Norwegian Centre of Excellence

CERAD

CENTRE FOR ENVIRONMENTAL RADIOACTIVITY

ANNUAL REPORT 2017

Norwegian University of Life Sciences

Norwegian Centre of Excellence

CERAD

CENTRE FOR ENVIRONMENTAL RADIOACTIVITY

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Coverpage (back): Zebrafish tank. Photo: Selma Hurem

Coverpage, inside: Lake Glubokeye in Chernobyl. Photo: Hans-Christian Teien

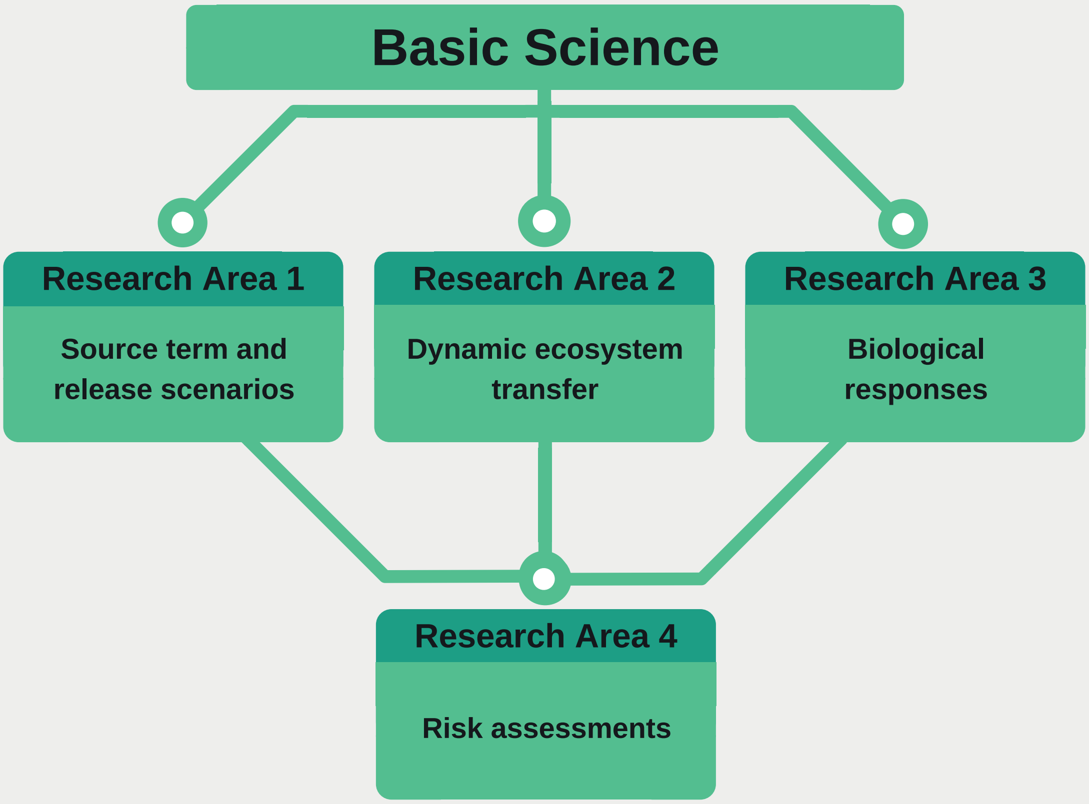
CERAD

CENTRE FOR ENVIRONMENTAL RADIOACTIVITY

WHO ARE WE?

CERAD Center of Excellence improves our ability to assess radiological impact and risks associated with environmental radioactivity, also in combination with other stressors. By focusing on key factors contributing to uncertainties, state-of-the-art tools and methods are developed to better manage those risks. The scope includes radionuclides released in the past, those presently released, and those that potentially can be released in the future from the nuclear weapons and fuel cycles as well as from non-nuclear industries.

RESEARCH ORGANIZATION



CERAD IN NUMBERS IN 2017

- **107** Full-time and part-time employees
- **10** Course modules at NMBU/CERAD
- **43** Internationally published articles
- **51.9** Revenues in MNOK

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Norwegian University of Life Sciences (NMBU)

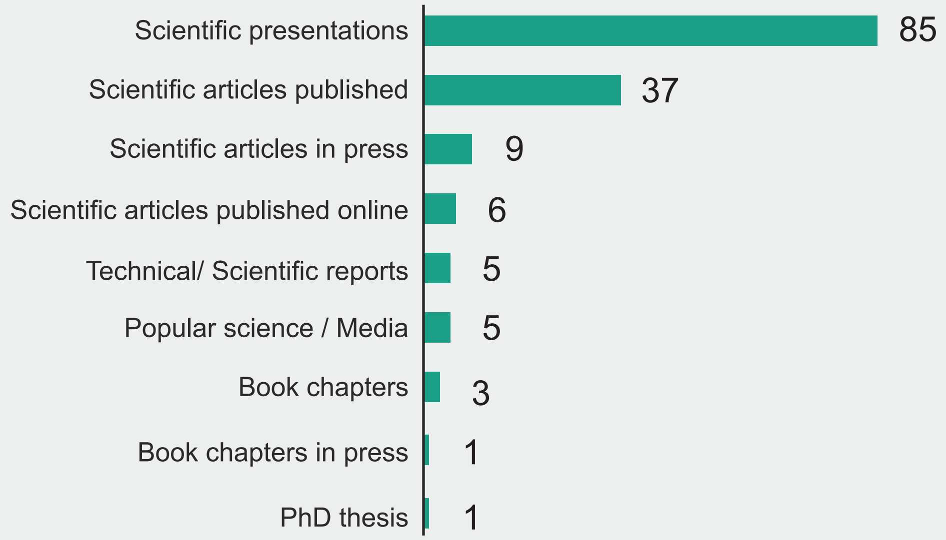
Statens strålevern – Norwegian Radiation Protection Authority

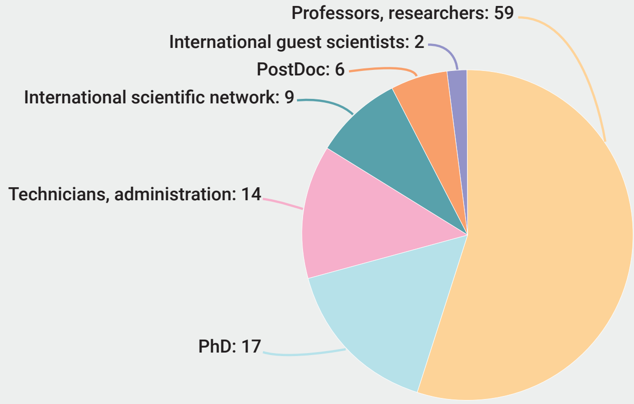
NIVA – Norwegian Institute for Water Research

Norwegian Institute of Public Health

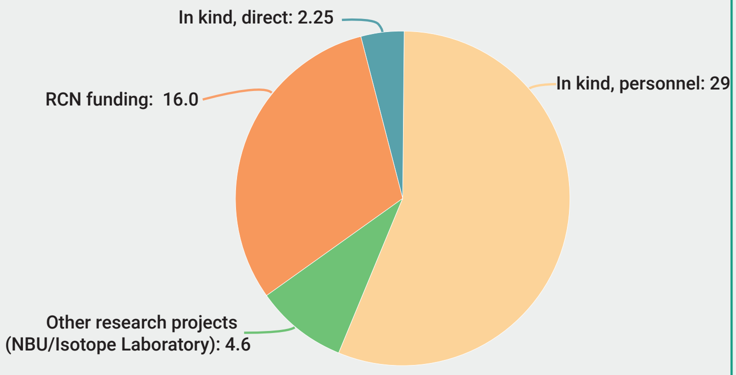
Meteorologisk institutt

Scientific results in 2017





Full- and part-time personnel in 2017



Funding 2017 in MNOK

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CERAD 2017 - In Short

According to the international Mid-term Evaluation Committee established by the Research Council of Norway (RCN): “CERAD is a global Centre of Excellence and a flagship for Norwegian science with an agenda that is also highly relevant for society.“ In the summary, they also stated: “The scientific results are excellent in terms of publication quantity and very good for publication quality.”, and that “CERAD is unique, both in the research field and support of policy development in Norway and internationally in the field of risks from radioactivity.“ We are therefore very pleased with the statements given by the RCN Evaluation Committee in 2017.

Since 2013, the Center of Environmental Radioactivity (CERAD), a Center of Excellence (CoE), has improved the ability to assess radiological impact and risks associated with environmental radioactivity. By focusing on key factors contributing to the uncertainties, new and state of the art tools and methods have been developed to better manage those risks. The scope includes radionuclides released in the past, those presently released, and those that potentially can be released in the future from nuclear weapons and fuel cycles as well as from non-nuclear industries. Thus, the research is linking source term and release scenarios to ecosystem transfer, biological uptake and effects in organisms exposed to radiation combined with other stressors. The assessments include possible impact on human and non-human organisms, as well as economic and societal consequences. As the present research effort of CERAD has contributed significantly to radioecology internationally, it is believed that the revised CERAD research focus (SRA 2017-2021) will play a major role when priorities are set on the international arena in the years to come.

MG Group

Professor Brit Salbu,
Center Director

Professor II Per Strand,
Deputy Director

Professor Lindis Skipperud,
Director of Education

Professor Deborah H. Oughton,
Director of Research

Jorunn Hestenes Larsen,
Management Director

CENTRE FOR ENVIRONMENTAL RADIOACTIVITY

Comments from the CERAD Director Brit Salbu

Following the RCN Mid-term evaluation in 2017, I am very pleased to conclude that the CERAD research initiated in 2013 has been successful with respect to the selected key research areas, to achievements obtained so far (more than 150 published articles), and to integration of more than 60 part time scientists representing different scientific fields, different culture and different institutions. By focusing on common goals, hypotheses and research questions, a holistic long-term research program on source terms and release scenarios, ecosystem transfer, biological responses forming the basis for impact and risk assessments has been developed. Thus, the scientific program of CERAD is much more ambitious than anything hitherto attempted within radioecology in Norway, and no single partner could achieve obtained results without the strong support from other partners or international collaboration.

Since 2013, CERAD CoE has improved the assessment of impact and risks from environmental radioactivity, also combined with other stressors. By focusing on key factors contributing to overall uncertainties, the overarching research objective has focused on 4 overarching Research Areas (RA1 – RA4). Extensive work has been performed within 4 promising research projects in progress:

• ***Potential nuclear events - Case studies:***
The hypothesis is that present impact and risk assessments are associated with unacceptably high uncertainties, especially due to conceptual problems. Thus, the goal is to reduce the overall uncertainties in the assessment, by linking 8 different models in a chain, from the source term implementing possible particle characteristics (RA1), via ecosystem transfer implementing dynamic concepts (RA2), to effects on early life stages of exposed organisms (RA3), utilizing site specific input data obtained from field expeditions. This combined model approach is utilized for a series of exposure scenarios such as emergency situations (incidents/accidents/malevolent acts) *e.g.*, sunken submarines, moving nuclear vehicles or existing exposure sites (alum shale areas) involving a series of radionuclides and metals. We were very pleased to see the EU CONCERT 1st Call text 2016, focusing on uncertainties in line with the CERAD concept.

• ***Linking particle characteristics to sources and effects:***
Following severe nuclear events, a major fraction of refractory radionuclides (U, Pu) is associated with particles, ranging from submicrons to fragments. The overall hypothesis is that the composition of particles depends on the source, while particle properties (size, structure, density, oxidation state) also depend on release scenarios. Based on the unique NMBU particle archive and close international collaboration as well as advanced technology, experiments have demonstrated particle retention in non-human organisms in laboratory experiments (*e.g.*, blue mussels, nematodes) and in free-living animals (snails) in the field.

• ***Comparative Radiosensitivity:***
The main research question is Why are some organisms more sensitive than others? The hypothesis is that an organism's capacity to mitigate oxidative stress and thereby maintain essential enzyme functions determines the ability to repair damage inflicted on essential macromolecules such as DNA. Based on the unique NMBU gamma facility and the development of the unique Biological Effect Toolbox, 12 different test organisms have been exposed to a range of gamma radiation dose rates/doses to identify responses. Thus, comparative studies on effects and mechanism are performed with emphasis on cellular processes that are particularly vulnerable to chronic gamma radiation, and on biological responses associated with protective mechanisms.

• ***Differentiating Uncertainties - variability:***
The hypothesis is that extrapolation of impacts from laboratory to the field is complicated; lab experiments give insights into mechanisms that are not possible in

the field, while field studies are the only opportunity for studying long term impacts of ionising radiation under natural conditions. CERAD has a number of different field based projects that should: 1) improve the links between field observations and field experiments mimicked in lab, and 2) address effects that are not possible to study using single species lab experiments. Comprehensive fieldwork initiated in Chernobyl and Fukushima should allow exposure and effects observations to be compared, such as the implementation of clean fish into contaminated lakes in Chernobyl demonstrating that "handbook" transfer coefficients to fish need revision.

To support the CERAD research, the infrastructure has been renewed, access to different international advanced platforms has been obtained, and expeditions to a series of radioactive contaminated sites have been organized in close collaboration with international partners. CERAD politics include collaboration with other organisations nationally and internationally. Thus, the centre has participated in a series of EU projects since 2013, including the EU CONCERT SHAMISEN, CONFIDENCE and TERRITORIES projects from 2016, focusing on uncertainties in impact and risk assessments in accordance with the CERAD policy.

An essential ingredient in CERAD is researcher training and education (MSc, PhD) to produce candidates that are internationally competitive. We are therefore very pleased to have recruited a total of 24 PhDs (6 defended their work) and 9 PostDocs to CERAD since 2013. The MSc in Radioecology and the established Research School are unique in Europe. The course modules (in English) are run intensively to make access possible for international students. EU projects (*e.g.*, CONCERT) contributed to MSc course modules also in 2017, and the EU STAR/COMET E&T platform developed by NMBU (www.radioecology-exchange.org/) is the international link to education in Radioecology. Based on close collaboration with other universities, Memorandum of Understanding (MoU) agreements concerning research and E&T have been established with a series of universities and research institutes. Intensive field courses have also been given abroad such as the EU COMET field course within the Chernobyl exclusion zone in Ukraine.

In addition to NMBU (4 faculties), CERAD includes 4 partners (NRPA, MET, NIVA, NIPH). Due to reorganization, Prorector Øystein Johnsen, NMBU, was appointed Chairman, Professor Sjur Baardsen was appointed NMBU member and Research Director Lars-Anders Breivik was selected MET member of the CERAD Board in 2017. In January 2017, a successful CERAD conference was organised at the Norwegian Academy of Science and Letters with more than 75 participants, including representatives from CERAD's international network (SAC) and national stakeholders (RAC).

CERAD plays an active role on the international arena (*e.g.*, ICRP, UNSCEAR, IAEA, IUR). More than 80 conference presentations were given in 2017. During the years, a series of CERAD supported international conferences and workshops have been organised nationally and internationally (*e.g.*, the ICRER conference, Berlin, and the ICCE conference, Oslo, in 2017).

It has been a 5-year long pleasure to be the director of CERAD, a research organization with highly competent scientists producing highlights, in close collaboration with a strong international network including the Scientific Advisory Committee, with the support of national stakeholders included in the Relevance Advisory Committee.

Professor Brit Salbu,
Center Director
Photo: Gisle Bjørneby

Comments from the Chair of the CERAD Board Øystein Johnsen

CERAD will provide new scientific knowledge and tools for better protection of people and environment from harmful effects of radiation. In 2017, an international committee of experts conducted the mid-term evaluation of CERAD, according to high international quality standard procedures. The board of CERAD regards the statements in the evaluation report as a benchmark of profound scientific progress in terms of quality, quantity and societal impact. We are both proud and impressed by the scientific achievements obtained so far. Thus, halfway through its program period, CERAD is accomplishing what it set out to do: To be a centre of excellence in its field!

The Strategic Research Agenda (SRA) for 2017 – 2021 points to further progress and success for the next five years, and all the partners will most likely continue their collaborative commitments even after the financial support from the RCN ends. Thus, CERAD will certainly develop an exit strategy that will benefit all the partners involved, and the scientific progress in the fields of radioecology and radiological protection.

The evaluation report acknowledged and recognized an outstanding, visionary leadership, an organization with a "strong sense of collective responsibility", empowered by the management group and team leaders, and enhanced by the excellent work of the scientific and administrative staff. There is no easy way to attain the ambitious aims of CERAD, other than hard work, performed by scientists with strong intellects and creative minds, enthusiasm, good sense of humor, and a mixture of young mid-career researchers, ph.ds, postdoctoral fellows, associate professors and experienced professors.

CERAD is unique in the sense that the research targets wicked and very complicated problems, requiring an interdisciplinary approach, involving policy development aspects in Norway and internationally in the field of risks assessments from radioactivity. Thus, there is a continuing need to bring together the diversity of competence and skills from all the collaborating partners in their work to identify, characterize and quantify important uncertainty factors.

Moreover, the evaluation committee anticipate that CERAD certainly will influence international research priorities in radioecology, such as the SRA of the European Radioecology Alliance and provide valuable contributions to international organizations, including The United Nations Scientific Committee on the Effects of Atomic Radiation, the International Commission on Radiological Protection, the International Atomic Energy Agency and the International Union of Radioecology. This indicates that CERAD represents the state of the art research, setting the agenda of the international knowledge, as well as pinpointing knowledge gaps.

On behalf of the board, I am grateful for the contribution from our international collaborators, the huge effort from all researchers, research leaders, the administration, and the impressive work done by the program director, Professor Brit Salbu. It has been a great pleasure to be part of the CERAD Board together with representatives from our four partners, Norwegian Institute of Public Health, Norwegian Meteorological Institute, Norwegian Institute for Water Research and Norwegian Radiation Protection Authority. Thanks for the enthusiastic engagement, collaboration and friendly atmosphere.

Øystein Johnsen,
Chair of the Board
Photo: Gisle Bjørneby

Radiation warning at Figaro
Photo: Bjørn Johnsen

Management and Administration

The CERAD Board

The CERAD Board has 8 members, representing all partners and the scientific staff from all the partner institutions, where NMBU Pro-Rector of Research is chair and CERAD Management Director acts as secretary for the board. The CERAD Deputy Centre Director, Research Director and Education Director take part as observers only. The board meets twice a year to secure cooperation within CERAD, financial issues as well as effective well-functioning collaboration between the partners.

The CERAD Board members until November 2017 have been:

- Pro-rector Halvor Hektoen, NMBU, Chair
- Director General Ole Harbitz, NRPA, Deputy chair
- Department Head Jan Vermaat, NMBU
- Division Director Toril Attramadal, NIPH
- Deputy Managing Director Tor-Petter Johnsen, NIVA
- Research Director Hilde Fagerli, MET
- Scientist Dag Anders Brede, NMBU
- Centre Director Brit Salbu, CERAD

Due to reorganization, the CERAD Board members from December 2017 are:

- Pro-rector Øystein Johnsen, NMBU, Chair
- Director General Ole Harbitz, NRPA, Deputy chair
- Dean Sjur Baardsen, NMBU/MINA
- Division Director Toril Attramadal, NIPH
- Deputy Managing Director Tor-Petter Johnsen, NIVA
- Research Director Lars-Anders Breivik, MET
- Scientist Dag Anders Brede, NMBU
- Centre Director Brit Salbu, CERAD

CERAD Scientific Advisory Committee

The CERAD Scientific Advisory Committee (SAC) is CERAD´s international scientific network, headed by the CERAD Research Director and includes 9 internationally well–merited scientists from 8 countries (USA, Ukraine, Slovenia, Belgium, Sweden, Canada, Australia, Japan). SAC members have been actively involved in the development of the Strategic Research Agenda (SRA) and are invited once a year to the CERAD annual conference. The Scientific Advisory Committee (SAC), CERAD international network 2017, has been:

- Dr. David L. Clark, National Security Education Center, Los Alamos National Laboratory, USA
- Professor Valeriy Kashparov, National University of Life and Environmental Sciences of Ukraine, Ukraine / Professor II, NMBU
- Professor Koen Janssens, University of Antwerp, Belgium
- Professor Peter Stegnar, Jožef Stefan Institute, Slovenia
- Professor Carmel Mothersill, McMaster University, Canada
- Professor Colin Seymour, McMaster University, Canada
- Professor Tom Hinton, Fukushima University, Japan / Professor II, NMBU
- Dr. Clare Bradshaw, Stockholm University, Sweden
- Professor Janet Bornman, Curtin University, Australia

CERAD Relevance Advisory Committee

The CERAD Relevance Advisory Committee (RAC) is headed by the CERAD Deputy Director and includes representatives from key Norwegian stakeholders/end-users. The RAC meets once a year at the CERAD conference. In 2017 the RAC includes members from:

- The Ministry of Health and Care Services, Lisbeth Brynildsen
- The Ministry of Climate and Environment, Ingvild Swensen
- The Ministry of Foreign Affairs, Anja Polden
- Norwegian Radiation Protection Authority, Kristin Frogg

CERAD Research Management

The CERAD Management Group (MG) is responsible for running the research management of the Center and consists of the CERAD principal investigators, headed by the CERAD Director (Fig. 1). The Management Director is in charge of the day-to-day running, including budgeting, according to decisions made by the Centre director and MG. The CERAD MG reports to the CERAD Board, and includes:

- CERAD Director: Brit Salbu, Professor, NMBU
- Deputy Centre Director: Per Strand, Department of Nuclear Safety and Environmental Radioactivity, NRPA / Professor II, NMBU
- Education Director: Lindis Skipperud, Professor, NMBU
- Research Director: Deborah H. Oughton, Professor, NMBU
- Management Director: Jorunn Hestenes Larsen, NMBU

The Extended MG includes the MG and the Research Area (RA) leaders (2 leaders per RA, RA1-4), representing all CERAD partners. The RA leaders report to the CERAD MG and CERAD Research Director. The CERAD research area leaders in 2017 were:

- RA1: Ole Christian Lind, NMBU and Heiko Klein, MET
- RA2: Justin Brown, NRPA and Hans-Christian Teien, NMBU
- RA3: Peter Aleström, NMBU and Ann-Karin Olsen, NIPH
- RA4: Knut Erik Tollefsen, NIVA and Astrid Liland, NRPA

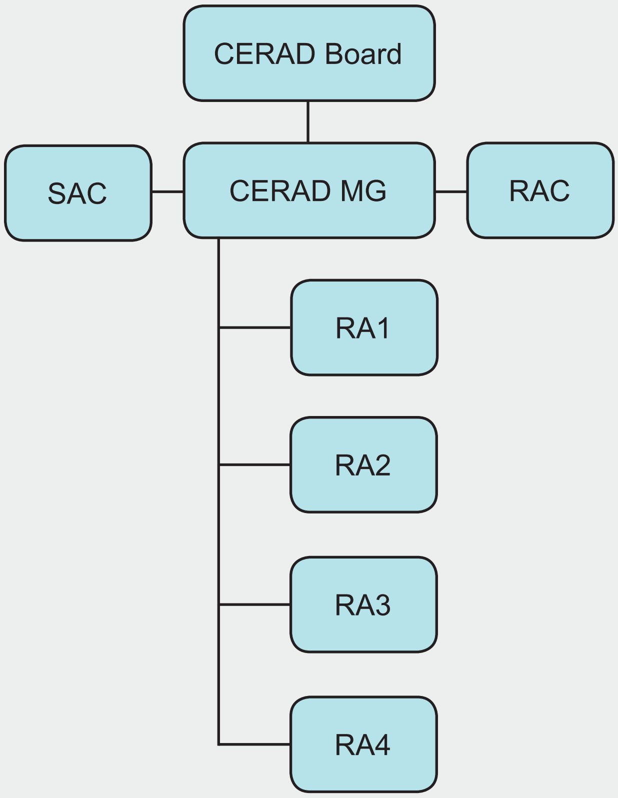

Figure 1. *The CERAD research organization*

The Extended MG meets once a month to follow the progression of the funded research, to report findings that should be pursued, to suggest new or revised research topics, and to ensure that the research is of an international standard.

Research and Strategic Research Agenda

CERADs research is organized around four Research Areas (RA) outlined in the CERAD Strategic Research Agenda (SRA). This means that CERAD's research is structured according to science rather than partner locations, which fosters a high degree of interinstitutional and interdisciplinary collaboration. 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.

The SRA 2013 was structured around four overarching Research Areas together with a transient research area RA5 focusing on UV Exposure. In 2015, emphasis was put on eight large umbrella projects within the RAs, while the UV research was merged into RA1-4 in 2017 in accordance with the original research plan. The current CERAD SRA (2017-2021) presents an overview of CERAD research activities and achievements, hypotheses and approaches to testing those hypotheses, and sets priorities for the next five year period (see www.nmbu.no/cerad). All research areas include participation of at least three CERAD partners.

The links between the research areas are illustrated in figure 1: by linking sources and associated release scenarios (RA1) via ecosystem transfer (RA2) as well as biological uptake and effects (RA3) to impact and risks as well as the overall uncertainties associated with model predictions should be assessed (RA4). By focusing on those factors contributing the most to uncertainties, the predicting power should be improved.

The following sections present the overarching objectives of the four research areas and underlying umbrella projects, together with selected research highlights from 2017. An overview of the major achievements over the past five years can be found in the full SRA as well as the Annual Report for 2016. The full SRA also provides more details on the priority research areas for 2017-2023. References can be found in the list of scientific articles in appendix A.

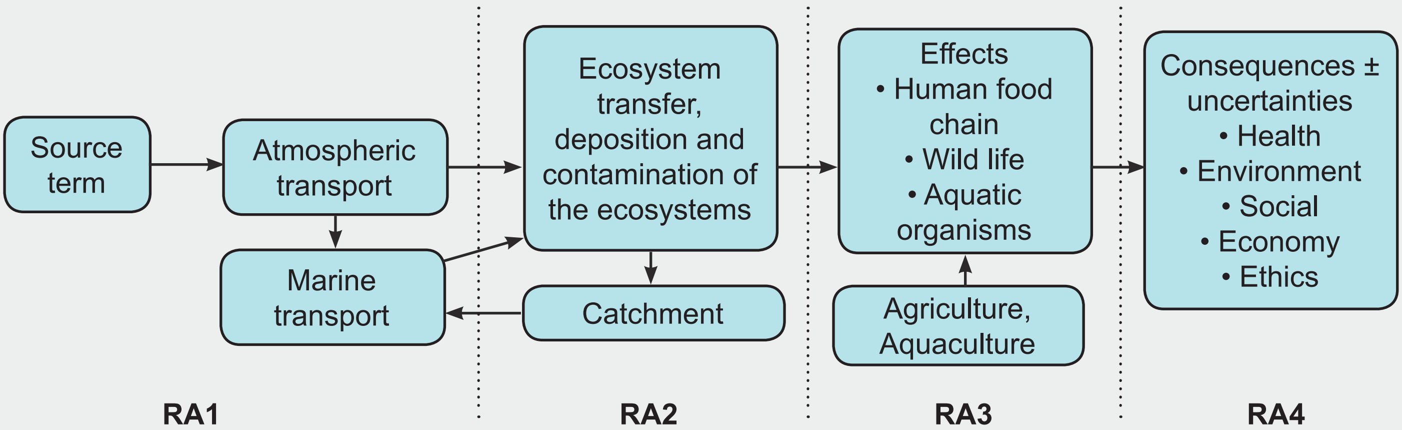

Figure 1. *Linking models from source term via an ecosystem transfer to the impact for humans and the environment, for the society, economy and ethics. The research within RA1 to RA4 should reduce the overall uncertainties associated with modelling the impact and risk.*

Research Area 1 – Source Term and Release Scenarios

Research Area Leaders: Ole Christian Lind, NMBU and Heiko Klein, MET

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, as well as for 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:

Umbrella 1A: Particle Sources (Ole Christian Lind, NMBU)
The main research focus is to improve advanced techniques for characterization of particles (*e.g.*, 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 conceptual uncertainties in the model assessment of the environmental impact of radioactive contamination, as particles behave very differently from the – often presumed – ionic species on which models are based.

Umbrella 1B: Dispersion Modelling: Atmospheric and Marine (Heiko Kleine, MET)
The main objective is to improve atmospheric and marine dispersion models for predicting transport of radioactive releases and to enable identification of unknown sources contributing to radioactive releases. As most atmospheric and water dispersion models suffer from large uncertainties due to poor parametrization, emphasis is put on source term input codes as well as improved resolution and probability of transport from a given source. Improvements of marine modelling is focused on coupling Lagrangian transport models (*e.g.*, LMM species, colloids and particles) to the ROMS ocean model.

Umbrella 1C: UV/Ionising Radiation and Dosimetry (Terje Christensen, NRPA)
Dosimetry is a central task in CERAD and covers ionizing radiation, also in combination with UV. This includes the implementation of dosimetry systems, at the NMBU gamma irradiation facility, and improving field dosimetry and wildlife dosimetry. The development of a common dose concept for ionizing and UV radiation is performed to utilize the UV – network and the UV-dose maps within areas affected by radioactive contamination.

PhD and Post Docs Positions:
PhD M. Simonsen (MET/NMBU), PhD J. Antonio (NMBU), PhD I. Byrnes (NMBU), PhD L. Rossbach (NMBU), PostDoc E.L. Hansen (NRPA)

RETENTION OF RADIOACTIVE PARTICLES IN WILDLIFE BIOTA

NMBU: *O.C. Lind, S. Cagno (SCK-CEN), B. Salbu*
Warsaw University of Technology: *J. Jaroszewicz*
University of Seville: *R. Garcia-Tenorio, I. Vioque*
University of Antwerp: *K. Janssens, G. Nuyts, F. Vanmeert*

Objectives: As demonstrated by Salbu *et al.* (2018), information on the ecosystem behaviour of radioactive particles is scarce and there is a need to integrate radioactive particles into environmental impact assessments. To achieve this, key challenges include the linking of particle characteristics to specific sources and to ecosystem transfer, and linking particle characteristics to uptake and retention in biological systems of relevance for dose estimates. Within the frame of the EU-funded COMET and RATE projects and in collaboration with the IAEA CRP on Environmental Behaviour and Potential Biological Impact of Radioactive Particles, state-of-the-art analytical technologies have been utilized to investigate samples from particle contaminated sites with respect to particle characteristics, weathering processes and retention of radioactive particle in organisms. One of the main objectives was to demonstrate radioactive particle retention in biota that could be of relevance for the human food pathway and to characterize the exposure to biota. Much effort was put into investigating the impact of the residual actinide particle contamination in the semi-arid ecosystem around the Palomares village that was affected by a nuclear weapon accident in 1966.

Methods: Environmental samples collected in the U/Pu particle contaminated area in Palomares, Spain, were subjected to digital autoradiography (HD CR35, Dürr) and gamma spectrometry combined with sample splitting to identify elevated activity concentrations indicating the presence of radioactive particles within sample matrices. High absorption material inclusions were localized in 3D rendered volumes of soil or sediment aggregates as well as in whole organisms or in dissected organs, and characterized with respect to relative density, particle size, surface area and porosity using submicron resolution X-ray absorption contrast computed tomography (nano-CT, XRADIA-400).

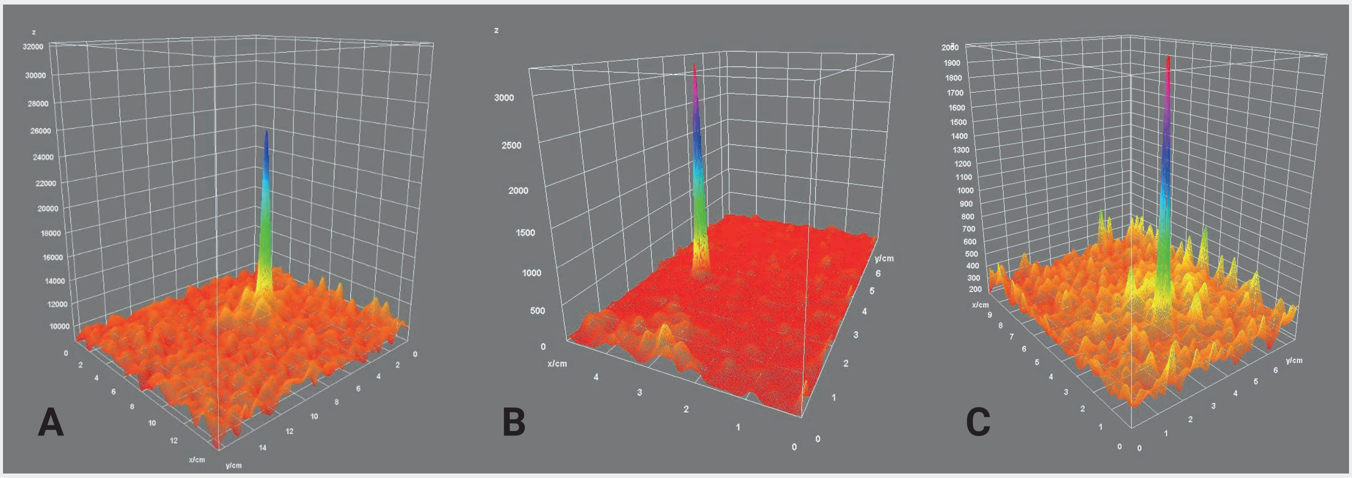

Figure 1. *Photo-stimulated luminescence (PSL) autoradiography of soil and snail samples from Palomares contaminated by actinide particles. A) Autoradiography of a soil sample from Palomares contaminated by actinide particles. B) Autoradiography of soft tissues of a snail contaminated by actinide material. C) Autoradiography of a piece of shell from a snail contaminated by actinide material. The x and y axis refer to the 2D dimensions of the sample spread thinly on a substrate. The z axis are of relative PSL intensity (energy deposited per unit area), and, while not calibrated to emission activity, are used here to visually demonstrate that the actinides are predominantly contained within small particles shown as a 3D surface plot.*

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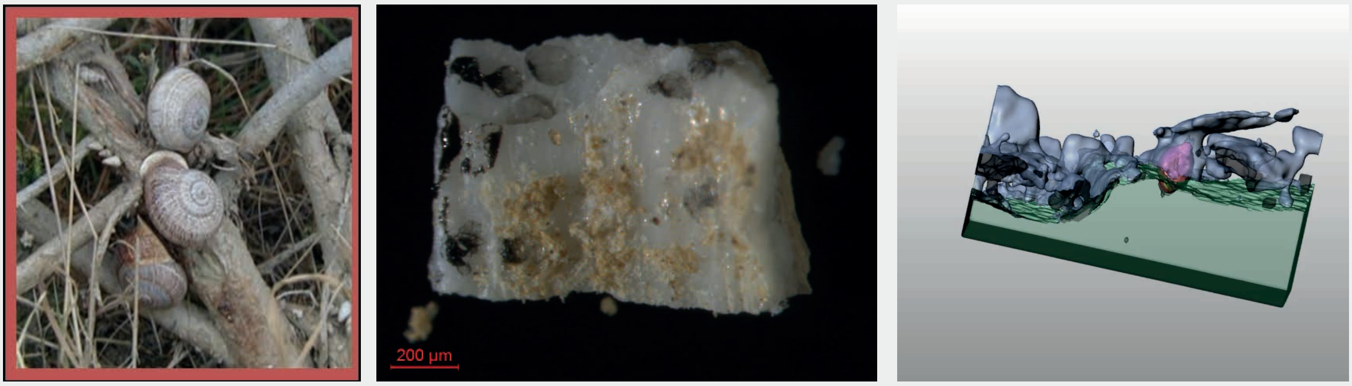


Figure 2. *Retention of a U/Pu particle in snails at Palomares. A) Snail shells collected in the contaminated zone 2 of Palomares. B) Piece of snail shell contaminated with ^{241}Am. C) Nano-CT rendering of the shell piece showing the 10 µm U/Pu particle (marked with yellow circle) as high absorption material (violet). The tomographic rendering has been rotated to show that the particle is partially embedded within the shell.*

Elemental compositions were confirmed and elemental distributions determined using bench-top micro X-ray fluorescence (XRF, M4 Tornado, Bruker) or synchrotron radiation based submicron XRF (SRXRF) at beamline P06, Petra III, Hamburg.

Results: Radioactive heterogeneities were found in both soil and biota samples within the contaminated areas of the Palomares village, including in faeces of rabbit and snails (Fig. 1). Thus, Palomares rabbits and snails are exposed to radioactive particles. By means of nano-CT and submicron SRXRF analysis (not shown), both U/Pu particles originating from the Palomares nuclear weapons accident and naturally occurring U/Th containing particles were identified in snail faeces demonstrating that these soil dwelling organisms also are also exposed to NORM particles. Furthermore, a combination of nano-CT and bench-top micro-XRF analysis was utilized to demonstrate that U/Pu particles were embedded within the shell of snails (Fig. 2). Such retention in biota would be expected to influence the long-term dose to the animals and potentially also to humans as snails are considered a local delicacy.

Conclusion: Radioactive particle retention in biota calls for better exposure characterization in impact assessments of particle contaminated areas, in particular when the biota is of relevance for the human food pathway such as rabbits and the local gastropod delicacies of Palomares.

References:

Salbu, B., Kashparov, V., Lind, O.C., Garcia-Tenorio, R., Johansen, M., Child, D.P., Roos, P., Sancho, C. (2017). Challenges associated with the behaviour of radioactive particles in the environment, Journal of Environmental Radioactivity, 186, 101-115.

COMBINED COMPUTED NANOTOMOGRAPHY AND NANOSCOPIC X-RAY FLUORESCENCE IMAGING OF COBALT NANOPARTICLES IN *CAENORHABDITIS ELEGANS*

NMBU: *S. Cagno, D.A. Brede, B. Salbu, O. C. Lind*
University of Antwerp: *G. Nuyts, F. Vanmeert, K. Janssens*
ESRF: *A. Pacureanu, R. Tucoulou, P. Cloetens*
DESY: *G. Falkenberg*

Objectives: Synchrotron X-ray nanoimaging represent state-of-the-art techniques for nanometer spatial resolution of elemental distribution and speciation including oxidation states and crystallography analysis.
The objective of the current project was to investigate uptake, internal distribution, and toxicity of nanoparticles at the cell level in an intact organism. The nematode *C. elegans*, a model organism featuring a transparent body, short life cycle and small size (1 mm), was ideal for this purpose.

Methods: Full life cycle exposure of nematode *C. elegans* (ISO10872, 2010) to cobalt nanoparticles (Co-NP, 17-17000 µg/L). The effect endpoints were development, growth, fertility, reproduction and mortality. Tissue and cell distribution of the Co-NP were localized using synchrotron radiation phase-contrast computed nanotomography (nano-CT) and two- and three-dimensional (2D and 3D) submicron and nanoscopic X-ray fluorescence (nano-XRF) ESRF ID16A and Petra III P06 synchrotron beam lines.

Results:
Nano-CT imaging of *C. elegans* anatomy.
Synchrotron radiation phase-contrast computed nano-CT was performed on whole nematodes. This facilitated the construction of anatomical 3D renderings of selected tissues and organs. Proper sample preparation and stability during the tomographic scans are required to successfully obtain such nanoscale 3D data. The reconstructed 3D images gave a large sample overview with a voxel size of 130 nm and a more detailed view of selected regions of interest with a voxel size of 50 nm (Fig. 1). Such high-resolution images facilitated assignment of elemental distribution information obtained from XRF to specific organs, tissues or even cells in the nematode. The same samples were subsequently scanned with 2D and 3D nanoscopic X-ray fluorescence (nano-XRF) to obtain elemental distribution maps.

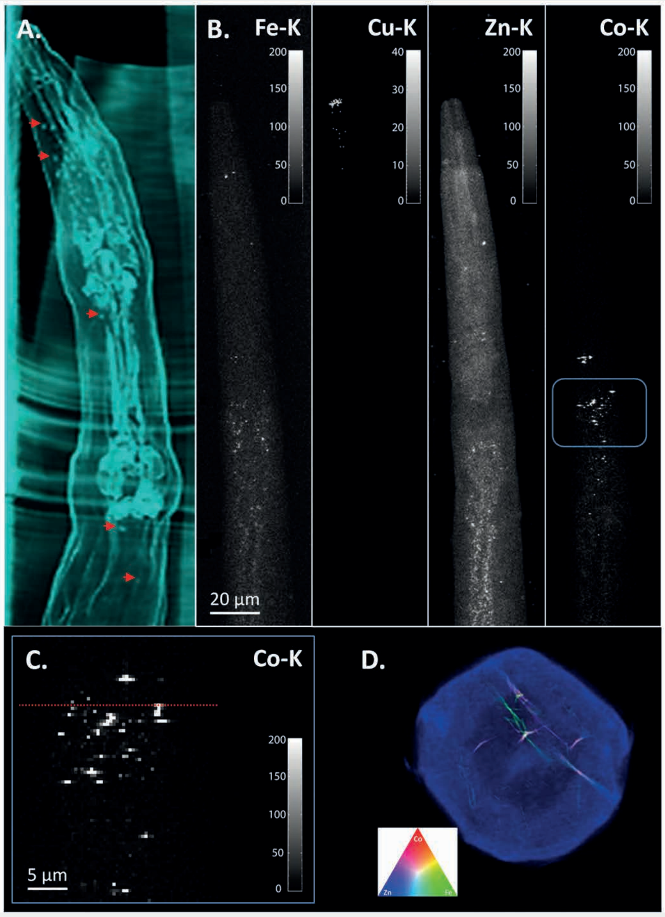


Figure 1. *A) Three-dimensional reconstructed phase nano-CT image of the pharynx of an exposed non-depurated nematode. Arrows indicate the position of suspected NP aggregates. B) 2D XRF elemental distribution maps of a depurated animal.C) Close view of section posterior to pharyngeal/intestinal valve. D) 2D XRF tomogram (position of the virtual cross-section indicated by the red line in panel C) of Zn (blue), Fe (green), and Co (red), demonstrating the presence of Co-NPs in the anterior part of the intestine.*

Nano-XRF elemental mapping.
As a first step, 2D elemental distribution maps of entire individual nematodes or parts of them were acquired. This allowed detailed mapping of essential elements, including metals such as Zn, Fe, Mn and Cu. Elements such as Zn and Fe were visible in the entire nematode body, and also present in µm - sized Zn immobilization/storage lysozymal organelles. Iron hotspots that accumulated along the entire length of the intestine as part of ageing process was clearly visible.
The ESRF ID16A facilitates highly sensitive detection of these elements. On the basis of natural Zn abundance in unexposed nematodes, an estimation of the Zn limit of detection (LOD) was performed and resulted in about 0.01 fg/spot (20× 37 nm^2) for 100 ms exposure. Trace elements were visible in certain body parts, *e.g.* Cu was found in a ring like structure localized in the pharynx, presumably associated with neuronal cell structures (Fig. 1).

Nano-CT and nano-XRF assessment of Co-NP.
Co-NPs were readily ingested by *C. elegans*, but nematodes were able to develop normally and reproduce even at high concentrations of NP. Toxic effects/reproduction failure occurred at the highest concentrations of NP. The uptake and internal distribution of Co-NP in exposed *C. elegans* individuals was investigated by means of 2D and 3D nano-XRF. These maps showed Co-NP to be predominantly present within the intestine and the epithelium. NP were not co-localized with Zn granules found in the lysosome-containing vesicles or Fe agglomerates in the intestine. Iterated XRF scanning of a specimen at 0° and 90° angles suggested that NP aggregates were translocated into tissues outside of the intestinal lumen. Translocation of individual Co-NP aggregates from the intestinal lumen was investigated by iterated XRF scanning and 2D XRF tomography virtual slicing, combined with holotomography, which substantiated Co-NP inside the uterus and within embryos (Fig. 2). This could potentially cause reprotoxic effects.

Conclusion: This study has established a system for nanometer scale non-invasive image analysis of internal distributions of essential elements, as well as toxic metals, in an intact animal using *C. elegans* as a model. This study has demonstrated that it is now feasible to achieve nm resolution and detection limit at 10-17g for the characterization of radionuclide uptake in tissues or in intact animals.

References:
Cagno et al. Analytical Chemistry. 2017 Nov 7;89(21):11435-11442.

This work was selected for Beauty of science in ESRF News, July 2015.

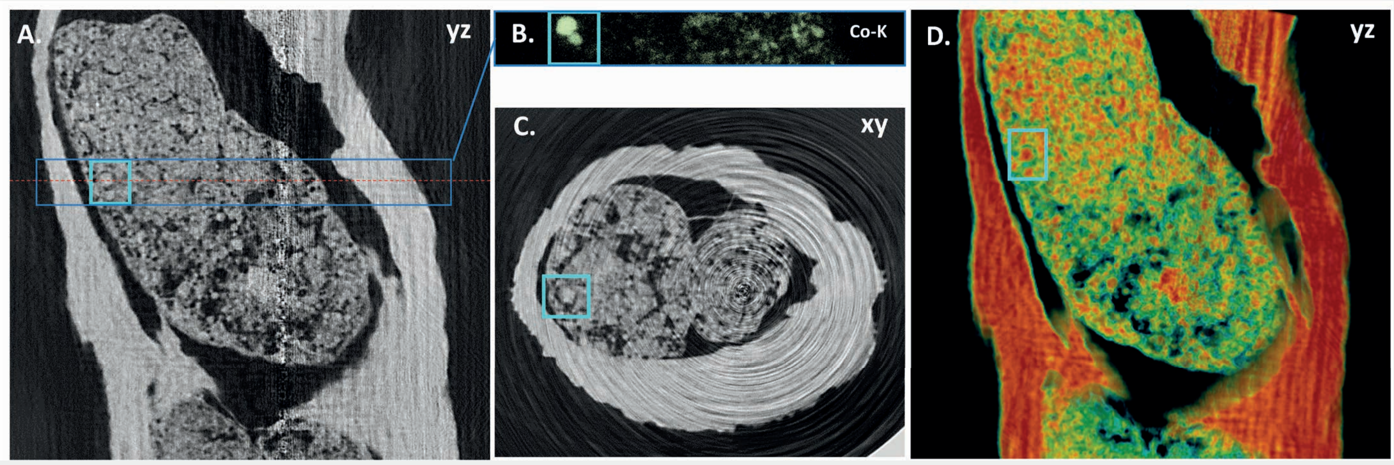


Figure 2. *Identification and localization of NP (cyan box) inside embryo by combined phase-contrast nano-CT and XRF. A) Phase-contrast nano-CT (voxel size 50 nm) longitudinal virtual slice (yz) showing Co-NP aggregate. B) Two-dimensional XRF Co element distribution map of the section indicated by cyan box (ROI 32.6 × 4.0 μm^2; step size 40 nm). C) Phase-contrast nano-CT transversal virtual slice (xy). Dotted red line indicated in the longitudinal virtual slice (panel A) marks its position. D) Virtual slice with temperature color scale of the uterus and embryos.*

IMPORTANCE OF PARTICLE CHARACTERISTICS FOR MEDIUM AND LONG DISTANT ATMOSPHERIC TRANSPORT OF NUCLEAR DEBRIS

MET: *H. Klein, J. Bartnicki*
NRPA: *J.E. Brown, J.E. Dyve, A. Hosseini*
NMBU: *O.C. Lind, B. Salbu*

Objectives: Atmospheric transport of particles emitted to the atmosphere is known to be influenced by both size and weight of the particles (Baklanov and Sørensen, 2000). Radioactive particles of varying composition and properties have been released from nuclear sources more frequently than usually anticipated. (Salbu *et al.*, 1994; Salbu, 2015) Particle characteristics play an important role for the transport and the distribution pattern of radioactive deposition following an accident.

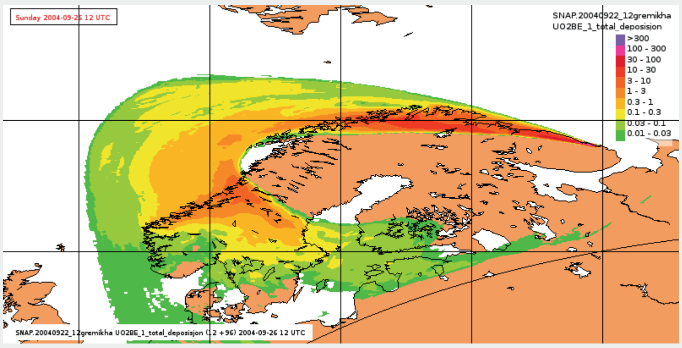


Figure 1. *Distribution pattern of particles with 0.5 µm diameter deposited from a hypothetical release at Gremikha Bay.*

Methods: This study investigates the influence of particle characteristics on atmospheric transport and subsequent deposition following different hypothetical accidents, *i.e.*, in Sellafield in the UK, at Gremikha Bay at the Kola peninsula and from a nuclear driven vessel at a distance of 200 km from the Norwegian cost. A large range of particles have been analyzed, starting from small and light particles of 0.5 µm diameter and 0.1 g/cm^3 density as in red oil to 50 µm and a density of 8 g/cm^3 as in uranium-oxides. The total influence on deposition in Norway and the maximum influence for hotspots in Norway has been analysed.

Results: As can be seen in the figures 1 and 2, small and light particles are transported much further than heavier and larger particles. Particles above 20 µm contribute only to the local scale within 50 km from the source. Medium sizes particles, around 2-5 µm, are still strongly effected by gravitational settling and do not contribute much to large scale depositions, but can lead to local hotspots.

Conclusion: The distribution pattern of depositions following atmospheric transport changes significantly when particle characteristics in the source term are different. Variation in particle size can lead to up to 4 times larger depositions in hotspots at distances of about 200 km from the source.

References:

Baklanov, A. and Sørensen, J.H., Phys. Chem. Earth (B), Vol: 26, Issue: 10, 2001

Salbu, B., Krekling, T., Oughton, D.H., Østby, G., Khasparov, V.A., and Day, J.P. The Significance of Hot Particles in Accidental Releases from Nuclear Installations. Analyst, 119, 125-130, 1994.

Salbu, B. Journal of Environmental Radioactivity, Volume 151, Part 2, 2015

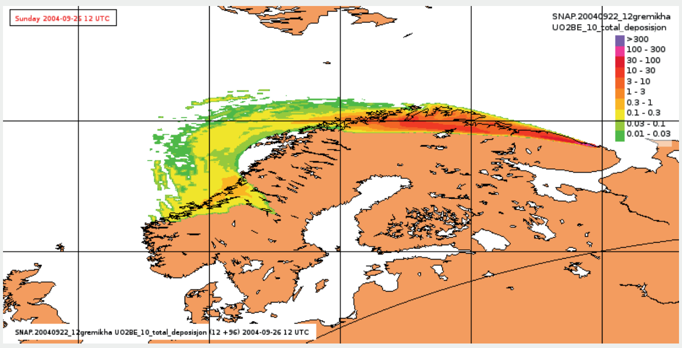


Figure 2. *Distribution pattern of particles with 5 µm diameter deposited from a hypothetical release at Gremikha Bay*

THE IMPACT OF TIDAL AND MESOSCALE EDDY ADVECTION ON THE LONG TERM DISPERSION OF Tc-99 FROM SELLAFIELD

MET: M. *Simonsen, Ø. Saetra, P.E. Isachsen (UiO)*
NMBU: *O.C. Lind, B. Salbu*
NRPA: *H.K. Skjerdal, J.P. Gwynn*
IMR: *H.E. Heldal*

Objectives: Model study of the fate of the historical Tc-99 discharges from Sellafield after 1994 with a specific focus on the role of mesoscale eddy and tidal advection on the transport and dispersion of this radionuclide.

Methods: Comparison of a global coarse-resolution model, where the eddy transport is either completely absent or fully parametrized, and a regional 'eddy-permitting' high resolution model which resolves large parts of the ocean eddy field. The importance of tidal advection is investigated by comparing transport in the eddy-permitting model when run either with tides included or with tides filtered out.

Results: The coarse-resolution model can reproduce the general features of the observed time-space Tc-99 distribution if the diffusivity in its eddy parametrization scheme is suitably chosen, however, with a systematic bias in the transport across continental slopes. The eddy permitting model captures regional details better and shows an overall higher prediction skill, with the model predictions agreeing with the observations within a factor of two to four (Fig. 1). The model correctly simulates both the initial transport and the decrease in activity concentrations following the reduction in discharges. Transport out of the Irish Sea is greatly affected by the tides as these cause a net northward wave-induced drift through the Irish Sea. Specifically, this additional northward drift causes a reduced transport of Tc-99 into the Celtic Sea via St. George's Channel (compared to simulations in which tides are not included). This in turn impacts the Tc-99 activity concentration levels as far away as the Barents Sea and the Arctic Ocean.

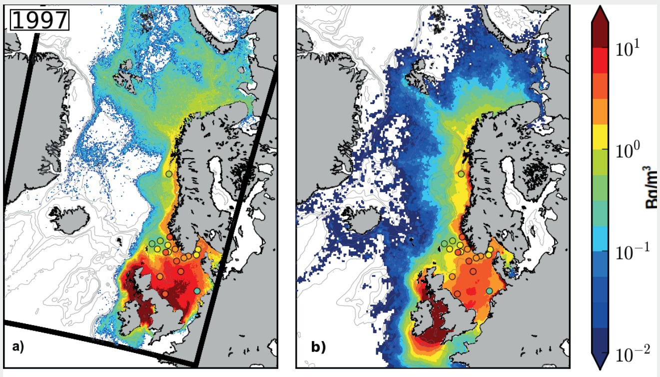


Figure 1. *Estimated upper 50 m mean activity concentration of Tc-99 in 1997 from a: High resolution model and b: Low resolution model with additional eddy diffusion. Colour points are observed activity concentrations.*

Conclusion: Including tides and mesoscale eddy advection improves the ability of the model to predict both the near- and far-field transport and dispersion of Tc-99 discharges from Sellafield. Both the high and lower resolution model simulations describe the dispersion of the Sellafield Tc-99 discharges in consistency with the available observations. Importantly, the high-resolution simulations shed new light on the role of the mesoscale eddy field and tidal currents for the transport of this radionuclide.

References:

Simonsen, M., Saetra, Ø, Isachsen, P.E., Lind, O.C., Skjerdal, H.K., Salbu, B., Heldal, H.E., Gwynn, J.P., The impact of tidal and mesoscale eddy advection on the long term dispersion of Tc-99 from Sellafield, J. of Env. Rad., 177, 2017, 100-112

Research Area 2 - Dynamic Ecosystem Transfer

Research Area Leaders: Hans Christian Teien, NMBU and Justin Brown, NRPA

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 most often placed on empirical ratios such as distribution coefficients: Kds, concentration ratios (CR) and transfer coefficients (TF/TC/Tag, BCR). Although available data compilations on such ratios are comprehensive, simple to use and offer great utility in screening assessments, these approaches assume that equilibrium conditions are valid and do not: a) capture the dynamics of 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, but are seldom included in international literature. Where data gaps with regard to transfer parameters are evident, various extrapolation methods are applied to provide surrogate values, such as the use of taxonomic (related to phylogeny) analogues, parameters based upon allometry, as well as the use of Bayesian statistics. The efficacy of these approaches is still needed to be documented.

Umbrella 2: Dynamic Transfer

The overall objective of RA2 is to improve the parameterization 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 within Umbrella 2 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.

RA-2 is considered an important link between the 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.

PhD and PostDoc Positions:

PhD F. Wærsted (NMBU), PhD C.B. Strømme (NMBU), PhD M. Kleiven (NMBU), PhD S. Scheibener (NMBU), PhD E. Alvarenga (NMBU/NIBIO), PostDoc S. Nehete (NMBU), PostDoc P. Lebed (NMBU)

DYNAMIC TRANSFER OF RADIONUCLIDES IN THE CONTAMINATED LAKE GLUBOKOYE CHERNOBYL EXCLUSION ZONE

NMBU: *H.-C. Teien, B. Salbu*
NIPH: *L. Sareisian, L. Valle*
UIAR: *V. Kashparov, S. Levchuk, V. Protsak*

Objectives: To identify ecologically relevant dynamics in uptake and depuration of radionuclides in freshwater fish and possible toxic effects

Methods: The experiment took part in Lake Globokoye and Lake Kashovka, one contaminated and one "clean" lake, in the Chernobyl exclusion zone. Caught fish from the clean Lake Kashovka were put into cages in contaminated Lake Glubokoye, and vice versa, to follow uptake and depuration of radionuclides over time (Fig. 1).
In addition, clean silver crucian carp was included in the contaminated water for fish species comparison. The uptake/depuration of radionuclides were followed over time by determination of radionuclides in tissues of dissected fish. Physiological changes in fish were followed by analysis of blood samples. DNA damage and ROS were identified using comet assay in field, and comparison of results from control fish.

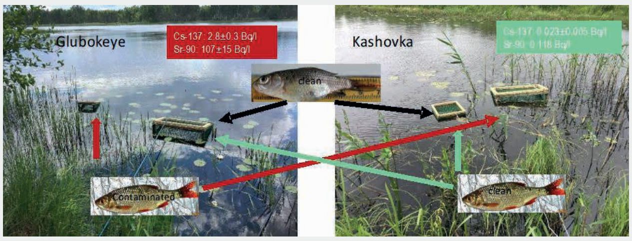


Figure 1.*Experimental design of the field experiment with clean and contaminated rudd (Scardinius erythrophthalmus L) and clean silver crusian carp (Carassius gibelio).*

Results: Seasonal variation was observed in transfer of radionuclides to fish; high uptake and depuration rate from June to October with water temperature >15°C, and low transfer at low water temperature (<10°C) from October to December (Fig. 2). Due to bioaccumulation of radionuclides (Cs-137, 12 kBq/kg, and Sr-90, 500 kBq/kg) the internal dose especially from Sr-90 to fish was higher than the external dose. The internal dose was unevenly distributed.

Conclusion: New data on dynamic transfer of radionuclides to fish in the field have been generated, being rather different to the IAEA handbook data. Metabolic activity in fish seems essential for transfer of both Cs-137 and Sr-90, and should to be taken into account when transfer to biota is assessed

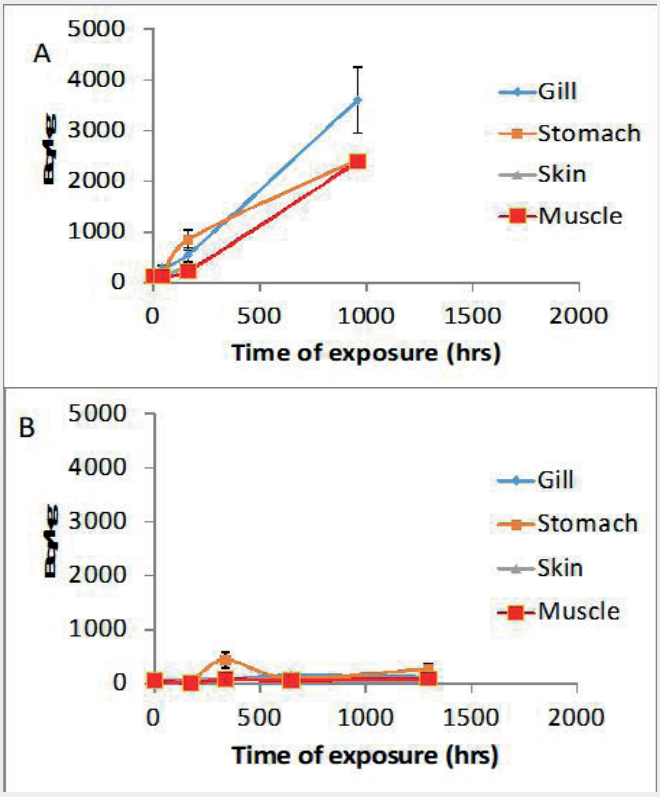


Figure 2. *Activity concentration of Cs-137 in tissues of rudd as a function of time after transfer to contaminated water in June (20°C) and in October (< 5°C) respectively*

CENTRE FOR ENVIRONMENTAL RADIOACTIVITY

INVESTIGATION OF THE VERTICAL DISTRIBUTION AND SPECIATION OF ^{137}CS IN SOIL PROFILES AT BURNT AND UNBURNT FOREST SITES IN THE BELARUSIAN EXCLUSION ZONE

NRPA: *J. Brown, M. Dowdall,*
NMBU: *L. Skipperud, M. Pettersen*

Objective: To establish whether persistent effects (on the form and behavior of radionuclides within soils) from fire events exist at locations in the Belarusian Exclusion Zone.

Methods: Both burnt and unburnt areas were selected at 3 sites (Fig. 1) based on visual indicators. Multiple cores were sampled and soil characteristics (pH, organic content, grain size) determined.
Radionuclide depth profiles (^{137}Cs and ^{241}Am by γ-spectrometry, Pu by α-spectrometry) were used to calculate relaxation mass depths (the depth where the radionuclide concentration is 1/e of that at the ground surface).
Geochemical phase association was analysed by sequential extraction considering water soluble, easily exchangeable, redox sensitive fractions, residual irreversibly bound phases.

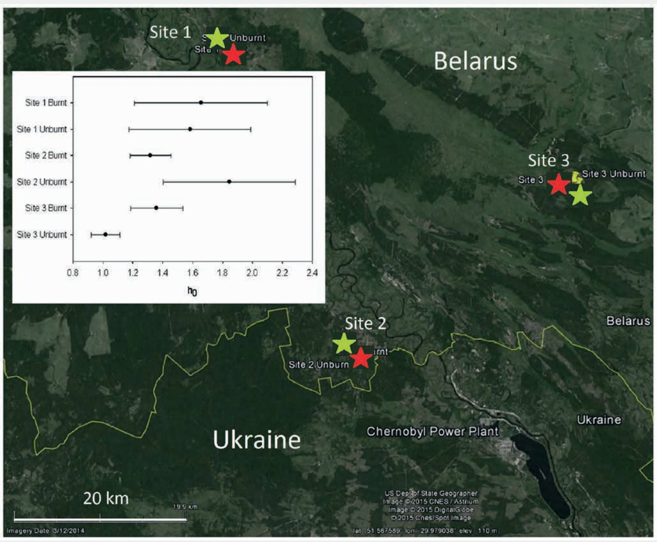


Figure 1. *Study locations (red : burnt, green : unburnt). Mean and range of relaxation mass depth (h_0 parameters in g/cm^2) for each of the studied sites.*

Results: At Site 1 there was no difference in ^{137}Cs relaxation depth between burnt and unburnt sites (Fig. 1). Site 3 clearly displayed significantly greater penetration at the burnt site reflecting possible downward migration of ash materials. Site 2 exhibited an apparent greater penetration by ^{137}Cs at the unburnt area potentially explained by burning of litter/humus layers, solubilisation and cycling. Sequential extraction data showed distinctive differences in ^{137}Cs geochemical associations at several depth increments for sites 1 and 2.

Conclusion: The high heterogeneity of contamination and presence of hot particles confounded data interpretation. Differences between the proportions of ^{137}Cs present in redox sensitive phases (*e.g.*, Fe and Mn oxides and associated with organic matter) at Sites 1 and 2 appeared to be the strongest indicators of fire impacts.

References:

Dowdall, M. et al. / J Environ Radioact., 175-176 (2017); 60-69.

RADIOECOLOGICAL MODELING OF POLONIUM-210 AND CAESIUM-137 IN LICHEN-REINDEER-MAN AND TOP PREDATORS

Lund University: *B.R.R. Person*
NRPA: *R. Gjelsvik*
University of Gothenburg: *E. Holm*

Objectives: To develop dynamic models for radioecological concentration processes of (i) ^{210}Pb and ^{210}Po in a vulnerable food-chain (lichen-reindeer-man) and (ii) ^{210}Po and ^{137}Cs in large predators.

Methods: Atmospheric deposition of ^{210}Pb and ^{210}Po was predicted by use of Partial Least Square Regression. Dynamic modelling of the concentration with differential equations was fitted to sample data. Values for reindeer lichen consumption, gastrointestinal absorption, organ distribution and elimination were derived from review. ^{210}Pb in human skeletons was modelled from kinetics and levels in blood from lead-workers. Descriptive data, ^{210}Po and ^{137}Cs in blood, muscle, liver and kidney from lynx, wolverine and wolf were analysed and modelled with multivariate data processing methods; Principal Component Analysis, Projection to Latent Structures and Partial Least Square Regression.

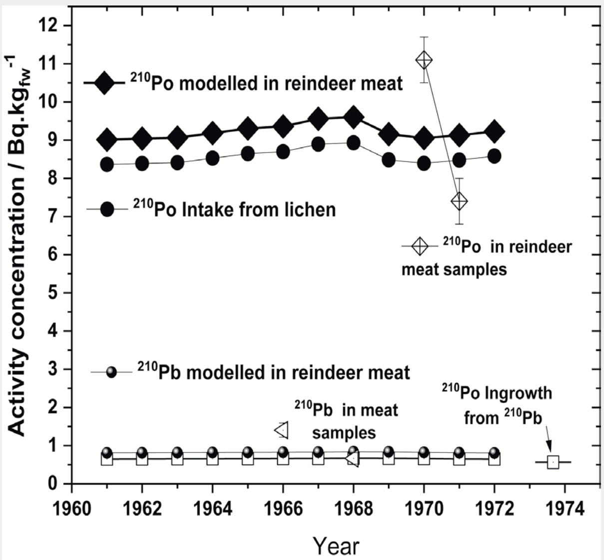


Figure 1. *^{210}Po and ^{210}Pb in reindeer meat at Funäsdalen, Sweden*

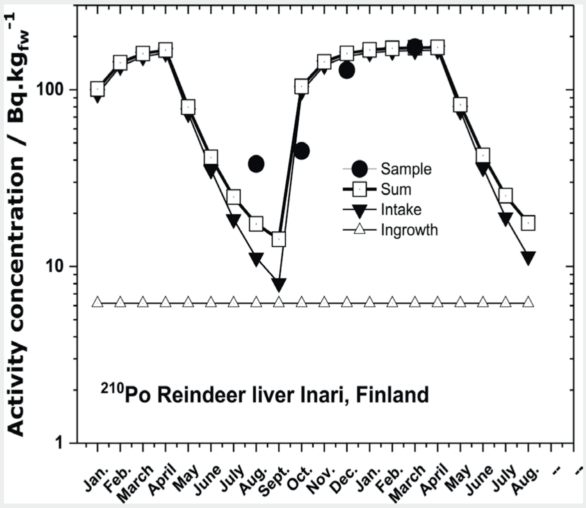


Figure 2. *^{210}Po in reindeer liver from Inari, Finland 1966-67*

Results: Dynamic modelling of ^{210}Pb and ^{210}Po to reindeer meat, liver and bone from lichen consumption, fitted well with data from Sweden (Fig. 1) and Finland (Fig. 2). Results from modelling ^{210}Pb and ^{210}Po in skeleton matched concentrations in teeth from reindeer breeders and autopsy bone samples in Finland. ^{210}Po activity in large predators was higher in liver and kidney than muscle and blood. ^{137}Cs had the opposite pattern. Sex was the most important variable for predicting ^{210}Po concentrations in wolves, indicating higher food intake by males. Geographical location was of most importance for lynx and wolverine reflecting regional differences in precipitation. For ^{137}Cs, a strong influence of latitude reflected Chernobyl-fallout.

Conclusion: Dynamic models can predict temporal and seasonal variations in various radioecological compartments with only a few data available. By modelling, it is possible to predict important variables influencing changes in activity with time.

References:

Persson, B.R.R., et al. Journ. Environ. Rad. 2017. Vol. 186, 54-62.

Research Area 3 - Biological Responses

Research Area Leaders: Ann-Karin Olsen, NIPH and Peter Aleström, NMBU

The main aim of RA3 is to generate new knowledge related to biological responses in organisms exposed to ionizing radiation that have implications for risk assessment and radioprotection of humans and the environment, to reduce the existing uncertainties (Fig. 1). In this respect a major data-gap exists on effects following exposure of low doses and low dose rates of ionizing radiation to both humans and wild-life. Such effects cover apical endpoints like reproduction, embryonal development, behaviour and cancer. 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 focuses on three interlinked umbrella projects: UMB3A - Mechanisms determining species radiosensitivity; UMB3B - Combined toxicity and cumulative risk assessment; and UMB3C - Transgenerational hereditary, reproductive and epigenetic effects.

Umbrella 3A: Radiosensitivity
(Dag Anders Brede, NMBU)

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 regard 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.

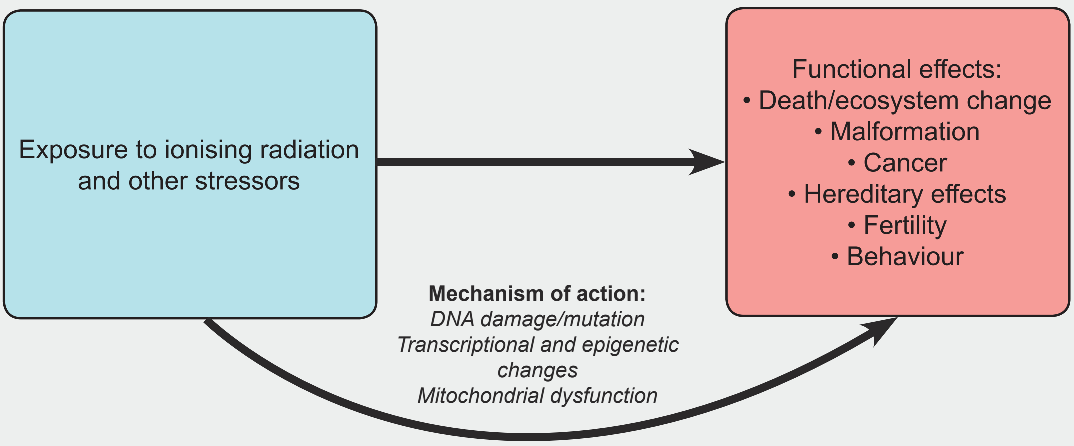


Figure 1. *The work strategy in RA3. Biological systems are exposed to ionizing radiation - alone and in combination with other stressors- adverse functional effects are measured and are pursued by identification of the underpinning mechanisms of action.*

Umbrella 3B: Combined Toxicity and Cumulative Risk
(Knut Erik Tollefsen, NIVA and Terje Christensen, NRPA)

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, including lack of nutrient and antioxidants (i.e. suboptimal selenium levels). Using a suite of bioassays ranging from cell-based assays to analyses of whole organisms, experimental studies will focus on mode of action (MoA) assessment, behavioral and adverse effect endpoints in selected species. These will in turn feed into a suite of predictive models applied in RA4.

Umbrella 3C: Transgenerational and Reproduction Effects
(Ann-Karin Olsen, NIPH and Peter Aleström, NMBU)

Following gamma exposure, the main focus is on reproduction and genotoxic effects as well as on 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.

PhD and PostDoc positions:

PhD S. Hurem (NMBU-VET), PhD D. Blagojevic (NMBU-IPV), PhD E. Maremonti (NMBU-MINA), PhD H. Dahl (NIPH), PhD L. Xie (NIVA), PhD J. Kamstra (NMBU-VET), PhD L. Martin (NMBU-VET), Post Doc L. Lindemann (NMBU-VET), Post Doc T. Gomes (NIVA), Post Doc A. Graupner (NIPH).

Experimenting with ecosystems
Photo: Tanya Hevrøy

URANIUM AND GAMMA RADIATION EFFECTS IN ATLANTIC SALMON (*SALMO SALAR*) DEVELOPING EMBRYOS

NMBU/MINA: *H.-C. Teien, D.A. Brede, Z. Keke, A.K. Yetneberk, Y. Lee, O.C. Lind, B. Salbu*

Objectives: To identify effects in Atlantic salmon (*Salmo salar L.*) embryos exposed to uranium (U) and gamma radiation from fertilization of the eggs to hatching

Methods: Toxicity of U and gamma radiation toxicity in Atlantic salmon embryos were studied separately and in combination in exposure experiments using the 60Co source at Figaro, NMBU. US EPA very soft water, at 5.9±0.3°C and pH 6.7±0.4, were used. Dry stripped eggs from three different female were dry fertilized (one male), and placed with water in three parallel exposure tanks (Fig. 1). Each exposure unit received water from a reservoir in a recycling system. Eggs were exposed for 92 days, from the time of fertilization until hatching, and then transferred to no exposure condition to follow long term effects on developing alevin during 6 months. The exposure protocol was based on the standardized OECD guidelines 210 (OECD 2013). Nominal U concentrations were 0.05-1.00 mgU/L and gamma dose rates were 0.4 to 40 mGy/h. Toxic mechanisms in exposed embryos were explored by combining metabolomics profiling, histopathology, DNA-damage, and ROS-defence enzymes activity.

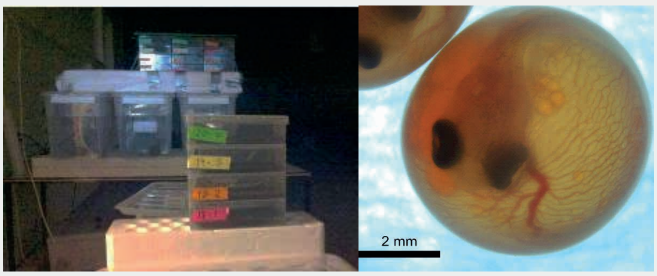


Figure 1. *Experimental set up*

Results: Both U and gamma radiation exposure of eggs from fertilization until hatching demonstrated dose-dependent responses at both the molecular and the individual level, also at similar endpoints. Results demonstrated uptake of U in eggs, effects

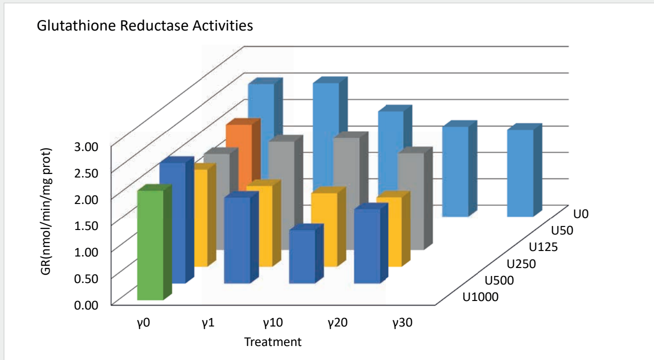


Figure 2. *Enzyme activity of glutathione reductase (GR)*

on development at 0.25-0.5 mg U/L (earlier hatching, deformities) and 100 % mortality at 1 mg U/L. Gamma radiation exposure caused deformities and mortality in all embryos at dose rates of 30-40 mGy/h (total dose 6.0-5.8 Gy). At 20 mGy/h delayed hatching and development of the yolk sack fry were observed as well reduced survival from hatching to swimup, while at 10 mGy/h or lower, no deformities or effects on hatching was observed, and the alevin seems to develop normally. Responses in metabolites were linked to DNA damage and oxidative stress, also demonstrated by comet assay and changes in enzyme activity (CAT, SOD, GRx) (Fig. 2 and 3).

Conclusion: Findings highlight that gamma dose rates between 20-40 mGy/h and uranium between 500-1000 µg/L are critical for embryonal development of Atlantic salmon. Gastrula is the most sensitive stage of embryogenesis, and both DNA damage and oxidative stress are induced.

Norwegian University of Life Sciences

Norwegian Centre of Excellence

COMBINED EFFECTS OF GAMMA RADIATION AND URANIUM ON ATLANTIC SALMON: MECHANISTIC UNDERSTANDING

NIVA : *Y. Song, K.E. Tollefsen*
NMBU-MINA: *B. Salbu, H.C. Teien, O.C. Lind, B.O. Rosseland*
NMBU-Vetbio: *Ø. Evensen*

Objectives: Characterize and compare the modes of toxic action (MoAs) of sublethal exposure levels of gamma radiation and depleted uranium (DU), individually and in combination, in juvenile Atlantic salmon.

Methods: Juvenile salmon were exposed to 70 mGy external gamma radiation delivered over the first 5 hours of a 48 hours period (14 mGy/h), 0.25 mg/L DU continuously for 48 hours and a combination of the two stressors. Stress responses were characterized using a suite of methods including microarray gene expression analysis, quantitative real-time RT-PCR assay, plasma glucose measurement and histopathology. The concentrations and bioaccumulation of DU in salmon after single and combined exposure were also determined.

Results: Results from the transcriptomic analysis showed that differentially expressed genes (DEGs) involved in a number of toxicity pathways were common between γ-radiation, DU and a combination of the two. These DEGs were associated with several known MoAs of γ-radiation and DU, such as induction of oxidative stress, DNA damage, perturbation of mitochondrial oxidative phosphorylation (Fig. 1), thus confirming the earlier findings from our research group. However, there were also a considerable number of DEGs that were stressor-specific, and many of these grouped into common higher functional categories such as immune responses, cellular stress and injury, metabolic disorder and programmed cell death.

Conclusion: Gamma radiation and DU may affect several common targets, however, the toxic mechanisms affecting these targets may be dissimilar between the single stressors as well as their combination. The results have supplied substantial mechanistically-based knowledge for better understanding the MoA of gamma radiation and DU for future assessment of multiple stressor effects.

References:

Song, Y., Salbu, B., Teien, H.-C., Evensen, O., Lind, O.C., Rosseland, B.O., Tollefsen, K.E., Hepatic transcriptional responses in Atlantic salmon (Salmo salar) exposed to gamma radiation and depleted uranium singly and in combination. Sci. Total. Environ. 2016, 562, 270-9.

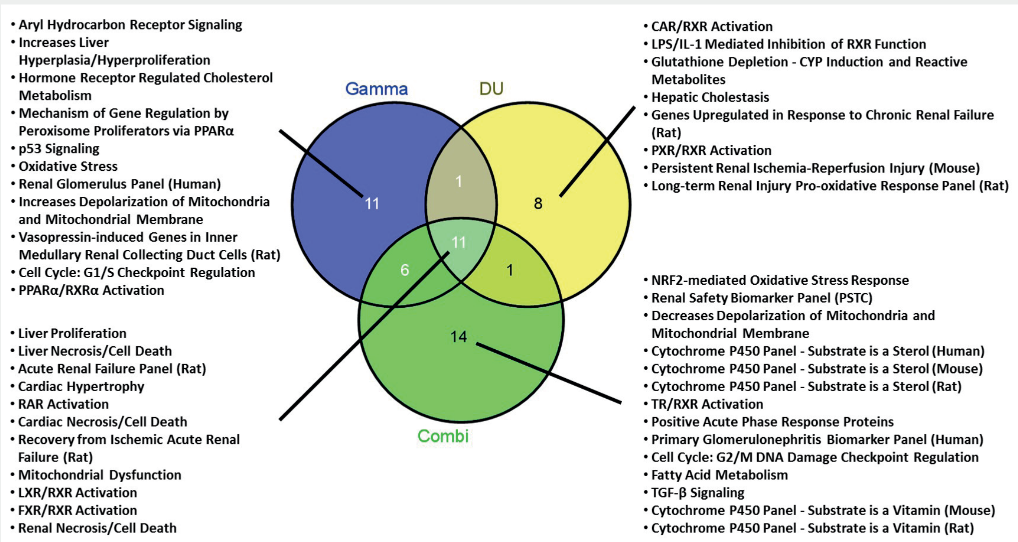


Figure 1. *Venn diagram analysis of toxicity pathways that were affected in the liver of juvenile Atlantic salmon (Salmo salar) after exposure to γ-radiation (Gamma), depleted uranium (DU) and their combination (Combi) (Song et al., 2016).*

DECIPHERING THE COMBINED EFFECTS OF ENVIRONMENTAL STRESSORS ON GENE TRANSCRIPTION: A CONCEPTUAL APPROACH

NIVA: Y. Song, K.E. Tollefsen
NMBU-MINA: B. Salbu
Ghent University: J. Asselman, K.A.C. De Schamphelaere

Objectives: Characterize different types of transcriptional responses as consequences of additive, synergistic and antagonistic responses of the stressors; Identify key toxicity pathways displaying synergistic effects; Propose a conceptual workflow for quantitative mixture modelling of transcriptomics data.

Methods: Re-analysis of published microarray datasets on combined effects of gamma radiation (γ) and depleted uranium (DU) in Atlantic salmon. The independent action (IA) prediction model was used for combined effect modelling.

Results: 3120 differentially expressed genes (DEGs) displaying additive effects, 273 showing synergy and 6 showing antagonism. Multiple toxicity pathways (Fig. 1) relevant for the modes of action (MoAs) of gamma and DU (*e.g.* oxidative stress responses, cell cycle regulation, lipid metabolism and immune responses) were associated with additivity and synergism, whereas only a few MoAs were associated with antagonism.

Conclusion: The IA model is suitable for predicting the combined effects of multiple stressors on gene transcription. Multiple types of joint actions of the stressors were identified, further demonstrating the utilization of toxicogenomics (OMICS) data in multiple stressor effect assessment.

References:

Song, Y., Asselman, J., De Schamphelaere, K.A.C., Salbu, B., Tollefsen, K.E. Deciphering the Combined Effects of Environmental Stressors on Gene Transcription: a Conceptual Approach. (Under review in Environ. Sci. Technol.)

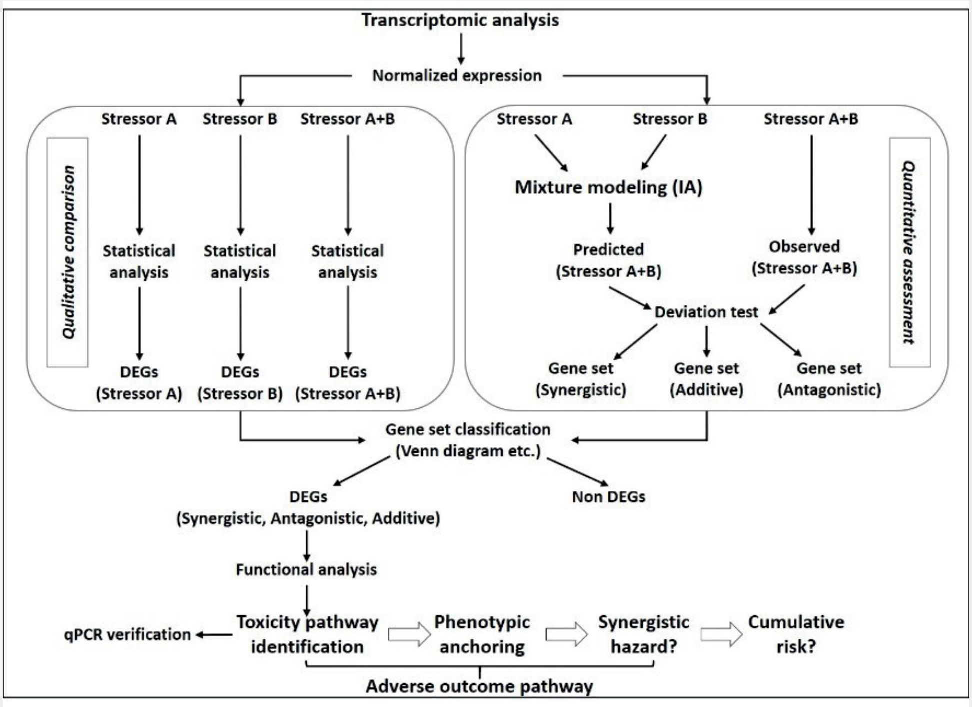


Figure 1. *Proposed workflow for mechanistically-based assessment of low-dose interactive effects of combined stressors using transcriptomics data. DEG: differentially expressed gene; CA: concentration addition; IA: independent action. qPCR: quantitative real-time reverse-transcription polymerase chain reaction (Song et al., under review).*

TRANSGENERATIONAL STUDY OF F1, F2 AND F3 ZEBRAFISH EMBRYO ENDPOINT, HISTOPATHOLOGY AND OMICS ANALYSES.

NMBU-VET BasAm: *P. Aleström, H. Aanes, J.H. Kamstra, L. Lindeman, V.H. Lobert (Utrecht University), L.M. Martin (Camaguey University), R. Nourizadeh-Lillabadi*
NMBU-VET MatInf: *V. Berg, S. Hurem, S. Mutoloki, J.L. Lyche, E. Skjerve*
NMBU-VET ProdMed: *I. Mayer*
NMBU-MINA: *D.A. Brede, Y.A. Kassaye, O.C. Lind, D.H. Oughton, B. Salbu, H.-C. Teien,*
NIPH: *K.B. Gutzkow, A.-K.H. Olsen*
NIVA: *T. Gomes, K.E. Tollefsen*
NRPA: *T. Christensen, E.L. Hansen*
UiN: *I. Babiak*
Utrecht University: *J. Legler*
Camaguey University: *A. Arenal*
McMaster University: *C. Mothersill, C. Fernandez*

Objectives: The hypothesis is that subchronic gamma radiation (0.4-40 mGy/h) exposure during embryogenesis will affect zygotic genome activation (ZGA), thereby altering gene networks that control early development and organogenesis. Additionally, exposures during gametogenesis are hypothesized to affect reproductive organs and germ cells that lead to developmental and irradiation specific effects in F1 offspring, which eventually can be inherited by F2 and following generations. State-of-the-art genome-wide omics sequencing analyses is applied to correlate changes in the epigenome with observed endpoint effects (Fig. 1).

Methods: Gamma radiation exposure of zebrafish (Danio rerio) strain AB embryos (2 hpf) to 0.4-40 mGy/h for 3, 48 and 96 hours. Exposure of adult fish to 8.7 and 53 mGy/h for 27 days. Macro/microscopic observations, fluorometric (ROS), colorimetric (LPO), Comet assay, histopathology. Transcriptomics by mRNA sequencing, DNA methylation by whole genome (WGBS) and amplicon bisulfite sequencing (BisPCR2), short non-coding RNA (sncRNA) sequencing and locus specific histone modifications (chromatin immunoprecipitation PCR, ChIP-PCR).

Results: Direct exposure effects of embryos revealed deformities (Fig. 2) at 5 days post fertilization (dpf) for all doses (37-3,500 mGy) and increased mortality for the highest dose. RNA sequencing after 3 hours exposure (during blastula stage 2.5-5.5 hpf) with total doses of 1.6-33 mGy revealed dose dependent effects with 18 to 556 differentially expressed genes (DEGs).
Irradiated parents exhibited effects on ovaries (but not testes) and showed a large number

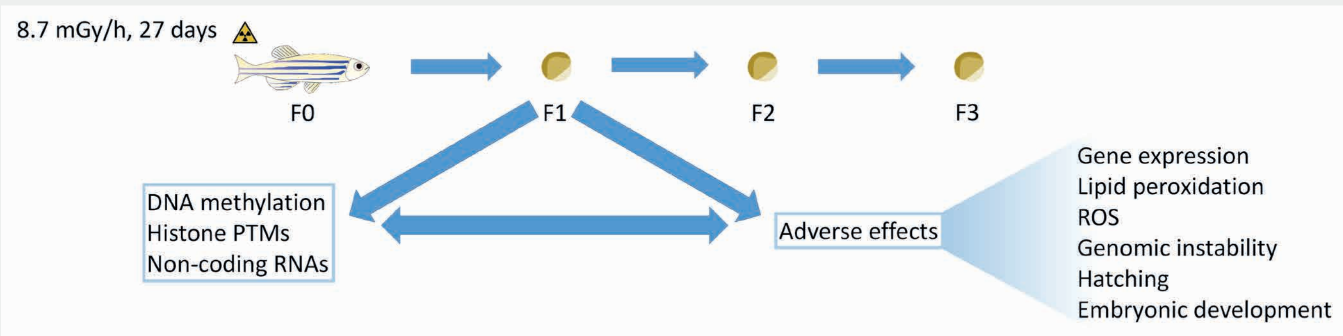


Figure 1. *Correlation between epigenetic patterns (DNA methylation, histone PTMs and noncoding RNA profiles) and phenotypic effects in F1 progeny of exposed parents (10 mGy/h).*

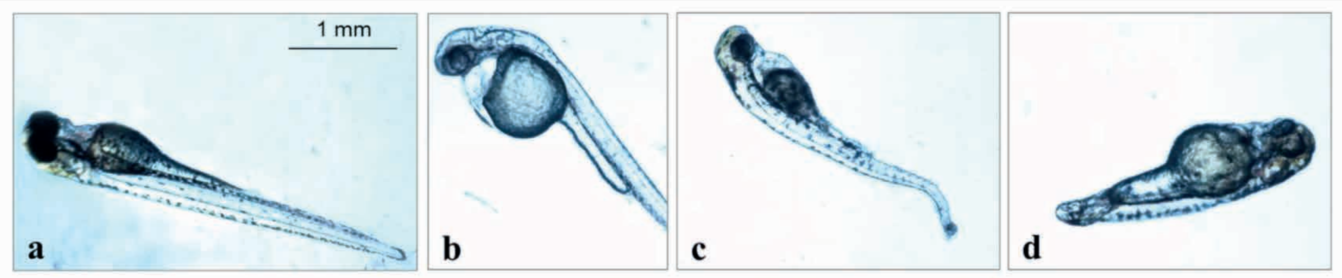


Figure 2. *Zebrafish embryo deformities after 3 days exposure (a is unexposed control).*

of previtellogenic follicles (Fig. 3). This was accompanied by lower embryo production (F1). The F1 embryos showed early hatching, as well as increased mortality and increased frequency of deformities i.e., changes in eye morphology, as also observed for salmon embryos. ROS formation and bystander effects increased at one month, but not one year after parental irradiation. LPO and DNA damage increased one year after parental irradiation. mRNA-seq of 5.5 hpf F1 embryos revealed 39 and 5079 DEGs from the low and high dose group respectively. One year after exposure the 53 mGy/h group had become infertile and all offspring died during early development. At the same time point the 8.7 mGy/h group displayed an increase from 39 to 2390 DEGs of which 1514 overlapped with the 5079 at one month from the high dose exposure, but were oppositely regulated. DNA WGBS analysis counted 5658 differentially methylated regions (DMRs) (Fig. 4). IPA analysis showed major overlap of enriched pathways between gene expression and DNA methylation. BisPCR2 DNA methylation analysis demonstrated persistent transgenerational effects (F1, F2 and F3) at specific loci, sncRNA-seq revealed 22 DE miRNAs in F1 embryos. Among the 22 DEmiRs, miR-21, let-7g and miR-150 have previously been described as modulated by ionizing radiation in mice and human cells. Functional significance of the observed changes in the context of DEGs versus DMRs will be further explored.

ChIP-PCR analyses of zebrafish F1 embryos revealed changes relative to controls in histone PTMs at several selected loci. Histone H3 lysines displayed hypermethylation (K4) and hyperacetylation (K9) around transcriptional start

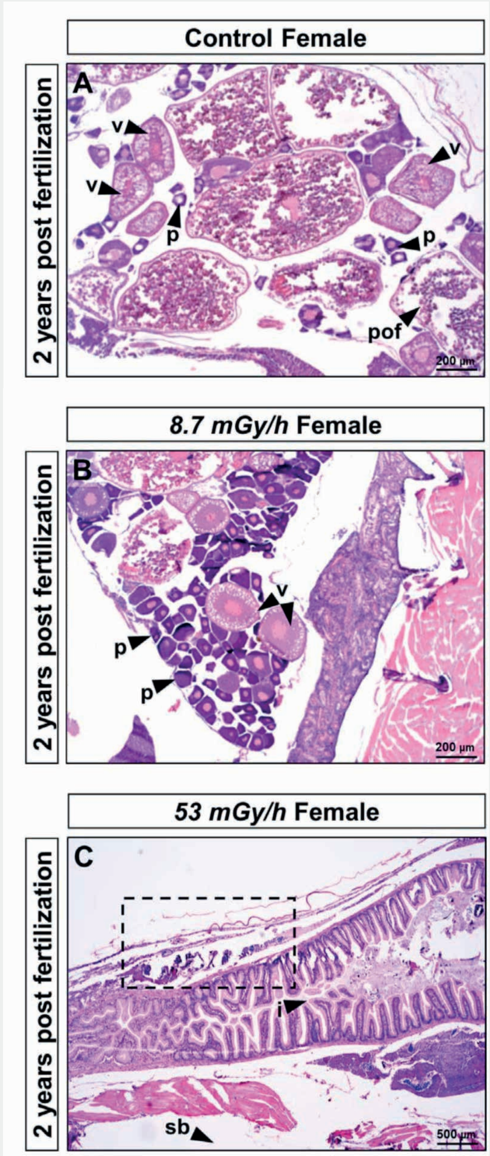


Figure 3. *Histological sections of ovaries.*

sites of hnf4a, cebpa, vegfab and gmnn. From an evolutionary point of view, comparable changes on histone PTMs were observed in zebrafish and salmon with gamma radiation induced higher enrichment of H3K4me3 in the house keeping gene beta actin.

Conclusion: Gametogenesis is a sensitive developmental timeframe for radiation induced adverse effects. Direct exposure of embryos reveal significant dose response effects on DEGs, but developmental phenotypes were only observed after prolonged exposures (48 and 96 hpf). A follow-up transgenerational study should uncover if observed effects can result in phenotypic changes. Parental radiological stress (ROS, LPO, DNA damage) can be transmitted to progeny. Embryos from exposed parents exhibit a generational effect on DNA methylation, miRNA expression and histone PTMs, giving indications of a relation between these marks and genes linked to demographic endpoints. Further analysis will focus on possible correlations between different types of epigenetic signatures, differential gene expression and observed functional phenotypes. A series of references are available in the Annual reports

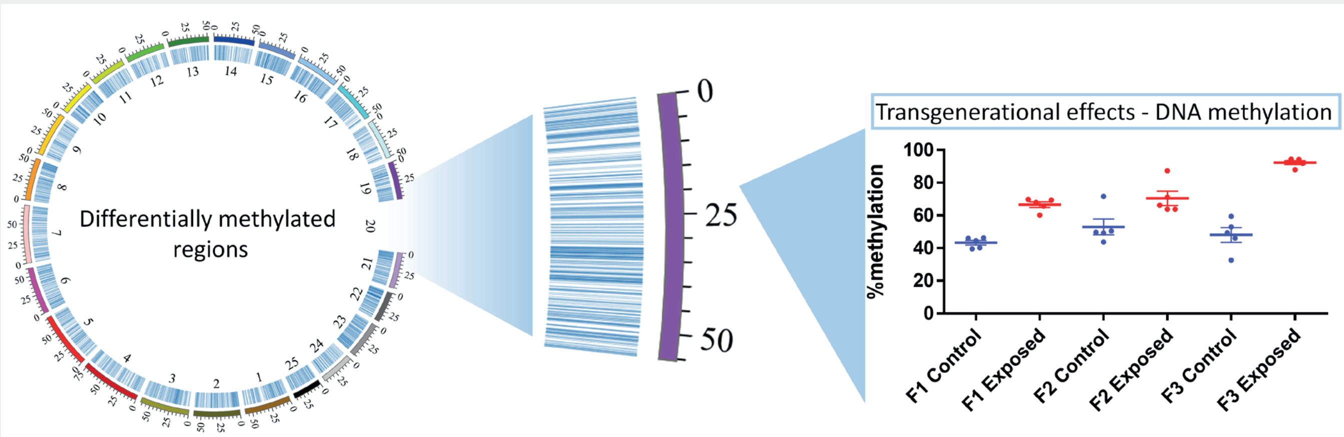


Figure 4. *Transgenerational DMRs: 5 of 15 validated from WGBS dataset, demonstrated by BisPCR2 in F1-F3 5.5 hpf offspring from 8.7 mGy/h exposed parents.*

CHRONIC LOW DOSE RATE (LDR) γ IRRADIATION AND LOW SELENIUM DIET ARE REPROTOXIC IN MALE MICE

NIPH: *J. Andersen, G. Brunborg, H. Dahl, D.M. Eide, A. Graupner, T. Hofer, C. Instanes, A.-K. Olsen*
NMBU: *DA. Brede, B. Lindeman, D.H. Oughton, B. Salbu*
NRPA: *R.W. Doughty*

Objectives: Germ cells are known to be sensitive to radiation, but this relates to high acute dose regimens and little is known about chronic low dose rate (LDR) exposure scenarios. Moreover, reduced availability of selenium, being an essential antioxidant, may aggravate effects of radiation. Human blood levels of Se are declining in Norway and other parts of the world due to changes in intake of foodstuffs. Our hypotheses were:

1) Chronic continuous exposure to LDR γ-radiation of spermatogonial stem cells hampers reproduction,
2) Low Se level and DNA repair deficiency of oxidative DNA damage aggravate reproduction.

Methods: Male mice were exposed to LDR γ-radiation (1.4 mGy/h) for 45 days resulting in males carrying sperm originating from exposed stem cell spermatogonia, that were mated with unexposed females from day 77-90, and propagated further to F2. Se-depletion was obtained by 2-generation feeding of mice with low Se forage. An array of methods was used: fertility measurements (fertility, fecundity, litter sizes, cannibalism, time-to-pregnancy), testis weights and pathology, testicular sperm head counts, testicular DNA damage and packaging (Comet analyses and vas deferens sperm-chromatin structure analyses (SCSA)) and epididymal sperm fluid protein carbonylations.

Results: Se-deficiency induced through 2-generation depletion of Se led to sterility. F0 males with spermatozoa originating from stem cells exposed to chronic LDR γ-radiation showed reduced reproductive capacity. Changes were observed in testis weights, testis pathology (reduced seminiferous tubule diameters and tubular epithelium heights), testicular sperm head counts, testicular DNA damage (strand breaks and oxidized DNA bases) levels, SCSA (Fig. 1) and epididymal sperm fluid protein carbonylation. Se-deficient mice exposed to gamma irradiation showed higher DNA damage levels and more pronounced pathological changes in the testis. Fertility was normal in male F1-offspring.

Conclusion: Chronic LDR γ-radiation of male mice is reprotoxic, leading to reduced fertility, impaired sperm production and to sperm with changed DNA damage levels and changes in DNA packaging. Effects are more pronounced if Se – deficient mice are exposed to LDR γ.

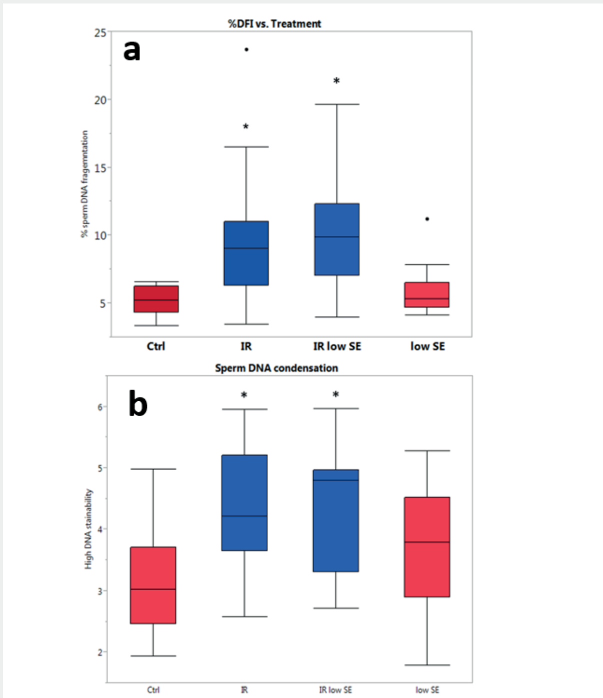


Figure 1. *Epididymal sperm chromatin structure analyses (SCSA). Vas deferens sperm collected at irradiation stop (day 45). SCSA show sperm chromatin integrity in mice dependent on treatment. Effect of irradiation for 45 days (Ctrl vs IR) and selenium (selenium deficient - low Se), or both. Plot a) shows percent sperm with high DNA fragmentation (i.e., cells with increased level of single-stranded DNA) and plot b) shows percent cells with high DNA stainability (i.e., considered to be immature sperm cells with an incomplete chromatin condensation). Compared with Ctrl p<0.05 is considered statistically significant, and is marked with asterix*

Norwegian University of Life Sciences

Norwegian Centre of Excellence

USE OF A NOVEL MOUSE MODEL FOR ACUTE MYELOID LEUKAEMIA (AML) TO STUDY CANCER RISK AFTER LOW DOSE RATE RADIATION

NIPH: *D.M. Eide, A.-K. Olsen*
NMBU: *D.A. Brede*
PHE: *L. Brown, C Badie*

Objectives: This is a multidisciplinary research project to study

- The risks of leukaemogenesis after radiation exposure to better estimate the magnitude of the risk at low dose-rate chronic radiation exposures (<6 mSv/h)
- The dose and dose-rate effectiveness factor (DDREF) by comparing low dose rate and high dose rate exposures
- Molecular signatures of leukaemia induced by radiation

The key hypotheses to be tested are that leukaemia induction from low dose rate exposure (2.5 mGy/h) will show non-linear dose-dependency and that the dose responses will differ between low dose rates and high dose rates (100 mGy/h) . The experiments will also allow tests of the impact of dose and dose rates on molecular signatures (Behjati 2016) and other biomarkers.

Methods: Male mutant mice were exposed to γ-radiation (2.5 mGy/h, 100 mGy/h) until total doses of 0.1, 1.0 and 3.0 Gy plus controls. The study uses a unique mouse model developed by Public Health England (PHE). In this CBA mouse model, two molecular 'hits' have been identified in leukaemia induction. The first hit is the loss of one copy of the haematopoietic transcription factor Sfpi1 ; the second hit, a point mutation occurring on the undeleted Sfpi.1/PU.1 allele making these mice extremely sensitive to radiation-induced leukaemia. The mice will be kept until signs of Acute myeloid leukaemia (AML), which normally occurs before 300 days, then culled for pathology and genetic analyses.

Results: DDREF and linear dose effects in the low dose rate area are calculated from the time of exposure to AML symptoms in these mice (Fig. 1). The DDREF accounts for the fact that low dose rate radiation may be less harmful than high, which was supported by the pilot study which showed a very large dose rate difference for one dose. Since the model appears to be more sensitive than standard wild type mice, follow up studies will use 4 doses at 2 dose rates to enable improved risk ratios to be estimated for low dose/low dose rates. This should also enable us to find quantitative biomarkers of exposure to predict AML risk.

Conclusions: Since leukaemia development is less complex than solid cancers, AML is an ideal model system to study radiation-induced cancers and low dose/dose-rate radiation. The CBA mouse model experiment demonstrated a difference in induction between two different dose rates.

References:

Behjati, S. et al. Nat Commun. 2016 Sep 12;7:12605.

Brown, N. et al. Mutat Res Genet Toxicol Environ Mutagen. 2015 Nov;793:48-54.

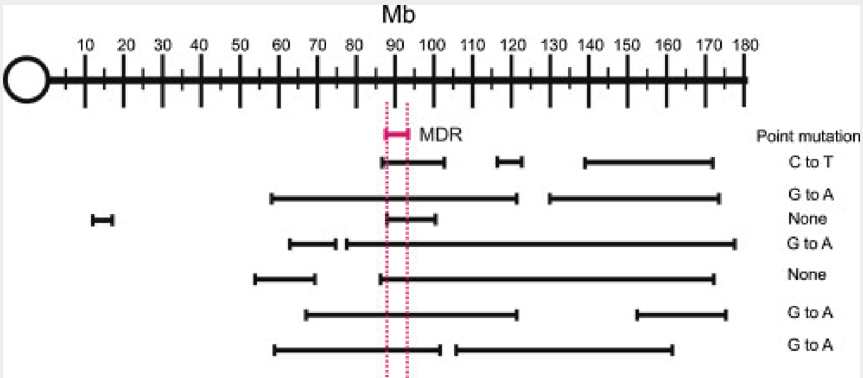


Figure 1. *7 out of 47 neutron-induced AMLs presented with multiple del2 events. These events are represented in the figure along with the location of the MDR in red. The presence or absence of a point mutation at R235 of Sfpi1/PU.1 is shown to the right. (Brown et al. 2015)*

GENOTOXICITY OF GAMMA RADIATION AT LOW DOSE RATES IN RELATION TO ANTIOXIDANT DEPRIVATION, ARSENIC CO-EXPOSURE AND CANCER IN MICE

NIPH: *A.-K. Olsen*
NMBU: *D. Brede, L. Skipperud, B. Salbu*

Objectives: The main objective was to determine the genotoxicity of chronic continuous exposure to low dose rate (LDR) γ-radiation, since genotoxicity is linked to cancer development. Moreover, we aimed at understanding if antioxidant deprivations such as selenium deficiency aggravate a genotoxic response, and if genotoxicity observed in blood may act as a biomarker for cancer.

Methods: Three comprehensive mouse experiments have been conducted: In the first experiment Se – deficient mice were exposed to one single low dose rate γ-radiation continuously for 45 days (1,41 mGy/h, 1.48 Gy). A battery of three stand-alone, yet complementary, assays was applied, covering three classes of genotoxic effects (flow based micronucleus assay, point mutations by the Pig-a assay and pre-mutagenic DNA lesions in the comet assay). Secondly, mice prone to gastrointestinal cancer (Min-mice) were exposed to another LDR of γ-radiation at two different total doses (2.2 mGy; 1.7 and 3.2 Gy) and acute X-rays (1.3 Gy/min, 2.6 Gy), to confirm previous findings and compare with similar acute exposures, and to investigate the correlation between cancer development and blood based genotoxicity. A third experiment was conducted, exposing yet other mouse lines (3) to several dose rates to establish dose-relationships, with simultaneous exposure to the co-stressor As.

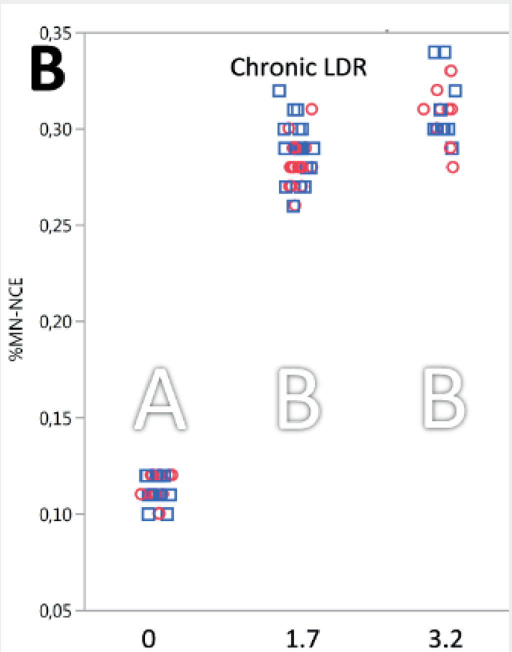


Figure 1. *Micronuclei assay. Mice chronically exposed to gamma-rays (2.2 mGy/h, total dose of 1.7 and 3.2 Gy). Each data point represents one mouse: red open circles for CBAB6 F1 Apc+/+ (i.e., wild type) and blue open boxes for ApcMin/+. The percentage of (A) micronucleated normochromic erythrocytes (% MN-NCE) are displayed. Dissimilar letters indicate significant difference between groups (P<0.05).*

Results: Chronic LDR exposure gave rise to genotoxic effects in blood cells (Graupner et al. 2016), with no significant interaction with Se-deficiency or DNA repair status of the mice. In the second experiment we confirmed the genotoxicity of LDR γ-radiation in different mouse line after LDR-exposure at two different total doses (Fig. 1; Graupner *et al.*, 2017). No correlation of blood-based genotoxicity with the carcinogenic-prone genotype of these mice were observed. In the third experiment we demonstrate a clear dose-response relationship between dose rate of γ-radiation and genotoxicity.

Conclusion: Chronic LDR γ-radiation is indeed genotoxic in exposure scenarios that are realistic for humans, supporting the hypothesis that even LDR γ-radiation may induce cancer.

References:

Graupner, A., et al. Gamma radiation at a human relevant low dose rate is genotoxic in mice. Sci Rep. 2016 Sep 6;6:32977.

Graupner, A. et al. Environ Mol Mutagen. 2017 Aug 30.

COMPARATIVE RADIOSENSITIVITY IN TERRESTRIAL PLANT SPECIES

NMBU/BIOVIT-IPV: *D. Blagojevic, Y.K. Lee, J.E. Olsen*
NMBU/MINA: *D.A. Brede, O.C. Lind, Salbu B., K.A. Solhaug*

Objectives: To compare radiosensitivity in seedlings of the conifers Scots pine, Norway spruce and the herbaceous model plant *Arabidopsis thaliana*.

Methods: Seedlings were exposed to gamma dose rates from 1-540 mGy/h for 144 hours and in *A. thaliana* also for 360 hours. Phenotypic effects, histology, DNA strand breaks and expression of selected genes (cell cycle-, antioxidant-, DNA repair-, general defence-related genes) were assessed at termination of exposure, and as after-effects of the gamma studied.

Results: At termination of gamma exposure, length of the conifer seedlings was reduced and DNA damage increased with increasing gamma dose rate. In *A. thaliana*, no effect on shoot growth was observed, but the number of lateral roots was reduced at the highest dose rates, and DNA damage increased with dose rate. Significantly increased expression of specific cell cycle- and DNA repair genes was observed for the highest dose rates in *A. thaliana*. In the conifers, such genes and antioxidant genes also showed increased expression, but at lower dose rates. After gamma exposure, growth was negatively affected in the conifers at ≥40 mGy/h with increasingly disorganised apical meristems and increased mortality with increasing dose rate (Fig. 1). In *A. thaliana* there was no mortality and no visible cellular damage, but flower bud formation and inflorescence stem elongation were conistently delayed at ≥400 mGy/h independently of gamma duration (Fig. 1), but this effect was transient only. However, in all species persistent DNA damage was observed 1.5 months after termination of the gamma exposure.

Conclusion: Scots pine and Norway spruce seedlings show similar, high sensitivity to gamma as compared to the highly resistant *A. thaliana*. However, persistent DNA damage in all species indicates higher tolerance to such damage in *A. thaliana*.

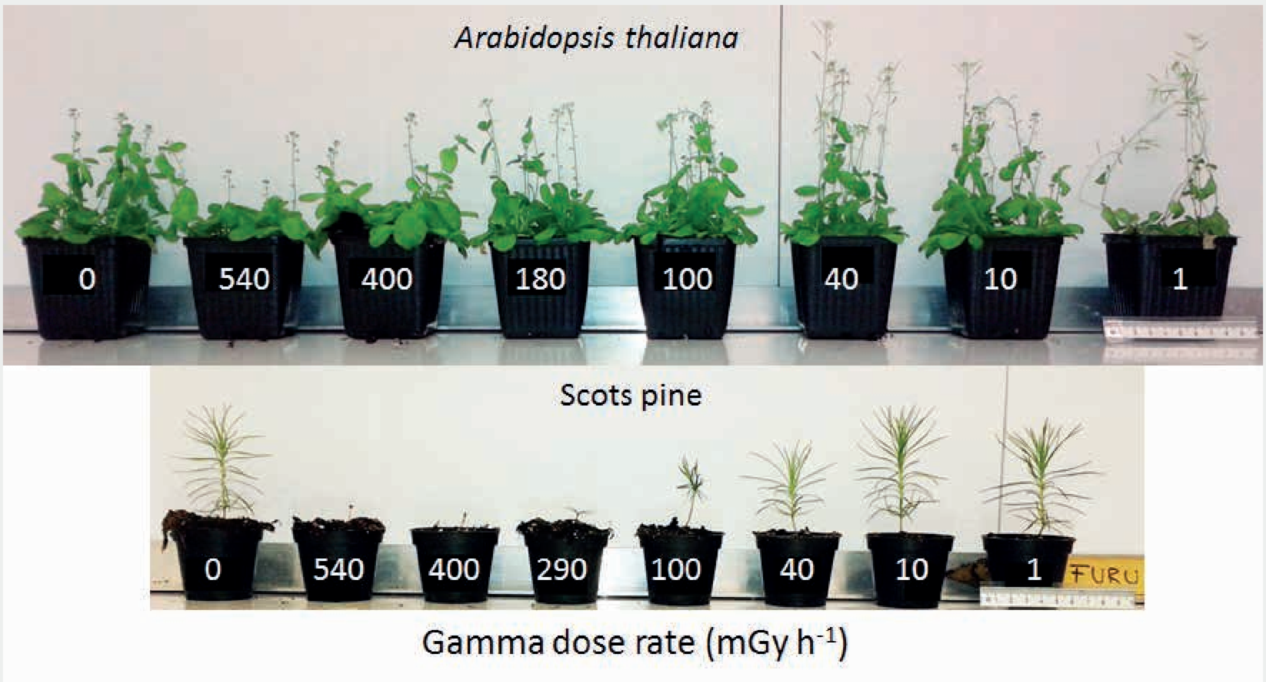


Figure 1. *Plant phenotypes and histology 1.5 month after termination of gamma exposure.*

CHARACTERIZATION OF THE TOXICITY OF γ- AND UV-RADIATION IN *LEMNA MINOR*

NIVA: *K.E. Tollefsen, L. Xie*
NMBU-MINA: *D.A. Brede, O.C. Lind, B. Salbu, K.A. Solhaug,*
NRPA: *B. Johnsen*

Objectives: This project aimed to assess the toxicity of gamma radiation (γ) and ultraviolet radiation (UV) singly and in combination in the aquatic plant *Lemna minor*.

Methods: *L. minor* was exposed to UVR (0, 0.25, 0.5, 1, 2, 4 W/m^2) and γ-radiation (10, 20 and 40 mGy/h) individually for 7 days and a combination of the two (γ: 10, 20 and 40 mGy/h; UV: 0.5 W/m^2) to characterize the responses on growth, photosystem II (PSII) activity, reactive oxygen species (ROS) formation, lipid peroxidation (LPO), pigmentation (Chlorophyll *a*, Chlorophyll *b* and carotenoids), uncoupling of oxidative phosphorylation (OXPHOS) and frond malformations.

Results: Both the γ and the UV exposure enhanced the oxidative stress and caused adverse effects on pigments, photosynthesis, energy formation and growth at high does rates. A combination of γ and UV caused apparent antagonistic effects on carotenoid synthesis, ROS and OXPHOS formation, whereas PSII activity was inhibited in an additive manner. Apparent synergistic effects were observed in terms of reproductive output (fronds number) at gamma dose rates equal to or below 13 mGy/h (Fig. 1).

Conclusion: UV and γ-radiation have similar MoA (ROS formation) and toxicity pathway in *L. minor*. No clear enhancement of toxicity was observed at the lowest levels of biological organization when lemna was exposed to both stressors in combination. UV potentiated γ-induced inhibition of photosynthesis and growth.

Relevance: This work provides better understanding of the effects of UV and γ-radiation when exposed singly and in combination. The data generated will improve the knowledge of how molecular and cellular responses cause adverse effects, and contribute to reducing the uncertainty associated with predicting multiple stressors effects.

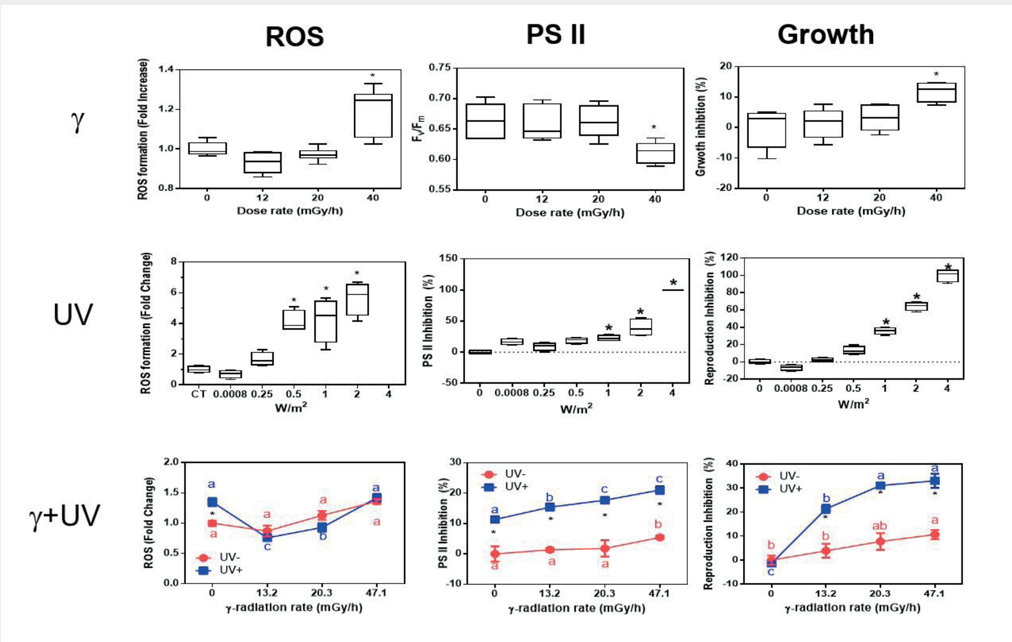


Figure 1. *Responses of L. minor after 7 days exposure to UV and gamma radiation*

Research Area 4 - Risk Assessment and Ecosystem Approach

Research Area Leaders: Knut Erik Tollefsen, NIVA and Astrid Liland, NRPA

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
- Which factors contributed the most to the overall uncertainties in impact and risk models, and how can these be improved?
- 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 socioeconomic impacts of potential nuclear events?

By interfacing models linking sources and associated release scenarios via ecosystems to impact and risk assessments, the overall uncertainties associated with model predictions should be assessed. By focusing on those factors contributing the most to uncertainties, the predicting power should be improved. Secondly, there is an increasing focus on 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 in recent years, not least due to purported effects at doses much lower than those seen in the laboratory. Finally, there is an increasing recognition that radiation protection needs also to address socioeconomic impacts.

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. To address the RA4 objectives, research is focused on 3 umbrella projects.

Umbrella 4A: Ecosystem Approach (Alicja Jaworske, NRPA)

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.

Umbrella 4B: Potential Nuclear Events - Impact and Risk Assessment (Ole Christian Lind, NMBU)

The main aim is to evaluate and improve impact and risk assessment tools for establishing a scientifically based set of decision criteria associated with different nuclear events. 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, and by focusing on these factors, processes, mechanisms within RA1-3, the predicting power of impact and risk modelling should be improved.

A set of prediction models developed in RA3 will be evaluated under RA4, including mode of action (MoA), adverse outcome pathway (AOP) analysis, as well as combined effects and cumulative risk assessment (CRA) for multiple stressors. These models will be applied to CERAD relevant stressors, exposure scenarios, effect endpoints and species/ life stages.

Umbrella 4C: Societal Impacts (Astrid Liland, NRPA)

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, incorporating a range of economic, societal, and ethical impacts. Evaluation of these aspects requires multidisciplinary approaches between natural and social scientists to understand 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, cost-benefit analysis would inform what mitigating effort would be needed to counteract the foreseeing impact and risks.

PhD and Post Doc positions:

PhD Y. Tomkiv (NMBU-MINA), PhD A. Liland (NRPA), PhD K.J. Aurland-Bredesen (NMBU-HH)

There is no such thing as bad weather... during fieldwork
Photo: Frøydis Meen Wærsted

ASSESSMENT OF FUKUSHIMA-DERIVED RADIATION DOSES AND EFFECTS ON WILDLIFE IN JAPAN

NRPA: *P. Strand, J. Brown*

Objectives: To review reports/publications on environmental impacts following the Fukushima Daiichi accident from 2011

Methods: Review of literature and establish where differences between the original (UNSCEAR) assessment and field-reported data are apparent

Results: Morphological abnormalities have been observed in some, but not other studies, e.g. Watanabe *et al*. (2015). The figure 1 shows that Japanese fir tree populations near FDNPS exhibit a significantly increased number of morphological defects. The observation of such effects is nonetheless compatible with international assessments. Severe effects, relevant to population integrity, continue to be reported *e.g.*, Hiyama et al. have built upon earlier work by the same group (Fig. 2), studying the pale grass blue butterfly. Severe direct effects on populations have also been reported where abundances of butterflies, cicadas and birds decreased with increasing radiation levels (various publications by

Figure 1. *Watanabe et al. (2015) showing morphological disturbances in coniferous trees*

Figure 2. *Hiyama et al. [2012] showing abnormalities in butterflies*

A.P. Møller and T. Mousseau). Some of the studies reviewed were in contrast to the comprehensive assessments of IAEA and UNSCEAR, wherein the conclusion was drawn that severe, regional population level impacts on wild plants and animals following releases of radioactivity from the Fukushima accident were unlikely.

Conclusion: There are limitations regarding the initial UNSCEAR assessment, but further validation of some recent studies is also required some of which arguably suffer from poor dosimetry and inadequate accounting of confounding factors etc. It seems apparent that disturbances induced by stressors cannot be entirely grasped from knowledge of the stressor's effects on individual organisms, which may necessitate the introduction of an ecosystem-based approach to assess, more realistically, environmental impacts.

References:

Strand, P. et al. / J Environ Radioact., 169-170 (2017); 159-173

THREAT ASSESSMENT TO NORWAY FROM TWO HYPOTHETICAL ACCIDENTS: SELLAFIELD AND K-159

MET: *H. Klein, J. Bartnicki*
NRPA: *J.E. Brown, A. Hosseini*
NMBU: *O.C. Lind, B. Salbu*

Objectives: Radioactive debris released to the atmosphere following a nuclear accident can result in severe contamination several hundred kilometers away from the source. Norway is located within the range of radioactive fallout from potential nuclear events involving dumped nuclear waste, nuclear power plants and nuclear reprocessing sites. Both the source terms, which include the amount (Bq) and speciation of radionuclides released, and the meteorological conditions during the release play an important role for the consequences.

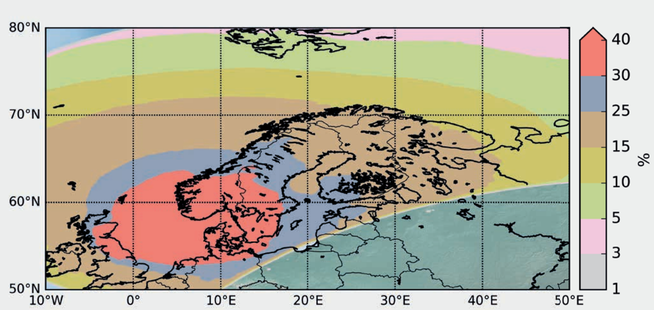


Figure 1. *Climatological probability of deposition above 10 Bq/m² from Sellafield.*

Methods: This study used two hypothetical accident scenarios to investigate the potential transport to Norwegian territories and the subsequent deposition: a hypothetical accident at the Sellafield reprocessing plant, and an accident involving the recovery of the sunken Russian nuclear submarine K-159. A meteorological database with 33 years of meteorological conditions has been used to simulate the atmospheric transport with the SNAP atmospheric dispersion model. Statistical properties have been derived using threshold values of 10 Bq/m^2.

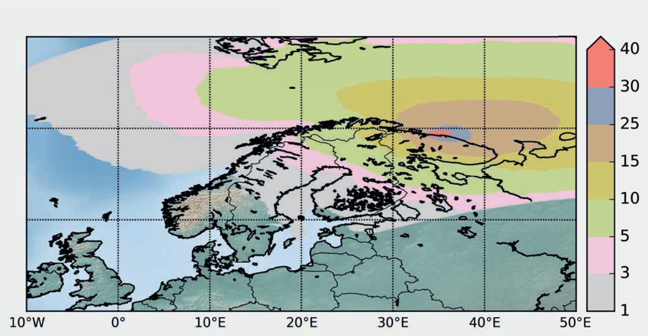


Figure 2. *Climatological probability of deposition above 10 Bq/m² from K-159.*

Results: Prevalent meteorological conditions coupled with Norway's geographical position render the south-western region of the country potentially vulnerable to a release from Sellafield. The K-159 represents a much smaller source term, but the distance to Norway is shorter and the environment of northern Norway is more vulnerable to radioactive contamination. The figures 1 and 2 show the climatological probability of deposition of more than 10 Bq/m^2 of ^{137}Cs.

Conclusion: The statistical analysis shows that the threat to most parts of Norway, except to the most northern regions, are much lower from K-159 than from Sellafield. In 67% of all cases for Sellafield, and 48% for K-159, the predicted deposition in Norway could be higher than 10 Bq/m^2.

References:

Klein, H., Bartnicki, J. (2018). In: Air Pollution Modeling and its Application XXV 72. ITM 2016. Springer Proceedings in Complexity.

Hosseini, A., Amundsen, I., Brown, J., Dowdall, M., Dyve, J.E., Klein, H. StrålevernRapport 2017:12. Østerås: Statens strålevern, 2017.

Norwegian University of Life Sciences

Norwegian Centre of Excellence

PRENATAL EXPOSURE TO CHERNOBYL FALLOUT IN NORWAY: NEUROLOGICAL AND DEVELOPMENTAL OUTCOMES IN A 25-YEAR FOLLOW-UP

Univ. of Bergen: *R.T. Lie, D. Moster*
NRPA: *P. Stand*
NIPH: *A.J. Wilcox*

Objectives: Identify possible effects of low radiation doses early in life that may cause later neurodevelopmental problems.

Methods: An extensive radiation exposure survey was conducted in Norway in the three years following the Chernobyl Accident. Internal and external radiation doses were estimated for municipalities, a cohort of all Norwegian pregnancies during the three-year period of radiation measurement and appropriate unexposed reference groups were established. Cohorts were followed to adulthood and risks of cerebral palsy, retardation, schizophrenia, epilepsy, vision/hearing problems, school dropout, and low income were estimated.

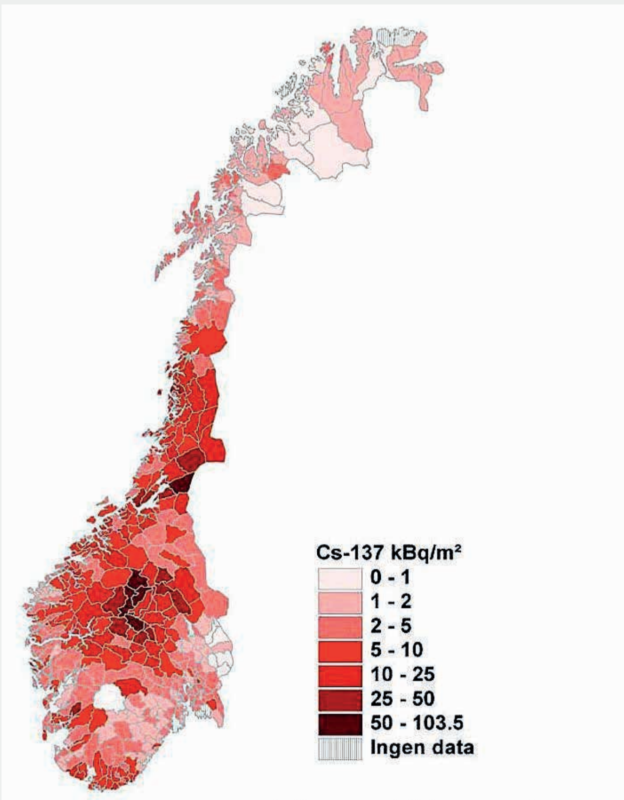


Figure 1. *"Deposition of Chernobyl ^{137}Cs in Norway"*
Photo: Norwegian Radiation Protection Authority

Photo: *Shutterstock*

Results: Little evidence of increased risk biological or mental problems associated with radiation exposure. An increase in failure to complete high school (p=0.05), but no increase in the proportion with low income (p=0.38) was observed. Older siblings exposed during pregnancy had relatively lower mathematics grades than their younger (unexposed) siblings, but not lower Norwegian language grades (p=0.11).

Conclusion: No evidence that the fallout in Norway from the Chernobyl accident (Fig. 1) had effects on a range of serious neurodevelopmental conditions. A tendency was found for older siblings exposed in pregnancy to perform more poorly in mathematics at middle school than their younger siblings. While this finding may be due to chance, it is consistent with findings from Sweden, and supports the possibility that low-dose radiation may produce sub-clinical effects on the developing brain.

References:

Lie, R.T., Moster, D., Strand, P. et al. Eur J Epidemiol (2017) 32: 1065. https://doi.org/10.1007/s10654-017-0350-z

CENTRE FOR ENVIRONMENTAL RADIOACTIVITY

DEVELOPMENT OF ADVERSE OUTCOME PATHWAYS FOR GAMMA RADIATION-MEDIATED REPRODUCTIVE EFFECTS IN DAPHNIA MAGNA

NIVA: *T. Gomes, J. Thaulow, Y. Song, K.E. Tollefsen , L. Xie*
NMBU-MINA: *D. Brede, Y. Kassaye, B. Salbu,*
NMBU-Imaging Center: *Y. Lee*
Newcastle University: *G. Caldwell, F. Lyne*

Objectives: Develop the first conceptual adverse outcome pathway (AOP) linking excessive reactive oxygen species (ROS) production to reproductive effects in arthropods; Evaluate the conceptual AOPs experimentally using gamma radiation as a prototypical stressor.

Methods: Conceptual AOPs developed on basis of literature survey and data mining; Reproductive effects evaluated using 21d chronic *Daphnia* reproduction test (OECD TG211); Short term exposure (8-day) and functional endpoints assessed using NIVA's *Daphnia* Effect Assessment Toolbox.

Results: The reproduction test showed that 1 mGy/h and 100 mGy/h gamma radiation caused reproductive decline after 21-day exposure. After 8-day exposure, increased production of cellular and mitochondrial ROS, induction of apoptosis, suppression of mitochondrial membrane potential and decrease in lipid storage were observed in *D. magna*. Comparative analysis showed that the reproduction effects were strongly correlated with increased cellular ROS formation and decreased lipid storage.

Conclusion: Gamma radiation affected the reproduction through multiple toxicity mechanisms along a conceptual network of AOPs (Fig. 1). The first AOPs describing the reproductive effects of gamma radiation in *D. magna* has been submitted to the AOPWiki (https://aopwiki.org/aops/216; https://aopwiki.org/aops/238).

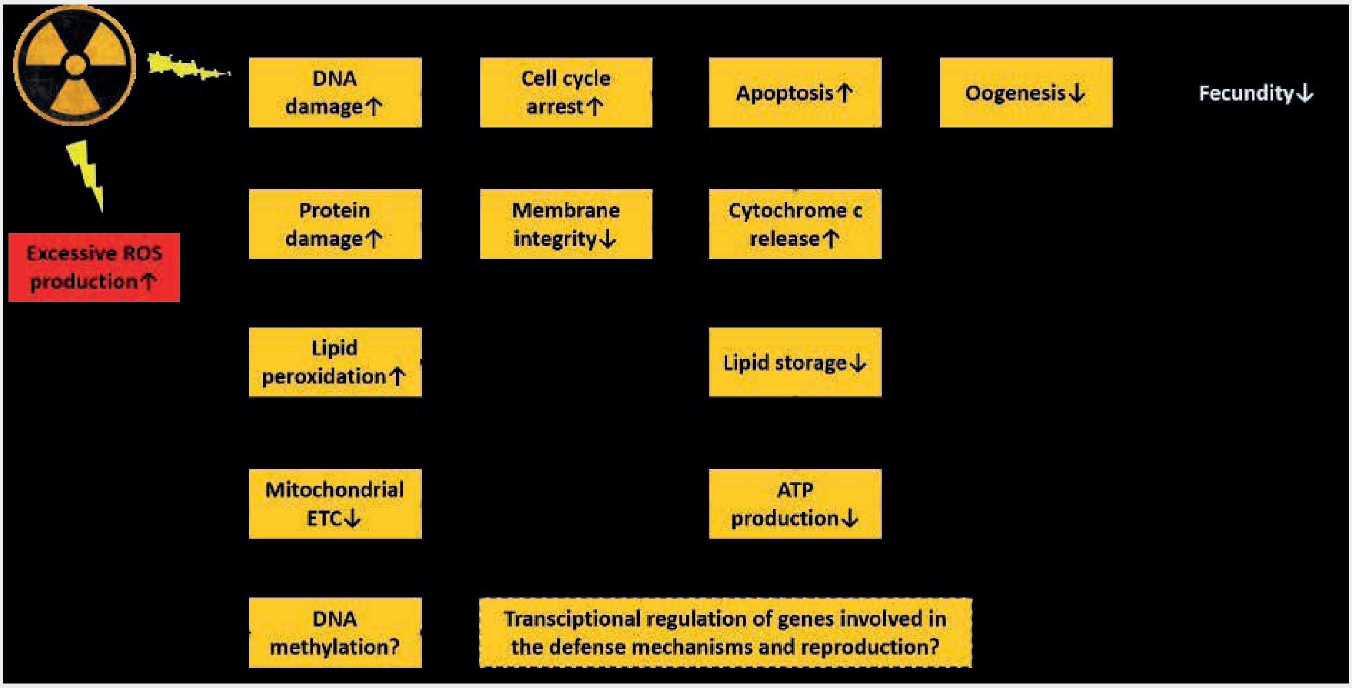


Figure 1. *A network of adverse outcome pathways (AOPs) linking gamma-induced excessive reactive oxygen species (ROS) production to reproductive decline in Daphnia magna.*

AOP-INFORMED HAZARD AND RISK ASSESSMENT OF NORM AND METALS FROM ALUM SHALE RICH WATERS

NMBU-MINA: *L. Skipperud, H.-C. Teien, F. Meen Wærsted*
NIVA: *K.E. Tollefsen*

Objectives: This project aimed to conduct cumulative hazard and risk assessment of NORM and metals in alum shale rich waters.

Methods: A combination of source characterization using *in situ* fractionation, ICPMS analyses of mobilized metals and NORM in waters from alum shale rich areas of RV4 at Gran (Norway), hazard and risk assessment using the ERICA tool and the NIVA Risk Assessment database (NIVA RAdb™) were conducted.

Alum shale rich waters from RV4 at Gran

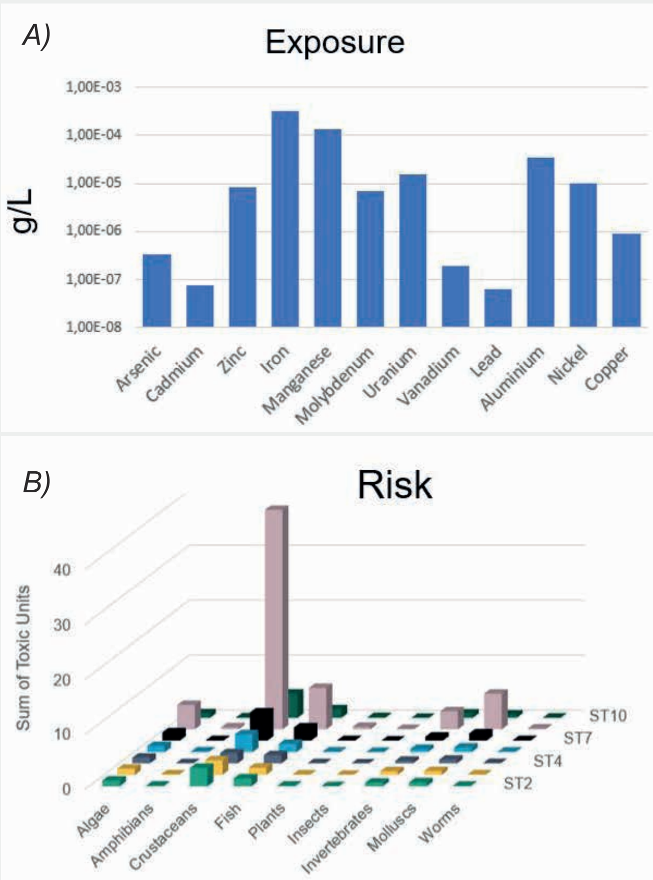


Figure 1. *A) Exposure assessment of metals and NORM and B) risk predictions using the ERICA Tool and NIVA RAdb™*

Results: Highly variable concentrations of metals and NORM were identified in the waters from the alum shale rich areas (Fig. 1). Predictions by the NIVA RAdb™ and the ERICA tool identified site- and taxa-specific risk scenarios that could be related to both chemical and radiological toxicity.

Conclusion: The NIVA RAdb™ and ERICA tool are complementary Risk Assessment tools that collectively address both chemical and radiochemical risk. Chemical risk seemed to be a larger risk driver than radiological risk at many locations. The most susceptible species were identified to be algae, crustaceans and fish.

Relevance: This work provides a complementary toolbox for addressing the risk of multiple stressors and will aid the assessment of cumulative hazard and risk of ecologically relevant exposure scenarios.

References:

Skipperud, L., Alvarenga, E., Lind, O.C., Teien H.-C., Tollefsen, K.E., Salbu, B., Meen Wærsted, F. (2016). Effekter og miljørisiko knyttet til inngrep i områder med sulfidrike mineraler. Ås, Norway: NMBU.

International Collaboration

CERAD has during 2017 further built upon its bilateral and international collaborative efforts. CERAD maintains its activities within the Arctic Council and contributes updated knowledge to the Arctic Monitoring and Assessment Programme (AMAP) such that Arctic challenges with respect to radioactive contaminants and climate change are met with a firm foundation of reliable scientific information. CERAD is active within a number of ongoing Nordic Nuclear Safety Research (NKS)-projects, consolidating its position as an active contributor to the strengthening of relevant competencies in the Nordic region. On the wider field, CERAD remains prominent within European radioecology research initiatives and activities such as the European Radioecology Alliance (ALLIANCE), the European Platform on preparedness for nuclear and radiological emergency response and recovery (NERIS), the Multidisciplinary European Low Dose Initiative (MELODI) and the European Radiation Dosimetry Group (EURADOS). During 2017, CERAD commenced work as a partner within the EU Projects TERRITORIES (integrated and graded risk management of humans and wildlife in long-lasting radiological exposure situations) and CONFIDENCE (uncertainties in the area of emergency management and long-term rehabilitation) and continues as a partner in the European Joint Programme for the Integration of Radiation Protection Research (CONCERT).

CERAD/NMBU retains its position as the only European MSc in radioecology, and this effort is supported by collaborative agreements (MoU) with a number of universities abroad (*e.g.*, Ukraine and Japan). Close international cooperation continues to provide access to leading experimental facilities in France, Germany, Australia, Spain and Australia) as well as contaminated sites (*e.g.*, Chernobyl, Fukushima) facilitating field work activities in support of CERADS research activities. This broad international engagement is reflected in the spectrum of co-authors in CERAD publications (see Publication list).

CERAD continues its active participation in several international bodies, such as The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), International Atomic Energy Agency (IAEA), International Union of Radioecology (IUR), and the International Commission on Radiological Protection (ICRP). In addition to individual experts (Per Strand and Justin Brown), the sixty-fifth session of UNSCEAR will be held in June of 2018 and for the first time Norway has been invited to attend. This reflects the growing international stature of Norwegian radioecological science and ensures that Norwegian interests in the area of radioecological science are well represented.

IAEA activities continue to feature CERAD members in areas such as radioactive particles (chair IAEA CRP), revision of technical safety guides and ongoing work on the societal impacts of Fukushima. CERAD collaborates closely with the IUR in further development of an Ecosystem Based Approach for radioecology. CERAD experts are involved in ICRP task groups and participated in three co-expertise dialogues in Fukushima and one final international workshop on the ICRP dialog initiative. CERAD's Research director is a member of UNESCO's World Commission on the Ethics of Scientific Knowledge and Technology. CERAD has cooperated with the intergovernmental OECD-Nuclear Energy Agency (NEA), in facilitating cooperation among countries with respect to advanced nuclear technology infrastructures, and the OECD NEA: Expert group on Management of Radioactive Waste After a Nuclear Power Plant Accident, both chaired by the CERAD Deputy director.

Professor Per Strand, Deputy Director

Experimental Facilities, Models and Tools

A clear Vision for the Scientific Output from CERAD CoE is to provide:

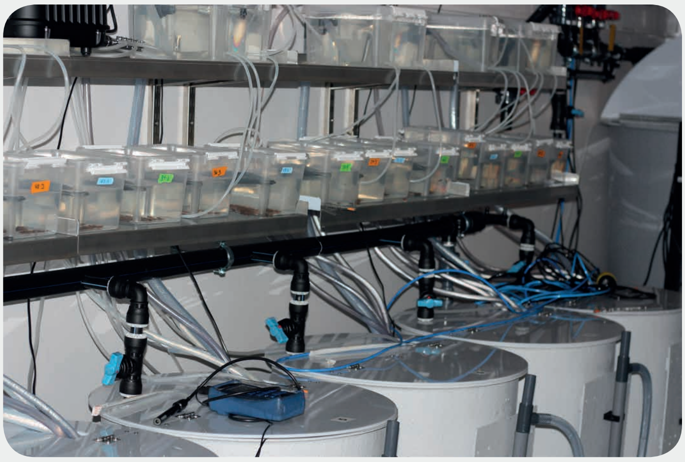
- Novelties: major progress at the interface between disciplines
- New concepts: integrated concept for human and the environment, integrated concept for contaminants, integrated concept for ionizing and UV radiation, and explore an effect unit for non-human organisms
- Cutting edge: combination of advanced tools from other disciplines
- Dynamic models: time and climate dependent variables

To meet the scientific requirements, the CERAD CoE has the possibility to perform cutting edge research due to access to unique experimental facilities, models and tools, both within CERAD and in collaboration with partner institutions and also internationally. Below, the experimental facilities, models and tools are listed in short. More information on each tool and infrastructure item can be found in the 2016 CERAD annual report.

Radionuclide, Element and Isotope Ratios

CERAD is well equipped when it comes to determining radionuclides and other elements in the environment:

- At NMBU Isotope Laboratory and NRPA instrumentations and methods for determination of gamma- , beta- and alpha-emitting radionuclides are available.
- At NMBU, three Agilent 8800 Triple Quadrupole ICP-MS (ICP-QQQ-MS) are utilized for the determination of long-lived radionuclides, including isotope ratios, and a large range of other elements in the periodic table.
- At NMBU a new Bruker M4 Tornado micro-XRF is installed.
- At very low concentration levels, the AMS facilities at Australian National University, Canberra, Australia and Centro Acceleradores, University of Seville, Spain are utilized.



Fish tanks in the fish Laboratory
Photo: Hans-Christian Teien

Particles, Speciation and Fractionation Techniques

CERAD has 30 years of experience within speciation and fractionation of radionuclides and other elements in the environment. Therefore, equipment utilized for *in situ* and in lab speciation analysis are important tools, and include:

- At the Isotope laboratory, NMBU, CERAD has a unique particle archive containing sub-micrometer to millimetre sized radioactive particles released from different sources, varying with respect to composition, particle size, crystalline structure and oxidation states. The well characterized anthropogenic and naturally occurring particles originate from different historical sources and release scenarios such as nuclear weapon tests, conventional detonation of nuclear weapons, reactor accidents, accidental and routine releases from nuclear reprocessing facilities, different NORM sites, as well as the use of depleted uranium and particles associated with dumped waste.
- *In situ* fractionation systems such as chromatography-hollow fibre and tangential flow systems are available at NMBU Isotope Laboratory, and these are used in field expeditions all over the world where CERAD/ NMBU is involved in aquatic research projects

- A FIFFF-ICP-MS (flow field flow fractionation) system is utilized for speciation work at the laboratory, together with a HPLC-ICP-MS system.

Synchrotron X-Ray Radiation Facilities and Imaging Tools

Based on many years of close collaboration with scientists nationally and internationally, CERAD/NMBU has access to and has utilized:

- ESEM-EDX, TEM, TOF-SIMS, nano-CT, synchrotron radiation nano-and microscopic techniques. These SR techniques (*i.e.*, 2D/3D µ-XRF – elemental distributions, µ-XRD - structure, µ-XANES – oxidation state) utilized for particle research at facilities such as PETRA, Germany, and ESRF, France, have been developed by NMBU, University Antwerp and the beamline scientists. In addition, access to synchrotron microscopic techniques is also obtained in Australia (ANSTO).
- The Imaging Centre Campus Ås is aiming at a state-of-the-art status within microscopy (ESEM-EDX, TEM, confocal laser SEM, light microscopy, live cell imaging and spectroscopy (x-ray, RAMAN micro imaging etc). Within the roadmap, CERAD acts as an important node with respect to competence and instrumentation (stereo microscope with micromanipulation, micro-XRF, micro-XRD).

Solar UV monitoring
Photo: Bjørn Johnsen

CERAD Experimental Facilities

CERAD has access to different experimental facilities both at NMBU, but also at partner institutions. These facilites includes:

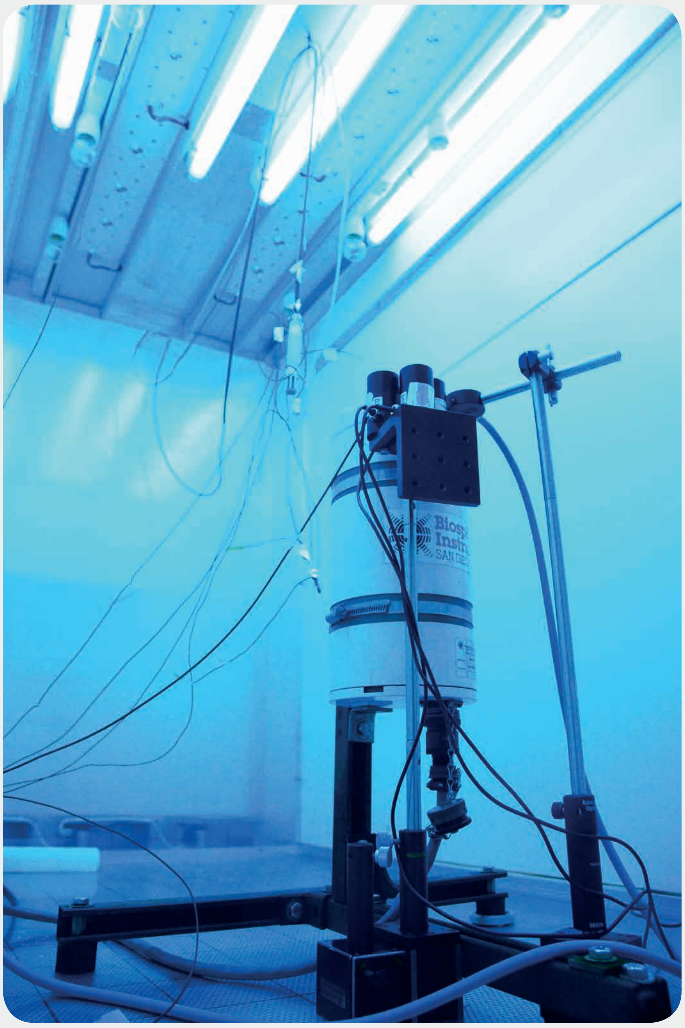
- The NMBU low-medium dose gamma radiation exposure facility (figaro). The NMBU constructed gamma irradiation source at Ås is the only one of its kind, provides a continuous dose rate field from 3 Gy/h down to 400 µGy/h, and allows simultaneous chronic exposure of samples over the whole dose-rate field. The CERAD/NMBU facility opened in 2003, and was upgraded in 2012, supported by the EU DoReMi project. The facility is utilized for a series of chronic exposure experiments (including combined gamma/alpha and multiple stressor studies) on various test organisms
- Fish Experimental Facilities - Transfer and Effects Experiments on Fish - both Freshwater and Marine Fish Species (NMBU).
- Zebrafish platform – transfer and effect studies on Zebrafish (NMBU).
- Mouse platform – transfer and effect studies on mice (NIPH).
- Greenhouses/Plant uptake and effect experiments (NMBU phytotron).
- Climate chambers for combined UV and gamma exposure (NMBU).

THE CERAD Biological Effects Toolbox

The CERAD consortium has established a toolbox for systematic interspecies comparison of harmful effects of chronic exposure to radioactivity as part of Research Area 3. The toolbox has been designed to serve as a framework for investigation of radiosensitivity, and combined stressor scenarios including radionuclides, toxic metals and UV.

The aim is to investigate the apparent differences in radiosensitivity and to identify mechanisms at the molecular level that determine susceptibility to chronic low/medium dose rate gamma radiation alone, and in combination with other stressors.

The toolbox focuses on selected model species including mammals, fish, invertebrates and plants. The toolbox includes standardized experimental designs and protocols with a common set of biological effects endpoints. To ensure comparable exposure scenarios, standardized dosimetry and a core set of dose rates are employed for all model species. Additional dose rates are customized for each model species to establish a dose-response.



Calibration chamber
Photo: Bjørn Johnsen

Models

At CERAD, a key focus is to link models describing radionuclides released from a source term, via dispersion, deposition, and ecosystem transfer to biological uptake and effects to estimate impact and risks for human and the environment as well as consequences for the economy and the society. Therefore, a series of models available at the CERAD partners are interphased:

- Dispersion and Transfer Models: Advanced air/marine transport models and real time/historic/future prognostic meteorological data are further developed by MET and NRPA.
- Ecosystem transport models: Advanced fresh water (NIVA) and terrestrial (NRPA) models, advanced models on dosimetry (NRPA), as well as human food chain and wild life food chain models (NRPA) are also utilized at CERAD.
- Models for impact and risk assessment including the ERICA assessment tool and Cummulative Risk Assessment (CRA), are available (NRPA, NMBU, NIVA) to predict the hazard and risk of single stressors and combinations of these (multiple stressors).
- The economic modelling under CERAD covers three main parts linked to Potential nuclear events:
  1) scenario specific assessment of economic consequences for agriculture due to potential accidental release and radioactive contamination,
  2) scenario specific assessment of economic consequences for recreational fisheries due to potential radioactive contamination, and
  3) economic assessment of catastrophic risks utilizing an extended expected utility framework.

Field Studies and Expeditions

Several expeditions and fieldwork have been performed every year within CERAD. Since the start of CERAD, fieldwork or expeditions concerning accidental release of radionuclides, nuclear test sites, naturally occurring radioactivity (NORM) sites and fieldwork concerning case studies have been performed. The CERAD fieldworks input to all CERAD research areas (RA), as investigations carried out relate to the speciation of radionuclides (RA1), mobility and transfer in the environment and bioavailability to aquatic and terrestrial organisms (RA2) and also possible effects in the studied organisms from both radionuclides and other stressors (RA3). Thus, most results feed into the environmental risk assessment performed in RA4.
For 2017 the focus of the fieldwork has been in the Chernobyl exclusion zone, studying radionuclides in the environment from the Chernobyl accident in 1986, but also field studies of I-129 and I-131 have been performed.

Field course arranged 2017:
In June 2017, CERAD and the National University of Environment and Life Sciences (NUBIP), Ukraine, co-organized a successful field course within the Chernobyl exclusion zone in Ukraine. The aim of the course was to obtain practical skills of fieldwork within radioactively contaminated territories like Chernobyl exclusion zone (ChEZ), through solving actual problems within radioecology. The course participants were trained in field sampling techniques and worked within project teams on one of the following problems:

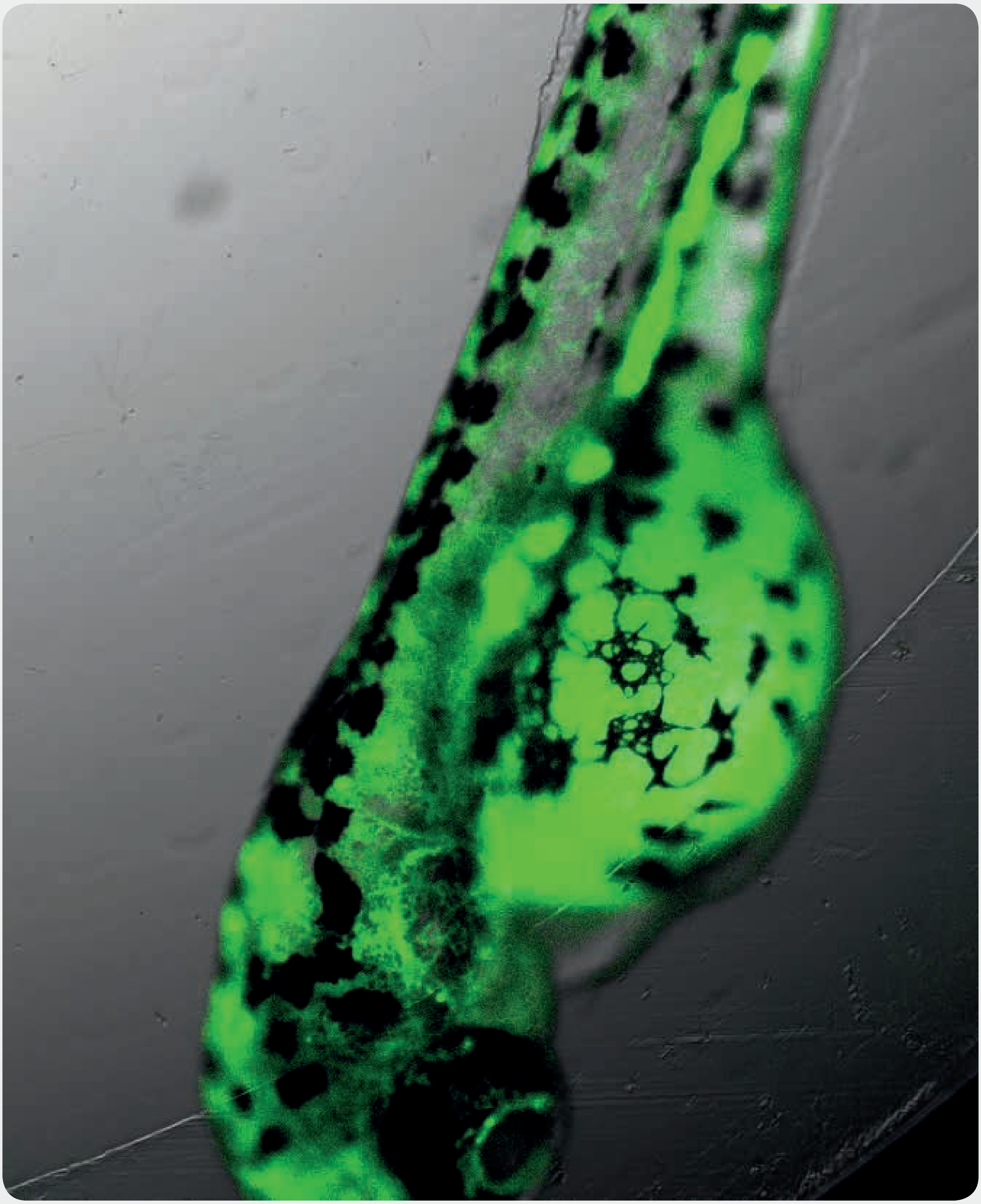
1. Forest fires in ChEZ: risk assessment and recommendations for preventive actions.
2. Nuclear power plant cooling pond drainage: environmental impact assessment and providing recommendations for further implementation.

The course will be arranged again June 1st-15th, 2018 in Chernobyl and Kiev.

Fieldwork concerning accidental release of radionuclides to the environment:
The Chernobyl exclusion zone (CEZ), Ukraine, were visited both in June and October 2017 to do in-field experiments. The fieldwork was performed in close collaboration with Ukraine partners at National University of Life and Environmental Sciences of Ukraine (NUBIP). The campaign focus on aquatic environment, *i.e.*, collection of water samples, zooplankton and fish species both to identify radionuclides and biomarkers (Fig. 1).

The CERAD field tracer experiments:
Controlled tracer experiments with I-131 have been performed at NIBO's facilities at Apelsvoll and Furuneset, an inland and west coastal area, respectively. The transfer of I-131 in terrestrial environments with grass and barley was studied during several comprehensive fieldworks together with NIBIO, which covers the entire growing season. A total of 6 fieldworks were carried out, including collection of rainwater, soil profiles, grass and barley.

Figure 1. *PhD student Shane Scheibener on fieldwork in Lake Glubokeye, Chernobyl Photo: Hans-Cristian Teien*



Formation of reactive oxygen species (green) in a zebrafish embryo after an ultraviolet B exposure
Photo: Selma Hurem

Education and Training Program

An essential ingredient in CERAD is researcher training and education (MSc, PhD) to provide an internationally attractive research environment, and to produce candidates that are internationally competitive within radioecology and ecotoxicology. The EU supported MSc in Radioecology is unique in Europe, forming a useful recruitment base for PhD education. All courses are given in English and most courses are run intensively to make access possible for international students. The ultimate aim of the education and training effort of CERAD is to ensure a sustainable workforce in radioecology. To do this we are dependent on interactions with the wider radioecology community, through outreach to students, teachers, employers and employees, and to stakeholders outside of our networks. Since radioecology is a multidisciplinary science, students on MSc or PhD projects in radioecology have a wide range of future carrier opportunities, and one of our goals is to put students in contact with potential employers and research projects, as well as to ensure that training and education in radioecology meets the needs of those employers.

EUROPEAN MSC PROGRAM IN RADIOECOLOGY

The only MSc in Radioecology in Europe has been established at NMBU. Students from within Europe and outside have attended individual course modules or the whole MSc program. Expert teachers are also from institutions from different countries in Europe and in North America.

In short, the EU MSc in Radioecology is a tailored two year, Bologna accredited (120 ECTS) MSc programme consisting of obligatory and voluntary stand-alone course modules, with expert teachers from national and international institutions. At present the MSc is hosted at the NMBU, but, as for any EU MSc, students are free to obtain credits by taking ECTS accredited courses at other institutions and at collaborating universities. Within CERAD, the MSc programs focus on radioecology, radiochemistry and ecotoxicology. The courses are also implemented in large European projects due to the fact that NMBU holds the only EU MSc in Radioecology. The main courses provided by NMBU/CERAD are listed in the table page 53.

In 2017: a new course within CERAD was admitted into the NMBU course portfolio: FMI 330 “Effect and biomarker methods in (eco)toxicology”. This course was run for the first time in August 2017 with invited lecturers from the CERAD consortium, both national and international experts. Knut Erik Tollefsen (NIVA, prof II NMBU) is responsible for the course.

Every year, CERAD has MSc students working on their MSc research projects associated with CERAD projects.

PHD EDUCATION AT CERAD

The MSc and PhD education at NMBU and collaborating universities are programmes given to provide relevant stakeholders their future workforce. Of particular concern to the stakeholders (EU Commission, authorities, industry and professionals) are the significant and persistent needs for post-graduates with skills in radiochemistry, radioecology, radioecotoxicity, environmental modelling, radiation protection including radiobiology and dosimetry.

In 2017: Jorke Kamstra defended his PhD thesis November 3rd, 2017.

In total, 24 PhD students have been/are associated with CERAD by date. We can therefore expect several dissertations in the next coming years:

- Six PhDs students have already defended their work (2 in 2014, 1 in 2015, 2 in 2016, 1 in 2017), and two will defend their PhD work early 2018
- Sixteen students are currently working full time or associated to CERAD (per. 31st of Nov 2017)
- Two new PhD positions will be filled early 2018.

The CERAD course portfolio within the fields of radiochemistry / environmental radioactivity / ecotoxicology

COURSE CODE	TITLE	ECTS	COURSE SYLLABUS IN SHORT	COURSE RESPONSIBLE
KJM350	Radiation and Radiochemistry	10	http://www.nmbu.no/course/kjm350	Lindis Skipperud
KJM352	Radiation and Radiation Protection	5	http://www.nmbu.no/course/kjm352	Lindis Skipperud
KJM351	Experimental Radioecology	10	http://www.nmbu.no/course/kjm351	Ole Christian Lind
KJM353	Radioecology	5	http://www.nmbu.no/course/kjm353	Ole Christian Lind
MINA310	Project Management and Research Methods	10	http://www.nmbu.no/course/mina310	Lindis Skipperud
KJM360	Assessing Risk to Man and Environment	10	http://www.nmbu.no/course/kjm360	Deborah H. Oughton / Per Strand
MINA410	Environmental Radiobiology	5	http://www.nmbu.no/course/mina410	Deborah H. Oughton
FMI309	Ecotoxicology	10	http://www.nmbu.no/course/fmi309	Hans Christian Teien
FMI310	Environmental Pollutants and Ecotoxicology	15	http://www.nmbu.no/course/fmi310	Hans Christian Teien
FMI330	Effect and biomarker methods in (eco)toxicology	5	http://www.nmbu.no/course/fmi330	Knut Erik Tollefsen

INTERNATIONAL COOPERATION

During the first years of CERAD, Memorandum of Understanding (MoU) have been signed between NMBU and several universities and research institutes:

- Moscow State University, Russia.
- National University of Life and Environmental Sciences of Ukraine, Ukraine.
- University of Fukushima, Japan.
- Chalk River, Canada.
- Tomsk Polytechnical University, Russia.
- University of Seville, Spain.
- CIEMAT, Spain.

In 2017: A Cotutelle agreement will be finalized with the University of Seville (UoS), Spain, giving credits to both NMBU and UoS for common PhD student. Early 2018, a MoU with National Physical laboratory, UK, will be signed for exchange of students and common research projects.

Within the CINCH-II project, Letter of intent (LoI) and ERASMUS+ Inter-institutional agreement 2014-21 has been signed with all participating universities: Czech Technical University in Prague (CTU, Czech Republic), Chalmers University of Technology (CHALMERS, Sweden), University of Helsinki (UH, Finland), Loughborough University (LU, United Kingdom), University of Leeds (UNIVLEEDS, United Kingdom) and University of Oslo (UiO, Norway).

Through projects funded by Norwegian Centre for International Cooperation in Education (SiU), bilateral cooperation projects Norway – Russia and Norway – Ukraine have been established. These projects provides common courses, travel funding for students and lecturers, and also funding to MSc students from Russia or Ukraine following the European MSc programme at NMBU.

CERAD is also one of the founding members of the The European Network on Nuclear and Radiochemistry (NRC) Education and Training, legally created in 2016: http://nrc-network.org/. The objective and functions of the European NRC Network are to cooperate in NRC education and training in Europe, to promote development of NRC education and training in Europe, to represent NRC education and training community towards other organizations and society, to promote and organize student and teacher exchange between partners and to organize common courses in NRC.

INTERNATIONALLY ORGANIZED COURSES

During 2013 – 2017, CERAD has arranged several international short courses, either at NMBU or at other host institutions.

In 2017: The National University of Life and Environmental Sciences of Ukraine (NUBiP) and Ukrainian Institute of Agricultural Radiology (UIAR) organised in collaboration with CERAD/NMBU a course on "Experimental Radioecology and Radiobiology" from the 18th to 28th of June 2017 as part of a SiU project collaboration Norway – Ukraine.

CERAD-NMBU was in 2016 awarded two EU CONCERT projects to further provide two courses internationally for 2017: 1) The KJM351 "Experimental Radioecology" course was given in January 2017, and the 2) KJM360 "Environmental Risk Assessment" course was given in June 2017.

RADIOECOLOGY E&T PLATFORM and LINK TO OTHER EDUCATION AND TRAINING PLATFORMS

CERAD-NMBU courses are presented at NMBU websites for education programmes and courses, and on the CERAD website (https://www.nmbu.no/en/services/centers/cerad). The MSc programme and courses are also linked to several EU projects and platforms. See the following websites for more information:

- Radioecology exchange: https://wiki.ceh.ac.uk/display/radex/The+Radioecology+Exchange
- CINCH Nuclear chemistry: https://nucwik.wikispaces.com/
- DoReMi training & education: http://www.doremi-noe.net/training_and_education.html

CERAD has developed an education and training platform, included in the Radioecology Exchange webpage, linking education within different nuclear disciplines together (Fig. 1). The Radioecology Education and Training Platform is a website focal point for students and professionals interested in radioecology. The platform presents an overview of education and training course modules within radioecology/environmental radioactivity presently offered by the COMET consortium, and will be further developed by the CONCERT-TERRITORIES project, and maintained by the ALLIANCE platform.

The ultimate aim of the education and training platform is to ensure a sustainable workforce in radioecology. This platform holds a lot of different courses within radioecology and ecotoxicology ranging from MSc and PhD courses to workshops and professional development. The Radioecology E&T platform also provides links to other E&T platforms, such as those within Radiochemistry, Radiobiology and Radiation Protection. This is an important outreach mechanism for the Radioecology E&T platform, as – for example – many of the basic course modules within radioecology are also relevant for other nuclear science students, and vice versa.

THE RADIOECOLOGY/ECOTOXICOLOGY PHD NETWORK

The Radioecology/Ecotoxicology network is an international networking forum hosted by CERAD/NMBU and Stockholm University (SU) aimed primarily at PhD students in radioecology and other relevant nuclear sciences. Most European PhD students are expected to take some accredited courses as part of their PhD training. These courses are often relevant and attractive for professional training as well. The network is also open to PhD students worldwide.

The PhD course in Environmental Radiobiology (MINA 410) is a 5 ECTS course, and is part of the international Radioecology Research School and aims to give students an overview of the fundamental principles of radiobiology, but within the context of effects on non-human biota. The course covers both the history and the state-of-the-art of our knowledge on the biological effects of radiation on humans, but concentrated specifically on those issues and applications of most relevance for other organisms. The MINA410 course has also been co-funded by the DoReMi project/platform two times to ensure access for international radiobiology students.

Professor Lindis Skipperud, Director of Education

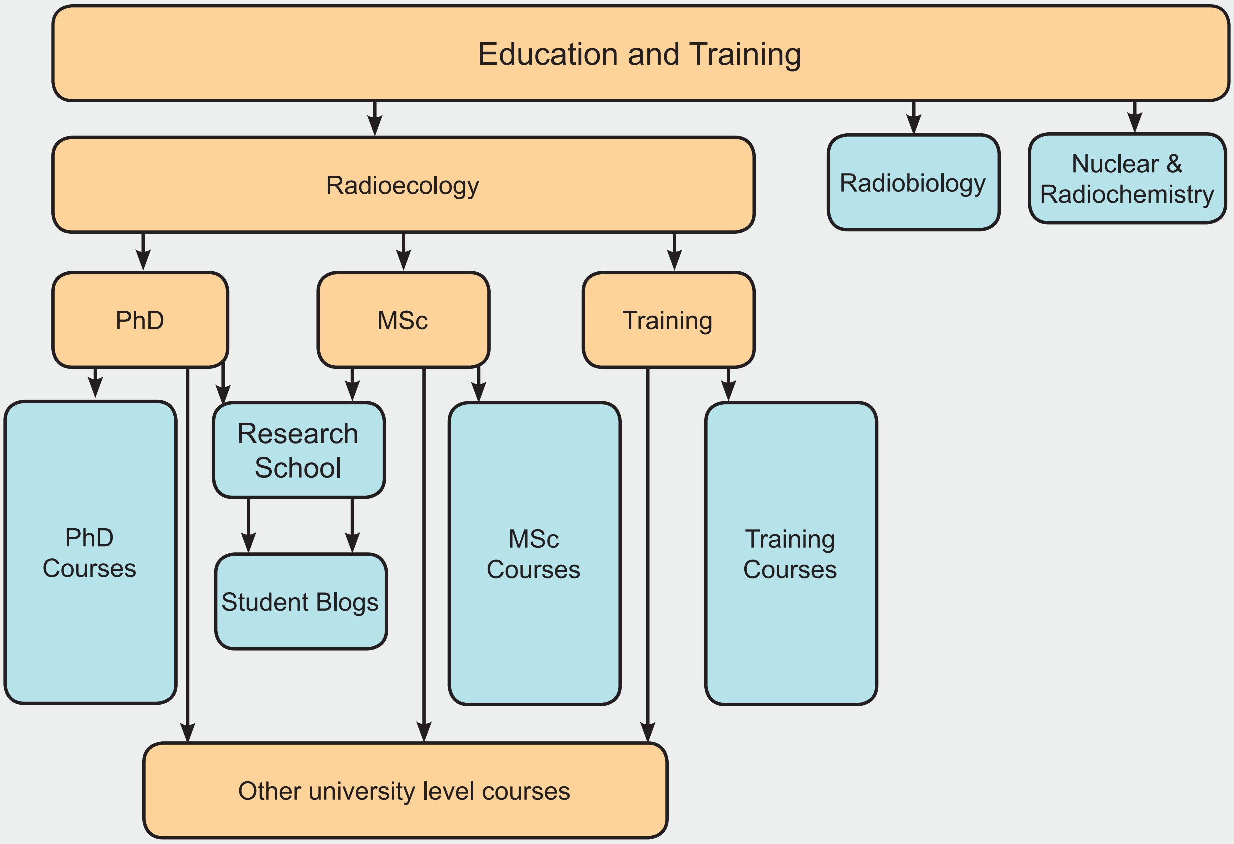


Figure 1. *The E&T platform on the Radioecology Exchange website.*

Funding and Expenditures 2017

The present account reflects a high level of activity in CERAD CoE in 2017.

The CERAD CoE project financing constitutes of funding from the RCN and of a substantial in kind contribution from all CERAD partner institutions. In addition, several ongoing RCN (EU) funded projects at NMBU/Isotope Laboratory are included as a financial source for CERAD.

The turnover for CERAD in the fifth operational year is MNOK 51.9.

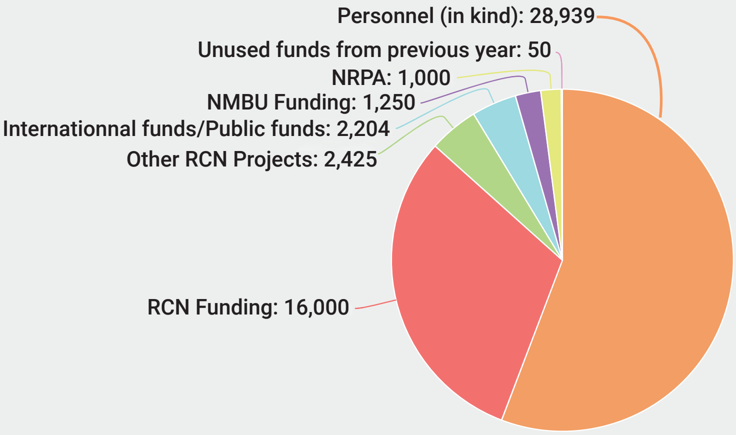
In 2017, the direct core funding contribution from RCN was MNOK 16. Other cash contributors (MNOK 2.25) are the Norwegian University of Life Sciences (NMBU) and The Norwegian Radiation Protection Authority (NRPA). The In kind personnel contributions from partner institutions are estimated to about MNOK 29.

On the expenditure side, salaries amounted to MNOK 38; the sum includes overhead covering indirect costs.

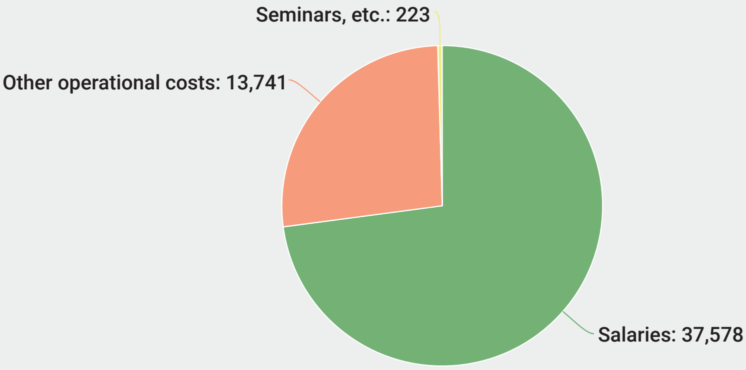
Other running expenses amounted to MNOK 14.

CERADs financial situation provides a solid foundation for stable and flexible project management and long term research in the years ahead.

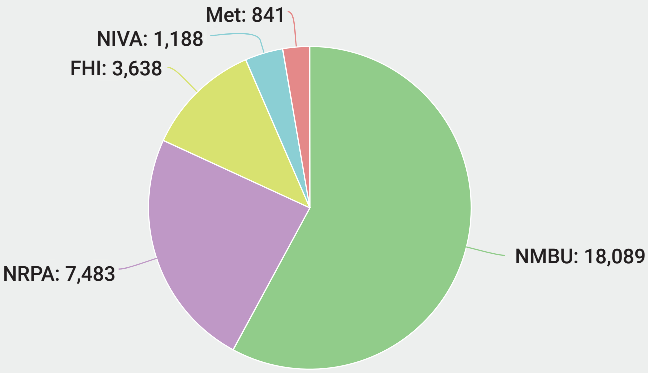
Jorunn Hestenes Larsen, Management Director



Revenues 2017



Expenditures 2017



Specification of partners in kind contributions 2017

CERAD Annual Conference 2017

The annual CERAD conference was held at the Norwegian Academy of Science and Letters in Oslo, Norway, February 8th – 9th, 2017. The conference attracted about 80 of CERAD's scientists, the Board, the international Scientific Advisory Committee (SAC) and the Relevant Advisory Committee (RAC).

The aims of the 2017 annual conference were to present CERAD on the international arena, the education and training platform of CERAD and to discuss the upcoming revision of the strategic research agenda (SRA 2017 – 2021). The presentations fuelled constructive discussions on priorities as well as on the way forward. The panel discussion was especially valuable with respect to the revision of the SRA, with input from SAC members present during the meeting or via e-mails.

Following the first day presentations and discussions, all enjoyed HYBRIS, the CERAD House-band concert, prior to dinner.

Concert by the CERAD House-band HYBRIS prior to dinner.
Photo: Quentin Mennecart

Participants at the CERAD conference, Norwegian Academy of Science, February 2017
Photo: Quentin Mennecart

Societal Impact

As detailed in the International Collaboration section, CERAD's research is of importance for a large number of national and international policy makers. CERAD members have participated in, and CERAD research has been used to support, many high level reports, white papers and policy documents. Since the start of the project, these include Three White papers for The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), and numerous Reports from International Atomic Energy Agency (IAEA), International Union of Radioecology (IUR), International Commission on Radiological Protection (ICRP), and the Arctic Monitoring and Assessment Programme (AMAP). Further details can be found in the International Section.

ICRP stakeholder diologue in Minamisoma, Fukushima

In 2017, work carried on the ecological and societal impacts of Fukushima by CERAD for UNSECAR and IAEA continues to attract a high degree of international attention, not only because of the scientific relevance, but also due to the considerable socioeconomic consequences of the accident and the scientific controversy surrounding the potential impacts, both to humans and the environment. Follow up to UNSCEAR work has included evaluation of the possible reasons for discrepancy between claims of environmental effects, calling for more focus on field dosimetry and confounding factors.

As part of the EU SHAMISEN project (Nuclear Emergency Situations: Management and Health Surveillance), CERAD co-ordinated the work leading to the development of 28 new recommendations for health surveillance of affected populations after a nuclear accident (Fig. 1). This included an assessment of ethical challenges from thyroid screening and communication challenges with affected populations. CERAD (NRPA/NMBU) has participated in co-expertise stakeholder dialogues organised by the ICRP and Hiroshima/Nagasaki University. These involved participation of a wide-range of stakeholders (international and Japanese authorities and scientists) including members of the affected population in Fukushima, thus having a direct influence on both policymaking and society.

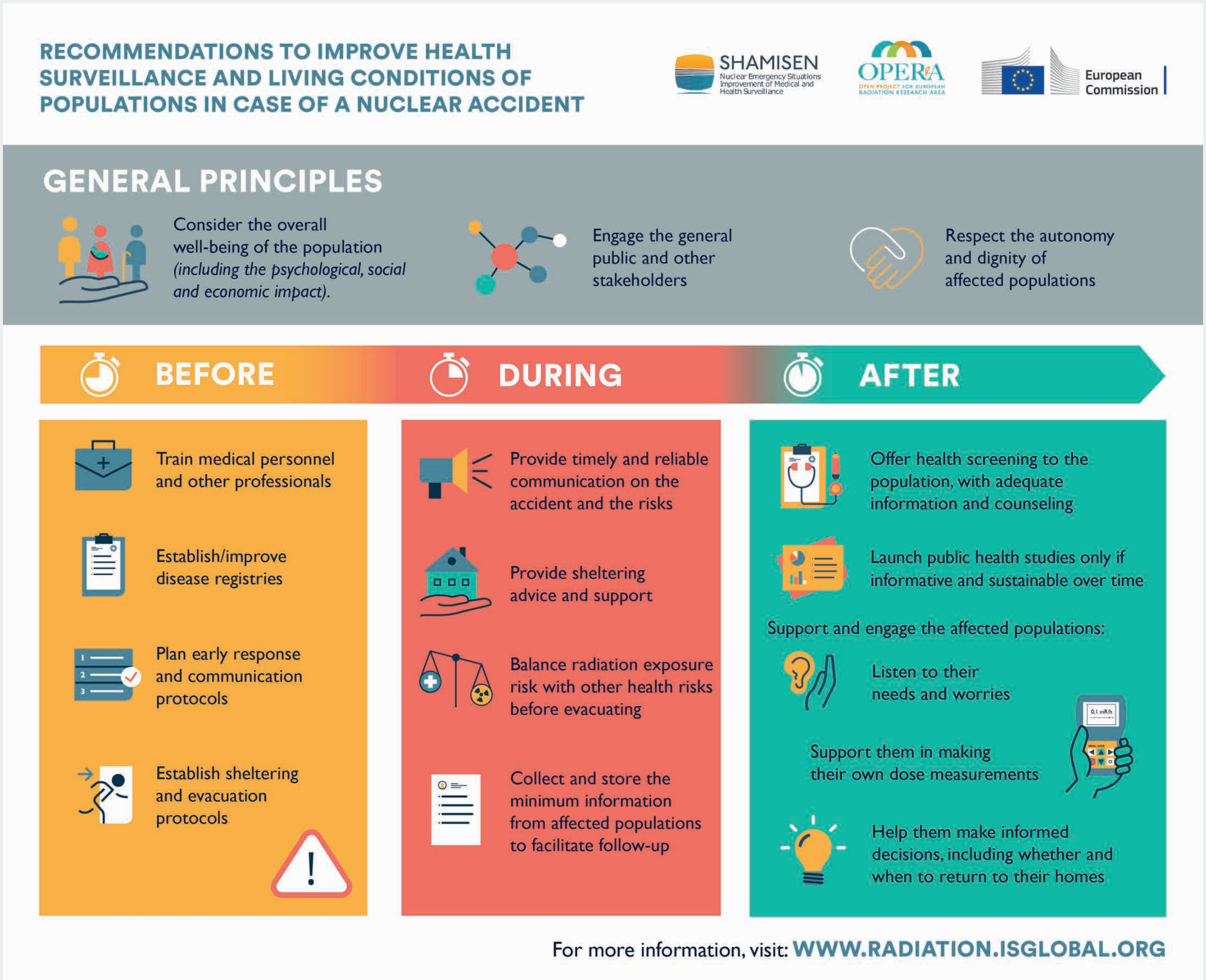
CERAD continues to cooperate with the intergovernmental OECD-Nuclear Energy Agency (NEA), in facilitating cooperation among countries with respect to advanced nuclear technology infrastructures, and the OECD NEA: Expert group on Management of Radioactive Waste after a Nuclear Power Plant Accident, both chaired by the CERAD Deputy director.

UNESCO's World Commission on the Ethics of Scientific Knowledge and Technology is currently preparing a Declaration on Water and Ocean Ethics in collaboration with the Intergovernmental Oceanographic Commission (IOC). The Research director is a member of the Commission (nominated by the Norwegian Ministry of Education and Research), and has fronted both CERADs and Norwegian research and policy interests feature (*e.g.*, radioactive waste discharges, oil industries, OSPAR). A water and ocean ethics seminar will be held in Oslo in 2018.

CERAD continues to be involved in work on the socioeconomic aspects of accident scenarios, including the economic impacts of countermeasures. Stakeholder dialogues have the advantage of facilitating dissemination of CERAD's research as well as an increased understanding of the technical, organisational and socioeconomic challenges of radiation risks.

CERAD members participate in most of the EC H2020 EURATOM programme boards, and as such have been instrumental in formulating topics and text for the recent EU CONCERT calls and the next EURATOM call. These calls include a specific focus on uncertainties, impact and risk as well as risk communication, risk perception and societal aspects of radiological protection within EU research, which is fully in line with CERADs multidisciplinary approach and inclusion of research on social and ethical aspects in addition to its strong natural science foundation.

Professor Deborah H. Oughton, Director of Research

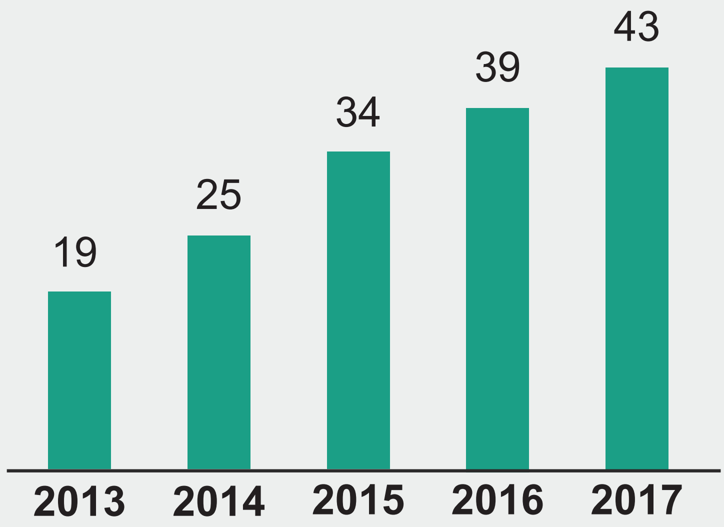


Dissemination and communication 2017

From 2013 to 2017, CERAD CoE has published the total of 160 publications in international journals with referee, if we also include the papers published online during 2017. This shows an increasing number of articles each year. In 2017, the total for 43 articles have been published in international journals with referee, 37 articles in regular printed journals versions and 6 articles online awaiting actual printing (paper version will be available early 2018).

Every year the CERAD people have been very active in presenting their research at international conferences, workshops and seminars. In this annual report, only the publications and dissemination for 2017 are presented, but earlier publications (2013 – 2016) can be found on the CERAD webpage: https://www.nmbu.no/en/services/centers/cerad.

CERAD Scientific publications (2013 - 2017)



CERAD PhD student Yevgeniya Tomkiv participated in the Researcher Grand Prix on September 26th 2017.

She presented results of her media study, where she looked at the way radiation risks were communicated in the newspapers after the nuclear accident in Fukushima in 2011. She received one of the top scores from the professional judges.

PhD student Yevgeniya Tomkiv presenting in front of the Forsker Grand Prix jury

Winner of the CERAD photo contest: The salmon twins.
Photo: Yetneberk Kassaye and Dag Brede

Publication List

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Oughton, D.H., Albani, V., Barquinero, F., Chumak, V., Clero, E., Crouail, P., Fattibene, P., Kesminiene, A., Laurier, D., Liutsko, L., Ohba, T., Ostroumova, E., Pirard, P., Rogel, A., Sarukhan, A., Schneider, T., Tanigawa, K., Tomkiv, Y., Vale, L., Cardis E. (2017). Recommendations and procedures for preparedness and health surveillance of populations affected by a radiation accident. Shamisen report, pdf available at: https://issuu.com/isglobal/docs/recommendations_booklet.

Sørensen, J.H., Schönfeldt, F., Sigg, R., Pehrsson, J., Lauritzen, B., Bartnicki, J., Klein, H., Hoe, S.C., Lindgren, J. Added Value of uncertainty Estimates of Source term and Meteorology (AVESOME). NKS-402, (2017) ISBN 978-87-7893-490-1, Nordic nuclear safety research.

Presentations 2017

Bernhoft, A., Falk, M., *et al*. (2017). Improved muscle selenium concentrations in growing pigs fed organic selenium. 16th Conference on Trace Elements in Man and Animals 26-29 June.

Blagojevic, D., Lee, Y., *et al*. (2017). Comparative sensitivity to gamma radiation in terrestrial plants. Norwegian Plant Biology, 21-22 June.

Blagojevic, D., Lee, Y., *et al*. (2017). Does UV-B affect sensitivity to gamma radiation in plants? Modulation of plant UV-responses by environmental factors; 27-28 June.

Brede, D.A., Oughton, D.H., *et al*. (2017). CERAD Biological Effects Toolbox. EU-COMET Final Event; 25-27 April, Bruges, Belgium.

Brede, D.A., Kassaye, Y., *et al*. (2017). Adverse outcome of chronic gamma irradiation during embryogenesis links molecular events to developmental and toxic effects i Atlantic salmon (Salmo salar L.). 4th International Conference on Radioecology & Environmental Radioactivity (ICRER), 3-8 September, Berlin, Germany.

Brown, J., Hosseini, A., *et al*. (2017). Environmental Impacts from hypothetical accident scenarios involving the recovery of the dumped Russian submarine K-27. 16th International Conference on Chemistry and the Environment (ICCE) 18- 22 June, Oslo, Norway.

Brown, N.L., Finnon, R., *et al*. (2017). A new mouse model to underpin the application of a DDREF to improve estimated leukaemia risk at low doses/dose rates in humans. The 12th International Conference and 5th Asian Congress on Environmental Mutagens (ICEM-ACEM 2017), 12-16 November, Incheon, South-Korea.

Brown, N.L., Finnon, R., *et al*. (2017). A new mouse model to underpin the application of a DDREF to improve estimated leukaemia risk at low doses/dose rates in humans. The 4th ICRP Symposium on the system of radiological protection and the 2nd European Radiological Protection Research Week, 10-12 October, Paris.

Brunborg, G. (2017). Calibration of the comet assay using x-rays. The 12th International Comet Assay Workshop (ICAW). 29-31 August, Pamplonas, Spain
Cardis, E., Liutsko, *et al*. (2017). SHAMISEN Recommendations and procedures for preparedness and health surveillance of populations affected by a radiation accident. European Radiation Protection Week, 9-12 October, Paris.

Dahl, H., Olsen, A.-K., *et al*. (2017). Grandfathers legacy following exposure to chronic low dose rate gamma radiation. 16th International Conference on Chemistry and the Environment (ICCE) 18-22 June, Oslo, Norway.

Eide, D.M., Olsen, A.-K., *et al*. (2017). Effects of gamma radiation on reproductive parameters in male mice exposed to different doses and dose rates at different stages of spermatogenesis. The 4th ICRP Symposium on the system of radiological protection and the 2nd European Radiological Protection Research Week, 10-12 October, Paris.

Eide, D.M., Olsen, A.-K., *et al*. (2017). Gamma radiation effects on reproductive parameters in mice exposed to different doses and dose ranges at different stages of spermatogenesis. The 12th International Conference and 5th Asian Congress on Environmental Mutagens (ICEM-ACEM 2017), 12-16 November, Incheon, South-Korea.

Eide, D.M., Olsen, A.-K., *et al*. (2017). Effects of gamma radiation on reproductive parameters in male mice exposed to different doses and dose rates at different stages of spermatogenesis. The 12th International Comet Assay Workshop (ICAW). 29-31 August, Pamplonas, Spain.

Enciso, J.M., Gutzkow, K.B., *et al*. (2017). Increasing the sensitivity of the alkaline comet assay by detection of DNA lesions using different human and bacterial repair enzymes. The 12th International Conference and 5th Asian Congress on Environmental Mutagens (ICEM-ACEM 2017), 12-16 November, Incheon, South-Korea.

Enciso, J.M., Gutzkow, K.B., *et al*. (2017). Performing the Comet Assay in combination with different human and bacterial repair enzymes in order to increase its sensitivity and specificity. The 12th International Comet Assay Workshop (ICAW). 29-31. August, Pamplonas, Spain.

Falk, M., Framstad, T., *et al*. (2017). The influence of selenium intake on some erythrocyte-related blood parameters in high-yielding Norwegian sows. 9th European Symposium of Porcine Health Management; 3-4 May.

Galvan, J., Lind, O.C., *et al*. (2017). Radioactive particle abiotic transformation processes. 4th International Conference on Radioecology & Environmental Radioactivity (ICRER), 3-8 September, Berlin, Germany.

Gjelsvik, R., Kålås, J.A., *et al*. (2017). Spatial and temporal patterns of Cs-137 transfer in two herbivore game birds in Norway. 4th International Conference on Radioecology and Environmental Radioactivity (ICRER) 3-8 September, Berlin, Germany.

Graupner, A, Eide, D.M., *et al*. (2017). Genotoxicity of different low dose rates of gamma radiation in three strains of mice. 16th International Conference on Chemistry and Environment (ICCE), June 2017, Oslo.

Graupner, A., Eide, D.M., *et al*. (2017). Genotoxicity of different low dose rates of gamma radiation in three strains of mice. The 12th International Conference and 5th Asian Congress on Environmental Mutagens (ICEM-ACEM 2017), 12-16 November, Incheon, South-Korea.

Graupner, A., Eide, D.M., *et al*. (2017). Genotoxicity of different low dose rates of gamma radiation in three strains of mice. The 4th ICRP Symposium on the system of radiological protection and the 2nd European Radiological Protection Research Week, Paris, 10-12 October, Paris.

Guedon, R., Ingrid; I., *et al*. (2017). Contribution of epigenetic processes in the sensitivity and hereditability of the response of Carenorhabditis elegans to chronic exposure to ionizing radiation. 4th International Conference on Radioecology & Environmental Radioactivity (ICRER), 3-8 September, Berlin, Germany.

Gutzkow, K.B., Lilleaas, E., *et al*. (2017). Establishment of genotoxicity testing using teh comet assay of metabolically active 3D liver spheroids cultures using X-rays and Arsenic trioxide. The 12th International Conference and 5th Asian Congress on Environmental Mutagens (ICEM-ACEM 2017), 12-16 November, Incheon, South-Korea.

Gutzkow, K.B., Lilleaas, E., *et al*. (2017). Establishment of genotoxicity testing using the Comet assay of metabolically active 3D liver spheroid cultures. The 12th International Comet Assay Workshop (ICAW). 29-31 August, Pamplonas, Spain.

Gutzkow, K.B., Låg, M., *et al*. (2017). Bruk av 3D leverkulturer for å måle DNA-skade ved komet-metoden. Poster NSFTs winter meeting, January.

Hansen, E.L. (2017). Demonstrating a dosimetry framework for FIGARO - to make life easier and exposures reproducible. SIU/CERAD/NMBU workshop on Environmental Radioactivity, 16-17 October, Oslo Norway.

Hofer, T. (2017). Restoration of cognitive performance in mice carrying a deficient allele of 8-oxoGuanine DNA glycosylase by x-ray irradiation. Oral contribution at the Joint Meeting Neurotoxicity Society and International Neurotoxicology Association. 20-24 May, Florianopolis, Brasil.

Hosseini, A., Amundsen, I., *et al*. (2017). Health and environmental risk assessment of the dumped Russian submarine K-27 in the Arctic. 4th International Conference on Radioecology and Environmental Radioactivity (ICRER), 3-8 September, Berlin, Germany.

Hurem, S., Gomes, T., *et al*. (2017). Parental exposure to gamma radiation induces oxidative stress in zebrafish (Danio rerio) progeny. 4th International Conference on Radioecology and Environmental Radioactivity (ICRER), 3-8 September, Berlin.

Hurem S., Gomes, T., *et al*. (2017). Gamma radiation causes adverse reproductive and heritable effects in zebrafish. 16th International Conference on Chemistry and the Environment (ICCE), 18-22 June, Oslo. (1st prize winner).

Kamstra, J.H., Saenen, E. (2017). Are transgenerational changes induced by chronic exposure to gamma radiation? COMET Final Event, 25-27 April, Bruges, Belgium.

Kamstra, J.H., Bastos Sales, L., *et al*. (2017). Differential DNA methylation at conserved non-genic elements and transgenerational inheritance following mono(2-ethylhexyl)phthalate and 5-azacytidine exposure in zebrafish. 10th European Zebrafish Meeting, 3-7 July, Budapest.

Kamstra, J.H., Hurem, S., *et al*. (2017). Generational effects of low dose ionizing radiation on DNA methylation in zebrafish. 16th International Conference on Chemistry and the Environment (ICCE), 18-22 June, Oslo.

Kamstra, J.H., Hurem, S., *et al*. (2017). Generational effects of low dose ionizing radiation on DNA methylation in zebrafish. 10th European Zebrafish Meeting 3-7 July, Budapest.

Kamstra, J.H., Hurem, S., *et al*. (2017). Generational effects of low dose ionizing radiation on DNA methylation in zebrafish. 4th International Conference on Radioecology and Environmental Radioactivity (ICRER), 3-8 September, Berlin.

Liland, A., Tomkiv, Y., *et al*. (2017). The power of collaborative deliberation in stakeholder dialogue seminars. SIU/CERAD/NMBU workshop on Environmental Radioactivity, 16-17 October, Oslo Norway.

Lind, O.C., Brede, D.A., *et al*. (2017). State-of-the-art tools for characterisation of particle exposure. 4th International Conference on Radioecology and Environmental Radioactivity (ICRER), 3-8 September, Berlin, Germany.

Liutsko, L., Oughton, D.H., *et al*. (2017). The SHAMISEN project: from LESSONS learnt from the past nuclear accidents to IMPROVEMENT of preparedness of post-accident response on medical and health issues (RECOMMENDATIONS) RICOMET, 27-29 June, Vienna.

Maremonti, E., Oughton, D.H., *et al*. (2017). In vivo assessment of ROS defense response and oxidative stress management in Caenorhabditis elegans subjected to chronic gamma irradiation.. 4th International Conference on Radioecology and Environmental Radioactivity (ICRER); 3-8 September, Berlin.

Olsen, A.-K. (2017). Known and unknown regarding radiation – a health perspective. The Norwegian Institute of Public Health's day of science, 16 June, Oslo.

Oughton, D.H., Lapied, E., *et al*. (2017). Ecological effects of ionising radiation on earthworms 16th International Conference on Chemistry and the Environment (ICCE), 18-22 June, Oslo.

Oughton, D.H. and Beauglin, K. (2017). Field Sampling and Dosimetry, Comet Meeting, 25-27 April, Bruges.

Oughton. D.H., Cardis, E., *et al*. (2017). Health surveillance and management of populations affected by a radiation accident – can ethics help? 2nd European Radiation Protection Week, 9-12 October, Paris.

Oughton, D.H., Tomkiv, Y., Cardis, E. (2017). Communicating Uncertainty - A case study on Thyroid Contamination. 4th International Conference on Radioecology and Environmental Radioactivity, 3-8 September, Berlin.

Oughton. D.H., Cardis, E., *et al*. (2017). Ethical challenges in health surveillance: a case study of thyroid screening after Fukushima. RICOMET 27-28 June, Vienna.

Oughton. D.H., Cardis, E., *et al*. (2017). Socioethical Challenges of Health Surveillance, WHO, 3-4 June, Geneva.

Oughton. D.H., Cardis, E., *et al*. (2017). Recommendations and procedures for preparedness and health surveillance of populations affected by a radiation accident: NERIS Workshop, 15-16 May, Lisbon, Portugal.

Popic, J.M., Skipperud, L. (2017). Transfer of radionuclides to wild forest flora species: comparison of legacy mining and undisturbed naturally rich radionuclide sites. 4th International Conference on Radioecology & Environmental Radioactivity (ICRER), 3-8 September, Berlin, Germany.

Rossbach, L.M., Maremonti, E., *et al*. (2017). Multigenerational exposure to silver ions and nanoparticles changes the toxic response in the nematode c. elegans. SETAC, 7-11 May, Berlin.

Salbu, B., Kashparov, V., *et al*. (2017). Challenges associated with radioactive particles in the environment - a COMET-RATE Position Paper. COMET Final Event, 25-27 April 2017, Bruges, Belgium.

Salbu, B. (2017). Overview of findings from the International projects dealing with radioactive particles. IAEA CRP meeting, June, Vienna.

Salbu, B. (2017). Linking Nano-Micrometer Sized Radioactive Particle Characteristics to Environmental Behaviour and Biological Responses IAEA CRP meeting, June, Vienna.

Salbu, B. and Lind, O.C. Radioactive Particles in the Environment - Sources and potential impact, ICCE, 20 June, Oslo.

Salbu, B. and Kashparov, V. (2017). Challenges associated with radioactive particles in the environment, 4th Int. Conf. on Radioecology and Environmental Radioactivity, 3-8 September, Berlin.

Salbu, B. (2017). Why is Basic Radiecological Research relevant to regulators?
Int. workshop: Regulatory Supervision of Legacy Sites: The Process from Recognition to Resolution", 21 November, Lillehammer.

Salbu, B. (2017). Challenges associated with radioactive particles released to the environment, Invited lecturer, Tsukuba University, March 2017, Japan.

Simonsen, M. (2017). Marine transport modelling. SiU/CERAD/NMBU Workshop on Environmental Radioactivity, 16-17 October, Oslo, Norway.

Simonsen, M., Saetra, Ø., *et al*. (2017). The impact of tidal and mesoscale eddy advection on the long term dispersion of 99Tc from Sellafield.

4th International Conference on Radioecology & Environmental Radioactivity (ICRER), 3-8 September, Berlin, Germany.

Skipperud, L. (2017). Development of Education and Training within Radioecology in Europe. 16th International Conference on Chemistry and the Environment (ICCE) 18- 22 June 2017, Oslo, Norway.

Skipperud, L. (2017). Exposure, effect and risk of NORM and metals - Case: Road- and Tunnel-construction in alum shale areas. The 5th International Nuclear Chemistry Congress (INCC).

Skipperud, L. (2017). How to handle multiple stressors in legacy sites?. Regulatory Supervision of Legacy Sites: the Process from Recognition to Resolution, 21-23 November, Lillehammer, Norway.

Skipperud, L., Bradshaw, C. (2017). Education and training - creating talent. COMET Final Event, 25-27 April, Bruges, Belgium.

Skipperud, L., Wærsted, F., *et al*. (2017). Exposure, effect and risk of NORM and metals - case Road and Tunnel Construction in alum shale areas. 4th International Conference on Radioecology & Environmental Radioactivity (ICRER), 3-8 September, Berlin, Germany.

Skuterud, L., Thørring, H., *et al*. (2017). Dynamic modelling of 137Cs in reindeer 30 years after Chernobyl. 4th International Conference on Radioecology and Environmental Radioactivity (ICRER), 3-8 September, Berlin, Germany.

Song, Y., Villeneuve, D. *et al*. (2017). Development of invertebrate Adverse Outcome Pathways (AOPs) for mechanistically-based risk assessment. Presentation at the International Symposium on Chemicals Risk Prediction and Management (ISCRPM-2017). 25th April.

Song, Y., Villeneuve, D., *et al*. (2017). Development of invertebrate Adverse Outcome Pathways (AOPs) for mechanistically-based risk assessment. Keynote lecture at the China's 4th Symposium on Ecotoxicology, 24 April, Hangzhou.

Song, Y., Villeneuve, D., *et al*. (2017). Development of invertebrate Adverse Outcome Pathway (AOPs) for mechanistically-based risk assessment. Invited lecture at Nanjing University. 23 April, Shanghai.

Song, Y., Asselman, J., *et al*. (2017). Deciphering multiple stressor effects of gamma radiation and uranium on Atlantic salmon (Salmo salar): Transcriptomics-based mixture modeling. 16th International conference on chemistry and the environment, 18-22 Oslo.

Song, Y., Tollefsen, K.E. (2017). Application of Adverse Outcome Pathways (AOPs) to link mechanistic information to adverse endpoints (toxicity). Invited lecture at the SKLEC-NIVA Centre for Marine and Coastal Research i Shanghai. Shanghai, 21 April.

Strand, P., Brown, J. (2017). Assessment of Environmental Impacts from Ionising Radiation following the Fukushima Accident – A review of published works. 16th International Conference on Chemistry and the Environment (ICCE) 18- 22 June, Oslo, Norway.

Tollefsen, K.E. (2017). Adverse Outcome Pathways (AOPs)-Application to research & regulatory needs. Keynote lecture at the China's 4th Symposium on Ecotoxicology. 24 April 2017, Hangzhou.

Tollefsen, K.E. (2017). Cumulative hazard and risk assessment - Linking MOA to adversity under ecologically relevant exposure scenarios. Keynote lecture at the International Symposium on Chemicals Risk Prediction and Management (ISCRPM-2017). 25 April, Hangzhou.

Tollefsen, K.E. (2017). Adverse Outcome Pathways (AOPs) - Application to research & regulatory needs. Invited lecture at the Nanjing University, 23 April, Shanghai.

Tollefsen, K.E. (2017). Deciphering toxicity and risk of multiple stressors by computational and experimental efforts. Invited lecture at the SKLEC-NIVA Centre for Marine and Coastal Research i Shanghai (China), 21 April, Shanghai.

Tollefsen, K.E. (2017). Adverse outcome pathways–a framework to organize mechanistic information and identify research needs. Invited keynote lecture at NSFT Annual Spring meeting Practical implications of mechanistic studies in toxicology. 30 March, Norway.

Tollefsen, K.E., Gomes, T., *et al*. (2017). Adverse Outcome pathways (AOP)-assisted hazard and risk assessment of ionising and ultraviolet radiation in aquatic organisms, 18-22 June, Oslo.

Tomkiv, Y., Oughton, D.H. (2017). Uncertainties in media – a study of Fukushima and Chernobyl anniversaries. 4th International Conference on Radioecology and Environmental Radioactivity, 3-8 September, Berlin.

Tomkiv, Y., Oughton, D.H., *et al*. (2017). Post-Chernobyl experience: Sami reindeer herders in Norway. Training course: Late phase nuclear accident preparedness and management, Belarus.

Turcanu, C., Perko, T., *et al*. (2017). To leave or not to leave? Insights from an empirical study on expected evacuation behaviour. 4th International Symposium on the System of radiological Protection of ICRP and the 2nd European Radiation Protection Research Week, 10-12 October, Paris.

Vioque, I., Garcia-Tenorio, R., *et al*. (2017). Transuranic signals in snails collected at the contaminated terrestrial site of Palomares (Spain). 4th International Conference on Radioecology and Environmental Radioactivity (ICRER), 3-8 September, Berlin, Germany.

Wærsted, F.M., Teien, H.-C., *et al*. (2017). Mobility and bioavailability of NORM and toxic metals in alum shale. 4th International Conference on Radioecology and Environmental Radioactivity (ICRER), 3-8 September, Berlin, Germany.

Xie, L., Solhaug, K.A., *et al*. (2017). Monitoring of physiological responses to gamma radiation in Lemna minor. 16th International conference on chemistry and the environment, 18-22 June, Oslo.

Xie, L., Song, Y., *et al*. (2017). Multiple stressor effects of ionising (gamma) and non-ionising (UV) in duckweed (Lemna minor). 16th International conference on chemistry and the environment, 18-22 June, Oslo.

CERAD in the Media

NRK Dagsnytt 18, 27 February 2017 https://radio.nrk.no/podcast/dagsnytt_atten/nrkno-poddkast-3720-115041-27022017183600

Forskning.no 20 April 2017, «Hvor mange tonn mat er det forsvarlig å kaste for å hindre ett krefttilfelle?» https://forskning.no/meninger/kronikk/2017/04/hvor-mange-tonn-mat-er-det-forsvarlig-kaste-hindre-ett-krefttilfelle

NATIONEN 15 August 2017, «Rema-kritikk får støtte» http://www.nationen.no/landbruk/rema-kritikk-far-stotte/

Salangen Nyheter 14 September 2017, http://www.sn-produksjon.no/webtv/index.php?main_page=document_general_info&cPath=4_13&products_id=2197

Salangen Nyheter 15 September 2017, http://salangen-nyheter.custompublish.com/presenterte-sin-forskning.6029049-28288.html

NRK2 «Researcher Grand Prix», 13 January 2018 (recorded autumn 2017). https://tv.nrk.no/serie/kunnskapskanalen/MDDP17002917/13-01-2018

CERAD
CENTRE FOR ENVIRONMENTAL RADIOACTIVITY

Personnel 2017

Professors, scientists and academic personnel	Academic Grade	Employed
Brit Salbu, Professor	Dr. Philos	NMBU
Lindis Skipperud, Professor	Dr. Scient	NMBU
Ole Christian Lind, Associate Professor	PhD	NMBU
Deborah H. Oughton, Professor	PhD	NMBU/CERAD
Bjørn Olav Rosseland, Professor	Dr. Philos	NMBU
Hans Christian Teien, Scientist	Dr. Philos	NMBU/CERAD
Dag Brede, Scientist	PhD	NMBU/CERAD
Keke Zheng, Scientist	PhD	NMBU
Estela Reinoso-Maset, Scientist	PhD	NMBU/CERAD
Knut Asbjørn Solhaug, Professor	Dr. scient	NMBU/MINA
Line Nybakken, Associate Professor	Dr. scient	NMBU/MINA
Peter Aleström, Professor	Fil.dr.	NMBU/VET
Jan Erik Paulsen, Professor	Dr.med.vet	NMBU/VET
Ian Mayer, Professor	Dr. Scient	NMBU/VET
Jan L. Lyche, Professor	Dr.med.vet	NMBU/VET
Eirik Romstad, Associate Professor	PhD	NMBU/HH
Ståle Navrud, Professor	Dr. Scient	NMBU/HH
Olvar Bergland, Associate Professor	PhD	NMBU/HH
Jorunn E. Olsen, Professor	Dr. Scient	NMBU/BIOVIT
Sissel Torre, Associate Professor	Dr. Scient	NMBU/BIOVIT
YeonKyeong Lee, Scientist	PhD	NMBU/BIOVIT
Per Strand, Director	Dr. philos	NRPA
Unn Hilde Refseth, Director	Dr. scient	NRPA
Åste Søvik, Head of Section	PhD	NRPA
Justin Brown, Senior Scientist	PhD	NRPA
Alicia Jaworska, Senior Scientist	PhD	NRPA
Terje Christensen, Senior Scientist	PhD	NRPA
Håvard Thørring, Scientist	Cand. scient	NRPA
Martin Album Ytre-Eide, Scientist	Cand. scient	NRPA
Mikhail Iosjpe, Senior Scientist	PhD	NRPA
Lavrans Skuterud, Senior Scientist	PhD	NRPA
Tanya Helena Hevrøy, Scientist	PhD	NRPA
Bjørn Johnsen, Scientist	Siv. ing	NRPA
Hallvard Haanes, Scientist	PhD	NRPA
Runhild Gjelsvik, Scientist	Cand. scient	NRPA

Louise Kiel Jensen, Scientist	PhD	NRPA
Ali Hosseini, Senior Scientist	Cand. scient	NRPA
Jan Erik Dyve, Senior Adviser	Cand. scient	NRPA
Anne Liv Rudjord, Head of Section	Cand. real	NRPA
Malgorzata Sneve, Director	MSc	NRPA
Hilde Skjerdal, Senior Adviser	MSc	NRPA
William Standring, Senior Scientist	PhD	NRPA
Ann-Karin Olsen, Senior Scientist	Dr. Philos	NIPH
Dag Marcus Eide, Senior Scientist	Dr. Vet	NIPH
Nur Duale, Senior Scientist	Dr. Philos	NIPH
Kristine Bjerve Gutzkow, Senior Scientist	Dr. Philos	NIPH
Oddvar Myhre, Senior Scientist	Dr. Scient	NIPH
Birgitte Lindeman, Senior Scientist	Dr. Philos	NIPH
Tim Hofer, Senior Scientist	Dr. Philos	NIPH
Christine Instanes, Senior Scientist, Head of Department	Dr. Philos	NIPH
Knut Erik Tollefsen, Senior researcher/Prof II	Dr. Scient	NIVA
Karina Petersen	Dr. Scient	NIVA
Yan Lin	MSc	NIVA
Jens Thaulow	PhD	NIVA
Yang Lie	PhD	NIVA
Anders Ruus	PhD	NIVA
Jerzy Bartnicki, Senior Scientist	PhD	MET
Heiko Klein, Senior Scientist	PhD	MET
Øyvind Sætra, Senior Scientist	PhD	MET

PhD students		
Jose Antonio G. Moreno	MSc	CERAD/RATE
Hildegunn Dahl	MSc	NIPH/CERAD
Lisa Rossbach	MSc	NanoCharm
Lie Xie	MSc	NIVA
Merethe Kleiven	MSc	NMBU
Frøydis Meen Wærsted	MSc	NMBU
Yevgeniya Tomkiv	MSc	NMBU
Erica Maremonti	MSc	NMBU
Shane A. Scheibener	MSc	NMBU
Ian B. Byrnes	MSc	NMBU
Selma Hurem	DVM	NMBU/VET
Jorke Kamstra	MSc	NMBU/VET

Leonardo M. Martin	DVM	NMBU/VET
Kine J. A. Bredesen	MSc	NMBU/HH
Dajana Blagojevic	MSc	NMBU/BIOVIT
Magne Simonsen	MSc	NMBU/MET
Astrid Liland	Cand.scient.	NRPA/CERAD

PostDoc		
Anne Graupner	PhD	NIPH/CERAD
You Song	PhD	NIVA
Tânia Gomes	PhD	NIVA/CERAD
Sachin Nehete	PhD	NMBU/CERAD
Leif Lindeman	PhD	NMBU/VET
Elisabeth Lindbo Hansen	PhD	NRPA

Technical/Administrative		
Jill Andersen	Siv.ing	NIPH
Lena Sareisian	MSc	NIPH
Arip Ihksani		NIPH
Ståle Mygland	MSc	NIVA
Mirian Wangen	Senior Executive Officer	NMBU
Anja Nieuwenhuis	Consultant	NMBU/CERAD
Karl Andreas Jensen	Ing.	NMBU/CERAD
Marit Nandrup Pettersen	Ing.	NMBU/CERAD
Yetneberk A. Kassaye	Chief Engineer	NMBU/CERAD
Marie Vollset	MSc	NMBU/CERAD
Susanne Birkeland	MSc	NMBU/CERAD
Jorunn Hestenes Larsen	Management Director	NMBU/CERAD
Lene Valle	MSc	NMBU/CERAD/NIPH
Anne Marie Frøvig	Cand.polit	NRPA

International guest scientists	
Scientist II Simone Cagno	PhD
Jacub Jaroszewicz	MSc
Fern Lyne	PhD

International scientific network - SAC

Dr David Clarke		USA
Prof Valeriy Kashparov	NMBU Prof II	Ukraine
Prof. Koen Janssens		Belgium
Prof. Peter Stegnar		Slovenia
Prof. Carmel Mothersill		Canada
Prof. Colin Seymour		Canada
Prof. Tom Hinton	NMBU Prof II	Japan
Dr Clare Bradshaw		Sweden
Prof. Janet Bornman		Australia

CERAD Meetings and Workshops 2017

CERAD Annual Conference
The Norwegian Academy of Science and Letters, Oslo, Norway
February 8th - 9th, 2017
Organizer: CERAD

ICCE 2017
16th International Conference on Chemistry
and
the Environment, Oslo, Norway,
June 18th - 22th, 2017
CERAD/NMBU/MINA members of organizing committee

ICRER 2017
4th International Conference on Radioecology
and
Environmental Radioactivity in Berlin, Germany,
September 3rd - 8th, 2017
CERAD/NRPB members of organizing committee

CERAD/SiU Workshop
Environmental Radioactivity, Oslo, Norway,
October 16th - 17th, 2017
Organizer: CERAD

Workshop TERRITORIES
Key factors contributing to uncertainties in radiological risk assessment, Oslo, Norway
November 14th - 15th, 2017
Communication of uncertainties of radiological risk assessments to stakeholders,
November 16th, 2017
Organizer: NMBU/CERAD and CIEMAT, Spain

Norwegian Centre of Excellence

Norwegian University of Life Sciences

Statens strålevern
Norwegian Radiation Protection Authority

Norwegian Meteorological Institute

Norwegian Institute of Public Health

Norwegian Institute for Water Research