years, would significantly advance radioecology?'.

The SRA for radioecology presents a strategic vision of what research can achieve in the future through a directed effort and collaboration. Its development considers the state of the art in radioecology research and where appropriate allied sciences, stakeholder views, identified research needs and data gaps. The development of the SRA is driven by the need for improvement of mechanistic understanding across radioecological research, with a goal of improving research efficiency. By these means, we may more rapidly advance the science such that we can provide fit-for-purpose impact/risk assessments for human and wildlife encompassing any relevant exposure situation (i.e., planned, existing and emergency as defined by the International Commission on Radiological Protection – ICRP, 2007).

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[1] Multidisciplinary European Low Dose Initiative - https://www.melodi-online.eu
[2] European Radioecology Alliance - https://www.er-alliance.eu
[3] European Platform on Preparedness for Nuclear & Radiological Emergency Response & Recovery - https://www.eu-neris.net
[4] European Radiation Dosimetry Group - https://eurados.sckcen.be/
[5] European Alliance for Medical Radiation Protection Research - https://www.euramed.eu/
[6] Social Sciences and Humanities in Radiation Research - https://www.ssh-share.eu/

The SRA has three research Challenges which prioritise the major objectives that radioecology should complete and provides the key research lines deemed necessary to accomplish these. The Challenges refer to the three interlinked steps of radiological environmental impact and risk assessments:

i. the determination of the exposure of humans and wildlife to radioactive substances (Challenge One);
ii. the determination of ecological effects under realistic exposure conditions (Challenge Two);
iii. the characterisation of the risk with its associated uncertainties, including the evaluation of risk management options for both humans and wildlife (Challenge Three).

Implementation of the SRA, and the future of radioecology, relies upon adequate research infrastructures and capabilities (qualified personnel and financial support for the maintenance and development of observatory sites, facilities, equipment, methods, databases and models), and our ability to attract, recruit and retain new talents to the discipline. The two final challenges within the SRA, complementary to the research ones, present a strategic vision for Education & Training (E&T) and Infrastructures & Capabilities in radioecology. Implementation of the E&T aspects of our SRA will also ensure the qualification of a continued group of professionals who have the skills to meet the future needs of society, regulators, industry and other stakeholders.

Scientific 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 fundamentals of radioecology is to understand and be able to predict the transfer of radionuclides within environmental compartments, in order to estimate the exposure of humans and wildlife. This is needed for a wide range of sources, radionuclides and release scenarios, exposure situations and assessment contexts in atmospheric, terrestrial (agricultural, semi-natural, natural, urban) and aquatic (marine, freshwater, brackish water) environments.

The key processes that govern radionuclide behaviour and transfers through environmental compartments, and hence resulting exposures are to date not always well understood and in some instances, we lack data to parameterise models. This leads to models that have an incomplete, or potentially inaccurate, representation of the system or scenario under assessment. Whilst scientific knowledge is gradually being accrued through on-going improvements in our understanding of the 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. By making 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.

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.

The major aim under this Challenge is to develop mechanistic 'process-based' models of environmental radionuclide transfer and exposure to substantially improve human and wildlife dose and impact assessment by replacing/augmenting the empirical ratio-based approach which underpins most existing radioecological models. The priority research identified contributes to Game Changers **F.1** (robust prediction of food chain contamination), **F.2** (key processes influencing radionuclide behaviour), **G.1** (application of AI and big data) and **G.2** (further development of risk assessment for novel threats and accident scenarios) (Figure 1). Here we define process-based models as representing and simulating physiological and biogeochemical processes and their interactions with the abiotic environment by using functional relationships (after Larocque, 2016). Process-based models should be more generically applicable than ratio-based models as they should be parameterised in such a way as to take into account the important factors controlling radionuclide behaviour (e.g. Almahayni et al. 2019; Smith et al. 2000).

The SRA sets out a plan of how we will achieve this overall goal for Challenge One through the research lines described below.

