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

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

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

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**

30 **Research in radioecology: societal and technological** 31 **drivers**

32 Radioecology is a branch of environmental science devoted to studying the fate of radioactive substances in the
33 environment, the environmental exposure of humans and wildlife populations, and their consequences on
34 ecosystems. Its field of research is broad and multidisciplinary in nature, and embraces basic science to form the
35 foundation for environmental risk assessment and management. This includes the risks to human health, ecosystem
36 health and protection of biodiversity, and the development of prevention and mitigation strategies to reduce
37 exposure. Radioecology emerged as a science in the late 1940s and 50s in response to concerns about releases
38 from nuclear weapons production facilities and radioactive fallout from the use and testing of nuclear weapons. In
39 subsequent decades radioecology further developed along with the increased use of nuclear power for civil
40 purposes. Following the Chernobyl accident in 1986 European research in radioecology expanded, but was faced
41 with a substantial decrease in funding at the start of the 21st century. The accident at the Fukushima Daichi nuclear
42 power plant, in 2011, highlighted the limitations in experimental data and in the robustness of models to predict
43 the transfer of radionuclides in the environment and hence the human food chain (Raskob et al. 2018; Beresford
44 et al. 2020a) as well as the scarcity of qualified personnel.

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

- 56
- 57 *1. To provide independent scientific evidence and practical assessments to address public concerns about*
58 *radiological hazards and the interconnection between human health and the environment.*

59 The need for scientific evidence stems from the fact that present models used in risk assessment are still subject to
60 major uncertainties and sometimes even lack predictive power to demonstrate the (long-term) impact from major
61 radiological events (Garnier-Laplace et al., 2018). The divergent scientific opinions on the effects on human health
62 and wildlife in the Chernobyl exclusion zone are a typical example on this issue and do little good to public
63 confidence (Beresford et al., 2020b). Further to this, recent scientific advancements in areas such as epigenetic
64 changes, bystander effects, and genomic instability and population consequences from multigenerational
65 exposures are also relevant in radioecology (Mothersill et al., 2018; Horemans et al., 2019). Radioecology must
66 capitalise on the rapid advances in these scientific areas to help develop mechanistic explanations and early

67 warning biomarkers. Finally, addressing public concerns requires more realistic, site-specific dose assessment
68 tailored to the exposure conditions of the public or wildlife that is at risk. This implies further advancement of
69 existing assessment models but also the need to improve risk communication among stakeholders on uncertainties.

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

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

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

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

87

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

95 **Changing the game: research in radioecology to** 96 **impact and strengthen radiation protection**

97 The H2020 European Joint Programme CONCERT recently provided the opportunity to contribute to the
98 integration of research across radiation protection, through the building of a joint European research roadmap
99 (CONCERT, 2019a). Six European radiation protection research platforms contributed to this roadmap: MELODI¹
100 - health risks from low-dose ionising radiation exposure; ALLIANCE² - radioecology; NERIS³ - nuclear and
101 radiological emergency preparedness and response; EURADOS⁴ - radiation dosimetry; EURAMED⁵ - medical
102 radiation protection; SHARE⁶ - social sciences and humanities in ionising radiation research.

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

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

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

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

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/>

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

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

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

139 **Scientific Challenge One: To Predict Human and** 140 **Wildlife Exposure in a Robust Way by Quantifying** 141 **Key Processes that Influence Radionuclide Transfers** 142 **and Exposure**

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

148 The key processes that govern radionuclide behaviour and transfers through environmental compartments, and
149 hence resulting exposures are to date not always well understood and in some instances, we lack data to
150 parameterise models. This leads to models that have an incomplete, or potentially inaccurate, representation of the
151 system or scenario under assessment. Whilst scientific knowledge is gradually being accrued through on-going
152 improvements in our understanding of the underlying processes, the challenge faced by radioecologists is to
153 incorporate this knowledge into models capable of representing the behaviour of the radionuclides in a more
154 realistic way. By making models more realistic and process-based, we expect: (i) a significant reduction in model
155 uncertainty; (ii) a better quantification of environmental variability; (iii) identification of the most influential
156 parameters; and of parameters/factors contributing the most to the overall uncertainties, (iv) improved modelling
157 tools capable of predicting radionuclide migration overtime and subsequent exposure to humans and wildlife under
158 a variety of conditions, thereby enhancing predictive power and the robustness of both human and wildlife
159 assessments of exposure to ionising radiation, and; (v) to be able to provide scientifically justified safety
160 assessments for hypothetical future situations that need to take into account biogeochemical cycling of
161 radionuclides over large time scales, changing climate conditions, and changing landscapes.

162 *Our strategic vision is that over the next 20 years radioecology will have achieved a thorough mechanistic*
163 *conceptualisation of radionuclide transfer processes within major ecosystems (terrestrial, aquatic, urban) for a*
164 *wide range of source terms, release and migration scenarios and exposure situations, where relevant and needed,*
165 *and be able to accurately predict exposure to humans and wildlife by incorporating a more profound understanding*
166 *of environmental processes and assure that fit-for-purpose process-based models based on scientific modelling of*
167 *the radioecological mechanisms will have found a way into future assessment tools.*

168

169

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

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

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

184 Criteria will be developed to identify key processes that have a significant impact on radionuclide transfers in
185 atmospheric, terrestrial, aquatic and built-up (e.g. urban) environments. Amongst the model features considered
186 will be source-term-specific release scenarios, spatial and temporal dynamics in source term–environment
187 interfaces, migration and cycling pathways in specific ecosystems, and radionuclide uptake, accumulation,
188 redistribution and depuration by organisms. One of our goals is to identify the key processes, based on fundamental
189 physical, biogeochemical and ecological principles that govern the transfer of radionuclides within major
190 ecosystems types (e.g., agricultural, grasslands, coniferous forests, freshwater lakes and rivers, marine systems,
191 urban environments) and for different contexts (e.g. nuclear or NORM related industrial environments, waste
192 disposal environments).

193 *2) Acquire the data necessary for parameterisation of the key processes controlling the transfer of radionuclides*

194 Major data collection activities (such the IAEA handbooks of radioecological transfer parameters) have identified
195 significant data gaps and limitations for many of the empirical parameters which underpin dose assessment models
196 for humans and wildlife. The wide range of radionuclides, human foodstuff and species of wildlife means that,
197 pragmatically, we may never be in the position of having empirical data for everything. There is a need to consider
198 alternative approaches to address this lack of data for model parameterisation in the most robust manner possible
199 (rather than relying on highly conservative judgment to avoid analysing the problem in more depth, as is often the
200 case currently). Phylogeny (use of ‘common ancestry’ to categorise transfer data) and allometry (mass
201 dependence) have been suggested as approaches to extrapolate data across species (Beresford et al. 2016)). Initial
202 testing has shown that these techniques are promising but need further development (e.g. Beresford et al. 2020c).
203 Bayesian statistics allow a low number of empirical observations to be supported by inferences from more
204 comprehensive, larger datasets (Brown et al., 2016). The data for model parameterisation will require dedicated
205 laboratory-based work and field studies, as well as on-going reviews of published information from the wider
206 scientific community. Long-term data series obtained along routine surveillance programs can also provide
207 information for transfer modelling (Brimo et al., 2019).

208 3) *Develop process-based transfer and exposure models that incorporate physical, chemical and biological*
209 *interactions and associated kinetics, and enable predictions to be made spatially and temporally*

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

222 There is a need to assess wildlife exposure more realistically by considering spatial as well as temporal variability
223 in for instance, habitat utilisation, contaminant densities and interactions between organisms, all of which impact
224 animal movement and hence exposure in heterogeneously contaminated environments. Recent studies in which
225 GPS units and dosimeters were attached to free ranging animals show the potential impact of not taking these
226 factors into account in assessments (Aramrun et al., 2019; Hinton et al., 2020). Advances in this area would have
227 synergies with population modelling approaches (Alonzo et al., 2008; Vives i Batlle et al., 2012) being developed
228 to better predict ecosystem level effects (links with Challenge Two). Wildlife dosimetry is also in need of some
229 advancements (e.g. Stark et al., 2017). Current wildlife dosimetry models are simplistic and generally describe
230 organisms as single ellipsoid forms that are homogeneous in composition and contamination. We should evaluate,
231 in connection with Challenge Two on effects assessment, how important it is to incorporate radionuclide-specific
232 heterogeneous distributions within the body and microdosimetry measurement to be able to account for differences
233 in sensitivity among various organs and to better assess the dose-response relationships in particular situations for
234 improved future predictions.

235 4) *Represent radionuclide transfer and exposure at a landscape or large geographic scale with an indication of*
236 *the associated uncertainty*

237 The objective of this research line is to improve the current status by mapping radionuclide transfer and exposure
238 at the European or global scale based on thematic maps, including spatial and temporal variability, using the newly
239 developed process-based models. Since geographical distributions of radionuclides tend to be highly
240 heterogeneous, a detailed understanding is needed of radionuclide transfer processes at multiple scales, such that
241 transfer can be mapped at the landscape level. Within this research line we intend to design and implement a user-
242 friendly and state-of-the-art interface, facilitating mapping of radionuclide transfer and exposure at a landscape
243 level to identify sensitive environmental compartments/areas.

244 **Scientific Challenge Two: To Determine Ecological** 245 **Consequences under Realistic Exposure Conditions**

246 The regulatory requirements for the radiation protection of wildlife has shifted during the last two decades from
247 an implicit to an explicit requirement to be able to demonstrate an appropriate radiological environmental
248 protection. The IAEA's Fundamental Safety Principles (IAEA, 2006), the revised ICRP Recommendations (ICRP,
249 2007), the revised versions of the international Basic Safety Standards (BSS) (IAEA, 2011) and to a lesser extent,
250 the Euratom BSS (European Commission, 2013) promote developing guidance on wildlife radiological risk
251 assessments. As a consequence of these, there is a stringent need for ecological protection criteria (dose criteria,
252 benchmark or reference values) to optimize radiological protection of the environment in various environmental
253 exposure situations (Real and Garnier-Laplace, 2020). However, contrary to the radiation protection of human
254 populations, there is still no unified approach, nor consensus on the effects of radiation on the ecosystems. This
255 prevents the emergence of consensual approaches and criteria applicable for radiation protection of the
256 environment.

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

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

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

279 The major aim under this Challenge is to identify and link the key processes that drive the impact of radiation in
280 individuals, populations and ecosystems level at environmental relevant exposure situations (including existing

281 contaminated areas). The expected benefit for the ecological risk assessment approaches will be to bring
282 consensual ecological protection criteria applicable in various environmental exposure situations,

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

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

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

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

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

314 Even though the fundamental mechanisms that cause radiation damage seem universal, individual responses to
315 radiation exposure vary tremendously, depending on radiation type and duration, cell type; life stage, species and
316 level of biological organisation (UNSCEAR, 2008). This research line aims at highlighting the key drivers for
317 intra- and inter-species radiosensitivity differences and will strongly benefit from and combined with the first one
318 of this Challenge. This research line echoes the more general concern in radiation protection on the characterisation

319 and quantification of variation in response between population sub-groups/individuals because of genetic factors,
320 sex, co-morbidities, life history and environmental factors (Game Changer A.3). Knowledge on the range of
321 variation in susceptibility to radiation effects in populations would be informative for the development of the
322 system of radiation protection.

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

325 A shared vision with the Joint Roadmap is that a better understanding of the mechanisms involved in the long-
326 term effects of ionising radiation may be integrated with mechanisms resulting from the exposure to environmental
327 stressors, including the combined exposures with stable toxic substances (Game Changer A.3). Studying a
328 contaminant in isolation is necessary and provides critical information on the underlying mechanism resulting in
329 detectable effects and can be used to test the specificity of biomarkers but cannot predict possible interactions
330 among the many stressors to which organisms are exposed. In the longer term, an integrative protective system
331 should cover realistic multi-exposure scenarios. Research on the impact of multi-exposure scenarios will gain
332 considerable from the outcome of the first two research lines within this Challenge two as it is expected that this
333 will make it possible to better mechanistically understand the combined effects of ionising radiation and other
334 stressors.

335 More widely, new approaches adopted by environmental sciences in general, and ecotoxicology and ecology in
336 particular, emphasise that to properly determine the effects from any contaminant we must address the realistic
337 environmental conditions in which organisms are actually exposed. Realistic environmental conditions incorporate
338 natural abiotic factors (e.g., climate change, temperature, flooding events, snow and ice, air quality) as well as
339 biotic factors (e.g., physiological and life-history status of organisms; ecological processes such as competition,
340 predation, and food availability). Adding this realism will aid in developing integrated exposure assessment
341 approaches including the development of proper tools for the dose calculation for wildlife species that encompass
342 the dynamics over time and space during the entire life cycle of organisms (links with Challenge One).

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

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

348 A strong connection with evolutionary ecology is needed to study adaptive responses and modulation of effects at
349 a multi-generation scale following exposures to radiation. Understanding long-term effects of radiation on the
350 phenotypic and genetic characteristics of the population is crucial to assess the risk of population extinction and
351 its consequence for the maintenance of both genetic biodiversity and species biodiversity. This is true whatever
352 the radiation type and exposure pathways. The mechanisms involved in organism responses to chronic radiation
353 exposure, both within and between generations, are the subject of an active debate in the scientific literature (e.g.
354 Boubriak et al., 2016; Horemans et al., 2019; Møller and Mousseau, 2016; Goussen et al 2015) and are still far from
355 conclusive in particular when it comes to environmental relevant settings.

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

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

366 In radioecology, the importance of an ecosystem approach has been emphasised many times over the last decade.
367 Several publications and international workshops have led to a number of recommendations and consensus
368 statements (Bradshaw et al., 2014; Bréchnac et al., 2016; Mothersill et al., 2018, 2019; Haanes et al., 2020). In
369 relation to these issues, resolving the controversy with regard to chronic exposure effects on wildlife reported in
370 the Chernobyl and Fukushima exclusion zones is the priority Game Changer (Game Changer C.1). Resolving this
371 controversy would have a significant impact on the confidence and credibility of radiation protection of the
372 environment (e.g., robustness of 'no-effect' benchmark dose-rates).

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

385 **Scientific Challenge Three: To Improve Human and** 386 **Wildlife Protection by Integrating Radioecology**

387 The management of and the protection from risks that the presence of radionuclides in the environment may pose
388 to human health and wildlife can range from the minimal through ascending levels of complexity and details.
389 Although a significant amount of valuable knowledge exists for a wide range of exposure situations, it is
390 fragmentary with respect to constituting an integrated strategy sufficient to deal with complex, dynamically
391 changing conditions. Linked to this issue, the research outputs from the priorities described above for the exposure
392 assessment (Challenge One) and effects analysis (Challenge Two) will need to be integrated within an efficient,
393 balanced and adaptable assessment approach in planned, existing and emergency exposure situations. Beyond, the
394 individual contaminant-medium-pathway paradigm is changing towards a more integrated view of the
395 environment as a whole. Radioecology's position relative to this paradigm shift can be best advanced by embracing
396 the concept of integration.

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

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

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

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

408 Challenge One of the SRA identifies that radionuclide transfer and exposure have to be assessed at multiple
409 spatial scales, while Challenge Two emphasises that effects have to be characterised not only at the individual
410 level, but also at higher levels of biological organisation and the research outputs from both exposure
411 assessment and effects analyses will need to be integrated. For wildlife, this means that any risk assessment
412 at such integrated scales should simultaneously take into account: (i) variability of doses, depending on spatial
413 variability of radionuclide transfers, as well as behavioural heterogeneity among exposed species, (ii) and
414 variability in radiosensitivity among species, including gender- and life stage-dependencies. Variability of
415 doses and behavioural heterogeneity over space and time should also be taken into account in human risk
416 characterisation. Recent results from EJP CONCERT projects (TERRITORIES and CONFIDENCE) provide
417 improved, structured information about parameter uncertainty, conceptual model uncertainty, scenario
418 uncertainty as well as the role of variability together with analytical, probabilistic and Bayesian methodologies
419 to quantify and (where possible) reduce these uncertainties. In light of integration, these new developments
420 provide initial steps towards fulfilling the objectives of this research line. Nonetheless, the requirement still

421 remains to reduce uncertainties so that risks to humans and biota can be better quantified, whatever the situation
422 (low, as well as high risk situations; planned, existing and emergency situations).

