Gap analysis and research priorities from ALLIANCE
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1. Introductive background

The European Radioecology Alliance – the ALLIANCE – was founded in 2009 and officially registered in 2012 (http://www.er-alliance.eu/). Since its creation, the ALLIANCE has progressively grown, going from the 8 founding members in 2012 to 27 members, from 14 countries, in April 2017. The objectives of the ALLIANCE are to coordinate and promote research and recruitment in radioecology and to act as a Research Platform (Definition of priorities and research programmes, Promotion and Communication). The ALLIANCE members recognise that their shared radioecological research can be strengthened by efficiently pooling resources among their partner organisations and prioritising group efforts along common themes of mutual interest[1]. A major step in the prioritisation process was to develop a **Strategic Research Agenda** (SRA)[2] for radioecology. The SRA highlights the required scientific knowledge and methodological/technical know-how for the main components of any human and environmental risk assessment. It identifies three scientific challenges and fifteen associated research lines, consistent with a strategic vision of what radioecology can achieve in the future *via* a prioritisation of efforts. These challenges are:

- Challenge 1 - To Predict Human and Wildlife Exposure in a Robust Way by Quantifying Key Processes that Influence Radionuclide Transfers and Exposure;
- Challenge 2 - To Determine Ecological Consequences Under Realistic Exposure Conditions;
- Challenge 3 - To Improve Human and Environmental Protection by Integrating radioecology.

The SRA is being implemented by **topical roadmaps**[3] that were initiated by the COMET EC-funded project, with the help and endorsement of the ALLIANCE. The development of the roadmaps is driven by the need to provide fit-for-purpose human and environmental impact/risk assessments in support of the protection of man and the environment in interaction with society (interconnected sciences including social sciences and humanities, risk management including communication, economy), for all environmental exposure situations (*i.e.*, planned, existing, emergency). Where appropriate, collaboration between the existing European radiation protection platforms[4] is promoted.

Five scientific areas were selected to launch topical roadmaps:

- Atmospheric radionuclides in transfer processes;
- Marine radioecology;
- Human food-chain modelling;

[1] Muikku, M., Beresford, N.A., Garnier-Leplace, J., Real, A., Sirkka, L., Thorne, M., Vandenhove, H., Willrodt, C. (2018). Sustainability and integration of radioecology—position paper. J. Radiol. Prot. 38, 152-163.

[2] Hinton, T.G., Garnier-Laplace, J., Vandenhove, H., Dowdall, M., Adam-Guillermin, C., Alonzo, F., Barnett, C., Beaugelin-Seiller, K., Beresford, N.A., Bradshaw, C., Brown, J., Eyrolle, F., Février, L., Gariel, J.-C., Gilbin, R., Hertel-Aas, T., Horemans, N., Howard, B.J., Ikäheimonen, T., Mora, J.C., Oughton, D., Real, A., Salbu, B., Simon-Cornu, M., Steiner, M., Sweeck, L., Vives i Batlle, J. (2013). An invitation to contribute to a strategic research agenda in radioecology. J. Environ. Radioact. 115: 73-82

[3] Garnier-Laplace, J., Vandenhove, H., Beresford, N.A., Muikku, M., Real, A. (2018). COMET strongly supported the development and implementation of medium-term topical research roadmaps consistent with the ALLIANCE Strategic Research Agenda. J. Radiol. Prot. 38, 164-174.

[4] EURADOS: www.eurados.org/ for dosimetry; MELODI: http://www.melodi-online.eu/ for low dose risks; NERIS: http://www.eu-neris.net/ for emergency preparedness and post-accidental situations; EURAMED: http://www.eibir.org/scientific-activities/joint-initiatives/european-alliance-for-medical-radiation-protection-research-euramed/ for medical applications.

- Naturally-occurring radioactive materials (NORM);
- Inter- and intra-species radiation sensitivity and transgenerational effects.

Activities planned for a 5-year period within each topical roadmap extend from basic science (mechanistic understanding) to applications that would improve radiation protection (reduce the overall uncertainties), communication with society, assist decision-making processes (including risk mitigation where relevant). The research proposed interlinks the different challenges presented in the SRA.

2. Overview of radioecology research impact in radiation protection over the last decade

References cited throughout the text are some of the major publications. STAR & COMET produced ca. 70+ peer-reviewed articles.

The ALLIANCE activities and associated EC-funded projects or national programmes from ALLIANCE members made important progress in radioecology research over the last decade. This progress has focused on improvement of knowledge and tools to assess environmental radionuclides transfer and subsequent human and environmental exposure and risk assessment[5]. EC-funded projects (STAR, COMET) have developed and improved innovative models for quantifying radionuclide transfer to humans and wildlife and delivered guidance for development and validation of fit-for-purpose models[6]. For accidental situations, effort was dedicated to the characterisation of radioactive particles behaviour in ecosystems[7], and to marine dispersion modelling and marine biota impact assessment[8]. The relevance of studying the complex issue of the influence of multiple stressors in radiological risk assessment was clearly demonstrated through a literature review[9] and simplified case studies (e.g., combination of a stable metal, an organic substance and gamma radiation)[10], and research was initiated on transgenerational effects and epigenetics[11]. There have also been advances in the integration of human and environmental protection frameworks (*e.g.* CROMERICA tool). In addition, the establishment of a series of dedicated observatory sites[12] constitutes a unique opportunity to obtain a better understanding (and modelling) of environmental processes such as the migration and bioavailability of radionuclides, and the resulting exposure pathways and corresponding doses for humans and wildlife. Studying processes in the field, synergistically with laboratory experiments and modelling, is of high added value, notably regarding the complexity of environmental issues (and remediation) associated to long-lasting radiocontaminated sites, such as NORM sites[13]. Although considerable advances have been made since the Chernobyl and Fukushima accidents in predictive modelling to improve exposure estimates[14], there is a need to take into account more realistically key physical, chemical and biological processes in spatio-temporal predictive models. How environmental transfers and subsequent exposure (and dose) of humans and wildlife vary spatially and temporally is a key issue whatever the source term is (either artificial or naturally-occurring radionuclides). Improving the predictive capability of integrated models through comparison of

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[5] Beresford, N.A., Wood, M.D., Vives I Batlle, J., Yankovich, T.L., Bradshaw, C., Willey, N. (2016). Making the most of what we have: application of extrapolation approaches in radioecological wildlife transfer models. . J. Environ. Radioact., 151, 373-386

[6] Beresford, N.A., Yankovich, T.L., Wood, M.D., Fesenko, S., Andersson, P., Muikku, M., Willey, N.J. (2013). A new approach to predicting environmental transfer of radionuclides to wildlife: A demonstration for freshwater fish and caesium. Sci. Tot. Environ. 463–464: 284-292; Brown, J.E., Beresford, N.A., Hosseini, A. (2013). Approaches to providing missing transfer parameter values in the ERICA Tool – How well do they work? J. Environ. Radioact. 126: 399-411

[7] Salbu, B., Kashparov, V., Lind, O.C., Garcia-Tenorio, R., Johansen, M.P., Child, D.P., Roos, P., Sancho, C. (2017) Challenges associated with the behaviour of radioactive particles in the environment. J. Env. Radioact., in press

[8] Belharet, M., Estournel, C., Charmasson, S. (2016). Ecosystem model-based approach for modeling the dynamics of 137Cs transfer to marine plankton populations: application to the western North Pacific Ocean after the Fukushima nuclear power plant accident. Biogeosciences, 13, 499-516; Vives i Batlle, J., Aoyama, M., Bradshaw, C., Brown, J., Buesseler, K.O., Casacuberta, N., Christl, M., Duffa, C., Impens, N.R.E.N., Iosjpe, M., Masque, P., Nishikawa, J. (2018). Marine radioecology after the Fukushima Dai-ichi nuclear accident: Are we better positioned to understand the impact of radionuclides in marine ecosystems? J. Env. Radioact. 618, 80-92.

[9] Vanhoudt, N., Vandenhove, H., Real, A., Bradshaw, C., Stark, K. (2012). A review of multiple stressor studies that include ionising radiation. Environ. Poll. 168: 177-192.

[10] Lofts, S., Fevrier, L., Horemans, N., Gilbin, R., Bruggeman, C., Vandenhove, H. (2015). Assessment of co-contaminant effects on uranium and thorium speciation in freshwater using geochemical modelling. J. Environ. Radioact., 149, 99-109; Nascimento, F.J., Svendsen, C., Bradshaw, C. (2015). Combined effects from γ radiation and fluoranthene exposure on carbon transfer from Phytoplankton to Zooplankton. Environ. Sci. Technol. 49, 10624-10631.

[11] Gombeau, K., Bourdineaud, J-P., Ravanat, J-L., Camilleri, V., Cavalie, I., Armant, O., Camilleri, V., Cavalie, I., Floriani, M., Adam-Guillermin, C. (2017). Epigenetic, histopathological and transcriptomic effects following exposure to depleted uranium in adult zebrafish and their progeny. Aq. Toxicol. 184, 14-25.

[12] Muikku, M., Beresford, N.A., Garnier-Leplace, J., Real, A., Sirkka, L., Thorne, M., Vandenhove, H., Willrodt, C. (2018). Sustainability and integration of radioecology—position paper. J. Radiol. Prot. 38, 152-163.

[13] Michalik, B. (2017). NORM contaminated area identification using radionuclides activity concentration pattern in a soil profile. J. Env. Radioact., 173, 102-111

[14] Vives i Batlle, J (2015) Dynamic modelling of radionuclide uptake by marine biota: application to Fukushima assessment J. Environ. Rad 151, 502-511; Calmon, P., Gonze, M-A., Mourlon, (2015). Modeling the early-phase redistribution of radiocesium fallouts in an evergreen coniferous forest after Chernobyl and Fukushima accidents. Sci. Tot. Environ. 529, 30-39.

predictions *versus* observed data, alongside filling knowledge gaps on biogeochemical processes, are the key to reduce uncertainty in human and wildlife exposure estimates for all exposure situations. Marine and watershed radioecological modelling are key-priority domains to tackle. Post-accidental related issues and communication with stakeholders are research priorities clearly shared with NERIS, the social sciences and humanities community, and EURADOS if we refer to refinement of dose assessment.

Understanding biological effects of chronic ionising radiation exposure to low doses and dose-rates is still of major concern for both human and environmental radiation protection, especially with the aim of quantifying the risk to individuals (human and endangered species) and populations. Recently, mechanistic models based on the disturbance of basic metabolism in organisms exposed to ionising radiation have provided insight into the causes of observed effects and represent tools to develop more robust ecological protection benchmarks[15]. COMET proved the relevance of using epigenetic markers in non-human species and started to delineate genetic vs. epigenetic causes of transgenerational effects of chronic exposures[16]. The exploration of "omics" responses to ionising radiation has also been highlighted as a useful approach to unravel basic mechanisms of the biological response to ionising radiation[17]. These concepts could help us understand how co-contaminants/stressors might influence organism radiosensitivity[18]. Exploration of intra- and inter-species causes of variation in radiosensitivity and of the mechanisms of multi- or trans-generational effects[19] is a priority to improve basic knowledge and contribute to the validation of biomarkers as early warning tools (clearly synergistic with MELODI research).

Two projects on radioecology-related topics are ongoing (started January 2017), after being approved in the EJP-CONCERT 1st Call in 2016.
The **TERRITORIES** (To Enhance unceRtainties Reduction and stakeholders Involvement TOwards integrated and graded Risk management of humans and wildlife In long-lasting radiological Exposure Situations) project targets an integrated and graded management of contaminated territories characterised by long-lasting environmental radioactivity, filling in the needs emerged after the recent post-Fukushima experience and the publication of the International and European Basic Safety Standards. A graded approach, for assessing doses to humans and wildlife and managing long-lasting exposure situations (where radiation protection is mainly managed as existing situations), will be achieved through reducing uncertainties to a level that can be considered fit-for-purpose (notably by using existing empirical/experimental data). The overall outcome will be an umbrella framework, that will constitute the basis to produce novel guidance documents for dose assessment, risk management, and remediation of existing NORM sites and of radioactive contaminated sites long-term after an accident, with due consideration of uncertainties and stakeholder involvement in the decision making process. This project will also highlight important factors determining the uncertainty levels that should be focussed on in the future combining experimental and modelling approaches.

Within the **CONFIDENCE** (COping with uNcertainties For Improved modelling and DEcision making in Nuclear emergenCiEs) project, the WP3 addresses key challenges identified in the ALLIANCE Strategic Research Agenda and specifically those of the Human Food Chain Topical Roadmap. The work to be done builds on infrastructures established in the frame of the COMET (COordination and iMplementation of a panEuropean instrumenT for radioecology) project (radioecology Observatory sites like the Chernobyl Exclusion Zone), and will use various appropriate databases (*e.g.* on food chain transfer) held by ALLIANCE members.

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[15] Alonzo, F., Hertel-Aas, T., Real, A., Lance, E., Garcia-Sanchez, L., Bradshaw, C., Vives i Batlle, J., Oughton, D., Garnier-Leplace, J. (2016). Population modelling to compare chronic external radiotoxicity between individual and population endpoints in four taxonomic groups. J. Environ. Radioact., 152, 46-59; Vanhoudt, N., Horemans, N., Wannijn, J., Nauts, R., Van Hees, M., Vandenhove, H. (2014). Primary stress responses in Arabidopsis thaliana exposed to gamma radiation. J. Environ. Radioact. 129: 1-6 ; Lance, E., Alonzo, F., Garcia-Sanchez, L., Beaugelin-Seiller, K., Garnier-Laplace, J. (2012). Modelling population-level consequences of chronic external gamma irradiation in aquatic invertebrates under laboratory conditions. Sci. Tot. Environ. 429: 206-214.

[16] Gombeau, K., Bourdineaud, J-P., Ravanat, J-L., Camilleri, V., Cavalie, I., Armant, O., Camilleri, V., Cavalie, I., Floriani, M., Adam-Guillermin, C. (2017). Epigenetic, histopathological and transcriptomic effects following exposure to depleted uranium in adult zebrafish and their progeny. Aq. Toxicol. 184, 14-25.

[17] Van Hoeck, A., Horemans, N., Nauts, R., Van Hees, M., Vandenhove, H., Blust, R., (2017). Lemna minor plants chronically exposed to ionising radiation: RNA-seq analysis indicates a dose rate dependent shift from acclimation to survival strategies. Plant Sci. 257, 84-95; Song, Y., Salbu, B., Teien, H-C., Evensen, O., Lind, O.l., Rosseland, B.O., Tollefsen, K.E., (2016). Hepatic transcriptional responses in Atlantic salmon (*Salmo salar*) exposed to gamma radiation and depleted uranium singly and in combination. Sci. Tot. Environ., 562, 270-279.

[18] Margerit A., Lecomte-Pradines C., Svendsen C., Frelon S., Gomez E., Gilbin R. (2015). Nested interactions in the combined toxicity of uranium and cadmium to the nematode Caenorhabditis elegans . Ecotoxicol. Environ. Safety, 118, 139–148; Nascimento, F.J., Svendsen, C., Bradshaw, C. (2015). Combined effects from γ radiation and fluoranthene exposure on carbon transfer from Phytoplankton to Zooplankton. Environ. Sci. Technol. 49, 10624-10631

[19] Parisot F., Bourdineau J.-P., Plaire D., Adam-Guillermin C., Alonzo F. (2015). DNA alterations and effects on growth and reproduction in Daphnia magna during chronic exposure to gamma radiation over three successive generations. Aquat. Toxicol., 163: 27–36

In the 2nd CONCERT Call (May 2017) no project directly related with radioecology was approved.

3. Views from international organisations on radioecology science needs released after the last EC-funded radioecology project COMET

The EC-funded COMET project organised its final project meeting from 25-27 April 2017 in Bruges, Belgium in association with the ALLIANCE. At this workshop, key representatives of international organisations were invited and their recommendations and views on progress made in COMET and consequent future requirements were solicited (Table 1).

Table 1. Summary of the main recommendations from international organisations delivered during the final COMET event in Bruges, 2017 (from Garnier-Laplace *et al.*, 2017. D2.4 COMET).

Organisation	Recommendations given to ALLIANCE
UNSCEAR	▸ Effects studies: gain more insight into molecular mechanisms, in synergy with life sciences other than radioecology (From more descriptive research to understanding of basic processes). ▸ Modelling: move toward mechanistic models (From more empirical models to understanding of underlying mechanisms). ▸ Effect studies and modelling depend on each other (Models need to be supported by experimental data and must be able to explain something happening in real world).
ICRP	Focus on an integrated view of all benefits and impacts that includes consideration of protection of people and the environment.
IAEA	There is a lot of common interest between the IAEA MODARIA programme (Modelling and data for radiological impact assessment) and the ALLIANCE topical roadmap working groups and efforts should continue to maximize synergies: ▸ Seasonality of transfer processes and exposure pathways for accidents. ▸ Integration of monitoring and modelling. ▸ Management of exposures from NORM will remain important worldwide. ▸ Realistic evaluation of the importance of exposures to biota for radiation protection. ▸ Strengthen the role of assessments in decision making.
NEA	▸ Prevailing circumstances drive individual and collective behaviours, which drive individual and collective exposures: Models need to address a wide variety of individual and collective circumstances. ▸ Radioecology can contribute SIGNIFICANTLY to understanding cancer mechanisms and markers. ▸ A communications / dialogue strategy is needed to perform research that will appropriately address stakeholder concerns.
IUR	The integration concept proposed today is purely methodology-driven (broadly, same conceptual method applied to man and biota): ▸ Better to start from an integration concept that acknowledges the existing interactions between non-human species and man (i.e. the ecosystem concept). ▸ Need to accept complexity and think in a more ”systems-based” way. Both in experimental work and in modelling.
IRPA	▸ The SRA should specifically address communication with society and enhancement of decision support systems, to improve public communication capabilities and stakeholder engagement. ▸ The SRA may offer young researchers good opportunities to develop their careers in a field that must be maintained, updated and that shall address new challenges. ▸ A challenge not included in the SRA was: keeping and transferring knowledge through the generational replacement. ▸ The implementation of the research roadmaps, will contribute to improve relevant tools and methods for radiation protection of people and the environment.

3. Research needs and priorities

From the ALLIANCE SRA annual priority statement published in 2015, 2016 and 2017, the following research priorities were put forward (no specific order below):

- Environmental availability and impact of radionuclides in terrestrial, freshwater and marine ecosystems (including human food chain) and their interactions with atmosphere, incorporating physical, chemical and/or biological processes. Validated process-based model parameterisation, characterisation of variability and uncertainty, and guidance for fit-for-purpose models**; *only partially dealt with under TERRITORIES and CONFIDENCE (R&D focusing on NORM is only initiated under TERRITORIES and the project does not deal with the full range of source types nor with the various affected environments and remediation options)***

- Development of models/tools, and datasets for their calibration and validation and guidance to select and evaluate the effectiveness of different remediation strategies in long-lasting exposure situations (*e.g.* nuclear accidents and/or NORM/TeNORM)**; *only partially dealt with under TERRITORIES and CONFIDENCE. Same note as for the previous priority.***
- Biomarkers of exposure and effects in living organisms as operational outcomes of a mechanistic understanding of intra- and inter-species variation of radiosensitivity under chronic low dose exposure situations, with a focus on the added value for both human and non-human radiological protection**; *not dealt with under the CONCERT calls***
- Multiple stressors and modulation of radiation effects in living organisms; ***not dealt with under the CONCERT calls.***

Such research priorities are to be implemented and adapted to various exposure situations (consistently with those defined to support the joint roadmap under preparation by the EJP CONCERT WP3 (CONCERT D3.4 "First joint roadmap draft", Nov. 2017, 28 pages):

(i) normal operation or accidents of/at various types of nuclear facilities including the nuclear fuel cycle (from uranium mining and milling, to waste management and decommissioning, including research installations),

(ii) medical, industrial and scientific use of ionising radiation sources,

(iii) military use of ionising radiation, such as *e.g.*, fallout from former nuclear weapons, or releases from nuclear-powered vessels,

(iv) activities and legacy related to the use of natural resources, containing naturally occurring radionuclides, that are processed neither for their fissile nor their fertile properties (NORM / TENORM),

(v) contaminated legacy sites, and

(vi) natural radiation as source of ionising radiation: terrestrial and cosmogenic radiation, natural events leading to radionuclide releases.

Given the gap analysis and the on-going research, ALLIANCE proposes the elementary research lines to be focused. ALLIANCE's vision on key-future research priorities is perfectly in line with the research challenges and priorities put forward by the CONCERT on-going joint roadmapping activity. It highlights ALLIANCE own research priorities and their potential links to the common and multidisciplinary challenges as they were defined by the different radiation protection platforms for the purpose of mentioned joint roadmap (see CONCERT D3.4 "First joint roadmap draft", Nov. 2017, 28 pages).

Biological and ecological effects of low dose/ low dose rate exposure on biota (*some of the research lines potentially synergistic with MELODI and/or EURADOS)*

- Identification and mechanistic understanding of molecular and cellular processes following exposure to ionising radiation and resulting in adverse effects at the individual level on population-relevant functions (growth, reproduction and survival, mainly non-cancer effects for non-human species; making use where relevant of state oft heart approaches such as omics, systems biology and trying to find biomarkers or Adverse Outcome Pathway). This may include (i) understanding how effects may modulate for external or internal exposure pathways, and for different radiation types; (ii) revisiting the RBE concept for non-human species by shifting to deterministic population relevant endpoints
- Understanding variation of responses between species at the individual and population levels due to genetic, environmental and behavioural factors and the interactions between these; Exploration of intra- and inter-species causes of variation in radiosensitivity and identification and validation of biomarkers of exposure and effects for use in prospective and retrospective assessments
- Studying hereditary effects within populations of species, the molecular basis of adaptation (or vulnerability) gained through generations and the inter-population effects in the ecosystem; role of epigenetics in genomic instability and inheritance in organisms/cells exposed to radionuclides/ionising radiation and in adaptation of organisms under conditions of a pressure selection
- Mechanistic basis to understand how multiple stressor exposure modifies ionising radiation effects and linking these to risk assessment
- Ecological consequences of exposure to ionising radiation (exposure effects relationships in the field vs. in the laboratory may be modified due to the combination of radiotoxicity effects on growth rate/reproduction

and geographic gene diversity, competition, predation, and abiotic factors including pollutants other than radionuclides)

- Development of advanced methods for fit-for-purpose dose assessment to support and robustly interpret effects studies

Integration and optimization of environmental exposure assessment for ionising radiation and other stressors
(*some of the research lines potentially synergistic with Social Sciences and Humanities activities and/or MELODI and/or NERIS and/or EURADOS***)**

- Mechanistic understanding of radionuclide dispersion and transfer processes in and between the various components of the geosphere, biosphere and atmosphere, and associated mechanistic process-based modelling including foodwebs and biokinetics modelling. This mechanistic process-based modelling may integrate physical, chemical and biological processes; taking into account the influence of speciation and bioavailability of individual radionuclides (whatever their origins or the source-terms, including sequences of natural radionuclides constituting decay series in environmental components). This modelling may serve individual realistic human dosimetric assessment along with a better prediction of efficiency of countermeasures when required. This may include calibration and experimental validation of mechanistic models, characterisation of variability and uncertainty.
- Advanced methods to deal with scale extrapolation issues (from molecular processed observed *in vitro* to complete natural (eco)systems)
- Advanced modelling of process interactions at the various biosphere interfaces at the local, regional and global scales such as in (a) marine, brackish, estuarine and freshwater ecosystems, covering the watershed continuum from the source to the ocean and further afield at the global circulation level, and (b) terrestrial ecosystems (agricultural, forestry, natural and urban including NORM landfills); developing landscape-based models. This may include:
    - Interactions between natural hazards and radiologically contaminated areas (e.g., wind resuspension, wildfires or biogenic aerosol emission from contaminated areas or any hydro-meteorological events leading to redistribution of radionuclides through various processes)
    - Advanced methods for data treatments to cope with the large amount of data resulting from elaborated and comprehensive transfer assessment, environmental monitoring and improved dose assessment
    - Improvement /development of innovative methods to characterise the environmental contamination and its evolution in space and time in order to delineate the multiple-hazard footprint (*e.g.*, geostatistical interpretation of environmental, radiological, chemical data) of a site;
    - Integrated holistic modelling approach and advanced methods to identify the most significant sources of uncertainty related to the impact on human <u>and</u> environmental health
- Development of remediation methods and strategies in support of the management of radiocontaminated sites:
    - Innovative modelling approaches for evaluating the effectiveness of different remediation strategies to support decision making at various stages of assessment and remediation
    - Test of remediation strategies including bioremediation based on outcomes of mechanistic studies of radionuclide speciation and transfer in soils, waters and biota
    - Improved risk communication with stakeholders and development of multicriteria decision support tool for optimised remediation and management.

Radioecology-related research for optimising emergency and recovery preparedness and respons (*synergistic with NERIS activities***)**

- Customisation of atmospheric, river, marine, brackish water, terrestrial and urban dispersion models, food chain models and dose assessment models. Improvement of monitoring of the different environmental compartments, foods and goods. This includes the development and combination of different modelling and monitoring techniques (including data assimilation) to improve dose reconstruction and predictions of the impact of an accident.
- Development of more sophisticated parametrizations of processes of high health impact: environmental evolution of iodine speciation, low wind speed conditions, snow and fog events

- Improved understanding of countermeasures (mechanistic process-based models) to better build, select and implement countermeasure strategies at different times (preparedness, response, recovery) and in different geographical areas. This includes:
    - development of new countermeasures and remediation strategies, taking account for selection of level adopted to start decontamination, efficiency of decontamination and waste handling from an accident
    - integration of societal and ethical aspects including environmental characteristics into risk management. This should include methods for identification and priorisatoin of major socio-economical and ecological stakes inventories
    - further development of the participatory processes in emergency and recovery situations (advanced decision science, use of big data, communication strategies during the emergency and in the post-accident phases)