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

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. Amongst the model features considered will be source-term-specific release scenarios, spatial and temporal dynamics in source term–environment interfaces, migration and cycling pathways in specific ecosystems, and radionuclide uptake, accumulation, redistribution and depuration by organisms. One of our goals 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) and for different contexts (e.g. nuclear or NORM related industrial environments, waste disposal environments).

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 foodstuff 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). Phylogeny (use of 'common ancestry' to categorise transfer data) and allometry (mass dependence) have been suggested as approaches to extrapolate data across species (Beresford et al. 2016)). Initial testing has shown that these techniques are promising but need further development (e.g. Beresford et al. 2020c). Bayesian statistics allow a low number of empirical observations to be supported by inferences from more comprehensive, larger datasets (Brown et al., 2016). The data for model parameterisation will require dedicated laboratory-based work and field studies, as well as on-going reviews of published information from the wider scientific community. Long-term data series obtained along routine surveillance programs can also provide information for transfer modelling (Brimo et al., 2019).

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*

Process-based radioecological modelling reduces model conceptual uncertainty and can for instance reduce the uncertainty of model predictions, leading to a greater confidence in the results. For instance, assessments of the globally-circulating radionuclides ^{14}C and ^{3}H were greatly improved by including the influence of stable carbon, nitrogen and hydrogen cycles in radionuclide transfers (e.g., Schell et al., 1974). More recent examples are soil-plant system process-based models for modelling Cs and Sr uptake and the behaviour of radioactive particles (Beresford et al. 2020d). Process based models could be developed and applied to a wide range of sources encompassing existing (e.g. uranium mining and milling sites, NORM sites, post-accident situations), planned (e.g., new build, (geological) waste disposal, NORM involving industries, medical radioisotope and radiopharmaceuticals production facilities) and emergency (accident, incident, malevolent acts) exposure situations. The developed process-based models will begin to form part of the next generation of assessment tools and will contribute to addressing the need for an integrated approach to human and wildlife exposure assessment (Challenge Three).

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. 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., 2020). Advances in this area would have synergies with population modelling approaches (Alonzo et al., 2008; Vives i Batlle et al., 2012) being developed to better predict ecosystem level effects (links with Challenge Two). 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 Two 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.

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, a detailed understanding is needed of radionuclide transfer processes at multiple scales, such that transfer can be mapped at the landscape level. Within this research line we intend to design and implement a user-friendly and state-of-the-art interface, facilitating mapping of radionuclide transfer and exposure at a landscape level to identify sensitive environmental compartments/areas.

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

The regulatory requirements for the radiation protection of wildlife has shifted during the last two decades from an implicit to an explicit requirement to be able to demonstrate an appropriate radiological environmental protection. The IAEA's Fundamental Safety Principles (IAEA, 2006), the 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. As a consequence of these, there is a stringent need for ecological protection criteria (dose criteria, benchmark or reference values) to optimize radiological protection of the environment in various environmental exposure situations (Real and Garnier-Laplace, 2020). However, contrary to the radiation protection of human populations, there is still no unified approach, nor consensus on the effects of radiation on the ecosystems. This prevents the emergence of consensual approaches and criteria applicable for radiation protection of the environment.

Over the last 20 years, international efforts have focused on data and methodologies to develop Ecological Risk Assessment (ERA) approaches to assess the potential impact of radiation on wildlife (e.g. the ERICA integrated approach (Larsson, 2008)). Whilst the developed ERA approaches are a substantial advancement in radioecology, a lack of sufficient knowledge prevents current ERA analyses from fully accounting for the realistic environmental conditions and radiation level that organisms are exposed to. Environmental relevant exposure scenarios for which knowledge gaps still exist include (i) different exposures from external irradiation and internal contamination, (ii) variable dose rates in time, (iii) dose deposit heterogeneity in space (from molecular targets up to individuals and ecosystems), (iv) multi-contaminant scenarios. Likewise, the knowledge of the effects of ionizing radiation on wildlife species is very partial, and does not allow a robust description of (i) species variations in radiation sensitivity as a function of their life-history traits and habitats, and (ii) radiation effects on communities and ecosystems features, as illustrated by the scientific disagreement on the actual extent of the radiation effects on ecosystems in contaminated areas (Strand et al., 2017; Beresford et al., 2020b). This controversy challenges published ecological protection criteria and guidance for radiological exposures (UNSCEAR, 2008; ICRP, 2008; Anderson et al., 2009; Garnier-Laplace et al., 2010; ICRP, 2014) as well as the whole radiation protection system.

Such knowledge gaps are still accounted for via extrapolation (e.g. inference of effects at one level from well-known effects at another level of biological organisation) and the use of assessment factors (or safety factors) which, while ensuring sufficient conservatism in low tier (screening level) risk assessments, increase the associated uncertainties (see Challenge Three).

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.

The major aim under this Challenge is to identify and link the key processes that drive the impact of radiation in individuals, populations and ecosystems level at environmental relevant exposure situations (including existing contaminated areas). The expected benefit for the ecological risk assessment approaches will be to bring consensual ecological protection criteria applicable in various environmental exposure situations,

Studies will have to include an appropriate combination of laboratory studies and field studies, statistical data treatment and/or mathematical modelling. Common to all five research lines outlined below and in connection with challenge one, there is a crucial need for an improved dosimetric assessment to reduce uncertainty and enhance robustness of dose estimates. Additionally, radioecology will need to benefit from and collaborate across different disciplines such as ecology and ecotoxicology, stress ecology (Van Straalen, 2003) and the other European radiation protection research disciplines such as radiobiology (Mothersill et al., 2020). The priority research identified is directly linked to the Joint Roadmap issues on the health effects of radiation and the concept of dose (Figure 1) as identified here further.

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

As identified above considerable knowledge gaps on the effects induced by radiation still exist. This research line aims at identifying key molecular/cellular and individual characteristics driving radiation induced effects at the individual level, thereby taking advantage of advanced analytical methods from molecular biology for enhancing our mechanistic understanding of radiation induced responses at the sub-cellular levels and their consequences to individuals. This research line is shared between human and other organisms (Mothersill et al., 2018). Adverse Outcome Pathway (AOP) (Groh et al., 2015) and coupled Biokinetics/Dynamic Energy Budget (DEB) approaches can aid in understanding the metabolic mode of actions at the individual level (Kooijman, 2000). In the long term, the development of an integrative Systems Biology approach, through the organization of mechanistic toxicological data would help in better linkages of initial perturbation of a biological system by ionising radiation to the negative impacts at the individual or population level (Chauhan et al., 2021).

This research line shares many issues with the understanding and quantification of the human health effects of radiation exposure. It will also gain from the improvement of the concept of dose quantities, through refining our understanding of the physical interaction between radiation and matter (Game Changer **B.1**) and quantifying correlations between track structure and radiation damage (Game Changer **B.2**) for the dose calculation of inhomogeneous distribution of irradiation agents such as short-range α- and β- emitters in the case of internal contamination. Progress in fundamental understanding of the concepts of dose quantities' (i.e. Game Changers **B.1 and B.2)** would potentially help radioecology in the identification and validation of biomarkers of exposure and effects that are relevant for effects at the population level.

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 radiation type and duration, cell type; life stage, species and level of biological organisation (UNSCEAR, 2008). This research line aims at highlighting the key drivers for intra- and inter-species radiosensitivity differences and will strongly benefit from and combined with the first one of this Challenge. This research line echoes the more general concern in radiation protection on the characterisation and quantification of variation in response between population sub-groups/individuals because of genetic factors, sex, co-morbidities, life history and environmental factors (Game Changer **A.3**). Knowledge on the range of variation in susceptibility to radiation effects in populations would be informative for the development of the system of radiation protection.

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

A shared vision with the Joint Roadmap is that a better understanding of the mechanisms involved in the long-term effects of ionising radiation may be integrated with mechanisms resulting from the exposure to environmental stressors, including the combined exposures with stable toxic substances (Game Changer **A.3**). 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. In the longer term, an integrative protective system should cover realistic multi-exposure scenarios. Research on the impact of multi-exposure scenarios will gain considerable from the outcome of the first two research lines within this Challenge two as it is expected that this will make it possible to better mechanistically understand the combined effects of ionising radiation and other stressors.

More widely, new approaches adopted by environmental sciences in general, and ecotoxicology and ecology in particular, emphasise that to properly determine the effects from any contaminant we must address the realistic environmental conditions in which organisms are actually exposed. Realistic environmental conditions incorporate natural abiotic factors (e.g., climate change, temperature, flooding events, snow and ice, air quality) 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 in 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 One).

The last two research lines addressing this ALLIANCE Challenge are related to the understanding of radiation-related effects at ecologically-relevant levels:

4. *In a broader ecological context, understand the mechanisms of 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; Horemans et al., 2019, Møller and Mousseau, 2016; Goussen et al 2015) and are still far from conclusive in particular when it comes to environmental relevant settings.

To support the understanding and prediction of the evolutionary response of populations chronically exposed to ionising radiation there is a need to (i) increase knowledge on key processes driving radiation-induced changes in genomic stability e.g. coming from changes DNA damage, mutations or changes in epigenetic marks; (ii) distinguish between effects of chronic exposure of populations such as those currently living in Chernobyl/Fukushima and residual impact of historical exposures on today's populations/ecosystems; (iii) identify key factors determining the vast variation in wildlife populations' sensitivity to radiation; and (iv) identify and validate biomarkers of exposure and effects that are relevant for effects at the population level.

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

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; Haanes et a., 2020). In relation to these issues, resolving the controversy with regard to chronic exposure effects on wildlife reported in the Chernobyl and Fukushima exclusion zones is the priority Game Changer (Game Changer **C.1**). Resolving this controversy would have a significant impact on the confidence and credibility of radiation protection of the environment (e.g., robustness of 'no-effect' benchmark dose-rates).

If this research demonstrates that the ecosystem functioning processes are more sensitive to radiation than anticipated from current understanding of effects at the population level, then the robustness of current risk assessments that in effect rely only on interpretation of population-effect relevant data is highly questionable. On the other hand, if it is shown that the functional or structural redundancy of the ecosystems brings greater robustness against the effects of radiation, the conservatism of the current assessments would be confirmed. This is why the determination of the effects of radiation on ecosystem functioning (Game Changer **C.2**) is the long term priority for this research challenge. This involves using the combination of tailored experimental studies and population modelling to explore the potential population level consequences of ionising radiation in the context of ecological factors such as resource availability, migration, spatial heterogeneity and the impact of historical doses. One operational outcome, directly relevant to radioprotection of flora and fauna, will be to establish sound scientifically-based ecological protection criteria, thereby underpinning regulations and ensuring that ecosystems and their sub-organisational levels are protected.

Scientific Challenge Three: To Improve Human and Wildlife Protection by Integrating Radioecology

The management of and the protection from risks that the presence of radionuclides in the environment may pose to human health and wildlife can range from the minimal through ascending levels of complexity and details. 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. Linked to this issue, the research outputs from the priorities described above for the exposure assessment (Challenge One) and effects analysis (Challenge Two) will need to be integrated within an efficient, balanced and adaptable assessment approach in planned, existing and emergency exposure situations. Beyond, the individual contaminant-medium-pathway paradigm is changing towards a more integrated view of the environment as a whole. Radioecology's position relative to this paradigm shift can be best advanced by embracing the concept of integration.

By constituting an integrated strategy for radioecology, we expect: (i) a comprehensive integration of the sources of uncertainty and variability into risk characterisation; (ii) consistent assessment for both humans and wildlife radiation protection; (iii) balanced risk assessment frameworks for ionising radiation in regard to the other threats; (iv) an optimised decision-making system for radiation protection, and; (v) a better alignment of research with the values, needs and expectations of society.

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

Therefore, radioecology's future success, broadly defined as meeting stakeholder needs, will require integration in several ways and from different perspectives:

1. *Integrate uncertainty and variability from source term characterisation, transfer modelling, exposure assessment, and effects analysis into risk characterisation*

Challenge One of the SRA identifies that radionuclide transfer and exposure have to be assessed at multiple spatial scales, while Challenge Two emphasises that effects have to be characterised not only at the individual level, but also at higher levels of biological organisation and the research outputs from both exposure assessment and effects analyses will need to be integrated. For wildlife, 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. Variability of doses and behavioural heterogeneity over space and time should also be taken into account in human risk characterisation. Recent results from EJP CONCERT projects (TERRITORIES and CONFIDENCE) provide improved, structured information about parameter uncertainty, conceptual model uncertainty, scenario uncertainty as well as the role of variability together with analytical, probabilistic and Bayesian methodologies to quantify and (where possible) reduce these uncertainties. In light of integration, these new developments provide initial steps towards fulfilling the objectives of this research line. Nonetheless, the requirement still remains to reduce uncertainties so that risks to humans and biota can be better quantified, whatever the situation (low, as well as high risk situations; planned, existing and emergency situations).

2. Integrate humans and wildlife protection frameworks

Over recent 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 policies (ICRP, 2007; European Commission, 2013; 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; Brown et al., 2016; Bréchignac et al., 2016). However, in some important areas the methodologies for human and wildlife risk assessments still differ, e.g. the human dosimetric system accounts for the kinetics of radionuclides transfer within the body and differential sensitivity of organs to derive dose conversion factors whereas the environmental system does not. This may undermine credibility by its suggestion of inconsistencies causing difficulties for operators, stakeholders and regulators. A more integrated assessment and management (Game Changer **F.3**) – both in terms of the underlying philosophy and the practical application via appropriate tools and systems - will enable radiation protection to make more balanced decisions as it will take in the 'whole-picture' the assessments for both humans and wildlife. It also represents a more comprehensible approach when communicating to stakeholders (Game Changer **H.1**).

3. Integrate the risk assessment frameworks for ionising radiation and chemicals

Radionuclides and the associated risks posed to human health and wildlife populations 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 (Game Changer **H.1**) and directed towards better understanding of mixture effects (Game Changer **A.3**), as well as adapted risk assessment methods (Game Changer **F.3**), will make it possible to determine whether radiation protection criteria are robust in a multiple contaminant context, and aligned with the values, needs and expectations of society.

4. Provide a multi-criteria perspective including decision support systems for an optimised decision-making

In dealing with a range of actual or potential exposure situations, a gradient of integrated management approaches based on multi-criteria decision analyses and the means of creatively implementing them are required (Game Changers **F.3** and **G.1**). 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 (Game Changer **H.1**). The 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.

5. Towards better interaction of radioecology with social sciences and humanities (SSH)

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, but commonly 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 should 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. Not spectacular examples, but noticeably more often present are observed in non-nuclear industries involved in NORM issues. Those examples and existing information have been taken into consideration when developing the Joint roadmap for a better alignment of research with the values, needs and expectations of society (Game Changer **H.1**). Such alignment should always lead to an evidence-based approach to policy making, and the scientific method should be upheld in all radioecology research; in order to be useful, science must be independent and impartial. In addition, it is essential to communicate the scientific basis to society in an understandable way to increase acceptance.

Challenge for Education and Training: To Maintain and Develop a Skilled Workforce in Europe and Worldwide

Scientific research in radioecology and implementation of that knowledge into the radiation protection of human health and wildlife populations requires scientists and workers with adequate competence and appropriate skills. Research-based education and training (E&T) depends on radioecology being included in university programmes and access to relevant infrastructures and capabilities. 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[7]. The STAR project solicited stakeholder engagement (industry, regulators, academics, educators, etc.) in the development of a strategic plan for securing the long-term sustainability of education and training in radioecology (STAR, 2015).

To internationally secure the sustainability of E&T in radioecology, potential funding mechanisms were discussed by the ALLIANCE and other relevant organisations, to maintain the 'E&T Platform' initially developed by STAR (Bradshaw et al., 2013) in part these discussions are reflected in our action lines below.

Our 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.

The following 11 action lines are important in achieving this vision:

1. 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 fosters attendance of students at international radioecology conferences and placements in other laboratories by offering small supportive grants to students supervised by its members.
2. 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 professionals and researchers.
3. Allocation of funding for PhD, post-doctoral or other early career researcher positions in EU (and other large) funded projects.
4. Exploring joint EU MSc opportunities through the Erasmus Mundus programme, as well as the inclusion of radioecology modules in BSc and MSc degrees originated from the European Universities Initiative, which are transnational alliances, funded by the Erasmus+ programme. This would enable students to obtain a degree by combining studies in several EU countries, forming transnational creating teams to address societal challenges, especially those related to Sustainable Development Goals. This would include mechanisms to increase the number of accredited courses in radioecology that are given by European universities as well as to stimulate integration within the ALLIANCE.

[7] European Higher Education Area and Bologna Process - https://ehea.info/

5. Fostering links with other E&T programmes in nuclear and environmental sciences (e.g., radiation protection, emergency management, radiochemistry, ecology, ecotoxicology, environmental chemistry). Links with environmental sciences (e.g. via lectures on courses) should ideally be made at all educational levels, from schools to post graduate.
6. Providing courses and workshops for students, professionals and academics with both academic and vocational courses. This will ensure efficient use of resources and offer important networking opportunities for students, both across countries and disciplines, as well as with potential employees.
7. Increasing stakeholder and employer involvement in E&T through student placements, sponsored courses or university positions, and the development of focussed intensive courses designed to meet stakeholder needs. For professional training courses, particular focus will be placed on access to state-of-the-art methods and models.
8. Development of distance learning courses (including blended learning, i.e. a mix of self-learning and face-to-face sessions) (e.g. modelling, impact and risk assessment) to make courses more available to a wider audience.
9. Development of novel educational materials and approaches and promoting participation in science festivals to bring radioecology to the wider public.
10. Offering refresher courses and seminars at relevant regional and international conferences.
11. Organising international summer schools, field training courses and courses at specialised facilities.

Training and a well-defined communication strategy will also be required to ensure uptake of our scientific outputs.

Challenge for Infrastructures and Capabilities: To Maintain and Develop the Infrastructures Needed to Support Radioecology

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

The Radioecological Observatory sites were created as a focus for co-ordinated, hypothesis driven research to help answer scientific questions of the three scientific challenges of the SRA (Muikku et al. 2018; see https://radioecology-exchange.org/content/radioecological-observatories). They are considered as field laboratories where experiments can be conducted that support greater understanding of radioecological processes, enable model development, validations and improvement and forecasting of future radioecological conditions. Observatories are a unique tool for integration among different disciplines through common studies, shared data, and E&T activities. The concept has been successful, leading to broaden research collaborations and develop co-supervised PhD-studentships (e.g. Beresford et al., 2020b; Kaasik et al., 2020; Lecomte-Pradines et al., 2020).

In the recent past, several EURATOM funded projects have performed activities to drive the improvement of the awareness and use of radioecology infrastructures in Europe. The Network of Excellence on Radioecology STAR created an inventory of infrastructure, including databases and sample archives (STAR Deliverable 2.2). Within EJP-CONCERT efforts were subsequently made to increase visibility of radiation protection infrastructures including those of ALLIANCE members (see the AIR^{2}D^2 database[8] and AIR^2 bulletin[9]).

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. A network of collaborating organisations will allow maximum benefit of advanced platforms within Europe or more widely.

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

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

1. Identify the requirements for infrastructures and capacities and create the partnerships of excellence that bring together these required infrastructure and tools.
2. Maintain 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.

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[8] Access to Infrastructures for Radiation protection Research - http://www.concert-infrastructures.eu/
[9] Access to AIR^2 bulletin - https://www.concert-h2020.eu/en/Concert_info/Access_Infrastructures/Bulletins

3. Further development of the Radioecological Observatory sites (the Chernobyl Exclusion Zone, the Fukushima Exclusion Zone and NORM-impacted sites in Belgium and Poland are already established).
4. 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 more efficient use and further development of infrastructures.

Conclusions

The acquisition of new scientific knowledge and model optimization and development through research in radioecology is essential for protection of human health and wildlife populations from harmful effects of ionising radiation, responding to stakeholders concerns regarding the presence of radionuclides in the environment, and ensuring safe use of radioactivity from medicine to nuclear power and operation of NORM involving industries. Good science and robust models and associated assessments are important to society because over-estimation of exposures or effects could lead to unnecessary and costly restrictions or remediation; alternatively, under-estimation of risks may result in detrimental long-term effects for humans and wildlife.

Significant research is required to address the scientific challenges for radioecology presented above. The most effective way to provide timely and efficient solutions to these broad challenges is focused, hypothesis-driven research programmes with clear common goals and resources shared among the international radioecology community. For society to benefit significantly from radioecology in the future, a long-term, multidisciplinary and coordinated approach is needed that goes beyond national boundaries. Updating the SRA for radioecology in conjunction with the building of a Joint Roadmap for the European radiation protection research and identifying scientific game changers was a unique opportunity for a prioritisation of integrated research needs.

Importantly, the updated SRA for radioecology considers education and training, and the infrastructure required for our research. Sustaining knowledge and educating new scientists is crucial to the viability and sustainability of radioecology and is a concern expressed by stakeholders such as international organisations, regulatory bodies and industry.

It is our hope that the science-based SRA for radioecology which focusses and prioritises our collective efforts, will result in increased value and more rapid advancement of our understanding of environmental radioactivity, and in an improved ability to predict its effects on human health and the environment within reasonable uncertainties. We have evidence for future success from the joint activities conducted to address our initial SRA (e.g. Hinton et al., 2013; Garnier-Laplace et al., 2018). It is expected that further integration within the global radiation protection community and consideration and responsiveness to societal needs will maximise efficiency, completeness and societal relevance.

The SRA is a living document that will be updated on a regular basis, considering advances and developments that affect the research needs.

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Figures caption

Figure 1. ALLIANCE Challenges and Research Lines (1.x to 3.x, blue lines) links with the Joint Roadmap research challenges and Game Changers for radiation protection (A.x to H.x, green columns - CONCERT, 2019a): cross-cutting areas (gray) and specific topics (**x**) developed in the description of the 3 Scientific Challenges.

Figure 1

SRA - *Strategic Research Agenda for Radioecology*	**ALLIANCE Research lines**	**JRM** - *Joint Roadmap for Radiation Protection* / **JRM Game Changers**	A health effect of radiation				B concepts of dose		C effects on ecosystems		F environmental exposure and risk			G emergency and recovery		H RP & society
			A.1 non-cancer diseases at low dose	**A.2** processes of disease pathogenesis	**A.3** variation in response between individuals	**A.4** temporal and spatial var. in dose delivery	**B.1** spatial correlations of radiation interaction	**B.2** correlations between track and damage	**C.1** controversy in Chernobyl & Fukushima	**C.2** effects on ecosystem functioning	**F.1** human food chain contamination	**F.2** processes influence RNs behaviour	**F.3** integrating risk assess/management	**G.1** artificial Intelligence and big data	**G.2** novel threats and accident scenarios	**H.1** society values, needs & expectation
1 quantifying key processes that influence RNs transfers and exposure	**1.1**	identify and represent the significant key processes									X	X			X	
	1.2	acquire data for parameterisation									X	X			X	
	1.3	develop process-based models									X	X		X	X	
	1.4	large geographic scales and uncertainties										X		X	X	
2 ecological consequences under realistic exposure conditions	**2.1**	mechanisms from molecular to individual levels	X	X		X	X	X	X	X						
	2.2	intra- and inter-species radiosensitivity			X	X			X	X						
	2.3	interactions with other co-stressors							X	X						
	2.4	multi-generational responses			X				X	X						
	2.5	Effects at population, community & ecosystem level							X	X						
3 human and environmental protection by integrating radioecology	**3.1**	integrate uncertainty and variability											X			X
	3.2	integrate human and environmental protection											X			X
	3.3	integrate risk assessment for RNs and chemicals											X			X
	3.4	multi-criteria decision-making											X	X		X
	3.5	integration with SSH											X	X		X

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: