Senter for fremragende forskning

CERAD
CENTRE FOR ENVIRONMENTAL RADIOACTIVITY

CERAD Strategic Research Agenda 2017-2021

CERAD COE - IN SHORT

The CERAD CoE was established in 2013 to perform fundamental long term research to improve the ability to accurately assess the radiological risks from environmental radioactivity combined with other stressors. By focusing on key factors contributing to the uncertainties, CERAD represents a state-of-the-art research foundation for the advancement of tools and methods needed for better management of those risks. The scope includes man-made and naturally occurring radionuclides that were released in the past, those presently released as well as those that potentially can be released in the future from the nuclear fuel cycle and non-nuclear industries.

Using an ecosystem based scientific approach, The Strategic Research Agenda (SRA) of CERAD focuses on:

- different source term and release scenarios,
- transfer of radionuclides in terrestrial and aquatic ecosystems,
- biological responses in organisms exposed to radiation combined with other stressors such as metals and UV radiation under varying temperature/climate conditions,

to assess overall environmental impact and risks.

The assessments will include possible impact not only on man and non-human organisms, but also economic and societal consequences, and links to risk perception and communication. The assessments can also be utilized to prioritize our focus on nuclear sources in proportion to the radiological threats that they pose. The strategic research agenda covers a broad scientific field, and the program is based on the interdisciplinary effort from scientists representing 5 Norwegian organisations (NMBU, NRPA, MET, NIPH, NIVA) and a network of international specialists.

The present revised SRA focuses on the research priorities during 2017-2021, references are made to selected key publications, including the internal evaluation highlight papers. An extensive list of CERAD publications (125 articles) can be found in the Annual Reports.

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1 Overarching aims of CERAD

The Centre for Environmental Radioactivity (CERAD) will provide new scientific knowledge and tools for better protection of people and environment from harmful effects of radiation

Since 2013 the CERAD CoE has performed fundamental long term research to substantially improve assessment of the risks from environmental radioactivity, combined with other stressors. By focusing on key factors contributing to overall uncertainties, the aim has been to represent a state-of-the-art research foundation for the advancement of future tools and methods needed for a better assessment and management of those risks. The scope embraces man-made and naturally occurring radionuclides, and includes the nuclear fuel cycle and non-nuclear industries. It addresses a range of different sources of radionuclides in the environment, covering those released in the past (i.e., accidental and operational legacies), those currently being released, as well as those that potentially can be released in the future.

1.1 The aims and background to the present SRA document

The CERAD Strategic Research Agenda (SRA) presents CERAD research areas (RA) and their main research focus, hypothesis and approaches to testing those hypotheses. In addition to describing key challenges within individual research areas, the SRA also forms the basis for decisions about needs and priorities for personnel, experiments, and equipment within CERAD. Following brain storming sessions and several workshops, the first SRA outline was completed in April 2013, with the involvement of over 40 scientists from all partner organisations as well as consultations with CERAD international partners. A second draft was finalized in February 2014, and at the end of 2014 research activities were reorganised into 8 umbrella research areas (see below). The current document represents an update of the current state of the art within the four research areas, together with an overview and evaluation of CERAD research activities and achievements over the past 4 years. This forms the basis for identification and prioritisation of research questions and testable hypothesis for the next 5 year period.

1.2 Key areas for long term research

The overarching research objective for CERAD is the development of an ecosystem based scientific approach to help protect people and the environment from ionizing radiation. The original CERAD CoE was structured around four overarching Research Areas: RA1 Source Term and Release Scenarios; RA2 Ecosystem Transfer, RA3 Biological Effects, RA4 Risk Assessment, together with a transient research area focusing on RA5 UV Exposure. The intention was that, when the UV research area had consolidated their joint scientific fundament, the group would merge into the other research areas. By the end of 2014, CERAD had supported 48 subprojects with budgets ranging from 50-650 kNOK. These ranged from small pilot studies to large projects involving all partners. At the beginning of 2015, in order to focus and to better stimulate cross-partner activities, the five research areas were reorganised into eight large umbrella projects: UMB1 – Particle sources and effects; UMB2 – Dynamic transfer; UMB3 – Radiosensitivity; UMB4 – Combined Toxicity and Cumulative Risk; UMB5 – Transgenerational effects; UMB6 – Ecosystem approach; UMB7 – UV/ionising radiation and dosimetry; and UMB8 - Case Studies and Scenarios. The present SRA merges the original research areas with these umbrella projects, and integrates the UV research into the four RAs.

2 Research Area Descriptions

2.1 Research Area 1 – Source Term and Release Scenarios

A series of nuclear/radiological and non-nuclear sources have contributed, are contributing or can contribute in the future to the release of artificially produced or naturally occurring radionuclides to the environment. Following nuclear events, a major fraction of refractory radionuclides such as uranium (U) and plutonium (Pu) will be present as particles, ranging from sub-microns to fragments. Thus, particles are an essential part of the source term, and particle characteristics are essential for the ecosystem transfer, accumulation and effects. To improve the predictive power of impact assessment models **the key research question of RA1 are:**

- *How do release scenarios impact the source term; radionuclide and multiple stressor composition and speciation, in particular the nm - μm sized particle characteristics*
- *What is the relevance of particles and colloids to air/water transport, deposition, ecosystem transfer and exposure models?*
- *Can a common dose concept be developed for UV and ionizing radiation?*

Research Area 1 comprises three umbrella projects: UMB1A Particle Sources; UM1B Dispersion Modelling: Atmospheric and Marine; UMB1C UV/Ionising Radiation and Dosimetry

The overall priority for 2017-2021 is: (1) *to link particle characteristics to defined sources and to use relevant particle properties in air and marine transport and ecosystem transfer models (RA2); (2) to assess doses and effects, including from uneven deposition of activity (RA3).*

2.1.1 Umbrella 1A: Particle Sources

The main research focus is to improve advanced techniques for characterization of particles (synchrotrons, micro-CT, AMS) from the unique NMBU archive, to link particle characteristics to specific sources and to link particle properties to ecosystem transfers (RA2) and biological effects (RA3). The underlying hypothesis is that failing to address the speciation of radionuclides can result in significant errors in the assessment and modelling of the environmental impact of radioactive contamination, since particles show marked differences in behaviour from the – often presumed – ionic species on which models are based.

Major Achievements 2013-2016

Key efforts have focused on the characterization of particles originating from different sources and release scenarios. Results show that particle composition depends on the source, while the release scenarios influence particle properties important for ecosystem transfer. CERAD data has been summarized in the 2nd edition Plutonium Handbook (Geickels, et al., in press). Research showed that radioactive particle and colloids influence transport (Wendel at al., 2015), that particles can be retained in biota (mussels, snails, nematodes) and cause skin damage (Jaeschke et al., 2015), and that exposure of fertilized salmon egg to U nanoparticles can delay hatching.

Characterization of radioactive particles represents an analytical challenge, and CERAD has further developed synchrotron based analytical techniques within radioecology, such as 2D and

3D XRF, XRD and XAS with submicron and nanometer-sized primary beams previously developed by the NMBU/CERAD – Univ. of Antwerp team (Salbu et al., 2001) at a micrometer scale, and has explored the state-of-the art technology characterizing particles at nm scale, using the recently installed nanometer resolution synchrotron beam lines at ESRF (Grenoble) and Petra III (Hamburg). The localization of nm particles surrounding nematode embryos performed at the ID16NI-A nanobeam line was selected as "The beauty of science" by ESRF in 2015 (Cagno et al., 2015).

Priorities for 2017-2021

Since 2013, RA1 has focused on improving advanced techniques for characterization of particles (synchrotrons, micro-CT, AMS), and has demonstrated retention of particles and corresponding effects in field biota. **From 2017, the main new focus is** on *particle properties of relevance for ecosystem transfers (weathering rates), microdosimetry and associated biological effects*, as well as *to utilize the advanced analytical toolbox for nuclear forensic purposes*.

Exposure characterization /Internal distributions within organisms/Toxicological mechanisms:

- Nano-analytical methods such as synchrotron radiation based x-ray techniques (x-ray fluorescence, x-ray diffraction and x-ray absorption fine structure spectroscopy) should be utilized not only to solid state speciation of radionuclides in radioactive particles, rocks, soil and sediments (size, structure, oxidation state), but also to localize and characterize particles retained within biota to shed light on transfer (RA2) and toxicity (RA3) mechanisms of radionuclides and metals that can be related to biological responses and risk (RA4).

Exposure characterization - uneven distribution and localized dose distribution

- Preliminary data from the EC RATE project indicate that the heterogeneous distribution of actinides in particles and the retention of such particle in biota in the Palomares ecosystem result in concentration factors (CF) varying a factor xE04. Thus nano-analytical techniques and microdosimetry are highly needed for samples obtained from the field.

Nuclear forensic - fingerprinting - source identification - safety and security

- Internationally, nuclear forensics is a strong discipline encompassing several scientific fields and a broad spectrum of analytical techniques that provide powerful tools for source identification. Thus, the advanced techniques utilized within CERAD should be valuable tools for tracing radionuclides when they are out of authorized control.

2.1.2 Umbrella 1B: Dispersion Modelling: Atmospheric and Marine

The main objective is to improve atmospheric and marine dispersion models for predicting transport of radioactive releases (e.g., implement particle codes) and to enable identification of unknown sources contributing to radioactive releases. Most atmospheric and water dispersion models suffer from large uncertainties due to poor parametrization of the source term input data, and the probability of transport from a given source is usually not accounted for. Improvements of marine modelling is focused on coupling Lagrangian transport models (e.g., LLM species, colloids and particles) to the ROMS ocean model.

Major Achievements 2013-2016

The application of long-term deterministic meteorological data and meteorological ensembles has contributed to a better understanding of climatological and meteorological impacts on transport and deposition of radioactive particles. Efforts have been put on the inclusion of particles codes into the air and marine transport models, and to improve the resolution of the modelling. Information on particle characteristics from the NMBU Particle archive has been used as input variables. For a given source, probability estimates based on real time meteorological observations during the last 33 years have been performed, demonstrating that sources in UK represent a higher risk to Norway than dumped objects in the Arctic (Bartnicki, et al., 2016). For "worst case scenario" associated with a potential Russian nuclear submarine accident at Kola, the implementation of particle codes in demonstrated that not only aerosols, but also radioactive particles of different size can reach Norwegian territory in a relatively short time.

Modelling the marine dispersion of fallout from the Fukushima accident revealed that much of the discrepancies between estimates from five different ocean models were due to differences in how mesoscale transport was parameterized. Marine modelling has been improved by the inclusion of a particle code/speciation and by implement small-scale resolution. Furthermore, parameterization of small-scale vertical mixing and lateral stirring by the oceanic eddy field has proved useful when utilized for the historic releases of ^{99}Tc from Sellafield into Nordic waters. In addition, focus has also been put on transformation processes affecting radionuclide species in mixing zones such as estuaries. There is currently no integrated model that takes into account source term, atmospheric transport and deposition, catchment run-off to estuaries and further marine transport.

Priorities for 2017-2021

In CERAD, the air dispersion models have been improved for predicting transport of the radioactive releases and to identify unknown sources contributing to radioactive releases, thus reducing uncertainties for emergency preparedness purposes. **A new focus is** *put on further development of meteorological ensembles for local scale, implementing µm – mm sized particles and utilizing data from radar and satellites for reducing uncertainty in model predictions related to cases in RA4.* Further improvement of marine modelling is focused on coupling Lagrangian transport models (e.g., LLM species, colloidal and particulate phases) to the ROMS ocean model.

Atmospheric modelling

- Development and application of optimal meteorological and terrain data in case of a nuclear accident in areas with complicated topography and subsequent interaction between water and land. Development of the meteorological ensembles for local scale.
- Investigation of atmospheric transport and deposition of radioactive particles of different size and density, in particular µm – mm sized particles in the local scale in case of a nuclear accident.
- Research on optimal application of additional meteorological data e.g. from radar and satellites for reducing uncertainty in model predictions of dispersion.
- To deal with contributions from different sources, development of an efficient methodology for backtracking radioactive releases from an unknown source into air or ocean is needed.

Marine modelling

- Further development of the Lagrangian marine transport model to improve real-world applicability, focusing on: a) the dynamic specification of transfer coefficients between dissolved, colloidal and particle phases, b) sediment dynamics (including transport and turbulent resuspension of particles from sediments), c) the estuary zone where freshwaters from the river mix with marine water masses, and d) the interaction with sea ice (enabling studies of long-range transports of radionuclides in the Arctic with sea ice).

Model connections and probabilistic improvements

- To improve the coupling (transfer of radionuclides) between atmosphere and ocean, and with ocean and sediments, vertical transport processes in the oceanic boundary layers (the surface and bottom mixed layers) need to be implemented within the models. This includes turbulent mixing and air-sea exchanges due to wind-driven waves.

2.1.3 Umbrella 1C: UV/Ionising Radiation and Dosimetry

Dosimetry is a central task in CERAD and covers both UV and ionizing radiation. This includes the implementation of dosimetry systems, characterizing and monitoring dose during irradiation experiments at the NMBU gamma irradiation facility, and improving field dosimetry and wildlife dosimetry. The research focus includes the development of a common dose concept for ionizing and UV radiation, in order to utilize the UV – network and the UV –dose maps within areas affected by radioactive fallout or NORM for risk assessment purposes.

Major Achievements 2013-2016

Work has focused on dosimetry associated with laboratory experiments where sources of errors for external exposure include irradiation geometry, scatter conditions, tissue heterogeneities, and set up reproducibility. Dosimetry calculations associated with internal exposure of test organisms exposed to tracers or particles, as well as in biota collected during fieldwork are ongoing, including evaluation of the uneven distribution of doses at the micrometer scale. Passive dosimeters have been mounted on GPS collars of moose and reindeer in order to improve assessment of doses to wildlife. In 2017, dynamic GPS dosimeters will also be applied to brown bears within the Scandinavian Bear Project.

CERAD has developed a unique gamma + UV climate chamber to study combined effects of these stressors, individually or as a mixed exposure (See also UMB3B). Dosimetric evaluations are ongoing with the aim to consolidate a common dose concept of gamma and UV exposure in view of their relative risk. So far a risk factor has been developed for UV and visible light exposure of sensitive persons, by which patients can be guided with respect to outdoor exposure. Using the UV-network data in risk assessment of human and environmental exposures, a UV-dose map has been constructed and could potentially be used in combination with a radioactive fallout map, in case of an accident. Albedo models have also been implemented to account for snow and land cover.

Priorities for 2017-2021

From 2017, the focus will be on *improving field and wildlife dosimetry* and *the development of a common dose concept for ionizing and UV radiation*, in order to utilize the UV – network and the UV –dose maps within areas affected by radioactive fallout or NORM.

Improving dosimetric models for gamma and UV exposure of organisms

- Utilising models to study the transport of photons in the optical range (e.g. Geant4)
- Microdosimetry, including relevant links to micrometer sized and nanoparticles
- Improving lab and environment dosimetric models for dose-response studies. Dynamic GPS dosimeters will be expanded and applied to brown bears within the Scandinavian Bear Project.

Implementing exposure/doses of UV in dose calculations for radioactive fallout scenarios

- Implementing data on exposure/doses of UV (e.g., UV maps) in order to calculate the combined exposure rate of UV and ionising radiation.
- Developing a General light protection factor that can utilise UV-network data to estimate the weighted dose for any biological effect. Dependence on latitude, time of year and day, clouds, albedo etc will be included. This study is a necessary part of the development of a unified dose concept for different radiation qualities, including UV and gamma.

2.2 Research Area 2 - Dynamic Ecosystem Transfer

In the field of radioecology and radiological protection, robust models are required to predict the partitioning of radionuclides between media compartments and their transfer through food-webs. Obviously, coupling of transport models with ecosystem transfer models is important. To improve the predictive power of impact assessment models, **the key research questions are:**

- *How does speciation, the presence of other contaminants and variable climatic conditions influence ecosystem transfer of radionuclides in a Nordic context?*
- *How do kinetic factors such as time dependent changes and non-equilibrium states impact on model accuracy?*

Internationally, there are robust arguments to support the view that over-reliance is often placed on empirical ratios such as distribution coefficients: K_ds, concentration ratios (CR) and transfer coefficients (TF/TC/Tag, BCR). Although the available data compilations on such ratios are comprehensive (e.g., IAEA, 2014), simple to use and offer great utility in screening assessments under equilibrium conditions (Brown et al., 2016a), these approaches do not: a) capture the dynamics of many environmental contamination situations; nor b) provide any insight to the underlying mechanisms influencing transfer. Moreover, detailed information on radionuclide speciation, the influence of environmental physical-chemical conditions, and interactions with molecules in organisms and other contaminants as well as UV are essential (Salbu, 2007), but are seldom included in international literature. Where data gaps with regards to transfer parameters are evident, various extrapolation methods (Beresford et al., 2016) can be been applied to provide surrogate values. Examples of such methods include the use of taxonomic (related to phylogeny) analogues and parameters based upon allometry, where the effect of mass on biological variables is considered. Bayesian statistics can be used to allow all sources of available information on transfer to be integrated (Hosseini et al., 2013). Although prior to CERAD, some work was carried out to consider the efficacy of these approaches (e.g. Brown et al., 2013), there was a need to establish how suitable such approaches are through more rigorous testing.

The overall priority of RA2 for 2017-2021 is to *expand the research carried out within field studies*, with the aim of improving the characterization of radionuclide transfer in the environment through a *systematic implementation of dynamic approaches* and refinement of extrapolation methods.

2.2.1 Umbrella 2: Dynamic Transfer

The overall objective of RA2 is to improve the characterization of radionuclide transfer in the environment through a systematic implementation of dynamic approaches and to refine extrapolation methods. The initial strategy involved the formulation of three research themes encompassing bespoke research questions and hypotheses. It was anticipated that addressing these themes would facilitate a reduction in uncertainty and allow better characterization of variability in the parameters defining radionuclide transfer. The research focused especially on:

- Mobility of radionuclides, taking speciation into account;
- Uptake and accumulation in organisms – influence of environmental factors, and
- Uptake and accumulation in organisms – influence of biological factors,

covering naturally occurring radionuclides, as well as transuranics and fission products.

RA-2 is considered an important link between all other RAs with the requirement to couple information between Source Term and Release Scenarios (RA1) and transfer, the efficacy of studying transfer in tandem with biological response (RA-3) and the fact that transfer forms an integral part of Risk Assessment (RA-4). Thus, RA2 includes field work performed in Norway or other countries, and is focused on improved understanding of dynamic transfers in relation to aquatic ecosystems and terrestrial ecosystems.

<u>Major Achievements 2013-2016</u>

Fieldwork: During the first years of CERAD, several fieldworks have been performed, studying mobility, transfer and biological uptake of radionuclides in the environment along with other contaminants (i.e. metals) to identify actual K_ds, concentration ratios (CR) and transfer coefficients (TF/TC/Tag, BCR). Field expeditions to both NORM sites and sites contaminated from nuclear accidents have been performed, including both aquatic and terrestrial environments. NORM sites include both U-rich sites (i.e. sites with alum shale) and a Th-rich Fen site in Norway. A series of field to accidental contaminated sites have been performed during the years, including extensive expeditions to the Barents and Kara seas (USSR K27 and K159 submarines), Palomaris, Spain, as well as in Chernobyl, Ukraine and Fukushima, Japan, representing different source terms and ecosystem transfers and allowing comparative studies to be performed (Fig.1).

Dynamic transfer studies: Mobility of radionuclides has been studied in several cases and in different ecosystems. To date, the most work has been on aquatic ecosystems, including *in situ* fractionation of radionuclides and metals in water (e.g., NORM sites, Chernobyl, Fukushima), investigation of radionuclide species in runoff (e.g., Chernobyl exclusion zone, Bondar et al., 2015), in-lab fractionation of species in water (e.g., changes in the U-speciation when exposed to UV radiation using FFF-ICP-MS), and identification of biomolecules in biological fluids and tissues (HPLC-ICP-MS). Extensive work has been put on uptake of uranium-species in Atlantic salmon, from fertilized eggs to swim-up, including the influence of environmental factors (pH, major ions, metals, temp) on the speciation of U and uptake in salmon (Gilbin et al., 2015). When fertilized eggs were exposed to U nanoparticles, hatching was delayed. The influence of biological factors on radionuclide transfer was explored by taxonomic relationships corresponding to radiocaesium transfer to marine biota and through dynamic model inter-comparison (Vives I Batlle et al., 2016). Controlled model experiments with daphnia and salmon have allowed the dynamics of U uptake, distribution and depuration to be characterized.

Extensive model experiments with Atlantic salmon have also allowed quantification of U distribution among tissues, demonstrating that gill deposition acts as a source to the liver. Recent results indicate that the uptake of radionuclides in fish is significantly lower than expected, when "clean" fish are installed in a contaminated Chernobyl lake during the autumn-winter season.

Mobility studies in terrestrial ecosystems include investigations of transfer of stable analogues to plants and animals at a reference site in Tjøtta, Norway (Thørring et al., 2016), and transfer of radionuclides to birch and pine in the Chernobyl and Fukushima exclusion zones. The studies in Chernobyl have shown very high uptake of Sr-90 from ground water, through birch and pine, to lichens growing on tree surface. Transfer of NORM nuclides along with metals have been studied from soil to plants and to earthworm in U-sites and in a thorium rich Fen area in Norway (Mrdakovic Popic et al 2014), as well as in Chernobyl and Fukushima. Based on extensive fieldworks in 2016, the mobility and transfer of radionuclides in terrestrial ecosystems will be investigated in more detail in 2017.

Comprehensive data related to Pu – isotopes and speciation, mobility and dynamic ecosystem transfer in the environment has also been summarized in the new revised 2nd Plutonium Handbook (Geickels et al, 2017). Detailed investigations on uptake and effects on biota in aquatic and terrestrial ecosystems will also come from the microcosms experiments performed in RA4.

Linking transport models and ecosystem transfer: The key efforts have been to develop methodologies that provide a link between transport models and ecosystem transfer models. This includes the application of the dynamic ERICA tool for the Fukushima impact assessment, which was used in three White papers to the UN General Assembly from a UNSCEAR committee chaired by the CERAD deputy (e.g., see UNSCEAR, 2014, Strand et al., 2014; Vives i Batlle et al., 2014). Other examples, include the provision of a system characterizing potential contaminant dispersal and transfer to Norwegian fisheries from any point within the NE Atlantic (Kauker et al., 2016) and (transfer based) risk indices for managing incidents involving the transport of nuclear materials in Northern Seas (Brown et al., 2016c). With regards to links with modelling in RA2 and RA4, dynamic transfer modelling has been an important factor for assessing impact from hypothetical releases from dumped nuclear objects in the Arctic (Bartnicki et al., 2016; Brown et al., 2016b). Ongoing studies on reindeer in the Jotunheimen area of Norway have allowed transfer to be modelled accounting for spatial and temporal factors. To improve knowledge on transfer of radioactive iodine, controlled I-131 tracer experiments with fistulated cows been performed to improve the biokinetic model. Field experiments with I-131 tracer were initiated at NIBIO's facilities in the west coastal area and inland in 2016, focusing the influence of climate/precipitation on transfer of iodine isotopes. Although dynamic transfer models have not, as yet, been included in standard assessment methodologies, the ongoing activities of Umbrella 2, in relation to extrapolation methods, have facilitated the further development of the ERICA Tool (Brown et al., 2016a).

Priorities for 2017-2021

RA2 research to date has demonstrated the influence of environmental and biological factors on radionuclide uptake in organisms, and for the first time dynamic transfer has been used to assess environmental impact following accidents (Fukushima). **From 2017, a new focus** will be on *characterizing transfer of radionuclides under field conditions* and comparison both between sites and between field and laboratory studies. *Controlled field experiments* will be performed to study uptake and depuration rates of radionuclides in organisms, and to simulate the impact of climate and nutrient status on transfer of I-131 and other RN/elements, *including comparative investigations between Chernobyl and Fukushim*a. Results will be used to further develop models which describe the dynamics of transfer within different ecosystems and accounting for the findings (e.g., ERICA dynamic tool).

The prevailing view is that further substantial progress can be made by parameterizing and validating (dynamic) models under controlled, experimental conditions and by comparative studies of areas with well described contamination. The key priorities for RA2 includes:

- Characterize the transfer of radionuclides under field conditions, identifying factors (physico-chemical, biological etc.) that influence the dynamics of transfer (e.g., observatory sites, field tracer studies). Thus, future studies within contaminated sites (observatory sites) such as Chernobyl and Fukushima, and NORM sites will be important to characterize transfer to both aquatic and terrestrial organism groups. Alongside field studies, controlled field experiments will be performed; 1) Controlled aquatic field experiment in contaminated lakes to study uptake and depuration rates of radionuclides in aquatic organisms, and 2) Controlled tracer field experiments to simulate deposition of I-131 and other RN/elements on agricultural land and study tracer redistribution between biological compartments.
- Investigate climate change impacts on transfer of radionuclides (characterize transfer at different temperatures) in different ecosystems and characterize transformation processes affecting radionuclides and stable analogues in aquatic mixing zones or estuaries where changes in speciation occurs, having major influence on biological uptake and effects.
- Quantify the effects of radionuclide speciation on dynamic uptake and biological half-life under controlled laboratory conditions (e.g., K_d, CR, TF/TC/Tag, BCR, tissue distribution and protein interaction). Thus, toxicokinetic studies in aquatic and terrestrial organisms will be prioritized to identify the impact of environmental parameters and competing ions along with studies of internal distribution in environmental organisms.
- Further development of models which describe the dynamics of transfer within different ecosystems and accounting for the findings (e.g., ERICA dynamic tool).
- Perform comparative investigations related to speciation, mobility and biological uptake as observed in Chernobyl and Fukushima

There are close connections between these priorities, and the model set up will be used in the experimental design: identifying what are the important parameters required by the model and how might these be derived through experimentation. The models can be used to make predictions and these can be tested through lab experiments and field observation. These considerations still hold true for the next 5 years.

2.3 Research Area 3 - Biological Responses

The main aim of RA3 is to generate new knowledge related to biological responses in organisms exposure to radiation that have implications for risk assessment and radioprotection of humans and the environment, to reduce the existing uncertainties. In this respect a major data-gap exists on effects following exposure of low doses and low dose rates to both humans and wild-life. Such effects cover apical endpoints like reproduction, cancer, embryonal development, and behavior. **The key research questions for RA3 are**:

- *Why are some organisms and life-stages more sensitive to stressors than others?*
- *How does the presence of other stressors, such as UV radiation, metals, changing temperature regimes etc., modify biological responses in organisms exposed to ionizing radiation?*
- *What mechanisms underpin the observed effects such as oxidative stress, genotoxicity, transcription and epigenetic regulation?*

To answer these questions, RA3 has been divided into three interlinked umbrella projects: UMB3A - Mechanisms determining species radiosensitivity; UMB3B - Combined toxicity and cumulative risk assessment; and UMB3C - Transgenerational hereditary, reproductive and epigenetic effects (Fig. 1).

The rationale is that each of these topics is essential to complete higher tiered risk assessments. Biological effects of radiation occur at the molecular/cellular level, and may affect individual organisms, populations or even entire ecosystems. The RA3 *primary tier* assessment (3A) considers single stressors and assessment of apical endpoints like mortality, growth, reproduction, cancer, pathological changes, embryonal development, tissue/cell damage, and behavior in individual species. Establishing and evaluating causal relationships between responses and effects occurring at different levels of organization is proposed, guided by principles outlined by frameworks such as Adverse Outcome Pathways, AOPs (Beyer et al., 2014; Groh and Tollefsen, 2015), genotoxicity, transcriptional changes and epigenetic regulation (Andersen et al., 2013, Aanes et al., 2013, 2014). *Secondary tiers* include 3B with focus on combined toxicity and cumulative risk in relation to multiple stressor exposure scenarios, and 3C transgenerational hereditary and epigenetics effects in directly exposed parents and their unexposed offspring. The data generated in RA3 will be used to populate and inform higher tiered risk assessment (RA4).

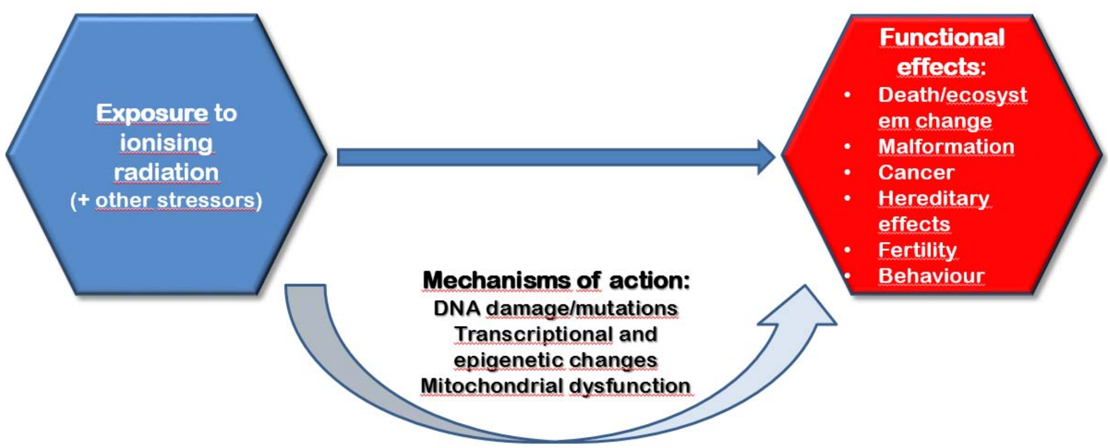

Figure 1. The work strategy in RA3. Biological systems are exposed to ionizing radiation (alone and in combination with other stressors, adverse functional effects are measured and are pursued by identification of the underpinning mechanisms of action.

The overall priority of RA3 for 2017-2021 is to *utelise comparative studies to explore mechanisms underlying radiosensitivity and variability between species and life-stages,* at using lower dose rates (sub mGy/h), to investigate processes affected at environmentally relevant doses, including antioxidant and nutrient status.

2.3.1 Umbrella 3A: Radiosensitivity

The overarching aim is to characterize differences in radiosensitivity between selected model species and to elucidate biological traits that determine the sensitivity of these species to ionizing radiation. Ultimately, identification of such traits should reduce uncertainties with regards to risk assessments and contribute to our understanding of why there are critical groups, both with humans and wildlife populations. Research is focused on chronic low to medium dose rate gamma radiation from the NMBU Co-60 source FIGARO, being uniform in terms of dosimetry and being relevant for rather contaminated ecosystems. The main hypothesis is that an organism's capacity to mitigate oxidative stress and thus maintain essential enzyme functions determines its ability to repair damage inflicted on essential macromolecules such as DNA. The indirect effects of ionizing radiation, particularly the formation of free radicals (ROS and RNS), can in turn damage cell components and cause perturbation in signaling systems and metabolism. It is further hypothesized that stem cells comprise the organismal function most susceptible to damage by radiation, and that 'late effects' such as developmental malformations, or reproductive defects, originate from damage to stem cell populations.

<u>Major Achievements 2013-2016</u>

A Biological Effects Toolbox has been produced, spanning twelve model organisms. The strategy is to develop a common set of tools and methods in order to conduct a systematic comparison of biological effects of low dose rate gamma radiation on model species, and to identify the cellular processes and underlying mechanisms that contribute to radiosensitivity. Experiments have been carried out on various life stages of salmon, zebrafish and daphnia, as well as plants, nematodes, earthworms and cell cultures (e,g, Song et al; 2014; Gomes et al., 2017; Graupner et al., 2016). The reasons for differences in radiosensitivity among species are not well understood at the cellular and molecular level, although factors like cell growth rate, DNA repair capacity, and life stage are known contributors. Accumulating evidence indicates that oxidative stress caused by radiolysis is an important modulator of toxic effect from chronic low dose rate radiation, and has been studied in CERAD both through comparison of response in different organisms, as well as in reporter organisms (nematodes).

Different mouse models have been exposed to gamma radiation: a DNA repair deficient model, two models prone to the development of blood cancer (acute myeloid cancer) and gastrointestinal cancer (colon cancer), and a model prone to developing Parkinson disease. Effects have been observed on functional endpoints such as reproduction, cancer development and behavior, all examples of adverse effects of ionizing radiation. Underpinning molecular changes such as genotoxic and mutagenic effects, genetic effects (Graupner et al 2016). Exposure of zebrafish show effects on hatching, embryonic malformation, DNA damage, oxidative stress, transcriptomics and epigenomics (see UMB3C for further details) and a dose-response effect on gene expression (Kamstra et al., 2015). Studies with early life-stage and juvenile salmonids show that tissue and transcriptional changes relevant for a number of toxic MoA were affected (e.g., Song et al, 2014). Experiments with *Daphnia magna* revealed that ionizing radiation caused ROS formation, lipid peroxidation, DNA damage (COMET), and transcriptional changes associated with known and novel toxicity pathways. Growth, development, photosynthesis and pigmentation was also affected in terrestrial and aquatic plants and algae (Gomes et al, 2017).

Table 1. The CERAD Biological Effects Toolbox.

Organism	Mortality	Growth/ Development	Histology/ Pathology	Reproduction	Genotoxicity DNA-Damage & Apoptosis	ROS/ Oxidative stress	Gene expression	Epigenetics	U3A Radiosensitivity Dose rate Range (mGy/h)	U3B Combined effects and cumulative risk	U3C Transgenerational, reproductive and epigenetic effects
Salmon	√	√	√	√	√	√	√	√	0.4-40	γ/U/Cd	ChpL
Zebrafish	√	√	√	√	√	√	√	√	0.4-40	γ /UV	F0-F3
Mice	√	√	√	√	√	√	√	√	0.2-100	γ /Se/As	F0-F3
Daphnia	√	√		√	√	√	√	√	0.4-100	γ /UV/U	DNAme
C. elegans	√	√	√	√		√			0.4-100	γ /U/Cd/As	
Earthworm	√	√	√	√	√			√	0.4-40		F0-F3
Norway spruce	√	√	√		√	√	√		1-540		
Scots pine	√	√	√		√	√	√		1-540	γ /UV	
Arabidopsis	√	√	√	√	√	√	√		1-540		
L. minor		√	√	√		√			10-100	γ /UV/As, Co, Zn, Mo, Cd, Cu, bifenox	
C. reinhartii		√				√	√		0.4-1600	γ /UV	
S. costatum		√				√			20-100	γ /UV	

Priorities for 2017-2021

Expanding and uteizing the CERAD Biological Effect Toolbox, **the new focus from 2017** *will be to investigate biomarkers at a functional level in selected model species and expand to include mechanisms such as mitochondrial dysfunction.* Comparative studies will focus on cellular processes that are particularly vulnerable to chronic gamma radiation, as well as biological responses associated with protective mechanisms, and adverse outcome pathway (AOP) analysis.

Toolbox development and biomarkers

- Potential target molecules/processes will be investigated at a functional level in selected model species, both mechanistically and for their usefulness as biomarkers of either exposure, effect or radiosensitivity.
- Preliminary results indicated that gametogenesis and stem cells are particularly susceptible to chronic radiation as well as the mitochondrial function and transcriptome changes, and will be prioritized within U3a. The Biomarker Toolbox will be refined and expanded in accordance with current new knowledge to include mechanisms such as mitochondrial dysfunction.

Comparative studies: effects and mechanism

- To progressively employ lower dose rate (sub mGy/h) experiments, enabling the investigation of processes that are affected at environmentally relevant dose rates

- To improve current understanding of effects induced by chronic radiation with emphasis on cellular processes that are particularly vulnerable to chronic gamma radiation, as well as biological responses associated with protective mechanisms

Comparative studies - radiosensitivity

- Common denominators between species or phylogenetic groups of species identified by canonical pathways and adverse outcome pathway (AOP) analysis, will serve to generate hypotheses for molecular mechanisms determining radiosensitivity.
- Based on current knowledge, it is anticipated that multigenerational exposures acerbate the effects of low dose rates. Thus U3A will employ suitable model organisms to perform multigenerational chronic exposures. Such experiments will be conducted in close proximity to transgenerational effects investigated within U3C

2.3.2 Umbrella 3B: Combined Toxicity and Cumulative Risk

In the environment, a series of stressors including inorganic and organics chemicals, radionuclides, and radiation (ionizing radiation and UV) can affect organisms. UMB3B aims to conceptually and experimentally characterize the impact of radiation (positive and negative effects) in combination with other stressors (metals, organic chemicals, UV) under different environmental conditions on ecological health, and to assess the cumulative risk. The main objectives are: 1) establish a thoroughly evaluated set of prediction models for combined effects and cumulative risk assessment (CRA) of multiple stressors ranging from the MOA to the adverse outcome; 2) apply these models to CERAD-relevant stressors, exposure scenarios, effect endpoints and species/life stages to experimentally and computationally characterized impact of multiple stressors having similar and dissimilar mode of action (MoA); 3) assess and reduce uncertainty CRA estimates of relevance for the approaches in RA4.

<u>Major Achievements 2013-2016</u>

A suite of bioassays ranging from cell-based assays (zebrafish cell line ZF4, human cell line TK-6, primary hepatocytes from salmonids) to analyses of whole organisms (algae, nematodes, crustaceans, fish, small aquatic plants, and earthworms) has been identified as suitable for combined toxicity assessments. Twenty stressors (including ionising radiation, UVA, UVB, metals and organic chemicals) out of approximately one hundred stressors assessed have been identified as significant on the basis of their MoA and environmental relevance. The role of an antioxidant (i.e. suboptimal selenium levels) on gamma exposed male mice demonstrated aggravated effects of gamma if the antioxidant status was poor (Graupner et al, 2015, 2016). Experimental studies focusing on MoA assessment, behavioral and adverse effect endpoints in selected species models (Scots Pine, *L. minor*, *C. reinhardtii*, zebrafish, salmon, zooplankton, human and fish cells) were used to decipher the combined effects of binary mixtures of selected multiple stressors such as ionizing radiation, UV and radionuclides (Song, et al., 2016, Jensen et al., 2016). Finally, recommendations on how to address combined toxicity and cumulative risk has been proposed (Beyer et al., 2016) and implemented in assessment of cumulative risk of radionuclides, metals and organic compounds under different ecologically-relevant exposure scenarios.

Priorities for 2017-2021

The main aim is to conceptually and experimentally characterize the impact of radiation (positive and negative effects) in combination with other stressors (metals, organic chemicals) under different environmental conditions, and to assess the cumulative risk. **The new focus from 2017** will be *an increased focus on the role of antioxidants and nutrients and to apply multivariate combined toxicity prediction models to identify additivity and departure from additivity (synergism and antagonisms) for relevant stressors*.

- Assess the combined effects of selected stressors as 1) binary mixtures, 2) ternary mixtures etc including antioxidants, in selected models and take speciation into account, using multivariate CT prediction models to identify additivity and departure from additivity (synergism and antagonisms) for relevant stressors.
- Characterize the role of stressor-stressor interactions, toxicokinetics and toxicodynamics on combined effects and CRA in collaboration with RA2.
- On the premise that the toxic action of radionuclides may have two MoAs: radiological toxicity and chemical toxicity, experimental studies will be performed with radioactive and stable isotopes of one specific nuclide to assess to which degree radionuclide toxicity is caused by chemical or radiation properties..
- Perform assessment and experimental studies with different radiation stressors and environmental/climate conditions (e.g. pH, temperature, sunlight, turbidity, salinity, nutrients/antioxidants, oxygen etc.) to assess the role of abiotic factors on the impact of single and multiple stressors.
- Expand, evaluate and demonstrate CRA approaches for CERAD relevant stressors and reduce prediction uncertainty so models can be successfully used for hazard and risk assessment purposes in RA4

2.3.3 Umbrella 3C: Transgenerational and Reproduction Effects

The main aim of this focus area is on reproduction, genotoxic effects and underpinning explanatory mechanisms involving transcriptomic and epigenetic regulation. Previous results obtained for selenium deficient male mice exposed to gamma had demonstrated reproduction failure when low antioxidant status is combined with stressors. By following the offspring of exposed parents (mice and zebrafish), it is possible to test the hypothesis that radiation exposures during gametogenesis can cause developmental and irradiation specific effects in offspring, and to link these to changes in gene expression and epigenetic landscape patterns.

Major Achievements 2013-2016

Parents and offspring from mouse models exposed in UMB3A have been followed and, a variety of endpoints are under analysis, and preliminary data indicate effects on behavior and development (learning), as well as global DNA methylation and the transcriptome (RNA sequencing; in prep) of both germline cells and somatic cells (Graupner et al, 2015). Information on transgenerational effects on reproduction in mice, with the low dose rates employed, suggest that the impaired reproduction in F0 is not propagated to the next generation .Zebrafish have been exposed during embryogenesis, gametogenesis and gametogenesis. Effects have been seen on hatching and embryonic malformation as well as transcriptomics and epigenomics (WGBS DNA methylation, ChIP-seq histone PTM and RNA-seq noncoding

RNA). The results of transgenerational studies demonstrate a wide spectrum of results from the endpoint analyses, including F2 and F3 effects on DNA methylation.

Priorities for 2017-2021

The main focus is to study mechanistic explanatory mechanisms that underpin reproduction and genotoxic effects. Results to date from mice and zebrafish, support the hypothesis that radiation exposures during gametogenesis can cause developmental and irradiation specific effects in F1 offspring and beyond, **From 2017 a new focus** will be to link these to *changes in gene expression and epigenetic landscape patterns*, in order *to support comparative studies and expand the mechanistic understanding of radiosensitivity*.

It is further hypothesized that stem cells comprise the organismal function most susceptible to damage by radiation, and that 'late effects' such as developmental malformations, or reproductive defects manifested subsequent to irradiation, originate from damage to stem cell tissues. These will be studied by experiments with selected species (mice, zebrafish) to obtain detailed understanding of apical effects and causal mechanistic changes (genotoxicity, reproduction, hereditary effects, transcriptomics, epigenetics). Specifically:

- Current efforts to generate radiation-induced landscapes of epigenetic regulation in selected species will be expanded, to obtain novel understanding of underpinning mechanisms as well as to perform comparative analyses between species, and establish links between epigenetic changes, molecular perturbations and adverse effects relevant for risk assessment in selected species.
- Resolve the importance of exposure of stem cells including germ stem cells for hereditary effects, embryo and relevant tissue stem cells for other apical effects. Since reproduction is an important effect with implications for humans and ecological systems, detailed studies of effects to the generation of germ cells will be pursued.
- Novel mechanisms of action identified in several species through transcriptome analyses during CERAD's first period will be pursued in more detail, such as mitochondrial dysfunctions/changes initiated as a result of low dose rate ionising radiation, as well as other environmental stressors.
- Development of a biomonitor zebrafish model will be initiated in 2017.

2.4 Research Area 4 - Risk Assessment and Ecosystem Approach

The aim of CERAD is to reduce the overall uncertainties in impact and risk assessments and thus increase the protection of man and the environment from harmful effects of ionising radiation, alone and in combination with other stressors. **Key issues in this regard** *include:*

- *How is uncertainty addressed in predictive modelling and risk assessment,*
- *What are the implications for risk management, decision-making, and risk communication?*
- *How might radiation effect ecosystems at the functional or ecosystem level?*
- *What are the socioeconmomic impacts of potential nuclear events?*

Firstly, by interfacing models linking sources and associated releases via ecosystems to impact and risks, and implementing research from RA1-RA4, the uncertainties associated with model predictions should be improved. Secondly there is an increasing focus on the effects and risk of low radiation doses at the community or ecosystem level, moving beyond the single species exposure and impact assessment. Field studies of the impacts of radionuclides have attracted much attention and controversy in radioecology in recent years, not least due to purported effects at doses much lower than those seen in the laboratory (Strand et al., 2014; Brechignac et al, 2016). Finally, there is an increasing recognition that radiation protection needs also to address socioeconomic impacts (IAEA, 2015). As an extension, the economic estimates can be used to make more informed choices on which studies for reducing uncertainties should be undertaken next – when time and funds are scarce.

The impact and risks associated with potential nuclear events, CERAD "Flagship Case Studies", have been selected to assess the potential impact to Norway, by linking a hypothetical source term and deposition to ecosystem transfer, biological uptake and effects relevant to man and the environment, to assess impact on health and the environment as well societal and economic consequences. By sensitivity analysis, factors contributing the most to the overall uncertainties can be disclosed, setting the priorities for the research in RA1-RA3.

To address these objectives, RA4 pursues the development and use of: 1) Laboratory and field studies in an **ecosystem approach** (UMB4A); 2) **Nuclear Events –** assessing impact and risk from specific sources (UMB4B), and **Societal impacts** associated with socioeconomics, risk communication, risk perception and stakeholder dialogue (UMB 4C). The work of RA4 is linked to source term characterization and dosimetry (RA1), assessment of transfer and exposure (RA2), organism and population effects (RA3) and field work conducted in all RAs.

The overall priorities for 2017-2021 are *to apply the ecosystem to improve links between field and laboratory studies*, to use *potential nuclear events* to assess impact and risk from specific sources, and to *assess societal impacts* associated with socioeconomics, risk communication, risk perception and stakeholder dialogue.

2.4.1 Umbrella 4A: Ecosystem Approach

The main aim is to evaluate the consequences of ionizing radiation and radioactive contamination on non-human biota on a higher level of organization, i.e. how do effects of radiation manifest themselves at the community/ecosystem level. The knowledge of radiation effects in radioecology today is mainly based on direct effects on single species in the laboratory or field. The key challenge is to translate this knowledge to cover multiple species ecosystems together with the abiotic part of the environment. Our overarching hypothesis is that ecosystem interactions and processes (e.g. food chain interactions, competition between and within species, changes in biodiversity) can result in indirect effects from exposure to ionizing radiation.

Major Achievements 2013-2016

CERAD's ecosystem approach research was initiated in 2015 and has important links to the International Union of Radioecology (IUR), including a task group for reviewing experimental ecosystem approaches (e.g., micro- and mesocosm studies). CERAD also co-organised the Miami Ecosystem Approach Consensus Workshop with IUR (Brechignac et al, 2016). An aquatic microcosm experiment was performed in 2016 and an extensive number of endpoints has been measured after extended low dose gamma radiation exposure. The soil - plant microcosm experiments are closely linked to fieldwork in Fen, where plant studies have been performed, including plant diversity mapping along a gradient of gamma radiation, soil fauna assessment. As part of the field studies in Chernobyl and Fukushima, sampling and mapping earthworm species diversity has also been carried out to assess whether changes to community structures could be documented.

Priorities for 2017-2021

Future priorities are based on the premise that stronger links between laboratory and field studies will improve understanding of the ecological impacts of ionizing radiation. The central hypothesis is that radiation can induce ecosystem changes through indirect effects that transcend direct impacts on individual species. **From 2017,** the focus will be on the continued *use and development of microcosms and improving links between laboratory experiments and field studies* by assessment of the same ecosystem compartments, organisms and endpoints. The central hypothesis is that radiation can induce ecosystem changes through indirect effects that transcend direct impacts on individual species. Information from laboratory experiments will help in understanding the responses of natural ecosystems that can be studied in the field (for example Fen, Chernobyl, Fukushima).

- Improve links between laboratory experiments and field studies by assessment of the same ecosystem compartments, organisms and endpoints, identifying confounding factors influencing ecosystem responses (contaminants, antioxidants, temperature, humidity, light etc.), and improving dosimetry linked to wildlife (passive or dynamic dosimeters on GPS labelled animals), and in field ecosystem studies (links to RA1 and RA2)
- Investigate possible adaptation (or increased sensitivity) of chronically exposed field species by testing their response to laboratory exposure of radiation (or other stressors)
- Combine studies on radionuclide transfer and effects in microcosms, on the hypothesis that the interplay of several species and abiotic microcosm components can impact both radionuclide transfer, uptake and effects.

2.4.2 Umbrella 4B: Potential Nuclear Events - impact and risk assessment

The main aim is to evaluate and improve impact and risk assessment tools for establishing a scientifically based set of decision criteria. Impact and risk assessments rely on compiling relevant information of the source term and deposition, ecosystem transfer, biological uptake and effect to determine if exposure scenarios encountered under normal conditions or emergency situations (incidents/accidents/malevolent acts) represent a risk to humans and wildlife. By sensitivity analysis, factors contributing the most to the overall uncertainties can be disclosed, thus setting the priorities for the research in RA1-RA3.

Major Achievements 2013-2016

The Western Norway case study, which covers the continuum from a source and release scenario to impact to man and the environments, is a cross-cutting activity that involves all CERAD partners and RAs. The success of coupling of various models has been demonstrated, linking the source and release scenario to impacts (i.e., atmospheric dispersion, aquatic/marine/terrestrial deposition and ecosystem transfer, uptake and potential effect in biota and man, as well as socioeconomic impacts). Models have been adapted to Norwegian conditions to predict the total impact of radioactive releases affecting Norwegian territories (e.g. Brown et al, 2016a). Key factors contributing to major uncertainties in each model have been identified and quantified and the need for model improvement defined. Several of the models have been applied to assess potential impact in Norway from the sunken Russian submarines K-27 at Novaya Zemlya (Bartnicki et al, 2016; Brown et al, 2016b; Hosseini et al, 2016a), and K-59 north of Murmansk (Gwynn et al., 2014).

CRA framework addressing the overall risk of NORM and chemical stressors has recently been introduced and demonstrated in several cases studies as described in RA3 (U3C). In addition, the development of a dynamic ERICA risk assessment tool is expected from RA2 (Brown et al., 2016a), and should be utilized for a variety of scenarios.

Priorities for 2017-2021

The main aim is to evaluate and improve impact and risk assessment tools by establishing a scientifically based set of decision criteria. **The main new focus for 2017** will be to include other relevant radionuclides than ^{137}Cs such as ^{131}I, ^{90}Sr, U and Pu isotopes in models, and *introduce new potential nuclear threats, including safety and security events of relevance for Norway*. This will be achieved by building on scenarios introduced during the first CERAD period.

- Identify factors contributing the most to the overall uncertainties in individual model predictions, and when combined, and quantify inherent (natural) variability
- Include other relevant radionuclides than ^{137}Cs such as ^{131}I, ^{90}Sr, U and Pu isotopes in models, and reduce uncertainties in the models by:
  - Obtaining and implementing local data in models for prioritized parameters
  - Implementing relevant processes as time functions and speciation e.g. log normal particle size distributions in the aquatic models
- Implement dynamic ecosystem transfer (agriculture, semi-natural, aquatic), and the Cumulative Risk Assessment framework to the model chain
- Develop probabilistic modeling methods to make quantitative estimates of uncertainties related to accident scenarios, transport and deposition, i.e. developing a) ensemble transport models (including optimal ways to perturb the ensemble members) and b) statistical analysis and presentation methods to go with ensemble datasets.
- New potential nuclear events to be investigated
  - Potential nuclear event within Norway
  - Potential nuclear events in the Arctic, on land or dumped in the seas
  - Safety and security events, also involving nuclear forensics

2.4.3 Umbrella 4C: Societal Impacts - socioeconomics, risk communication, risk perception and stakeholder dialogue

The overarching aim of UMB4C is to evaluate the broader consequences of radiation events and show that effects go beyond the direct effects of radiation contamination, and incorporate a range of economic, societal, and ethical impacts. Evaluation of these aspects requires multidisciplinary approaches between natural and social scientists to understand and present the total societal challenges. It is hypothesized that economic and societal impacts are, in turn, influenced by the way the risks are perceived and communicated. Stakeholder dialogue is adopted as a particularly important method of risk communication, as it can facilitate multidisciplinary assessment of risks. While sensitivity analysis carried out in UMB4B provides information on which factors contribute the most to the overall uncertainties, costbenefit analysis would inform what mitigating effort would be needed to counteract the foreseeing impact and risks.

Major Achievements 2013-2016

Two local stakeholder dialogue workshops directly related to the Western Norway scenario were arranged and proved that collaborative deliberation contributes to increased learning, networking, involvement and problem solving compared to pure information provision (Liland et al, in press). Socioeconomic analysis were undertaken for two case studies: valuing lost recreational value from restricting fishing in the Western Norway scenario and investigating the willingness-to-pay for radon risk reducing measures. These studies point to further applications using the extended expected utility and economics of information frameworks. The multidisciplinary competence within UMB4C has also supported a number of international studies and reviews of societal and ethical aspects of radiation protection and radioecology (Liland, 2015, Oughton, 2016). Risk communication and risk perception have been addressed in media analyses and highlighted unjustified bias in media presentation of radiation risks (Tomkiv et al, 2016).

Priorities for 2017-2021

The overarching aim is to evaluate the broader consequences of radiation events and show that effects go beyond the direct effects of radiation contamination. **The new focus from 2017** will be to *evaluate the social/ethical/economic aspects of remediation and mitigation actions*, including the cultural impacts of restricted ecosystem services (e.g., restricted access to recreational areas).

- Evaluate the social/ethical/economic aspects of remediation and mitigation actions, including the cultural impacts of restricted ecosystem services (e.g., restricted access to recreational areas). Assess the ethical implications of health surveillance and epidemiological studies after accidents, including the way in which variability between critical groups is addressed in radiation protection.
- Include risk perception and risk communication studies to improve the understanding of information needs and factors influencing public perception of radiation risk. Continue with stakeholder dialogues as a mechanism for improving case studies and scenario analysis.
- Investigate the scope for using the economics of information framework to make more informed choices on which studies have the greatest potential of reducing uncertainties.

2.5 Implementation Plan

A Gantt chart of the Implementation Plan is provided in Table 2. The timing of research activities has been adapted to promote co-ordination across the research areas, particularly with respect to field expeditions and experiments, the potential nuclear event case studies, and laboratory transfer and effect studies (including microcosms). The plan also considers how the obtained knowledge and data will feed into model, risk assessment and uncertainty analysis.

TABLE 1: Implementation Plan Gantt Chart

RA	Task	2017				2018				2019				2020				2021			
		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
RA1																					
U1A	Implement relevant particle properties in models	X	X	X				X	X	X	X				X	X	X	X			
U1A	Dose assessments of uneven depositions and UV/gamma		X	X	X	X					X	X	X	X	X	X				X	X
U1A	Risk estimation (emergency preparedness/nuclear forensic purposes)						X	X	X						X	X	X			X	X
U1B	Atmospheric modelling - topographical and particle property effects	X	X	X	X	X			X	X	X	X	X	X		X	X	X	X		
U1B	Implementation of radar, satellite and radiation detection network data			X	X	X			X	X	X	X	X	X		X	X	X	X		
U1B	Aquatic modelling		X	X	X	X	X	X	X	X	X					X	X	X	X		
U1C	Theoretical model for unified dose/risk concept											X	X	X	X	X	X	X	X	X	X
U1C	Combined dosimetry, implement with meteorological and UV-network modelling	X				X	X	X	X	X	X	X	X								
U1C	Ionizing dosimetry, Figaro and field	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
RA2																					
U2	Field studies- Chernobyl, Fukushima, Fen		X	X			X	X			X	X			X	X					
U2	Field studies - Jotunheimen		X	X																	
U2	Controlled field experiments with tracers - NIBIO		X	X			X	X			X	X			X	X					
U2	Controlled aquatic field experiment - Chernobyl, Fukushima						X	X			X	X			X	X					
U2	Controlled laboratory experiments (daphnia, salmon, plants)			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		
U2	Model development - dynamic reindeer	X	X	X	X																
U2	Model development linked to tracer field			X	X	X	X	X	X	X	X										
U2	Model development - Kinetic freshwater aquatic					X	X	X	X	X	X	X	X	X	X						
U2	Model development - generic dynamic ERICA	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
RA3																					
U3A	Development and Application of the Biomarker Toolbox - low dose rates	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X					
U3A	Investigate biomarkers at a functional level in selected model species				X	X	X	X	X	X	X	X	X	X	X	X	X				
U3A	Comparative studies using Adverse Outcome Pathways			X	X				X	X	X	X	X	X	X	X	X	X	X	X	X
U3B	Studies to assess Combined Effects in animals, plants and cells	X	X	X	X	X	X	X	X	X	X	X	X	X	X						
U3B	Studies to assess role of climate and antioxidants	X	X	X	X						X	X	X	X	X	X	X				
U3B	Expand, evaluate and demonstrate CRA approaches		X	X	X	X	X								X	X	X	X	X	X	X
U3C	Comparative studies, AOP and multigeneration	X	X	X	X						X	X	X	X	X	X	X	X	X	X	X
U3C	Link changes in gene expression and epigenetic landscape patterns				X	X	X	X	X	X	X	X	X					X	X	X	X
U3C	Stem-cell studies			X	X	X	X	X	X	X					X	X	X	X	X	X	
RA4																					
U4A	EA terrestrial field studies (biodiversity, indirect effects etc.)		X	X			X	X			X	X			X	X					
U4A	Aquatic and terrestrial radioecological microcosm studies			X	X	X	X	X	X	X	X	X	X	X	X	X					
U4A	Dosimetry for EA radiation effect studies and data analysis				X	X			X	X			X	X			X	X	X	X	X
U4B	Add new potential nuclear events	X	X						X	X						X	X				
U4B	Develop, improve and expand new and existing models		X	X	X	X				X	X	X					X	X	X	X	
U4B	Implement improved and new models					X	X	X				X	X	X	X				X	X	
U4B	Evaluate reduction in model uncertainties							X	X						X	X				X	X
U4C	Evaluate social/ethical/economic/cultural aspects of remediation/mitigation actions	X	X	X	X	X	X	X	X				X	X	X	X	X	X			
U4C	Perform risk perception and risk communication studies	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
U4C	Assess the economics of information as development prioritsation tool	X	X	X	X	X	X														

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