423 *2. Integrate humans and wildlife protection frameworks*

424 Over recent decades, the need was recognised for explicit demonstration of the protection of the environment from
425 the effects of radioactive contaminants, which also resulted in changes to international policies (ICRP, 2007;
426 European Commission, 2013; ICRP, 2014). Significant effort has been expended in that regard and a system of
427 environmental protection is emerging, along with the tools required to estimate exposure, evaluate risk and
428 demonstrate protection (Larsson, 2008; Brown et al., 2016; Bréchnac et al., 2016). However, in some important
429 areas the methodologies for human and wildlife risk assessments still differ, e.g. the human dosimetric system
430 accounts for the kinetics of radionuclides transfer within the body and differential sensitivity of organs to derive
431 dose conversion factors whereas the environmental system does not. This may undermine credibility by its
432 suggestion of inconsistencies causing difficulties for operators, stakeholders and regulators. A more integrated
433 assessment and management (Game Changer **F.3**) – both in terms of the underlying philosophy and the practical
434 application via appropriate tools and systems - will enable radiation protection to make more balanced decisions
435 as it will take in the ‘whole-picture’ the assessments for both humans and wildlife. It also represents a more
436 comprehensible approach when communicating to stakeholders (Game Changer **H.1**).

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

438 Radionuclides and the associated risks posed to human health and wildlife populations typically occur as part of a
439 complex suite of co-contaminants and other stressors that may act as confounding variables, as exemplified by
440 waste streams from nuclear and non-nuclear industries, complex legacy contamination and releases as a result of
441 accidents. There is a clear and long-standing gap in our understanding of contaminant mixtures that include
442 radioactive materials. Radioecological research integrated with other disciplines (Game Changer **H.1**) and directed
443 towards better understanding of mixture effects (Game Changer **A.3**), as well as adapted risk assessment methods
444 (Game Changer **F.3**), will make it possible to determine whether radiation protection criteria are robust in a
445 multiple contaminant context, and aligned with the values, needs and expectations of society.

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

447 In dealing with a range of actual or potential exposure situations, a gradient of integrated management approaches
448 based on multi-criteria decision analyses and the means of creatively implementing them are required (Game
449 Changers **F.3** and **G.1**). The development of appropriate tools – Decision Support Systems (DSSs) – for best
450 implementing such approaches must occur in tandem with the development of management objectives to ensure
451 that maximum benefit is derived. The need for integrated, graded management approaches and the tools to
452 implement them in handling the entire spectrum of possible effects of exposure and ensuring the productivity and
453 societal benefit of impacted areas will be a primary driver for radioecological research in the coming decades
454 (Game Changer **H.1**). The events at Fukushima in Japan exemplify these problems and the existing challenges.
455 Intrinsicly bound to this need is the requirement for sound, fundamental and progressive science to underpin and
456 derive maximum benefit from these efforts.

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

458 Radioactive contamination can occur as a result of a range of different scenarios, disparate in character and often
459 specific in their actual or potential impacts, but commonly of great concern to the public. Societal perception of
460 the technical capacity and resources required to prevent, mitigate or remediate impacts and ensure recovery of any
461 contaminated area after a release should take into account the disparities and specificities inherent in the exposure
462 scenarios, as they play a significant role in the assessment of consequences – in terms of economic considerations
463 and from a societal perspective. A continuum of effects includes societal concerns, varying degrees of economic
464 impact or loss of societal benefit, administrative disruption, health impacts or loss of life and impact on ecosystem
465 services. In addition to these impacts, the measures taken to address them may, in turn, incur societal and
466 environmental side effects. This complex interplay has been well demonstrated in the aftermaths of both the
467 Chernobyl and Fukushima accidents. Not spectacular examples, but noticeably more often present are observed in
468 non-nuclear industries involved in NORM issues. Those examples and existing information have been taken into
469 consideration when developing the Joint roadmap for a better alignment of research with the values, needs and
470 expectations of society (Game Changer **H.1**). Such alignment should always lead to an evidence-based approach
471 to policy making, and the scientific method should be upheld in all radioecology research; in order to be useful,
472 science must be independent and impartial. In addition, it is essential to communicate the scientific basis to society
473 in an understandable way to increase acceptance.

474

475 **Challenge for Education and Training: To Maintain** 476 **and Develop a Skilled Workforce in Europe and** 477 **Worldwide**

478 Scientific research in radioecology and implementation of that knowledge into the radiation protection of human
479 health and wildlife populations requires scientists and workers with adequate competence and appropriate skills.
480 Research-based education and training (E&T) depends on radioecology being included in university programmes
481 and access to relevant infrastructures and capabilities. The EC EURAC project (2005) and the Radioecology
482 Master Programme at the Norwegian University of Life Sciences (2007) have been important steps in promoting
483 environmental radioactivity as an academic discipline under the Bologna Model⁷. The STAR project solicited
484 stakeholder engagement (industry, regulators, academics, educators, etc.) in the development of a strategic plan
485 for securing the long-term sustainability of education and training in radioecology (STAR, 2015).

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

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

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

- 494 1. Increasing student and teacher/researcher mobility requires sustainable funding mechanisms within
495 radioecology. Actions such as travel grants for students and guest lecturer fees have a relatively low cost,
496 but need to be maintained. The ALLIANCE fosters attendance of students at international radioecology
497 conferences and placements in other laboratories by offering small supportive grants to students
498 supervised by its members.
- 499 2. Inclusion of bespoke E&T work packages in EU (and other large) funded projects with wide reaching
500 outreach activities to deliver training across all levels from the public to professionals and researchers.
- 501 3. Allocation of funding for PhD, post-doctoral or other early career researcher positions in EU (and other
502 large) funded projects.
- 503 4. Exploring joint EU MSc opportunities through the Erasmus Mundus programme, as well as the inclusion
504 of radioecology modules in BSc and MSc degrees originated from the European Universities Initiative,
505 which are transnational alliances, funded by the Erasmus+ programme. This would enable students to
506 obtain a degree by combining studies in several EU countries, forming transnational creating teams to
507 address societal challenges, especially those related to Sustainable Development Goals. This would
508 include mechanisms to increase the number of accredited courses in radioecology that are given by
509 European universities as well as to stimulate integration within the ALLIANCE.

⁷ European Higher Education Area and Bologna Process - <https://chea.info/>

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

529 **Challenge for Infrastructures and Capabilities: To** 530 **Maintain and Develop the Infrastructures Needed to** 531 **Support Radioecology**

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

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

544 In the recent past, several EURATOM funded projects have performed activities to drive the improvement of the
545 awareness and use of radioecology infrastructures in Europe. The Network of Excellence on Radioecology STAR
546 created an inventory of infrastructure, including databases and sample archives (STAR Deliverable 2.2). Within
547 EJP-CONCERT efforts were subsequently made to increase visibility of radiation protection infrastructures
548 including those of ALLIANCE members (see the AIR²D² database⁸ and AIR² bulletin⁹).

549 The approaches used to study and evaluate the behaviour and impacts of radiation and radionuclides on the living
550 world are changing. Consequently, the required infrastructures and capabilities are also changing. A robust long-
551 term vision is essential to successfully and sustainably develop, construct and operate radioecological (and
552 radiation protection) infrastructures and capabilities. A network of collaborating organisations will allow
553 maximum benefit of advanced platforms within Europe or more widely.

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

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

- 558 1. Identify the requirements for infrastructures and capacities and create the partnerships of excellence that
559 bring together these required infrastructure and tools.
- 560 2. Maintain a web-based catalogue on physical infrastructures, e-infrastructures and capabilities to ensure
561 an efficient and effective sustainable integration of resources and capacities at a European level and to
562 show stakeholders the radioecology capabilities available.

⁸ Access to Infrastructures for Radiation protection Research - <http://www.concert-infrastructures.eu/>

⁹ Access to AIR² bulletin - https://www.concert-h2020.eu/en/Concert_info/Access_Infrastructures/Bulletins

- 563 3. Further development of the Radioecological Observatory sites (the Chernobyl Exclusion Zone, the
564 Fukushima Exclusion Zone and NORM-impacted sites in Belgium and Poland are already established).
- 565 4. Promote the visibility and joint use of existing infrastructures. Encourage wider collaboration, not only
566 in the field of radioecology, but also in the broader area of radiation protection and with other related
567 disciplines, leading to more efficient use and further development of infrastructures.

568 **Conclusions**

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

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

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

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

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

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773 **Figures caption**

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

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: