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COMET PROJECT FINAL REPORT - *Advancement in science, integration and sustainability of European Radioecology*

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4.1. Final publishable summary report

4.1.1. Executive summary

The EC FP7 COMET (Coordination and iMplementation of a pan-European instrument for radioecology) was funded to strengthen the pan-European research initiative on the impact of radiation on man and the environment by facilitating the integration of radioecology research and development.

WP2 - Integrating and sustaining radioecology COMET has made progress in promoting the European Radioecology Alliance (ALLIANCE)[1], which is now established on a solid basis of 27 partners. Scientific collaboration has been strengthened globally, e.g. with participation of scientists from Ukraine, Japan, USA and Australia, as well as with interactions with international radiation protection organisations (e.g. IRPA, ICRP, IAEA, IUR, OECD-NEA and UNSCEAR). COMET and the ALLIANCE have especially encouraged collaboration with the European platforms on nuclear and radiological emergency response and recovery (NERIS[2]), low dose radiation risk (MELODI[3]) and dosimetry (EURADOS[4]). This interaction was enforced further via the projects OPERRA[5] and EJP-CONCERT[6].

The Strategic Research Agenda (SRA) initiated by the STAR[7] Network of Excellence and integrated in the research strategy implemented by the COMET consortium, defines a long-term vision (20 years) of the needs for, and implementation of, research in radioecology. The SRA is being complemented by topical roadmaps that have been initiated by COMET with the help and endorsement of the ALLIANCE following the establishment of criteria and processes for research prioritisation. The strategy underlying roadmap development is driven by the need for improvement of mechanistic understanding across radioecology, such that we can provide fit-for-purpose human and environmental impact/risk assessments in support of protection of man and the environment in interaction with society. Five-year roadmaps are being developed in the domain of Marine Radioecology, NORM, Human Food Chain, Transfer processes of atmospheric radionuclides and Transgenerational Effects and Interspecies Sensitivity. This short-term roadmap will be the basis of an implementation plan for the priority research activities that have been identified in the SRA.
State of the art research infrastructure and its optimised use are key for sustainable radioecology in Europe. A prominent ongoing task is the creation of Radioecological Observatories. These sites are being established in the Chernobyl and Fukushima affected areas as well as in NORM legacy sites in Poland and Belgium. Research programmes are being established at these sites. The Education and Training platform developed under COMET will contribute to ensuring a sustainable workforce in radioecology/radiation protection.

COMETs contributions to and legacy for radioecology are further described below.

WP3 - Improved models for risk assessment and for emergency and post-accident situations Part of the COMET research activities was centred on improving parametrisation of key processes controlling the transfer

[1] ALLIANCE: European Radioecology Alliance, http://www.er-alliance.eu/
[2] NERIS: European Platform on Preparedness for Nuclear and Radiological Emergency Response and Recovery, http://www.eu-neris.net
[3] MELODI: Multidisciplinary European Low Dose Initiative, http://www.melodi-online.eu
[4] EURADOS: European Dosimetry Group, http://www.eurados.org
[5] OPERRA: Open Project for the European Radiation Research Area, http://www.melodi-online.eu/operra.html
[6] CONCERT: European Joint Programme for the Integration of Radiation Protection Research, http://www.concert-h2020.eu/
[7] Network of Excellence STAR (Strategy for Allied Radioecology), http://www.star-radioecology.org

of radionuclides in the environment, with a specific focus on dynamic and mechanistic modelling approaches. The research was initially conducted within topical working groups on marine, forest, human food chain, NORM, wildlife transfer and particle behaviour. After an open research call initiated by COMET, these groups were complemented by two projects, FRAME (The impact of recent releases from the Fukushima nucleaR Accident on the Marine Environment) and RATE (RAdioactive particle Transformation procEsses). These new projects conducted additional investigations on the mechanisms for radionuclide transfer in the marine environment and on the behaviour of particle-bound radionuclides, respectively. COMETs activities have made significant contributions to improve radioecological modelling capabilities, thereby reducing uncertainties. For example, kinetic transfer models were improved to better capture the dynamic changes of activity concentration in both marine biota and sediments during post-accident situations, and improved trophic transfer models were developed. Both experiments and fieldwork contributed towards improved model parameterisation. For example, the scientific cruises conducted under the FRAME project provided data for both marine model improvement and validation, while experimental work on human food chain modelling and particle behaviour provided data on dynamic parameters for their respective models. COMET covered topics highly relevant for emergency and post-accident communities, such as updating decision support systems with regional parameters. Furthermore, interdisciplinary research was conducted, such as a very fruitful collaboration with oceanographers, and marine radioecologists.

WP4 - Epigenetic changes and their possible role in adaptation and trans-generational effects Our objective was to increase understanding of the effects of chronic low-dose radiation and the possible contribution of epigenetic mechanisms (epigenetic changes are stable heritable traits (or "phenotypes") that cannot be explained by *changes* in DNA sequence) to long-term and multi-generational effects. COMET performed controlled laboratory exposure experiments to investigate the role of epigenetic changes in the alteration of physiological functions of laboratory model organisms (zebrafish, earthworm and plant). In parallel field studies were performed on a range of indigenous species (earthworm, plant and frog) within contaminated areas (the Chernobyl exclusion zone and the Fukushima 100-km area) to investigate epigenetic changes in wildlife. DNA methylation (one of the major epigenetic processes) in addition to other molecular physiological markers was measured in order to investigate radiation effects. The results from field and laboratory studies showed limited impact of long-term exposure to radiation on DNA methylation but results suggest a role of methylation in the multigenerational response to radiation exposure under both field and laboratory conditions. These preliminary results should encourage further studies to better understand the contribution of DNA methylation and other epigenetic mechanisms in radiation response and to test their usefulness as biomarkers of radiation exposure/effects. In the present research, the comparison of field versus laboratory results showed that species sampled in the field were more sensitive (or responsive?) to radiation than those studied under laboratory controlled conditions. From the project results, there is no clear evidence of an increased sensitivity to radiation exposure over generations. Absence of clear effects may also point to adaptation.

WP5 - Knowledge exchange An important aspect of COMET was exchanging knowledge and expertise. Key objectives were to: (i) disseminate COMET activities (via website, social media, newsletters etc.), (ii) facilitate discussion of topical radioecological issues between researchers and users and (iii) develop training to maintain and enhance professional competence. The Radioecology Exchange website was created in 2011 under FP7 STAR and COMET has built extensively upon this work. The site has become the ‘hub’ for both projects and is the ‘gateway’ for information related to European (and wider) radioecological research. Recognising the value of bringing together the different communities involved in radiation protection, COMET ran four focussed workshops to debate topical issues ensuring better focusing and exploitation of scientific research. COMET developed an E&T web platform and arranged a number of courses for students and professionals, drawing on relevant expertise from the partner organisations. More than 30 PhD students and a large number of MSc students have been associated with COMET-related research and are part of the Radioecology PhD network. Within the Radioecology Exchange, COMET has developed the E&T platform, which contains information on courses within radioecology ranging from MSc and PhD courses to workshops and professional development. COMET partners have continued to develop and participate in the European Masters Programme in Radioecology held at NMBU, Norway. Two new intensive field courses were developed and held during COMET. A training course in ‘Radiological Protection of the Environment’ was held and COMET also co-organised a ‘young scientists session’ at Radiation Protection Week 2016 and held refresher courses at international conferences.

4.1.2. Project context and objectives

COMET was a response by the European Commission and the European radioecology community to the need to ensure the sustainability of radioecologial research in Europe. Through COMET, the ALLIANCE developed stronger ties with the wider European radiation protection community and the international radiological sciences and ecotoxicology communities. The trans-national structure developed will be capable of ensuring appropriate governance of radioecology research to meet the challenges identified within the radioecology strategic research agenda. s

Through COMET, the ALLIANCE has positioned itself as a strong component of the Horizon 2020 Radiation Protection Federating Association. Our scientific strategy was to structure radioecological research in the most effective way, through the further development of the Radioecology SRA and to develop mechanisms of joint programming and implementation. The research activities advanced knowledge and expertise in transfer, exposure and effect assessment through innovative multidisciplinary research. We have strengthened collaboration between the radioecology and (post)-emergency and low-dose research communities. The development of future common research lines and a Joint Programme of Activities and Implementation Plan between NERIS, MELODI and the ALLIANCE will increase efficiency, leading to the optimised use of research funds and infrastructure, and a more holistic approach to research. COMET activities have been effectively disseminated and E&T packages have been developed to maintain and enhance professional competence.

WP2 – Joint programming and implementation – Expanding the ALLIANCE

The ALLIANCE and the STAR NoE have taken the first steps towards joint programming of research activities in radioecology and a number of ALLIANCE/STAR organisations have begun to harmonise their research through common activities. They had also begun to explore infrastructure sharing and joint capacity development. Moreover, in interaction with the ALLIANCE, STAR has developed an SRA which has been generally well received and has been the subject of an open meeting in November 2012.

The overall objective of this work package under COMET was to build upon the foundations laid by STAR and the ALLIANCE to strengthen the pan-European research initiative on the impact of radiation on environment and man. COMET took the following actions in order to achieve this objective:

- Further developing the strategic research agenda (SRA) created under STAR/ALLIANCE in light of advances in knowledge, identification of new priority needs and to better align it with the SRAs of other radiation protection platforms.
- Developing a strategy for a roadmap and an associated implementation plan based on the SRA for Radioecology in association with the ALLIANCE
- Developing innovative mechanisms for joint programming and implementation of radioecological research in close collaboration with the ALLIANCE and the platforms of allied fields such as emergency management (NERIS) and low dose research (MELODI).

WP3 – Improving and validating radioecological models

Radioecology is a multidisciplinary science that studies the transfer of radionuclides in the biosphere, atmosphere and geosphere-biosphere interaction zone to predict radiation exposure to man and the environment and its resulting potential impact on both human health and ecosystems. This expertise is needed to understand and predict accidental and routine releases and existing exposure scenarios and to ensure the safe operation or management of nuclear industry, the NORM industries, releases from hospitals and research institutes, and legacy sites contaminated by past activities. The overall objectives of this work package was therefore to undertake joint research activities to improve and validate radioecological models of interest to both communities for better protection of humans and the environment in existing, planned and emergency exposure situations.

The research in WP3 aimed to centre on improving parametrisation of key processes controlling the transfer of radionuclides, with a specific focus on dynamic and mechanistic modelling approaches. It was guided by Challenge one of the Strategic Research Agenda of radioecology: ”To Predict Human and Wildlife Exposure in a Robust Way by Quantifying Key Processes that Influence Radionuclide Transfers and Exposure”, with its four associated research lines.

WP4 – Epigenetic changes and their possible role in adaptation and trans-generational effects

Epigenetic processes and transgenerational effects induced by ionising radiation have been put forward as priority research areas in the SRAs of both the ALLIANCE and MELODI. Epigenetic changes are hereditary traits which do not involve a change in the DNA sequence. Epigenetic states and certain environmental responses in mammals and spermatophytes (seed plants) can persist in the next generation. Epigenetic processes are induced by stressors (like radiation) and may lead to altered/less fit phenotypes or off-spring. Epigenetic changes may, however, also lead to increased resistance to adverse conditions. With only few studies that analyse in detail the involvement of DNA methylation and other epigenetic mechanisms in the complex process of radiation stress for man and wildlife, COMET intended to advance this innovative and scientifically challenging area.

The objective was to increase our understanding of the effects of chronic low-dose radiation and the possible contribution of epigenetic mechanisms to long-term and trans/multi-generational effects. Laboratory and field experiments stiudying different test organisms were performed. The following key research hypotheses were addressed: H1: Exposure to gamma-irradiation results in a changed radiosensitivity (or resistance) within and over generations; H2: Epigenetic mechanisms underlie changes in radiosensitivity (or resistance) observed in gamma-irradiated organisms; H3: Epigenetic changes observed in gamma irradiated organisms grown under controlled lab-conditions are similar to epigenetic changes observed in areas affected by a nuclear accident.

WP5 – Knowledge exchange and capacity building

Recognising the importance of knowledge exchange including the exploitation of results, spreading of excellence and capacity building we wanted to develop strong mechanisms for knowledge exchange and dissemination to enhance and maintain European capacity and skills in radioecology.

The overarching objectives of this work package were to enhance and maintain European capacity and skills in radioecology by establishing a dynamic interaction promoting effective collaboration between researchers, tool developers, regulators and industry.

The specific objectives that were addressed by this work package were (i) to establish a website as a hub for European radioecology; (ii) to facilitate discussion of topical radioecological issues between researchers and stakeholders; (3) to develop training packages to maintain and enhance professional competence.

This work should ensure a more effective 'take-up' of scientific advances by the user community and a stronger focus of radioecological research to address the needs of users.

4.1.3. Main S&T results

WP2 - Joint programming and implementation – Expanding the ALLIANCE

The overall objective of our joint programming and implementation task within COMET was to build upon the foundations laid by the FP7 STAR NoE (Strategy for Allied Radioecology) and the European Radioecological Alliance (ALLIANCE) platform which were to strengthen the pan-European research initiative on the impact of radiation on environment and man.

Evolving towards a pan-European network

The ALLIANCE platform now has a secure basis, having, in 2017, expanded from the initial eight founding members to 27 members from 14 countries (Belgium, Croatia, Finland, France, Germany, Greece, Ireland, Kazakhstan, Norway, Poland, Portugal, Spain, Sweden and United Kingdom). The ALLIANCE does not depend upon external funding, but is an association with members committed to sustainable cooperation. However, the funding available under COMET has helped the ALLIANCE develop its structural basis. During COMET a description of functioning and interaction mechanisms of the European Radioecology ALLIANCE has been produced (COMET D2.7 *Blueprint of the European Radioecology ALLIANCE functioning*, Muikku et al., 2017). The interaction mechanisms include both internal interaction between COMET and ALLIANCE partners, and interaction with other research organisations, universities, national competent authorities, stakeholders, international interest organisations as well as other platforms, mainly in the field of radiation protection.

A workshop with NERIS-ALLIANCE/STAR-MELODI and EC-OPERRA (Open Project for European Radiation Research Area) to prioritise topics for organizing a Competitive Call was arranged in 2013. The Competitive Call was launched together with OPERRA in December 2013. The COMET 2013 call was an essential part of the joint programming. A primary motivation of the Competitive Call was to engage the wider scientific communities to address scientific challenges that had been jointly identified as important by both the radioecology community and the low-dose or the (post) emergency communities. COMET organised the Call, partially to attract new expertise to the consortium and at the same time, guarantee the integration of new beneficiaries to the existing consortium. Two projects were integrated within COMET: FRAME (The impact of recent releases from the Fukushima nuclear accident on the marine environment, http://www.radioecology-exchange.org/content/comet-frame) and RATE (RAdioactive particle Transformation processes, http://www.radioecology-exchange.org/content/comet-rate).

Integration of the European radiation protection community has been enhanced by and during COMET. The four platforms: the ALLIANCE (European Radioecology Alliance), NERIS (European Platform on preparedness for nuclear and radiological emergency response and recovery), MELODI (Multidisciplinary European Low Dose Initiative) and EURADOS (the European dosimetry group) have strengthened their connections. They all signed a Memorandum of understanding in December 2013.

COMET partners, as representatives of the ALLIANCE, have participated in several meetings arranged by other European platforms and projects during 2013-2017. COMET also contributed to arrangements for Radiation Protection Week, organised in 2016 in Oxford, UK, which brought together complementary strands of radiation protection research, with the established European platforms MELODI, EURADOS, NERIS and the ALLIANCE as co-organisers, along with other relevant related areas. he COMET final event arranged in April 2017 brought together not only the other radiation protection platforms but also other organisations in the field (e.g. IUR, IAEA, ICRP, OECD-NEA). The final event centred around the discussion of position papers which highlight the major contributions of COMET to key areas of radioecology dealt with under COMET, the endeavour being to assure sustainability of radioecology in Europe and to capture views on the way forward. In addition, COMET partners, together with representatives of other platforms, have worked for the preparation a successful proposal and establishment of the new project EJP-CONCERT – European Joint Programme for the Integration of the Radiation Protection Research, under H2020. This project started in June 2015 and launched two calls for research proposals in 2016 and 2017. The work to promote radioecology will continue under the Euratom EJP-CONCERT.

The integration within radioecology has been enhanced by getting a wide variety of organisations to collaborate in radioecological studies. Integration with other programmes and platforms involving research and development in health and safety issues relating to ionising radiation in Europe has also been promoted by COMET. In addition, COMET has also been successful in enhancing collaboration globally; in particular, scientific collaboration has been strengthened, e.g. with participation of scientists from the USA, Australia and Japan as well as with interactions with international radiation protection organisations (e.g. IRPA, ICRP, IAEA, IUR, OECD-NEA and UNSCEAR).

The Strategic Research Agenda (SRA) and roadmap

The ALLIANCE Strategic Research Agenda (SRA) initiated by the STAR NoE and integrated in the research strategy implemented by the COMET consortium, defines a long-term vision (20 years) of the needs for, and implementation of, research in radioecology. The latest review of the SRA has been carried out in 2017 under COMET (COMET Deliverable 2.4 *Update of the SRA*, Garnier-Laplace et al., 2017). An ALLIANCE workshop was arranged in April 2017 following the COMET final event with the objectives of refining and coordinating the ALLIANCE roadmap, and of identifying the new drivers of the next version of the SRA due under EJP-CONCERT in November 2019.

The first short-term (5-y) scientific roadmap for Radioecology, released as a COMET deliverable in September 2013 (COMET D2.1, *Towards a First Phase Radioecology Alliance RTD Roadmap and Implementation Plan,* Vandenhove et al., 2013), was a first transitional implementation plan to structure and enhance interactions between the ALLIANCE and the European research platforms, NERIS and MELODI. These two documents, the SRA and the first transitional roadmap, have constituted two of the essential elements for preparing the EJP (European Joint Programming) scientific programme for radioecology in harmonisation with MELODI, NERIS and EURADOS. The strategy underlying the roadmap development is driven by the need for improvement of mechanistic understanding across radioecology such that we can provide fit-for-purpose human and environmental impact/risk assessment in support of protection of man and the environment in interaction with society (connecting science, communication, economy) and for the three exposure situations defined by ICRP (i.e., planned, existing and emergency). Some of the research areas for radioecology are also relevant for post-emergency management and low-dose effect research and provide a powerful catalyst to further develop collaboration between the four platforms of radiation protection, the ALLIANCE, NERIS, MELODI and EURADOS.

The SRA and transitional roadmap were complemented by 5-year topical roadmaps each dealing with specific scientific areas and/or complex environmental issues defined by the COMET project in collaboration with the ALLIANCE. Four topical roadmap working groups have been established under COMET, with participation of the ALLIANCE members, to make progress in addressing the challenges and priorities put forward in the Radioecology SRA in a structured way:

1) Marine radioecology
2) Radionuclides in the human food chain
3) Naturally Occurring Radioactive Materials (NORM) (coordinated by ALLIANCE members)
4) Transgenerational effects and species radiosensitivity.

Under the ALLIANCE an additional topical roadmap was launched on Atmospheric releases of radionuclides and their involvement in environmental transfer processes. Through the roadmap working groups mechanisms of joint programming and implementation following the establishment of criteria and processes for prioritisation of programming research have been developed and a sustainable implementation processes jointly with the ALLIANCE and in close interaction with the broader radiation protection arena represented by OPERRA and CONCERT has been set up. As a consequence of having the COMET-initiated topical roadmaps and roadmap working groups, the ALLIANCE now has the constituents to build a global roadmap up to Horizon 2020 which is to be released under CONCERT in November 2017.

Mechanisms of sustainable cooperation

Advancing infrastructure

A report containing information to researchers or institutions useful for facilitating research projects which are intended to be carried out at the European Radioecology Observatories or at the large infrastructures owned by the partners of COMET was produced (COMET D2.2 *Description of the protocols for access and mechanisms for supporting the research in the Radioecological Observatories and other large infrastructures*, Mora et. al. 2015). In the document, a brief description of the European Observatories for Radioecology is included as well as a list with the contact persons able to give support to perform research activities at the Observatories. Moreover a list of unique and to some extent large infrastructures, owned by the COMET partners and which could be of interest for use by COMET members and also by other researchers not in COMET, is presented as well as a list of contact persons. Finally, some examples for the preparation of a Memorandum of Understanding (MoU) between those institutions interested in the use of the observatories or other large infrastructures are annexed within the document.

The original idea of the Radioecological Observatories was that they are contaminated field sites that provide a focus for long term joint field investigations. The intention is to perform multidisciplinary joint research addressing the research priorities identified by the Strategic Research Agenda. The pooled, consolidated effort will maximise research progression, the sharing of data and resources as well as provide excellent training and education sites. The data collected from the Observatory sites will form a valuable international resource. In view of this long-term perspective, the Radioecological Observatories are closely linked to the Strategic Research Agenda, the long-term vision of radioecological research needed within the European Community. Four contaminated sites have been selected under the STAR NoE and COMET project as the most promising options for Radioecological Observatories:

- the Chernobyl Exclusion Zone;
- the aquatic environment of a previous coal mining and processing site in Poland (The Upper Silesian Coal Basin);
- a forest in the Fukushima prefecture in Japan (Yamayika);
- a waste landfill "Kepkensberg" from the Belgian phosphate industry.

More information on the Observatory Sites can be found on the Radioecology Exchange website (http://www.radioecology-exchange.org/content/radioecological-observatories). Observatory Working groups were formed under COMET to coordinate the RTD activities performed in the four Observatories selected.

SCK•CEN proposed, in collaboration with the University of Seville, to further characterise and monitor the forested Kepkensberg site. A monitoring station will be installed within the CONCERT project TERRITORIES. The station will be open to the other researchers of TERRITORIES and the ALLIANCE. A long-term sampling program will be established to further characterise the site and to further study the behaviour of natural occurring radionuclides in the environment. The results obtained (now and in the future) will be disseminated in conferences and peer review papers.

Thematic working groups

The ALLIANCE has formed four working groups on (1) Strategic Research Agenda & Roadmap, (2) Infrastructures and Sustainability, (3) Education & Training and (4) Stakeholder Involvement that will develop and promote the issues related to their topics in the future as seen necessary. COMET members have been actively working in the groups. The ALLIANCE working groups are now giving input to the relevant work packages of the EJP-CONCERT project.

National programmes

To get an overview of national programmes, funding schemes and requirements for radioecological research in Europe and begin the integration of national radioecology programmes to create a common framework for future research activities, a survey on nationally funded projects related to areas of research of OPERRA and COMET, covering the time frame between 2007 – 2013, was conducted under COMET WP2, in cooperation with OPERRA WP2. The survey was performed in two parts (COMET D2.3 *Inventory on national research projects related to radioecology*, Sirkka et. al. 2017). First, during 2014-2015, the information from EU member states was collected. Secondly, during 2016, the survey was extended to European countries other than EU members, and expanded internationally. The response rate to the survey was very low, and the results of the survey do not reflect the status of the national funding in the contacted countries. Therefore, it must be strongly emphasised that the report gives us some scattered information and examples from various countries, inside and outside EU, but it is not a description of national programmes and funding schemes since the scarce information we were able to collect clearly does not represent the reality. One conclusion that can be drawn from the survey is that the cooperation with national funders is very challenging and there seems to be lack of interest from their side to cooperate on international level, at least when measured by the responses to the survey.

Education and training

Within the Radioecology Exchange website, COMET has further developed the Education and Training platform that was initially set up by the STAR NoE (http://www.radioecology-exchange.org/content/training-education). It is a focal point for students and professionals interested in radioecology, linking education in different nuclear disciplines together (COMET D2.6 *Description of training and education coordinated platform*, Skipperud et al., 2017). The platform gives an overview of education and training course modules within radioecology/environmental radioactivity presently offered by the COMET consortium and will be followed up by the ALLIANCE post-COMET. The ultimate aim of the Education and Training platform is to ensure a sustainable workforce in radioecology.. This platform holds information on different courses within radioecology ranging from MSc and PhD courses to workshops and professional development, it also provides links to other Education and Training platforms, such as those within Radiochemistry, Radiobiology and Radiation Protection (DoReMi, CINCH II, etc.). 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. A possibility to submit a radioecology MSc application to Erasmus Mundus was also explored under COMET. Nine of the COMET partners were interested in being part of an Erasmus Mundus joint MSc programme application. There were sufficient number of Higher Education Institutions (5 universities from 4 countries) to fulfil the criteria for such an application though no application has been submitted so far. In addition, COMET has been engaged in discussions with the ALLIANCE for more long-term solutions to maintain the sustainability of radioecology Education and Training after the end of COMET.

In conclusion, several mechanisms for sustainable collaboration have been established by COMET. The activities of the ALLIANCE are organised within working groups, in which any interested member can participate. These working groups provide input to promote the ALLIANCE functioning, strengthen integration and sustainability of the developments achieved during the STAR and COMET projects. The Education and Training platform will ensure a sustainable workforce in radioecology.

WP3 - Improving / validating radioecological models and field studies

Introduction

The overall aim of work package 3 of COMET was to strengthen the pan-European links between the radioecology and the emergency and post-accident communities and to undertake joint research activities to improve and validate radioecological models of interest to both communities. The research in WP3 was centred on improving parametrisation of key processes controlling the transfer of radionuclides, with a specific focus on dynamic and mechanistic modelling approaches. The research was initially conducted within topical working groups on marine, forest, human food chain, NORM, wildlife transfer modelling and particle behaviour. After an open call, these groups were complemented by two projects, FRAME and RATE, in which additional investigations on the mechanisms radionuclide transfer in the marine environment and on particle behaviour, respectively, would further reduce the uncertainties associated with key transfer processes.

Marine modelling and field studies

The Fukushima nuclear accident in 2011 constitutes the most important accidental release of artificial radionuclides to the marine environment. The major sources of contamination as exemplified in Figure 1 are: (a) direct atmospheric emissions deposited onto the ocean; (b) river discharge and surface water runoff and (c) submarine groundwater discharges. Significant concentrations of ^{137}Cs have been measured in bottom sediments of Fukushima, which serve as both a long-term repository and a potential source of contamination.

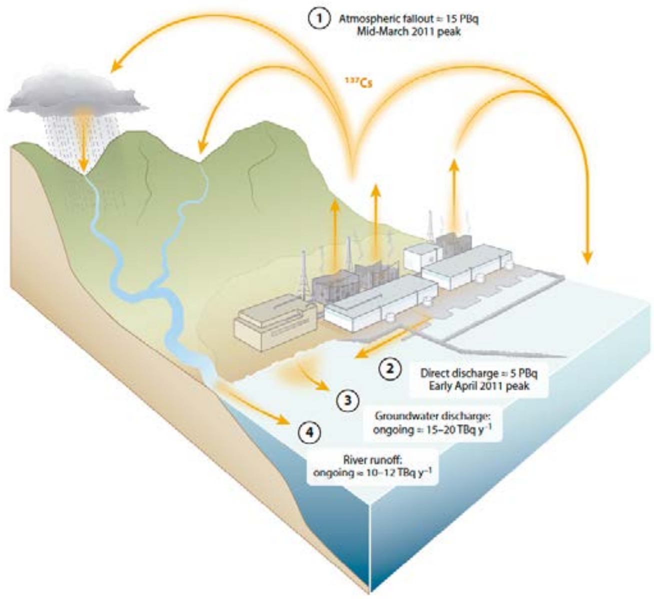


Figure 1: Schematic of Fukushima Daiichi–derived sources of ^{137}Cs to the environment. Atmospheric fallout (1) and direct discharge (2) are shown as total petabecquerels (PBq) released in the first month after the accident. Groundwater fluxes (3) and river runoff (4) are approximate ranges for the first year after the accident. Notice that (3) and (4) are expressed in terabecquerels (TBq). From Buesseler et al. (2017).

This unprecedented accident is one of the main reasons why a marine group emerged within the COMET. The main lines of research from Challenge One of the ALLIANCE SRA directly relevant to this marine group were (a) to identify and mathematically represent key processes (b) acquire the data necessary for parameterisation of these processes and (c) develop transfer and exposure models. This provided the reference point for the marine radioecology activities within COMET. Such activities focussed on how models designed to predict the transfer of radionuclides released by Fukushima into water to sedimentary deposits and non-human biota could be adapted to highly dynamic post-accident situations, improving the existing models by making them more dynamic and process-based, and trying to make more realistic estimates of transfer to biota with these models in order to assess radiological consequences, using improved data for parameterisation, calibration and validation of the models.

Improvements in marine radioecological models

Two main radioecological modelling topics were taken into account: Transfers and exchanges between water and sediments, and modelling of transfer to biota. Some simple models could be included in decision support systems for emergency situations. Others, more sophisticated, are available for use in a second step to evaluate and predict more accurately the post accidental situation. The main focus of the marine modelling activities was on the modelling tools adapted to emergency and post-accidental issues. Existing time-dependent models were used as a basis for the work with a view to improving some of them to achieve more sophisticated models.

One of the models improved in the course of COMET work was the IRSN model STERNE, which is designed to be operated for a first estimation in case of emergency situation. STERNE calculates both radionuclides transport using advection and diffusion equations offline from hydrodynamic calculation given from validated models, and radioecological transfers to biota with a simple model based on dynamic transfer equation. Needed radioecological parameters (concentration factors and single or multicomponent biological half-lives) have been compiled for some important radionuclides and for generic marine species (macroalgae, fish, molluscs, crustaceans). Dispersion and transfer calculations are carried out simultaneously on a 3D grid.

The second marine model further improved during the COMET work is the SCK•CEN D-DAT model, which simulates the dynamics of radionuclide uptake and turnover in marine biota. The model calculates activity concentration of ^{131}I, ^{134}Cs, ^{137}Cs and ^{90}Sr in seabed sediment, fish, crustaceans, molluscs and macroalgae from surrounding activity concentrations in seawater, with which to derive internal and external dose rates. The main specific improvement carried out during COMET was the inclusion of sediment processes. The model is now adapted to include particle scavenging, molecular diffusion, pore water mixing and bioturbation represented by a simple set of differential equations that is coupled with the biological uptake/turnover processes.

The third model that was improved during COMET was the NRPA box model, which uses an approach with time-dependent transfer of radionuclides within the food chain that can be described by first-order differential equations considering not only kinetic exchange between organisms and water but also transfer of radionuclides between prey and predators. For this, the NRPA model uses ingestion rates and absorption efficiencies governing the passage of radionuclide from one organism into another. The model is simplified by assuming that excretion/elimination rates are independent of the uptake route, assimilation efficiency is independent of food type, and predators do not to assimilate the activity concentration in gut content of their prey and zooplankton are a homogeneous group.

Lastly, in the course of COMET, IRSN, together with the University of Toulouse (France), has developed a dynamic model of radiocaesium transfer to marine biota taking into account large scale organism displacements in Fukushima area (Belharet et al., 2016). This model considers uptake of radionuclides from water and biological elimination by egestion and excretion, as well as exchanges between different organisms by grazing or predation. Radiocaesium activity in water was deduced from dispersion modelling using a coastal circulation model SYMPHONIE (Estournel et al., 2012), while biomasses of the different marine populations, grazing, excretion and egestion fluxes were obtained through application of a 3-dimensional ecosystem model composed of a bio-geochemical model NEMURO (Kishi et al., 2007) coupled with the bioenergetic model NEMURO.FISH (Ito et al., 2004; Megrey et al., 2007).

Application of models

The project FRAME led to further practical application of the D-DAT model. It was observed that, in recent years, a generally exponential decrease of activity concentrations with time occurs for all the main categories of marine biota as would be expected as contamination clears the local environment by dispersion and dilution. The fact that activity concentrations for marine biota decrease much more slowly over time than expected given their biological half-lives ($T_{B1/2}$'s) hints at hold-up processes by bottom sediments, which have become increasingly a source for radionuclides in the local environment, due to their ability to retain radiocaesium.

From our own analysis of the published data and the FRAME measurements, different rates of decrease are seen in different organism groups, being slowest (with consequently a higher residence half-time) for benthic biota and fastest for pelagic biota. This is compatible with differences in $T_{B1/2}$'s for these radionuclides. What the model was not able to reproduce was the a high variability of the monitoring data, because this is due to sampling, measurement or geographical variability but may be partially explained also (particularly in the latter years) by the presence of the previously mentioned secondary emissions (such as groundwater releases).

The complex time evolution of ^{137}Cs in marine biota from 2011 to present is now modelled by D-DAT as a multicomponent exponential decrease influenced by a bi-phasic depuration mechanism and the radionuclide hold-up processes by seabed sediments. This is better reproduced when using two $T_{B½}$s of the order of 4 and 54 days, helping to explain mathematically why biota activity levels remain somewhat elevated, as well as the long ecological half-lives observed in the field. The model has also been optimised with a flushing time of 2.2 ± 0.3 day for the clearance of water from the Fukushima coastal compartment, and by implementing local parameters derived from the marine cruises. For example, the sub-model for ^{137}Cs is now updated with a less conservative, more site-specific value of 0.061 $m^3\ kg^{-1}$, derived from pelagic fish data from the FRAME 2014 cruise. This resulted in a substantial improvement in prediction when comparing the model-predicted activity concentrations in benthic fish with the measurements carried out by the Japanese authorities (MAFF).

Using the ecosystem modelling implemented in the IRSN/Toulouse model, transfer to zooplankton was calibrated with in situ data. This model showed that maximum values of the ^{137}Cs concentrations in phytoplankton and zooplankton populations were mainly reached 1 month after the accident and were about 2 to 4 orders of magnitude higher than those observed before the accident depending on the distance from FNPP.

Field studies

The impact of the releases of radioactive isotopes from the Fukushima Dai-ichi NPP to the ocean due to the accident that occurred in March 2011 was investigated in the field by a consortium of international laboratories under the project FRAME. The main results of the project have been published elsewhere (Castrillejo et al., 2016, Buesseler et al., 2017, Vives Batlle, 2016a-b, Aoyama et al., 2016a-c) and other manuscripts submitted or in preparation), as well as in various conference proceedings (Buesseler, 2015c, Masqué, 2015, Buesseler, 2015b, Buesseler, 2015a), to quote a few examples, so only the key aspects will be mentioned here.

Important marine processes, such as the interaction of waterborne radionuclides with suspended particles and sediments, were investigated, invoking the large spatial scales incorporating ocean circulation and land-sea interactions. The main focus of the research was on ^{137}Cs, ^{134}Cs and ^{90}Sr, but attention was paid also to ^{129}I, ^{236}U and Pu-isotopes. Seawater samples, sediment cores and biota samples were taken in 2014 and 2015 on board the Japanese Research Vessel Shinsei Maru, covering the most heavily affected area off the coast of Fukushima. In addition to the artificial radionuclides, natural radium isotopes were analysed to quantify the fluxes of chemical elements associated with the offshore transport. Groundwater sampling along the shoreline was conducted to determine the rate of submarine groundwater discharge (SGD) along the Fukushima prefecture coastline to constrain the radiocaesium flux to the ocean.

Surface ocean concentrations of ^{137}Cs, ^{90}Sr and ^{129}I measured during the FRAME project were found to be higher near the FDNPS and they were above the global fallout levels, suggesting that there are still ongoing releases from the Nuclear Power Plant site. Particularly interesting was the evolution of atomic and/or activity ratios of $^{137}Cs/^{90}Sr$, $^{129}I/^{137}Cs$, $^{129}I/^{90}Sr$ with time, which helped to corroborate the ongoing releases of radionuclides to the coast off Japan. Evidence was found of groundwater-transported Fukushima radionuclides to the ocean both at the FDNPP site and further along the coasts, with a relatively constant ^{137}Cs fluxes of up to 10^{11} Bq d^{-1} in 2013-2014, down to several GBq per day in 2016.

In addition to radiocaesium, coastal inputs of ^{90}Sr are observed, though they are significantly lower, in the order of 2-8 GBq d^{-1} in 2013. We did not detect any signal of the presence of radionuclides such as ^{236}U and Pu isotopes. There is a reasonable inference that the main source of these ongoing releases is high contaminated water within the site. The fate of such radiocaesium and ^{90}Sr released in the ocean is largely driven by the oceanic circulation. The uptake of radionuclides by biota was also investigated using samples from the 2014 research cruise to the Fukushima area (the data from the 2015 cruise is not yet available). The results follow the expected decrease in concentrations with time since the accident. The radiological impact to fish was more significant for benthic species exposed to contaminated sediments, but after several years since the accident all radiation doses to marine biota are below the ERICA no-effects dose screening level (10 μGy h^{-1}). Potential impact assessment to humans due to ingestion of fish shows that this should not be of a concern at present time, since estimates of annual does would be a fraction of a mSv.

Perspectives for future work

The marine research performed under COMET has demonstrated that biokinetic models can better represent radionuclide transfer to biota in non-equilibrium situations, bringing more realism to predictions, and it has also enabled a better understand important marine processes, such as the interaction of Fukushima radionuclides with seawater, particulate matter and biota. The main achievement during COMET has been to directly address temporal dynamics in the assessment process. There has also been an attempt to involve more biological factors in the modelling process, by including (for example) $T_{B½}$'s, bioturbation, fish migration, trophic transfer and uptake/elimination. We are readier now than we were before Fukushima in terms of having models that can be applied to dynamic situations. In this sense, the objectives of the marine working group were met. The work provided six publications, and was the opportunity to present marine activities and results in three different international congress (ICOBTE, ICRER, and ASLO).

Investigations should continue in the future to further understand the complex mechanisms involved in the transfer of the radioactivity still accumulated on land and groundwater and bottom sediments to the water column and to marine organisms. Moreover, simple biokinetic models that consider accumulation and depuration terms seem to be efficient as operational tools that are necessary to evaluate the first trend after any accidental release, but a second generation of trophic transfer models that could better represent variability of transfers depending on considered organisms are to be developed, especially for mid to long term post-accidental contamination.

Another area that requires further effort is gathering new measurements, but also all data provided by Japanese Authorities and Universities, in order to provide further to improve and calibrate modelling tools, especially for radionuclides other than radiocaesium, because radionuclides' behaviour in marine environment in non-equilibrium situations is still poorly documented, such as the radionuclides' reactivity and partition between particulate and dissolved phase, transfers through the different trophic chains. On this depends the future development of properly validated dispersion models relevant for normal or accidental discharges from nuclear plants or ship wreckage, usable in decision support system or for different studies are needed, especially for coastal areas. The scope of marine radioecology is very large, the behaviour and fate of radionuclides is complicated to investigate due to the difficulty and the cost of getting measurement data. At the same time, Marine radioecology is of cross-border importance and needs to have more funded collaborative projects with the wider research community dealing with how other contaminants disperse and transfer to different parts of the environment.

Particle behaviour

A certain fraction of refractory radionuclides released to the environment from the nuclear weapon and fuel cycles are present as particles ranging from submicrons to fragments. Such particles can carry a substantial amount of radioactivity (e.g., fission and activation products, transuranics) and associated metals, and can act as point sources. Furthermore, U/Th particles (progenies, metals) are present at NORM sites.

Particle characteristics such as elemental/radionuclide composition as well as atom/isotope and element ratios will depend on the emitting source, while particle size, crystalline structure and oxidation states are closely linked to the release scenarios. Following deposition, ecosystem transfer of particle associated radionuclides are therefore delayed compared to mobile radionuclide species (i.e., ecosystem transfer is delayed until particle weathering and remobilisation of associated radionuclides occur). Thus, the environmental behavior and associated radioecological and radiological impact will be different from a situation when the radioactive contamination is present in ionic forms.

The RATE project has been devoted to improve the ability to quantify the processes of particle transformation in the environment and radionuclide leaching into various media, and to improve the assessment of ecosystem transfer in environments affected by radioactive particle contamination. With this end, systematic transformation experiments exposing well characterized particle samples to environmentally relevant media were performed, thus providing weathering rates to be linked to site-specific particle characteristics.

This quantification was performed by applying well defined abiotic and biotic leaching protocols to isolated radioactive particles of different origin previously characterized by means of advanced techniques (e.g., autoradiography, ESEM-EDX, TOF-SIMS, synchrotron radiation based x-ray techniques), giving information such as elemental composition and 3D distribution as well as crystallographic structure and oxidation states linked to particle weathering rates, extraction kinetics and potential bioavailability of remobilised particle associated radionuclides. The leaching protocols were mostly applied to radioactive particles collected in a) areas affected by local fallout generated by weapon tests (Semipalatinsk in Kazakhstan, Maralinga in Australia), b) areas contaminated by the accidental dispersion of the content of nuclear weapon (Palomares in Spain, Thule in Greenland), and c) high background natural radioactivity areas (e.g., Norway). In all cases, the relative (%) fractions of radionuclides leached from particles under different agent media (rainwater, HCl 0.16 M, rumen fluid) were quite low, indicating the refractory character of the particles and evidenced that in the terrestrial areas affected by this contamination the Kd values are quite high and not comparable with default values generally considered in modelling exercises. The need to use on-site specific transfer factors has been clearly demonstrated, and is essential if realistic conclusions from modelling exercises are to be obtained. In particular, the role of bacteria and enzymes forming part of rumen fluids in leaching processes has been demonstrated in the biotic experiments carried out with isolated radioactive particles and contaminated soils from Palomares (Pu) and Fen (Th). The environmental behaviour of radioactive particles , weathering rates and transformation processes have also been detailed investigated at sites within the Chernobyl exclusion zone were the areas were mainly contaminated with spent fuel particles.

The results showed that in the exclusion zone the fraction (%) of ^{90}Sr in extractable and mobile (i.e. , potentially biologically available) form has increased during the years and has presently reached its maximum value for the post-accident period due to fuel particles dissolution in topsoil and in the radioactive waste trenches. It has been demonstrated that the increasing uptake (dynamics) of ^{90}Sr in vegetation is mainly determined by the kinetics of fuel particle dissolution and by increased contribution of mobile ^{90}Sr in the root-layer. A monotonic increase of the concentration ratio (CR) of ^{90}Sr for grain was observed in the Chernobyl experimental area due to dissolution of the fuel particles and this coincides well with theoretical forecasts as it can be observed in Figure 2.

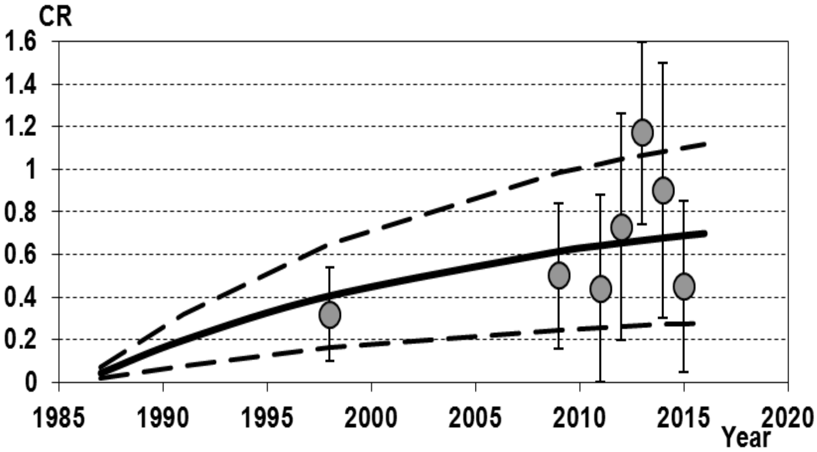


Figure 2: Dynamic of ^{90}Sr average Concentration Ratio (CR) for wheat (grain) cultivated in the exclusion zone (Otresko et al., 2014).

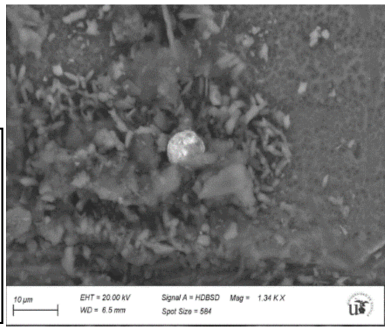
Weathering and dissolution of fuel particles in the drained bottom sediments of the cooling pond of the ChNPP were already investigated before the water level was decreased in 2015. Today, the water level has decreased by 4 m and the drained very contaminated bottom sediments have become exposed to air as observed in the Figure 3. Results show that the particle weathering rate was low when radionuclides were leaching from sediments from the ChNPP cooling pond, as the process seems to be controlled by a prolonged slightly alkaline pH in the sediment. The alkaline solution is caused by the presence of a large number of remnant shells of zebra mussels in bottom sediments of the ChPNN cooling pond. Hence, a sharp increase of radionuclide mobility should not be expected for the newly exposed sediments (Protsak and Odintsov, 2014).

(A) (B)

Figure 3: Water level of the ChNPP cooling pond in July (A) and in September (B) 2015.

It has been further demonstrated that radioactive particles in affecting ecosystems are of biological relevance. Previous laboratory experiments have demonstrated that particles given with food to organisms (goat, nematodes, Blue mussel) can be retained. In the field particles can be inhaled or ingested, and can be retained within organisms, acting as point sources. This fact has been evidenced in field studies performed with mammals in Taranaki (Australia), in muskoxen from Thule and in snails from Palomares (Spain). From these studies, it has been experimentally demonstrated that the transfer factors expressed as concentration ratios (CR) are affected, and default CR generally used in the radioecological models would be biased and would contribute to significant uncertainties in impact assessments. This fact is very important because until now bioavailability and uptake of particle-bound radionuclides compared with those existing as ions or simple molecules have so far largely been ignored when impact and risk are assessed. As a result, there is a high degree of scientific uncertainty about the long-term ecological consequences and risk to human health from radioactive particles present in the environment. Advances to reduce the uncertainties associated with particle contaminated sites have been reached, but it is essential to devote additional efforts to improve dosimetry models for proper evaluation of internal uneven distribution of dose and potential effects associated to high-specific activity particles, as described in the COMET Position paper (Salbu et al., in press).

Figure 4: Identification by SEM of a radioactive Pu particle embedded in the shellstructure of a *living snail collected in the contaminated* terrestrial *area of Palomares, Spain (R. Garcia Tenorio, Univ. Seville).*



Human food chain modelling

Intro – objectives/research question

The overall objective of this working group was to improve human food chain modelling in agricultural systems through regional customisation of relevant model parameters, by using novel and advanced statistical methods, and through studies of long-term dynamics of soil-to-plant transfer of radionuclides for different types of soil. Further description and main results for these three topics are given below.

Regional customisation

In the "Terrestrial Food Chain and Dose Module" (FDMT) used in the two standard European Decision Support Systems (DSS) for nuclear emergencies – ARGOS and JRODOS, many of the default parameters represent German (or Central European) conditions. In the present study, we identified important parameters to update – focusing on Nordic and Mediterranean regions. The most relevant of these parameters could be divided into four broad groups: (A) Contamination of plants due to direct deposition, (B) animal parameters, (C) human consumption habits, and (D) uptake from soil. Due to limited amount of time for this task, the actual updates performed within COMET were restricted to: (1) parameters of relevance to growing season and harvest periods of crops and grass, (2) animal feeding practice, and (3) human consumption of foodstuffs. Relevant data for all three categories were provided for Finland, Norway (three climate zones) and Spain. After regional customisation of models, we also used dry and wet deposition test scenarios to study the effect of parameter value updates on e.g. time development for activity concentrations (^{134}Cs, ^{137}Cs, ^{90}Sr, and ^{131}I) in foodstuffs and intake doses for different age groups (from small children to adults). For these test we used both FDMT and the SYMBIOSE simulation platform for performing radiological risk assessments used by IRSN. These case studies demonstrated that regional customisation may have considerable impact on the model outputs.

Advanced statistics

Hierarchical Bayesian modelling (HBM) was applied to the weathering loss parameter – i.e. the time-dependent reduction of radionuclide concentrations in plant foliage due to wind, rain, plant growth, etc. Weathering loss is an important parameter in accidental situations following foliar interception of radionuclides. The hierarchical framework incorporates a level of complexity, which enables studying the specific variations across elements, their physical forms and the different considered plant species. The models developed here demonstrated the influence of plant species and/or type of radionuclide on weathering, depending on type of data set (i.e. iodine field studies, other radionuclides – laboratory or field studies). Two case studies on propagation of parametric uncertainty were also performed – one being the hypothetical deposition scenario from above (only the dry deposition case), and the other were aimed at leafy vegetables growing in Fukushima prefecture (for the period April to September 2011). In both cases, interception and the weathering loss were among the most influential parameters on uncertainty. The SYMBIOSE modelling platform was used in the case studies.

Long-term dynamics of soil-to-plant transfer of radionuclides for different types of soil

In addition to the main activities described above, representatives of our working group performed long-term experimental studies in Ukraine relevant for Human food chain modelling. In one experiment, soil-to-plant transfer data for less studied ^{99}Tc and trans-uranic elements (^{241}Am, Pu-isotopes) were provided for several agricultural plants (lettuce, radish, wheat, potatoes). For ^{99}Tc, the importance of soil type and plant species on long-term time-development in transfer was demonstrated. Another study focussed on peat-bog soils from the Rokytne district showing particularly high radiocaesium bioavailability – resulting e.g. in high levels in milk from cows grazing in these areas. The present study compared root uptake of 'freshly added' and 'old' Chernobyl radiocaesium using spiny rush (*Juncus acutus* L.) as model plant. The experiment showed that equilibrium between 'freshly added' and 'old' Chernobyl radiocaesium was reached after 1–2 years.

Forest modelling

Introduction and objectives

In the COMET work on forest modelling, the main objective was to generate guidance on how to reduce the uncertainties in the modelling of short- and long-term impacts of radioactive contamination in forested areas through the production of guidance for modelers on topics such as model sensitivity analysis and parameterisation of key processes controlling the transfer of radionuclides, as well as advice on model parameter requirements. There was also some ongoing development of forest transfer models by the participants.

The key research questions requiring the production of appropriate guidance documentation for modelers, assessors and end-users were: (a) what are key modelling processes that need to be included in a radionuclide cycling forest model and (b) what are the variables/factors contributing most to the overall uncertainties in forest modelling. Due to the dynamic nature of these processes, emphasis was placed on time-dependent soil-water-atmosphere interactions (as expressed, for example, in the evapotranspiration as an engine for water fluxes in trees, interception of airborne radionuclides, parametric Kd (Kd= solid/liquid distribution coefficient) approaches to simplify the soil hydrology, etc.) and soil - plant transfers, with forest vegetation selected according to its importance for wildlife and human intakes. The work performed was in full agreement with Research Lines 1 and 3 of the SRA for Radioecology, namely, (a) to identify and mathematically represent key processes and (b) to develop transfer and exposure models that incorporate physical, chemical and biological interactions, and enable predictions to be made spatially and temporally.

Improvement of dynamic models

As part of the COMET work on forest modelling, SCK•CEN continued the development of the SVAT prototype model ECOFOR, which had its origins in the Belgian Research Policy Office project ECORISK but continued to be developed as part of the activities of this IRA. This model is an example of research, process-based model. It is currently applied to a Scots pine forest in Mol and focusses on uptake of radionuclides from soil in chronic situations (such as remobilisation of radionuclides from ground disposal). ECOFOR was presented in the Barcelona ICRER conference in 2014. . In the meantime the model has been used in process sensitivity analysis studies, and on determining data requirements for models of this type. As such, it provided input for the "parameter wish-list" document and the forest modelling guide.

There was also the development by IRSN of an approach to help decision-making by rapidly estimating the consequences of an accidental atmospheric fallout, with a special emphasis on the short-term phase (i.e., first few months) and hence focusing on modelling the deposition and plant interception process. This too was used as an example for the aforesaid guidance documentation.

Production of guidance

The COMET forest modelling team began with a successful workshop on the subject of experimentalists and modelers working together as part of the COMET workshop "Models fit for purpose" in Seville 2016. The results of this workshop are presented as part of the COMET Deliverable 5.5. The workshop dealt with the requirements for forest models (depending on research or assessment application), model-specific issues, model complexity and data requirement, sensitivity and uncertainty. Based on output from the "Fit for purpose" workshop, the forest modelling group could make a practical wish-list of modelling requirements to experimentalists for three types of forest models which culminated with the production of the Handbook titled 'Guidance on Forest models for contaminated sites'. The Handbook deals with specific aspects related to forest model development and application such as how to choose model complexity, how to identify model requirements depending on the model's purpose and how to deal practically with the challenges that inevitably modelling of radionuclides in such an ecosystem poses. The Forest modelling group has submitted a publication on the handbook to a peer reviewed scientific journal (Diener A. et al, submitted).

Future work

For the future, the most important challenge in European forest modelling post-COMET is to maintain expertise and modelling capacity in future projects (e.g. CONCERT). On the modelling side, it is proposed to use conceptual models to help design well-targeted field experiments and better models (i.e. following a heuristic approach). As part of model development, more attention should be paid to find out how the influence of climate changes on radionuclide cycling in forests can be realistically modelled, as well as modelling better the plant-animal pathway, which is currently considered only for specific animals (e.g. wild boar). Kinetic food chain transfer models should be linked to the forest ecosystem (for example transfer to game animals e.g. red deer, moose) to cover this in more detail.

In the laboratory, efforts should be directed to establishing a series of tracer experiments with trees in as close to field conditions as possible (e.g. mesocosm or lysimeter experiments), exposing them to various radionuclides to find out how they process them, so as to provide validation points for models. Apart from radiocaesium, other radionuclides for which there are poor data for forests and associated wild products should be considered. In the field, effort should focus on developing 'instrumented forests' where water and element flows in the trees are measured along with rainfall and the water fluxes in the soil. The SCK•CEN instrumented forest project at a Belgian NORM site under development as part of the EC project 'TERRITORIES' is an active example of this type of work.

General issues in forest modelling over the last few years have been model transferability, for example the re-parameterisation of the available dynamic models for specific conditions (permafrost, subtropical, boreal, etc.). The development of regional parameter databases covering these environments is desirable. Finally, in the future, it it is on one hand necessary to improve understanding of the processes involved in radionuclide transfer in forests and hence to focus more on a process-based approach. On the other hand, it is fundamental to be able to quantify the uncertainty inherent in the models by comparison with high-quality experimental data.

NORM modelling

Natural background radiation is present in natural environment elsewhere since the formation of Earth and is usually not considered to be harmful for man and wildlife . However, apart from very high background areas, selective accumulation of natural radionuclides caused by human activity often occurs, potentially leading to enhanced NORM concentrations and increased exposure. Broad industrial sectors deal with NORM (naturally occurring radioactive materials) during extraction, treatment, production and many of them have not been regulated in terms of radiation safety to date. The new graded system of authority control requires assessment of exposure to humans by NORM and to demonstrate that environmental criteria for long-term human health protection are met. This brings new challenges to industry operators as well as regulators, and a generic assessment method based on well-justified scientific guidance is needed.

Considering possible interactions of NORM affected industry with environment, the *sine qua non* conditions were identified when NORM may influence the environment: the existence of large amounts of deposited waste and release of contaminated water or air. It was therefore concluded that three scenarios cover the majority of NORM situations: landfills and water and stack emissions discharges. These three basic exposure scenarios were analysed in terms of secondary processes determined by the interaction of releases with the receiving environment. To define appropriate parameters for safety assessment studies, an approach based on features, events and processes (FEPs) was used. The key processes were then identified for each scenario, and basic rules for structured assessment were developed independently of a NORM generating industry.

This approach has been applied to assess the impact of radium rich mine water released into a lake environment. Existing circumstances at the Polish observatory site allowed identification of processes leading to accumulation of radium in bottom sediments and observation of its further behaviour in a decades'-time perspective. New data were collected during two-years monitoring campaign and compared with radioactivity in water and sediments in 1999. The radium-barium co-precipitation process was identified as the main source of sediments contamination, however, the radium chemical form resulting from this process is insoluble and not easy migrate to other environmental compartments, what was proved by low ^{226}Ra and ^{210}Pb transfer to water and biota measured. Comparison of distribution of ^{226}Ra, ^{228}Ra and ^{210}Pb in sediment profiles between both observation periods show lower than expected concentrations if only considering radioactive decay (Figure 5), which suggests that bio- or mechanical turbation (e.g. local flood) may be responsible for the significant ^{226}Ra deficiency observed.

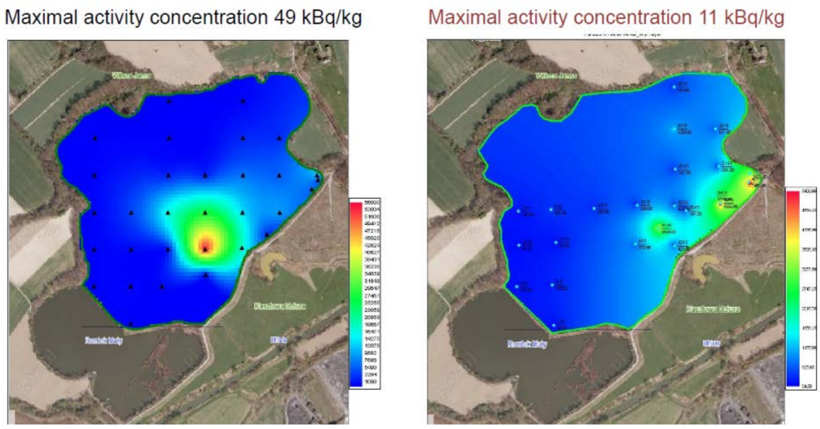


Figure 5. Comparison of radium distribution in bottom sediments, left -1999, right 2015/16.

ICRP reference sites – developing alternative transfer models for wildlife

The transfer of radionuclides to wildlife is generally described using the whole-organism concentration ratio. However, this parameter is highly variable and data are lacking for many organism-element combinations. In COMET (in collaboration with funded national programmes), we have tested the hypothesis: *radionuclides activity concentrations in (terrestrial) wildlife can be predicted using a taxonomic model which takes out the effect of site*.

At sites in Norway, Spain, Ukraine and the United Kingdom species falling within the ICRP definition of terrestrial Reference Animals and Plants (RAPs) were sampled and analysed to determine radionuclide and stable element concentrations. The resultant data Cs, Pb, Se, Sr and U have been used to establish Residual Maximum Likelihood mixed-model (REML) models. REML models were fitted to data using the *IBM SPSS Statistic* package with the fixed factor being the ICRP RAP classification (RAPs being defined at the taxonomic level of family) and the random factor being site. The output of the REML model is the relative values for organisms taking into account inter-site variation. This enables predictions to be made for organisms for which no data are available from those for which data are available at a given site:

$$\textit{Activity concentration in species } x = \frac{\textit{REML adjusted mean for species } x}{\textit{REML adjusted mean for species } y} \times \textit{activity concentration in species } y$$

For Cs and Sr there was a clear indication of site effect in the transfer to wildlife, however, this was not obvious for the other three elements.

In parallel to this work a separate project (http://tree.ceh.ac.uk/) has begun to establish REML models based upon data within the international wildlife transfer database (WTD) (Copplestone et al. 2013). To date this work has established REML models for terrestrial wildlife species at different taxonomic levels for Cs and at the species level for Sr. The Cs model has been shown to give reasonable predictions; the Sr model has yet to be tested. Comparing these models with those derived using the Reference Site data here shows does not show good agreement. This lack of agreement is likely to be the result of the different species included in the two models, there is considerable variation between species and the species level model, best describes the WTD data.

The models derived for Se, Pb and U during COMET represent the first application of the REML approach to these elements. The lack of site effect may reflect little variation between sites for these elements or perhaps the lower number of data available.

The application of REML modelling as a method of predicting radionuclide transfer has now been suggested for some time. The models derived here now need to be tested against data not used to establish them. Though perhaps it would be best first to merge the Reference Site data with the WTD and rerun the models using the larger database.

Conclusions for WP3

In conclusion, WP3 of COMET has contributed significantly to improve radioecological modelling capacities, both through model development and through improvement of model parameters. Dynamic modelling approaches have improved our ability to correctly predict ecosystem transfer and uptake of radionuclide species including particles, as well as to assess the potential exposure of and doses to humans and wildlife, while fieldwork and experiments have provided data for model parameters, as well as for model validation.

Although the modelling work in COMET WP 3 has made us better equipped to assess the consequences of past radioactive contamination of the environment, as well as to predict the impact of present and future releases, all the topical working groups in WP 3 have identified important future challenges that need continued attention from the radioecological community. The need for continued collaboration between modelers and experimentalist to continue model improvement focusing on the overall uncertainties and to validate models has been highlighted by several groups and will require sustained funding for European radioecological research.

WP4 - Contribution of epigenetic mechanisms in the effects induced by long-term exposure to radionuclides in the laboratory and field

Evaluating the effects of low dose radiation on organisms is clearly a shared challenge in research on human and non-human species. It is needed to understand the role of primary mechanisms at the cellular and sub-cellular level, when organisms are exposed to chronic low-dose radiation, to explain the potential consequences on physiological functions and health at the individual and population. Within this general framework, the objective of the Initial Research Activity (IRA) was to increase our understanding of the effects of chronic low-dose radiation and the possible contribution of epigenetic mechanisms to long-term and trans/multi-generational effects. Expected outcomes were to provide (i) data to reduce uncertainties in Environmental Risk Assessment (ERA), (ii) guidance on how to deal with low dose effects in wildlife protection regulation, (iii) statement on the relevance and useful of epigenetic biomarkers to assess low dose effects of radiation on the ecosystem.

Within the IRA, the following key research hypotheses were addressed: (H1): Exposure to gamma-irradiation results in a changed radiosensitivity (or resistance) within and over generations, (H2): Epigenetic mechanisms underlie changes in radiosensitivity (or resistance) observed in gamma-irradiated organisms, (H3): Epigenetic changes observed in gamma irradiated organisms grown under controlled lab-conditions are similar to epigenetic changes observed in areas affected by a nuclear accident.

The approach adopted intended to ensure a common set of core knowledge, experimental data and skills. It included the choice of common protocols and methods for data acquisition and interpretation for both lab-conducted experiments and field studies. The IRA was performed via (i) laboratory controlled exposure experiments to test hypotheses on the role of epigenetic changes in the alteration of physiological functions; this research was conducted on laboratory models (zebrafish, earthworm and plant) with fully sequenced genome and included species relevant to both ALLIANCE and MELODI; (ii) field studies on autochthonous species (earthworm, plant and frog) in part similar to the laboratory test species to investigate epigenetic changes in wildlife within contaminated areas (Chernobyl exclusion zone, Fukushima 100-km area).

As a common approach the total methylation levels (one of the major epigenetic processes) in addition to other markers were measured in order to investigate the effects. For field studies the concentrations of different radionuclides in organisms and environment sampled were additionally measured for an accurate quantification of individual organisms' absorbed dose of radiation. The main results and conclusion obtained from the 4 years study are summarised below.

Laboratory experiments

Methodology for DNA methylation measurement

DNA methylation using the MS-AFLP method was chosen as the common method to measure total DNA methylation, since this technique can be applied on a wide range of species, including those without a sequenced genome. The use of one common method also increased the possibility to compare results between species and field sites. However, this method only allows the assessment of modifications in methylation patterns at the cleavage sites of the two isoschizomers (5'-CCGG-3'). In addition, the MS-AFLP technique could not be optimised for *Arabidopsis thaliana* plants, due to a lack of repeatability. Therefore, other methods were used to complement the MS-AFLP analyses, i.e. UPLC-MS/MS reflecting effects at the whole genome scale (results shown in paragraphs below). Finally, bisulfite sequencing analysis was used on zebrafish and *Arabidopsis thaliana* samples to determine whether specific areas are impacted in the genome.

Relevance of DNA methylation in response to gamma radiation

Although no effects were observed at global DNA methylation in zebrafish, a changed methylation pattern was observed after exposure to 10 mGy h^{-1}, with an increased methylation at specific loci (Deliverable 4.3, figure 8). This increased methylation pattern was still present in the third generation of embryos, derived from a radiation exposed ancestral line. On *A. thaliana* plants two types of experiments were performed. The first one exposed plants for three consecutive generations to a 14-day exposure of 30-457 mGy h^{-1} and showed increased global methylation levels in the first (S1) and second (S2) generation after exposure to gamma radiation of 457 mGy h^{-1} (see Deliverable 4.3, figure 16 ; van de Walle, *et al.* in preparation). In a second experiment plants were chronically exposed to a low dose rate of 1 mGy h^{-1} from the moment of imbibition until seed setting. Although no significant differences in total methylation were found in these chronically exposed plants, the gene expression of methyltransferases, the enzymes involved in the DNA methylation process, showed a significant different pattern over time in the exposed compared to control plants indicating possible de novo methylation induced by the gamma exposure (data not shown, Horemans et al., in preparation). Bisulfite sequencing was performed on the *A. thaliana* plants exposed to different gamma levels for three generations. At this moment the sequencing has been done and data have been processed statistically but the biological interpretation of the data is still ongoing. Results of this experiment will be submitted as a paper together with the methylation results (van de Walle et al. in preparation). For earthworms, the effects on the global methylation status are limited (see Deliverable 4.3, figure 11). This may be due to the short-term nature of exposure that was used for this species.

The obtained lab results can be taken as a first indication that radiation induces changes in the methylation level. However, there is no clear evidence of an increased sensitivity over generations as suggested in the first and second hypotheses. This can be due to the use of non-clonal organisms which increase the potential for selection of alleles that may lead to evolution of tolerance in later generations in a multigenerational exposure experiment. Moreover, in *Arabidopsis thaliana* plants, an increased capacity for antioxidative enzymes was observed in the S1, possibly indicating an increased resistance of those plants to gamma radiation (van de Walle et al. 2016). Further research is needed however to demonstrate a possible correlation with changes in DNA methylation. Additionally it would also be interesting to study other epigenetic processes such as histone modification or micro RNA that could be involved in the change of sensitivity over generations.

Field studies

Earthworms, tree frogs and *Arabidopsis thaliana/Capsella bursa pastoris* plants were sampled in the course of 2015 and 2016 in both Chernobyl exclusion zone and Fukushima 100-km area. Sampling sites in both areas are given in Figure 6. here below and in Figure 5 of the deliverable 4.3.

(A) (B)

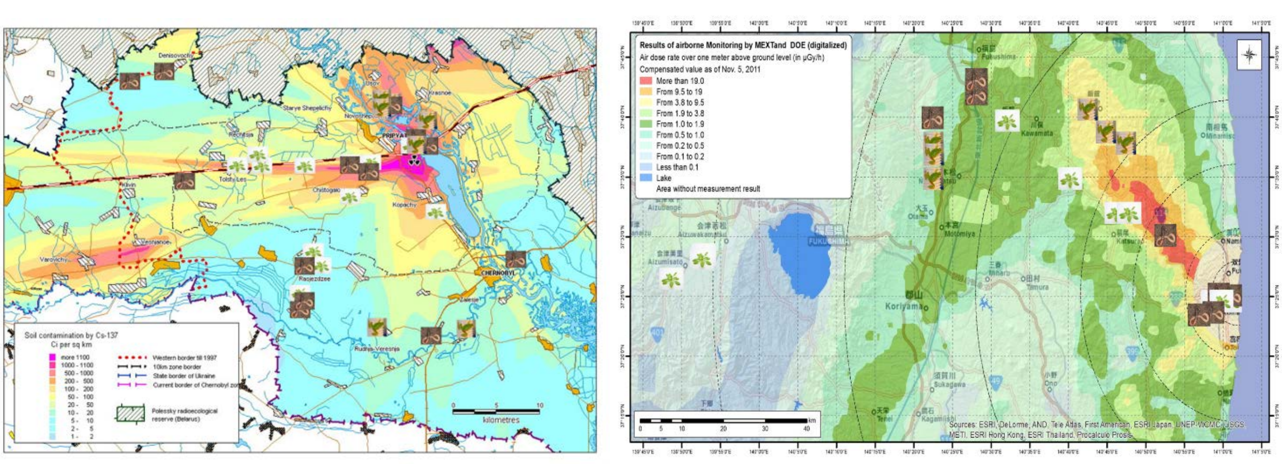


Figure 6: Overview of the different sampling spots in the Chernobyl exclusion zone (A) and the Fukushima 100-km area (B) for earthworms, tree frogs and Arabidopsis thaliana/Capsella bursa pastoris plants. In addition, Arabidopsis thaliana were also sampled near Slavutych as external control site for Chernobyl exclusion zone field study (not visible in this map).

Dosimetry in Chernobyl exclusion zone and Fukushima 100-km area

The ambient dose rates at the two sites (Chernobyl exclusion zone, Fukushima 100-km area) covered a similar range: lowest dose rates were ca. 0.1 µGy h^{-1} and highest dose rates from 12 - 50 µGy h^{-1}, with the exception of some earthworm sites at Fukushima 100-km area which were an order of magnitude higher. Total dose rates (TDR) were calculated with the ERICA tool based on the concentrations of Cs-137, Sr-90, Am-241, Pu-238/239/240 (Chernobyl exclusion zone) and Cs-134 and Cs-137 (Fukushima 100-km area) in soil and organisms sampled (Figures 7 and 8).

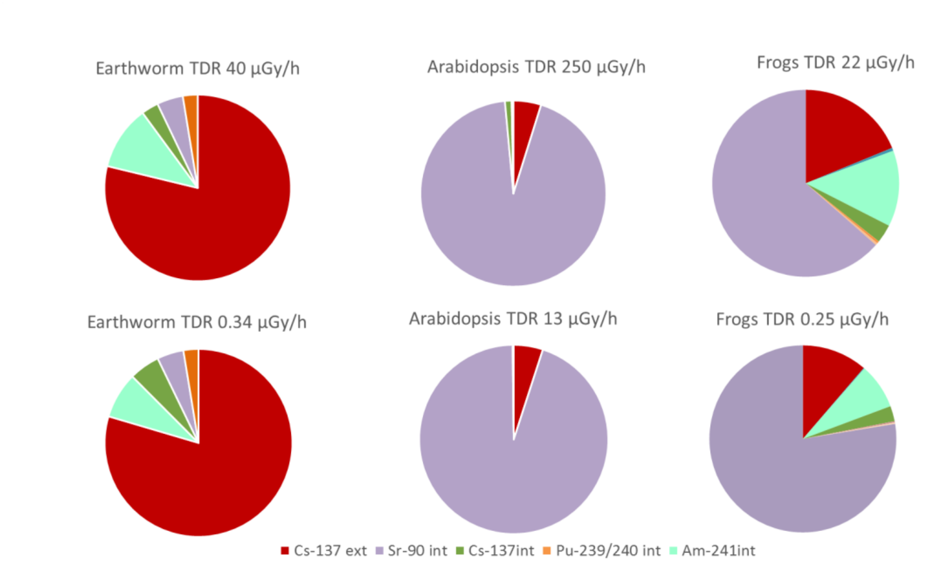


Figure 7: Relative contribution of radionuclides to the TDR for organisms sampled in Chernobyl exclusion zone.

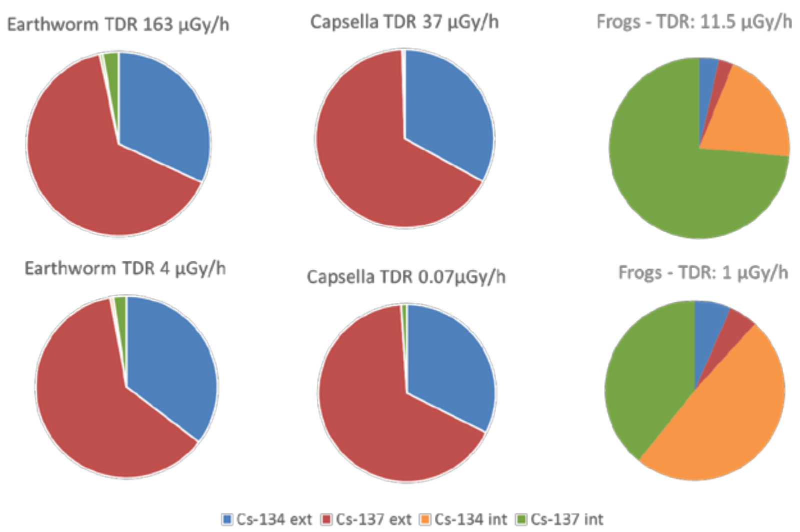


Figure 8: Relative contribution of radionuclides to the TDR for organisms sampled in Fukushima 100-km area.

TDRs generally agreed quite well with the measured ambient dose rates, except for *A. thaliana* sampled in Chernobyl exclusion zone, where the TDR was up to 20 times higher than the ambient dose rate (Figure 9). This can be related back to the high concentration of Sr-90 in *A. thaliana* plants compared to the other organisms (Figure 7). The relative contribution from internal and external dose, however, varied between sites and between species. For earthworms, external dose (from Cs-137) dominated at both sites, but were approximately a factor of two greater than the soil surface air measurements due to the organism living in rather than on the soil (data not shown). For tree frogs, internal dose (from Sr-90 and Am-241) and external dose (from Cs-137) were similar at Chernobyl exclusion zone, but internal dose dominated at most sites in Fukushima 100-km area (from Cs isotopes) (Data not shown). For the plants, >95% of the total dose was from external sources in Fukushima 100-km area, while in Chernobyl exclusion zone, 80% of the dose was due to internal contributions from Sr-90 (Figure 9).

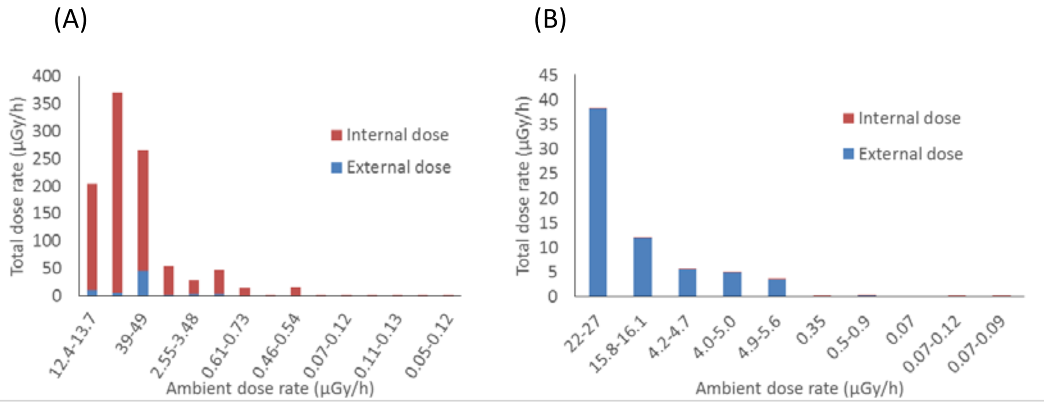


Figure 9: Contribution of internal and external dose rate to the total dose rate for plants sampled in Chernobyl exclusion zone (A) and Fukushima 100-km area (B).

Results from the present study highlighted the importance of considering the internal exposure which was a major source of radioactive exposure for frogs and *A. thaliana* plants. In addition, our robust dosimetry data have allowed us to show that, within-site, levels of individual contamination are highly variable among male Japanese tree frogs, stressing the fact that exposure of animals to a same ambient dose rate may correspond in fact to highly different TDRs, due both to the inclusion of the internal exposure pathway and the inter-individual variability.

DNA methylation on field sampled organisms

Field sample analyses are ongoing and there is currently only a limited amount of methylation data available for the field sampled organisms limiting the ability to draw robust conclusions. However, within our data an effect of radiation on total methylation was observed in earthworms from Chernobyl exclusion zone (Figure 10) and tree frogs in Fukushima 100-km area (See deliverable 4.3, figure 31). In contrast, no effect was observed in plants sampled in Chernobyl exclusion zone nor in Fukushima 100-km area (data not shown).

For plants, the age of the plant is an important factor influencing the DNA methylation level (Zhang et al. 2015, Ogneva et al. 2016). In fact the first results comparing lab-grown young leaves of *Arabidopsis* (taken before flowering) with those sampled in Chernobyl exclusion zone learned that the young leaves had on average 33% more methylation than the field samples (results not shown, *Horemans et al . in preparation*). Additional evidence for a decrease of methylation with development came from the plants chronically exposed in the lab. As age of plants cannot be estimated in field samples different ages conceivably can mask possible radiation-induced effects which are expected to be only a few % maximally.

In both collected earthworm species (*Aporrectodea caliginosa* and *Octolasion lacteum)*, site specific patterns of DNA methylation were found. The greatest change in methylation patterning was found for species that collected sites with intermediate exposure. For both species, the different in msAFLP patterns is significantly separated between background and medium contaminated sites on PC1 (see Figures 10a and 10b). In *Octolasion lacteum*, this difference is, however, lost between background site and high radiation sites (see Figure 10b). While observed changes in DNA methylation may indicate a response to radionuclide exposure, a caveat is that differences exist in prevailing ecosystem characteristics (e.g. wetland versus garden or forest sites). The potential confounding effects of habitat were clearly shown when the structure of the earthworm microbiome at different sites was considered in additional conducted work to better understand the drivers of methylation difference between samples. When community structure bacteria, fungi and eukaryotes in the earthworm gut microbiome, a clear segregation of sites between background, medium and high exposure levels sites. These differences are indicative of dietary difference and potentially disease burden for earthworms at different sites. This emphasises how at complex and large-scale polluted sites such as Chernobyl, cautious interpretation of field data is required before unequivocally ascribing observed effects to solely exposure. Samples have also been prepared for RNAseq analysis to allow assessment of gene expression, including for gene genes involved in DNA methylation (Robinson et al., in preparation).

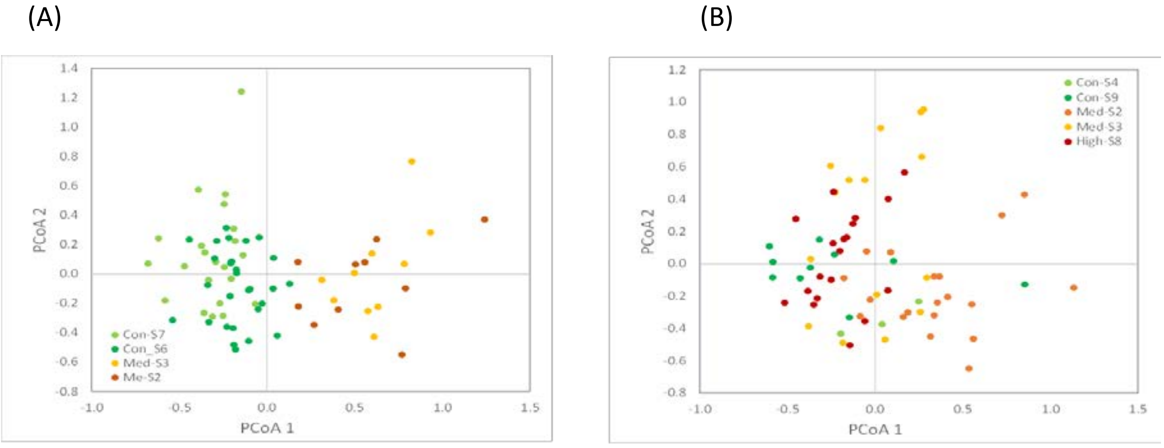


Figure 10: Principal co-ordinate analysis of putative methylated alleles identified from a MS-AFLP analysis of DNA samples for two earthworm species a) Aporrectodea caliginosa (left) and b) Octolasion lacteum (right) from sites within the Chernobyl exclusion zone. For both species, the different in MS-AFLP patterns is significant separated between background and sites with radiation levels of >3µGy h^{-1} on PC1.

Although no effect on methylation was observed in *Capsella bursa pastoris* plants sampled in Fukushima 100-km area, a hypermethylation response was observed in *Pinus sylvestris* sampled in Chernobyl exclusion zone (Volkova et al. submitted) which can point to adaptation processes in the exposed plant populations. Taken together with the effect of dose gradient on methylation in Chernobyl exclusion zone-collected earthworms and Fukushima 100-km area-collected tree frogs this can be an indication of a hypermethylation response to increased dose rates in chronically exposed organisms. Anyway, it is important to not only look at the changes in global DNA methylation, but to look at the effects that the changed methylation can cause. Confirmation of such effects require the use of combined genome wide DNA methylation mapping and transcriptomic approaches to establish the links between methylation change and expression phenotypes. To this end, muscles (Tibialis posterior) samples from frogs originating from three different contaminated sites from the CEZ were subjected to whole genome DNA extraction to prepare DNA sequencing library for the research of SNPs and structural variant. In parallel whole genome bisulfite sequencing library were produced from the same samples to search for potential changes in DNA methylation levels. The production of the raw sequencing data is currently ongoing.

From lab to field

Comparing the results from the lab and the field is not straightforward since the dose rates used in the lab were higher than the dose rates observed in the field. In addition, exposure in the lab is always for a limited time period (2 weeks for earthworm and *Arabidopsis thaliana*), while exposure in the field is a long-term/lifetime/multigenerational exposure. To overcome this difference we now have performed a chronic exposure experiment at 1 mGy h^{-1} on *Arabidopsis thaliana* and are setting up experiments using plants coming from seeds collected in Chernobyl exclusion zone and Fukushima 100-km area. Finally, in field conditions other confounding factors can play a role.

Conclusions and perspectives

Within this part of the project both lab- and field experiments have been performed on different species by the different partners in order to test the possible contribution to long-term and multi- or transgenerational effects of mechanisms governing the activation or the repression of the epigenome. More specifically the change of DNA methylation level after exposure to ionising radiation and its relevance as possible biomarkers of ionising radiation were addressed.

Results observed on the global DNA methylation level in the different studied species; lab and field conditions partially support a role of increased methylation in response to radiation which can be associated to an increase of DNA stability. However, measurement of the global methylation alone is not sensitive enough to show all biologically relevant differences induced by exposure to low dose rates; as a result differences might be located in specific sequences of the genome. The use of additional methods like bisulfite sequencing can improve the resolution to identify and assess specific genes/regulatory regions of interest that are differentially methylated in response to exposure to ionising radiation.

Methylation might be a key to transferring the response to ionising radiation to the next generation as seen in *A. thaliana* plants and zebrafish possibly indicating a role of methylation changes in long term adaptation to gamma radiation. Nevertheless, further experiments like detailed studies of which genome sequences are specifically methylated under gamma radiation (which will come from the bisulfite sequencing data analysis for example) will enable testing these hypotheses.

One of the conclusion from this research activities lies in the interpretation of changes in methylation patterns from field collected samples in relation to the principal driver of effects. These challenges relate mainly to the use of some autochtonous species, whose genome is scarcely sequenced, and to the influence of confounding factors (difference in habitat, environmental quality, soil and water chemistry and food availability…) which may mask the causal response due to ionising radiation exposure alone. Moreover the genetic diversity of species between isolated local populations sampled on field may lead to markedly different epigenetic responses to ionising radiation precluding the identification of a clear exposure response relationship. An opinion on the possible role for epigenetic mechanisms in radiologically-induced responses is written out as a statement paper by the different partners and will be submitted as a full paper in the coming months (Horemans et al to be submitted).

An important step further will be to compare the sensitivity and reliance of DNA methylation as a biomarker of ionising radiation exposure at environmentally relevant levels, with other epigenetic mechanisms such as histone modifications and microRNAs as well as with responses at higher level biological complexity e.g. changes in growth and reproduction. This integrated approach, as described in the Adverse Outcome Pathway concept (Groh et al. 2015), would enhance the ecological relevance of molecular biomarkers. To be able to continue this very interesting line of research a project proposal named BIOMARKERS (coordinated by IRSN) on which different partners of COMET-WP4 contribute is now submitted for the second CONCERT call.

Finally, a major strength of this study was the accurate dosimetry. Results obtained within the IRA showed that the relative contribution from internal and external dose varied between sites and between species. Thus, omitting the contribution of internal contamination to the exposure, as it is done when considering only the ambient dose rate, can lead to underestimations of the actual level of radiation received by the organisms.

WP5 - Knowledge exchange and capacity building

Exchanging knowledge and expertise are an important aspect of our science. Therefore, key objectives of COMET were to: (i) disseminate COMET activities (via website, social media, newsletters etc.) (ii) facilitate discussion of topical radioecological issues between researchers and users; (iii) develop training packages to maintain and enhance professional competence. These activities and outputs are reviewed below.

Dissemination

The Radioecology Exchange (www.radioecology-exchange.org) was created in 2011 under the EU FP7 STAR Network of Excellence. Subsequently, COMET has built upon this work and the site has become the 'hub' for both projects and European Radioecology. The Radioecology Exchange is the 'gateway' for information related to European (and wider) radioecological research and will be maintained by the European Radioecology ALLIANCE (www.er-alliance.org) when the COMET project ends. Resources hosted on the site include:

- The 'Training and Education Platform' (see below).
- The 'Virtual Laboratory' which contains radioecology facts, figures and data. It has links to radioecology datasets (which are grouped into topic areas: Chernobyl, freshwater, foodstuffs and crops, Fukushima, marine, natural radioactivity, nuclear weapons fallout, reindeer and wildlife), analytical methods, information about COMET project partner equipment, facilities and sample archives, an overview of human and wildlife assessment tools and links to frequently asked questions on topics related to radioecology.
- A 'Latest News' blog which is regularly updated with details of upcoming conferences, training courses, jobs, studentships and COMET project outputs and publications etc..
- Information about the SRA for radioecology and the five associated topical roadmaps.
- Overview of the Radioecological Observatories which are radioactively contaminated field sites aimed to provide a focus for joint, long-term, radioecological research. The four sites are: The Upper Silesian Coal Basin (Poland), the Chernobyl Exclusion Zone (Ukraine), a Belgian NORM (Phosphate industry) site and the Fukushima Radioecological Observatory. The ALLIANCE contact for each site is provided.
- Information and outputs from the STAR and COMET workshops (see below).
- The 'Information Exchange' provides links to radioecology resources such as a catalogue of the outputs from some EURATOM projects, radiological databases (e.g. Wildlife Transfer Database, FREDERICA and STOREDB), newsletters from other projects and platforms, an overview of some Fukushima related

research and links to other project websites of interest to radioecology and appropriate international organisations.
- Links to social media sites: facebook https://www.facebook.com/radioecology/ and twitter https://twitter.com/RadioXchange

COMET has produced five newsletters which were distributed via email and which are also available from the Radioecology Exchange website.

Workshops

Recognising the value of bringing together the different communities involved in radiation protection to debate topical issues ensuring better focusing and exploitation of scientific research COMET ran four focussed workshops. Reports from all four workshops can be found on: http://www.radioecology-exchange.org/content/workshops-0. Key aspects of each workshop are outlined below.

Transgenerational and Epigenetic Mechanisms of Radiation Toxicity at Chronic Doses (Oxford, December 2014)

The workshop focused on the role of epigenetics in (eco)toxicology and radioecology. Discussions encompassed long-term and transgenerational exposure, in laboratory studies of radiation and chemical effects, molecular biology relating to epigenetic mechanisms, human and ecological risk assessment and radiological protection.

Discussion groups considered the role of epigenetics in radiobiology and ecotoxicology from both an ecological and evolutionary biology viewpoint and also with a focus on mechanistic issues and systems biology. Key issues were outlined that unified studies across these areas, e.g., how the revolution in understanding of epigenetic mechanisms has provided a wealth of new methods and tools. To date the major focus has been on DNA methylation, however, the widespread availability of methods for analysis of miRNAs and histones suggests that these should also be a focus of future studies of epigenetic mechanisms relating to radionuclide and other stressor exposures. Experts in radiobiology and in genetics and systems biology need to work together to address hypothesis-driven questions and the meeting was a clear step in this direction. The workshop helped to focus activities within the transgenerational effects studies of COMET.

13th International Conference on the Biogeochemistry of Trace Elements (ICOBTE) and Fukushima COMET Workshop (Fukuoka and Fukushima, Japan, July 2015)

During the ICOBTE conference, COMET organised a 'special symposium': Understanding and mitigating the environmental behaviour of radiocaesium after the Fukushima accident. There were 73 presentations which focussed on: (i) estimation of radionuclide deposition and redistribution in Japan after the Fukushima accident and associated external doses; (ii) analytical techniques and speciation studies of radionuclides; (iii) dynamics of radiocaesium in soil, water, plants and animals; (iv) quantification and modelling of the short- and long-term fate of radiocaesium in agricultural, forest and aquatic ecosystems; (v) impact of radiocaesium on agriculture and the food chain and associated internal doses; (vi) estimation of radiation doses to, and associated impact on, biota; (vii) countermeasures and remediation after the Fukushima accident.

Following ICOBTE 2015 there was a COMET workshop held in Fukushima Prefecture. Speakers were selected to cover a range of topic areas and to summarise the current key findings and issues. The workshop included Fukushima University and scientists from the local prefecture and national Japanese organisations.

Presentations focused on soil, paddy fields, forests and catchments, and marine areas. Evaluation of recently acquired Fukushima data allow initial identification of where environmental data from post-Chernobyl studies were applicable and where they were not (this topic area has subsequently been incorporated into the IAEA's MODARIA II programme).

Models fit for purpose (Seville, June 2016)

Radioecological models are essential tools for use in assessing environmental impacts and risks from radionuclides in the environment, or as research tools for developing underpinning process understanding. A key aspect of this workshop, attended by about 60 scientists, was to improve the interaction between modellers and experimentalists from different fields of radioecology, since a closer co-operation is expected to create a better compatibility between model developments and experimental studies. The workshop initiated this dialogue should lead to closer collaboration and hence to improved quality and robustness of radioecological models making them more suitable for scientific applications and a broad range of assessment purposes, bridging to other radiation protection platforms and taking into account their specific user needs. The output of this workshop has been to some degree implemented in the newly initiated EU CONFIDENCE and TERRITORIES projects.

Thirty years after the Chernobyl accident: what do we know about the effects of radiation on the environment? (Chernihiv, August 2016)

April 2016 was the 30th anniversary of the Chernobyl accident. To mark this anniversary, a workshop was held to discuss what we have learnt from studies of the effects of radiation on the environment in the Chernobyl Exclusion Zone (CEZ), and what questions still remain. The topic of the workshop was selected because of the lack of consensus on the impacts of radiation on wildlife in the CEZ. A similar debate is beginning to evolve with respect to observations made within the vicinity of Fukushima. Participants were from regulatory organisations, nuclear related industries, an NGO, the media, chemical ecotoxicology and the social sciences and humanities fields as well as radioecology/radiation protection. Discussion sessions considered: 'how do we resolve the anomalies between field and laboratory studies?' and 'the implications of Chernobyl (and Fukushima) studies for current benchmark dose rates'. The workshop report includes a number of recommendations agreed by the participants, key amongst these were: (i) there are a large number of field studies reporting effects at dose rates which appear improbable and cannot be used in the derivation of benchmarks values for use in regulatory assessment; (ii) such data should not be dismissed - 'inconvenient truths' need to be acknowledged, not ignored; (iii) data from radiation effects studies need to be made openly and freely available (a significant step would be made to addressing the disagreement on the magnitude of effects due to exposure to ionising radiation observed in the CEZ/Fukushima areas if data were openly available).

A series of papers from the workshop will be published in a special issue of the Journal of Environmental Radioactivity (planned for 2018). Inclusion of the media in at the workshop has resulted in a number of articles in nature/photography publications.

Education and Training

The 2014 Strategic Research Agenda for Radioecology identified that the key challenge in Education and Training (E&T) was "To maintain and develop a skilled workforce in Europe and world-wide, through university candidates and professionals trained within radioecology" since "Scientific research in radioecology and application of that knowledge in the radiation protection of man and the environment requires scientists and workers with adequate competence and appropriate skills."

Radioecology is a multidisciplinary science, requiring teachers from many fields, who need to reach out to students with a range of backgrounds. Being a relatively small science, teachers and students are widely scattered geographically, which leads to the need for intensive courses to minimise costs, and/or online resources. In order to address these needs, COMET has developed an E&T web platform and arranged a number of courses for students and professionals, drawing on relevant expertise from the partner organisations.

More than 30 PhD students and a large number of Masters students have been associated with COMET-related research and are part of the Radioecology PhD network, which is also open to non-COMET students. The Radioecology PhD network is an international networking forum aimed primarily at PhD students in radioecology and other relevant nuclear sciences. There is a full list of students, with their research topics and contact details on the Radioecology Exchange E&T Platform, giving students a forum to make contact with each other (http://www.radioecology-exchange.org/content/radioecology-phd-network).

Education and Training web platform

Located on the Radioecology Exchange website, COMET has further developed the E&T platform which was initially set up by the STAR NoE (http://www.radioecology-exchange.org/content/training-education). It contains information on courses within radioecology ranging from MSc and PhD courses to workshops and professional development and also provides links to other E&T platforms, such as those within Radiochemistry, Radiobiology and Radiation Protection (DoReMi, CINCH II, etc.). Information on the Radioecology PhD Network is also available. The Radioecology PhD network is a virtual forum intended to promote networking and interaction between students and scientists and the rest of the radioecology community.

MSc and PhD level courses

COMET partners have continued to develop and participate in the European Masters Programme in Radioecology, held at NMBU, Norway, in particular the course modules Radioecology and Environmental Radioactivity (MSc course, October 2015) and Environmental Radiobiology (PhD course, June 2015), as well as on separate courses held at individual COMET organisations (e.g. Radiobiology course at SCK•CEN, 2015). NMBU, Norway have also continued to offer the MSc in Radioecology, a tailored two year MSc programme, Bologna accredited (120 ECTS), consisting of obligatory and optional stand-alone course modules which are accepted at all European universities following the Bologna model. This Masters programme is important in promoting radioecology as an academic discipline and in providing E&T for students and professionals. The modules were given as intensive courses to make it easier for international students and professionals to attend. A co-tutelle agreement between agreement between the University of Seville (Spain) and Norwegian University of Life Sciences (NMBU) allows a PhD student to take a joint PhD degree and represents an important collaborative mechanism.

Education and Training Field Courses

Two new intensive (4 day) field courses were developed, designed and held during COMET, with teachers from several of the COMET partner organisations:

- "Naturally occurring radioactive material (NORM) in the environment" (Katowice, Poland, September 2015). This course was aimed at both students and professionals, and focused on most aspects of environmental radiation impact and risks associated with enhanced natural radioactivity released from different NORM industries.
- "Chernobyl fallout in the environment" in Kiev, Ukraine, September 2016. This course was aimed at PhD and MSc students and focused on the impact and risks associated with enhanced radioactivity in the environment due to the Chernobyl accident fallout.

Both courses had more applicants than available places and received very positive feedback from the participants. Due to this success, the Chernobyl field course will be organised annually with the next being held in June 2017. The ALLIANCE intends to take these or similar courses further after the end of COMET.

Figure 11: Participants and lecturers from the Ukrainian field course in front of Chernobyl reactor 4 (Photo: V. Kasparov).

Training and refresher courses

In March 2017 a training course in 'Radiological Protection of the Environment' was held at CEH Lancaster, UK. The course covered aspects of environmental (non-human biota) radiological assessment, including application of the ERICA tool, radionuclide transfer, dosimetry, effects, benchmarks, dispersion and how to model atmospheric noble gases. The course was aimed at students and professionals COMET co-organised a 'young scientists session' at Radiation Protection Week 2016 and also held two refresher courses at the International Conference on Radioecology and Environmental Radioactivity in Barcelona, 2014. The refresher courses were on a) revisions to the ERICA Tool and b) assessment of noble gases for wildlife, and attracted 30-50 scientists. NERC-CEH also gave a short session entitled 'Protection of biota: Methodologies and assessment tools' at the 14th Congress of the International Radiation Protection Association, Cape Town, South Africa in May 2016 as part of their refresher course programme.

The future for knowledge exchange and capacity building with the ALLIANCE

The ALLIANCE are committed to maintain the Radioecology Exchange as a hub for European radioecology. Sessions and awards to promote knowledge exchange and young scientists will continue to be supported by the ALLIANCE at the annual Europe and Radiation Protection Weeks and the tri-annual International Conference on Radioecology and Environmental Radioactivity (ICRER). Support for topical and focussed workshops, as held by COMET, will be considered.

COMET has engaged in discussions with stakeholders for long-term solutions to maintain the sustainability of radioecology E&T. Despite progress in some areas, many of the challenges outlined in the 2014 SRA remain. Future plans within the ALLIANCE (and CONCERT) need to address sustainability options for E&T if radioecological competence is to be maintained and further developed in Europe.

4.1.4. Impact, main dissemination activities and exploitation of results

WP2 - Joint programming and implementation – Expanding the ALLIANCE

The foundation of COMET launched in 2013 was built on the STAR NoE (Strategic Network for Integrating Radioecology, EC 7th framework). The integration processes in radioecology and establishment of mechanisms to ensure long term sustainability under the European Radioecology Alliance (ALLIANCE), which was started in STAR, continued under COMET. COMET in its turn strengthened the pan-European research initiative on the impact of radiation on man and the environment by facilitating the integration of radioecological research. In close association with the ALLIANCE, and based on the Strategic Research Agenda (SRA), COMET developed innovative mechanisms for joint programming and implementation of radioecological research. To facilitate and foster future integration under a common federating structure, research activities developed within COMET were targeted at radioecological research needs identified in the SRA. The COMET Competitive Call launched together with OPERRA in 2013 was an essential part of the joint programming with the primary motivation being to engage the wider scientific communities to address scientific challenges that have been jointly identified as important by both the radioecology community and low-dose or (post) emergency communities. In addition, this kind of cascade funding (research calls within the projects) has allowed to react to quickly emerging needs, such as research related to Fukushima. The SRA was complemented by a transitional roadmap and topical 5-year roadmaps each dealing with specific scientific areas and/or complex environmental issues. Thus, COMET has fostered *integration of radioecological research over time*. The distinction between having a 20-year outlined programme defined through a Strategic Research Agenda (SRA) and a 5-year programme defined through Roadmaps is useful.

The *integration within radioecology* has been enhanced by getting a wide variety of organisations to collaborate in radioecological studies. The actions jointly taken by various European organisations under COMET have been able to slow down the gradual deterioration of expertise and knowledge in the field of radioecology. The funding available under COMET has also helped the ALLIANCE develop its structural basis. The ALLIANCE platform has a solid basis, having expanded from the initial eight founding members to 27 members from 14 countries (Belgium, Croatia, Finland, France, Germany, Greece, Ireland, Kazakhstan, Norway, Poland, Portugal, Spain, Sweden and United Kingdom) in 2017. The European project COMET has also been successful in enhancing collaboration globally. In particular, scientific collaboration has been strengthened, e.g. with participation of scientists from the USA, Australia and Japan. Additionally the interaction with international radiation protection organisations (IRPA, ICRP, NEA, IAEA, IUR, UNSCEAR) has been enforced as clearly demonstrated by the active high-level representation at the COMET final event. Although attempts to enhance *integration with ecological and other environmental sciences* have been made under COMET, there is still needs to be progress it further.

Integration with other programmes and platforms involving research and development in health and safety issues relating to ionising radiations in Europe has been enhanced by COMET. The four platforms (ALLIANCE, MELODI, NERIS and EURADOS) have strengthened their connections. They all signed a joint Memorandum of understanding in December 2013. COMET partners, together with representatives of other platforms, have worked for the preparation a successful proposal and establishment of the new project EJP-CONCERT – European Joint Programme for the Integration of the Radiation Protection Research, under H2020. The project started in June 2015 and launched two calls for research proposals in 2016 and 2017. In the short term the work to promote radioecology will continue under EJP-CONCERT (2015-2020) which aims to develop a sustainable structure for promoting and administering joint programming and open research calls in the field of radiation protection research for Europe. In the longer term, radioecological research will be facilitated by the ALLIANCE. However, external funding is required in order to be able to answer emerging research needs.

WP3- Improving / validating radioecological models and field studies

In WP 3 of COMET, significant contributions to improve radioecological modelling capacities have been made, both through model development, experimental and field investigations as well as through improvement of model parameters. Dynamic modelling approaches have improved our ability to correctly predict ecosystem transfer and uptake of radionuclides, particularly in the early phase after an accident, as well as to assess the potential exposure of and doses to humans and wildlife. Fieldwork and experiments have provided data for model parameters, as well as for model validation. In this respect, particle archives and access to time series data has been particularly valuable for dynamic modelling, and has allowed us to model radionuclide transfer and uptake in early, intermediate and late phases after radioactive contamination. Furthermore, data from different regional ecosystems, such as the Mediterranean and Nordic ones, has allowed us to customize radioecological models with regional parameters, leading to improved accuracy in model predictions. Hence, the work in COMET WP3 has also been highly relevant for the emergency and post-accident communities.

COMET has contributed significantly towards integration, both within the radioecological community in Europe and internationally, as well as with other scientific disciplines. Institutions from fifteen different countries participated in WP3, including researchers from countries that have been affected by major nuclear accidents, such as Ukraine and Japan. This provided opportunities for joint experiments and fieldwork, as well as access to unique data for model and parameter improvement. COMET also included partners from different regions in Europe, such as the Mediterranean and Nordic ones, which furthered work towards regionalisation of radioecological models to better suit these ecosystems. COMET fostered interdisciplinary collaboration through the two projects chosen in the open call, bringing new perspectives as well as new modelling capabilities into the consortium.

Marine modelling

The work conducted by FRAME allowed us to assess the impact of the contamination in the marine system over several years after the accident, attending to aspects that otherwise would have not been investigated to this extent. This includes, for instance, the implementation of the modelling of uptake of radionuclides by biota and the assessment of the radiological impact, as well as the evaluation of the relevance of groundwater discharge in the continuous inputs of radionuclides. Also, we assessed the presence of radionuclides almost not investigated, such as ^{236}U and Pu isotopes. Several papers in peer-reviewed journals have already been published and some others are submitted or in preparation. Also, public presentations at scientific conferences, universities and other venues have been given. Some of the studies are part of one PhD (Castrillejo). Overall, our studies allow to inform the public not versed on radioecology about the actual impact of the accident in the ocean. A scientific paper published in Annual Review of Marine Science was written aiming to a broad audience in science.

Overall, the marine radioecology research carried out within COMET project has improved the capacity to assess transfer in the marine environment, uptake by organisms and the resulting doses after that event. The two main achievements of the project are presented. Firstly, important marine processes, such as the interaction of waterborne radionuclides with suspended particles and sediments or biokinetic uptake and turnover of radionuclides, have been better quantified and mathematically described. Secondly, we have demonstrated that biokinetic models can better represent radionuclide transfer to biota in non-equilibrium situations, bringing more realism to predictions, especially when combining physical, chemical and biological interactions that occur in such an open and dynamic environment as the ocean. Thanks to the dynamic modelling work, COMET has particularly contributed to identify and quantify what processes are most relevant to explain the marine distribution of radionuclides and their uptake and turnover by organisms. As a result, we are readier now than we were before Fukushima in terms of having models that can be applied to dynamic situations.

Particle behaviour

The particle behaviour research performed has allowed important knowledge about the environmental behavior, impact and risk associated with radioactive particle contamination of different ecosystems. Environmental behavior has been linked to the source term and release scenario, as the associated particle characteristics such as composition, particle size, crystalline structure and oxidation state of the carrying matrix are essential variables influencing ecosystem transfer, biological uptake and potential retention of particles with organisms where particles can act as point sources. Microdosimetry and evaluation of internal uneven distribution of doses and associated effects are still questions to be answered in the future.

The particle characteristics is essential for weathering rates and the remobilization of particle associated radionuclides such as ^{90}Sr. In this context, a long-term prediction of the increase of the ^{90}Sr activity concentration in agricultural (grain) and forest (firewood) products has been obtained for territories affected by the Chernobyl accident. Particle retained in soils represent a delay in the ecosystem transfer. Due to weathering/dissolution, increasing remobilization of ^{90}Sr resulted in increasing uptake in vegetation 20 years after the accident. The dissolution rate of inert fuel particles in the drained bottom sediments of cooling pond of ChNPP has been evaluated and due to the alkaline sediment water the weathering/dissolution rate is estimated to be very low. The studies are essential for a proper evaluation of the doses received by humans, wildlife and biota in areas affected by radioactive particles, and should be taken into consideration when environmental impact of particle affected ecosystems is assessed.

As history has shown, radioactive particles ranging from submicrons to fragments have been released to the environment following all severe nuclear events. When refractory radionuclides are observed in the environments, particles should be expected. Thus, particle releases should also be expected for severe events occurring in the future. This underlines the importance to advance our knowledge on radioactive particles, to link particle characteristics to sources and release scenarios, and to link particle characteristics to ecosystem transfer, retention within organisms and associated biological effects on which sound environmental assessments can be made, as presented in this project.

The main results of this project have been and will be disseminated through publication in peer-reviewed international journals of high impact factor and through their exposition in international conferences devoted to radioecology, environmental radioactivity and radiation protection. The position paper on radioactive particles will be published in 2017 (Salbu et al, in press).

In addition, the results of the project are serving also as key information to the on-going IAEA Coordinated Research Project "Environmental behavior and Potential Biological Impact of Radioactive Particles". In this IAEA CRP, the work performed within COMET concerning radioactive particles has made advances within the field, and has demonstrated the benefit of close collaboration between the different COMET partners that have allocated the R&D to the particle issue. Thus, a Particle Roadmap will be prepared for the ALLIANCE.

Human food chain modelling

Particularly the work on regional customisation and Bayesian statistics are highly relevant in relation to emergency preparedness (and other radiation protection platforms). In parallel to the work performed in COMET, the topic of regional customisation is also considered within the on-going EURATOM-project "Harmonising Modelling Strategies of European Decision Support Systems for Nuclear Emergencies" (HARMONE) (funded by the Second call of OPERRA)[8]. HARMONE is using a slightly different approach, specifying a number of radioecological regions matching biogeographical regions of the European Environmental Agency. COMET parameter updates have been used within HARMONE. Moreover, the output from our work and HARMONE constitute the basis for further work within the European Radioecology Alliance, as described in task 2 of the Human food chain Roadmap. This work is expected to improve predictions on a regional basis and lead to an enhanced ability to plan and predict the effect of remediation.

Forest modelling

The Forest modelling group's "wish list" for modellers and experimentalists and the Handbook 'Guidance on Forest models for contaminated sites' will contribute to the organisation of future forest modelling work, because it provides a comprehensive and practical amount of information for using forest models or developing new ones. Each chapter stands on its own and can be consulted independently from the others.

[8] https://www.helmholtz-muenchen.de/en/iss/research/work-groups/integrative-modelling/projects/operra-harmone/index.html

The list of references available is extensive and allows for extended further reading on a specific topic. The Handbook should be used as a tool to check aspects related to forest models and to look for solutions when issues arise during modelling activity. Furthermore, it may help the reader to conduct a successful sampling campaign to collect necessary data for model validation and calibration. The Handbook will be used as lecturing material at the Master course in radioecology at the NMBU and it will be distributed as a hard-copy.

NORM modelling

Defining basic terms reflecting possible exposure scenarios and combine them with the sequences of technological processes applied in NORM generating industry IRA-NORM activities laid the grounds of a strategy to better understand the key processes that result in the release and that influence the environmental behaviour of naturally occurring radionuclides. This meets the expectation of industry operators as well as authorities both facing currently the needs of adequate assessment of potential effect of NORM exposed to the accessible environment. On the other hand, the lack of site and industry (technological process) specific data has revealed further obstacles in the proper assessment of NORM cases and indicated the need of continue research at multiple NORM sites for more abundant and accurate situation-specific data. However, considering very limited financial support at the European level, the future of NORM oriented radioecological research is of concern.

Results of IRA NORM were presented during scientific conferences and symposia focused on NORM and environmental radioactivity and in scientific articles submitted to high impact scientific journal.

ICRP reference sites – developing alternative transfer models for wildlife

The investigation of alternative transfer models may ultimately be beneficial to human food chain modelling; the applicability of REML modelling to food crops is currently being evaluated (http://www.ceh.ac.uk/tree). The work has significantly increased the data available for the ICRP RAPs and will contribute to the development of the ICRPs RAP framework. There is an on-going collaboration with the ICRP to improve transfer parameters for the RAPs and future ICRP reports will consider the use of REML models. Whilst not considered here the studies have yielded the first terrestrial wildlife CRwo values for some elements (e.g. I, S, P).

The data generated by the studies described above now needs to be incorporated into the international wildlife transfer database and used in establishing REML models in combination with the existing WTD dataset.

When considered as a whole, the data from the studies used here give us the ability to begin to look at relationships between different elements across biota as a potential approach to predicting radionuclide activity concentrations (i.e. ionomics).

WP4 – Contribution of epigenetics mechanisms in the effect induced by long-term exposure to radionuclides in the laboratory and the field

The research activities performed both at lab- and field level and on different species (earthworms, fish, frogs and plants) showed limited impact of long term exposure to radiation on the global DNA methylation level. However, taken together these results hint towards a role of methylation in the multigenerational response to radiation exposure in both field and lab conditions. These preliminary results encourage further studies to better understand the contribution of DNA methylation and other epigenetic mechanisms (like histone modifications and microRNA) in the radiation response and to test their usefulness as biomarkers of radiation exposure/effects.

These studies also highlighted the need of an accurate quantification of individual organisms' absorbed dose of radiation including external and internal dose, to improve the risk assessment for both human and wild biota in chronic exposure conditions like observed e.g. in Chernobyl and Fukushima.

The risk assessment process for chemicals and radionuclides is largely based on using results from short-term bioassays to predict the effects of exposures in the field. The validity of this laboratory to field extrapolation is one of the key uncertainties in risk assessment. In the present study, the comparison of field vs laboratory has shown that species sampled in the field were more sensitive to radiation than those studied under laboratory controlled conditions.

Such findings and insights reinstated a conclusion that the international communities have to revise their approaches to risk assessment of low dose exposures. The mechanisms that make it possible for the biological systems to successfully exist in the conditions of chronic radiation exposure require further studies to provide a baseline for the development of new approaches.

In efforts to attribute changes to specific stressor effects, the use of epigenomic approaches in combination with other measurement, including specific biomarkers and macroscopic responses, would enhance the ecological relevance of molecular biomarkers, as described in the Adverse Outcome Pathway concept. Given the critical need to establish the nature of the effects of prolonged low level exposures, this integrated approach seems a promising way forward, building as it does on existing site specific and mechanistic knowledge.

The main conclusions of this research activity have been or will be disseminated through publication in peer-reviewed international journals and through communications in international conferences devoted to radioecology and ecotoxicology.

Moreover, results from COMET WP4 research activities will be integrated in a project (BIOMARKERS) to improve the mechanistic understanding and predictability of ionizing radiation effects. This project was recently submitted in response to the 2017-CONCERT transnational call for proposals for "radiation protection research in Europe".

WP5 - Knowledge exchange and capacity building

For the overall dissemination of the COMET project, to date and into the future, we have developed the Radioecology Exchange Website (http://www.radioecology-exchange.org/). The site will be maintained by the ALLIANCE into the future and there has been a recent request by the co-ordinator of a proposal to the H2020 programme (via the CONCERT second call) to use the website as their dissemination route. Newsletters published by COMET have reached at least 1700 people. Social media (twitter @ RadioXchange and Facebook https://www.facebook.com/radioecology/) have been used to promote COMET activities and outputs, and to generally promote radioecology to a wider audience. This will continue into the future as more COMET outputs are published.

Recognising the value of bringing together the different communities involved in radiation protection to debate topical issues COMET ran four focussed workshops thus ensuring better focusing and exploitation of scientific research. Attendees came from a wide range of areas appropriate to the meeting in question including: ecotoxicologists, local scientists from Japan and former Soviet Union countries, regulators, industry, modellers, social humanities, Non-Governmental Organisations (NGO) and media. In addition to building the science area in question, the impact of the workshops has included the development of cross-disciplinary understanding and relationships, with beneficial implications for the newly initiated EU CONCERT projects (CONFIDENCE, TERRITORIES). Media representatives attended the workshop held in the Ukraine (*Thirty years after the Chernobyl accident: what do we know about the effects of radiation on the environment?*) resulting in four articles in a range of publications (*BBC Wildlife, BBC Earth, Outdoor Photography and Waitrose Weekend*) reaching relatively large and diverse audiences (e.g. *Waitrose Weekend* having a readership of about 400,000). The workshops held in Japan contributed to an evaluation of recently acquired Fukushima data being included as a topic area within the IAEA's MODARIA II programme. The workshop in Seville focusing on fit for purpose modelling and associated uncertainties will be followed up within the EU CONFIDENCE (though with a focus on process based modelling) and TERRITORIES projects.

A special issue of the *Journal of Environmental Radioactivity* will be published from the Ukraine workshop (paper submission deadline: August 2017). Papers will include unpublished data from the Ukraine, COMET studies, views from social humanities field and an NGO and the recommendations of the workshop attendees. The workshop recommendations included suggestions for improving field studies of radiation effects on wildlife, publication of 'no-effect' studies and that data from radiation effects studies need to be made openly and freely available. If acted upon significant steps would be made to addressing the disagreement between researchers on the magnitude of effects due to exposure to ionising radiation being observed in the Chernobyl Exclusion Zone/Fukushima (an aspect of radioecology which has a high media/public profile).

The COMET consortium reversed the decline in interest in radioecology through education and training, stakeholder participation and integration in support of the radioecological needs of industry, national authorities, and the public.

As early as 2000, the OECD/Nuclear Energy Agency's report: "Nuclear Education and Training: Cause for Concern?" stated that many nations were probably training too few scientists to meet the needs of their current and future nuclear industries. The OECD/NEA findings indicated that the European educational skill base had become fragmented to a point where universities in most countries lacked sufficient staff and equipment to provide education in all, but a few, nuclear areas. Of particular concern to the stakeholders (EU Commission, authorities, industry and professionals) were the significant and persistent needs for post-graduates with skills in radiochemistry, radioecology including environmental modelling, and radiation protection including radiobiology and dosimetry. These needs were reiterated at a stakeholder workshop held in 2011 during the EU-STAR project (see STAR Deliverable 6.1).

The Radioecology Education and Training Platform (E&T platform), incorporated on the Radioecology Exchange website, was initiated within the STAR NoE and further developed under COMET. It is a focal point for students and professionals interested in radioecology, and presents an overview of intensive education and training course modules within radioecology. The impact of COMET E&T activities have been to (i) continued to produce radioecology MSc. students via Bologna accredited courses through the European Credit Transfer and Accumulation System (ECTS) at collaborating universities and institutions (ii) establish the COMET flagship course module in Experimental Radioecology (iii) offer ECTS accredited PhD. courses (these have also been of value to professional and MSc. students) (iv) sign a co-tutelle agreement between University of Seville, (Spain) and Norwegian University of Life Sciences (NMBU), allowing PhD. students to take a joint degree (v) maintain the Radioecology Research School as a networking forum aimed primarily at PhD. students (vi) continue to provide bespoke training for professionals. 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 as many of the basic course modules within radioecology are also relevant for other nuclear science students, and vice versa.

COMET also ran two field courses, primarily aimed at students with an object of stimulating recruitment in the field. The Chernobyl field course, with approximately 30 participants from all over the world, was well covered by newspapers in Kiev. Due to its success, it will be organised annually with the next being planned for June 2017.

The ALLIANCE will continue to support E&T within European Radioecology in the future. Furthermore, the CONCERT funded CONFIDENCE and TERRITORIES projects include E&T activities and will further our efforts. The only MSc in Radioecology in Europe, organised by NMBU, will continue in the years to come. A challenge is to establish additional MSc. programmes in Radioecology in Europe as these would probably need external funding. The need for competence in radioecology is still valid; more nuclear power stations are under planning or construction, installations are being decommissioned and problems with waste and NORM will increase in the future. COMET has laid the foundations to helping Europe have the skills set needed to address these issues.

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4.1.5. Public website and contact details

More information on the project can be found on the following website:
http://www.radioecology-exchange.org/content/comet

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4.2. Use and dissemination of foreground

The plan should consist of:

Section A

The list with peer review articles, conference proceedings and theses can be consulted on the EC Participant Portal. The list with other dissemination activities can also be visited at the EC Participant Portal.

Section B (Confidential[9] or public: confidential information to be marked clearly)

Part B1

There are no patents, trademarks, registered designs, etc. related to the FP7 COMET project.

Part B2

Type of Exploitable Foreground[10]	**Description of exploitable foreground**	**Confidential Click on YES/NO**	**Foreseen embargo date dd/mm/yyyy**	**Exploitable product(s) or measure(s)**	**Sector(s) of application[11]**	**Timetable, commercial or any other use**	**Patents or other IPR exploitation (licences)**	**Owner & Other Beneficiary(s) involved**
General advancement of knowledge	Mathematical model "Dynamic Dose Assessment Tool" (D-DAT)	YES	Until future publication	Use of model for radiological impact assessment of marine releases on marine biota	Professional, scientific and technical activities – Scientific Research and Development (M72.1.9)	Ongoing	Intended for scientific publication	SCK•CEN (owner, developer)
General advancement of knowledge	Mathematical model "Multi-	YES	Until future	Use of model for radiological impact	Professional, scientific and technical	Ongoing	Intended for scientific publication	SCK•CEN (owner, developer)

[9] Note to be confused with the "EU CONFIDENTIAL" classification for some security research projects.

[19] A drop down list allows choosing the type of foreground: General advancement of knowledge, Commercial exploitation of R&D results, Exploitation of R&D results via standards, exploitation of results through EU policies, exploitation of results through (social) innovation.

[11] A drop down list allows choosing the type sector (NACE nomenclature) : http://ec.europa.eu/competition/mergers/cases/index/nace_all.html

Type of Exploitable Foreground[10]	**Description of exploitable foreground**	**Confidential Click on YES/NO**	**Foreseen embargo date dd/mm/yyyy**	**Exploitable product(s) or measure(s)**	**Sector(s) of application[11]**	**Timetable, commercial or any other use**	**Patents or other IPR exploitation (licences)**	**Owner & Other Beneficiary(s) involved**
	Analysis RadiologIcal aSSessment cAlculator" (MARISSA)		publication	assessment of marine releases on marine biota	activities – Scientific Research and Development (M72.1.9)			
General advancement of knowledge	RadioECOlogical FORest model (ECOFOR)	YES	Until future publication	Use of model for understanding SVAT (soil, vegetation, atmosphere) processes of radionuclide cycling in pine forests.	Professional, scientific and technical activities – Scientific Research and Development (M72.1.9)	Ongoing	Intended for scientific publication	SCK•CEN (owner, developer)
General advancement of knowledge	Mathematical model "Simulation du Transport et des transferts d'Eléments Radioactifs	YES	Until operationality and future publication	Use of model for radionuclide dispersion simulation and radiological impact assessment on marine biota	Professional, scientific and technical activities – Scientific Research and Development (M72.1.9)	Ongoing	Intended for scientific publication	IRSN (owner, developer)

Type of Exploitable Foreground[10]	**Description of exploitable foreground**	**Confidential Click on YES/NO**	**Foreseen embargo date dd/mm/yyyy**	**Exploitable product(s) or measure(s)**	**Sector(s) of application**[11]	**Timetable, commercial or any other use**	**Patents or other IPR exploitation (licences)**	**Owner & Other Beneficiary(s) involved**
	eN Environnement marin)" (STERNE)			after accidental marine contamination				
MSc in Radioecology	The only MSc in radioecology in Europe	No		MSc students	Nuclear sciences	Annual	Bologna model (120 ESTC)	NMBU, Norway
Course in Experimental Radioecology	Stand-alone intensive course (10 ESTC)	No		Student merits	Nuclear sciences	Annual	Bologna model (10 ESTC)	NMBU, Norway
Chernobyl Field Course	Stand-alone intensive course	No		Student merits	Nuclear sciences	Biannual	Diploma	National University of Environment and Life Sciences, Kiev, Ukraine and NMBU, Norway

D-DAT

Purpose: Improved during COMET and used in UNSCEAR Fukushima assessment, D-DAT as presently developed is a 2-compartment marine biota uptake and turnover using dual 1st order kinetics (multicomponent biological half-lives). It also has a 3-layer sediment sub-model with particle scavenging & mixing, molecular diffusion, pore water mixing and sedimentation, and a simple module for dispersion from regional compartment to far field factorising flushing

time. It can run 6 radionuclides (90Sr, 129I, 131I, 134Cs, 137Cs, 236U) and 6 biota (pelagic & benthic fish, crustacean, mollusc, algae, plankton). It can perform calculation of internal & external doses rates to biota with dose conversion coefficients compatible with ERICA dosimetry.
How the foreground might be exploited, when and by whom: To be exploited by the model developers at SCK•CEN as part of ongoing research
IPR exploitable measures taken or intended: Intended as research for scientific publication
Further research necessary, if any: This model is constantly evolving as part of ongoing research to better understand biological transfer mechanisms of radionuclides for marine biota and the effort will be made in future projects.
Potential/expected impact (quantify where possible): Improving assessment of impact of marine releases to marine biota in non-steady state situations

MARISSA

Purpose: Excel tool for batch dose rate calculations from measured data (biota, water, sediment) which was developed as part of the D-DAT family of codes. This can be used instead of the ERICA tool when radionuclide concentrations in biota are available from monitoring, the advantage of MARISSA is that it can process a large amount of data in batch mode. MARISSA was used to calculate marine biota doses using data from the FRAME cruises.
How the foreground might be exploited, when and by whom: To be exploited by the model developers at SCK•CEN as part of ongoing research
IPR exploitable measures taken or intended: Intended as research for scientific publication
Further research necessary, if any: This model is constantly evolving as part of ongoing research to better understand biological transfer mechanisms of radionuclides for marine biota and the effort will be made in future projects.
Potential/expected impact (quantify where possible): Improving assessment of impact of marine releases to marine biota in non-steady state situations

ECOFOR

Purpose Pre-existing model improved during COMET, containing a simplified, 1-D soil-groundwater-vegetation model to represent the cycling of water and 5 elements (Cl, Ca, K, Mg and Mn) in a Belgian Scots pine forest. The model contains a multi-layered soil column with simplified representation of the hydrology using Darcy law and Phillips' law. The vegetation is represented by means of a simplified 4-compartment model (roots, wood, foliage and litter) with simplified representation of sap flow, translocation and litterfall in relation to different parts of the tree. The water table height is variable according to the balance between precipitation, capillary rise, solar radiation, plant uptake and evapotranspiration. The element flux is assumed to follow the water flux in both soil and the trees, using retardation in soil and experimentally measured selectivity coefficients within the tree.

How the foreground might be exploited, when and by whom: To be exploited by the model developers at SCK•CEN as part of ongoing research

IPR exploitable measures taken or intended: Intended as research for scientific publication

Further research necessary, if any: This model is constantly evolving as part of ongoing research to better understand biological transfer mechanisms of radionuclides in forests and the effort will be made in future projects.

Potential/expected impact (quantify where possible): Improving process understanding, fundamental research of the cycling of radionuclides in forests in non-steady state situations.

STERNE

Purpose: The STERNE simulation tool is designed to predict radionuclide dispersion and contamination in seawater and marine species by incorporating spatio-temporal data. 3D hydrodynamic forecasts are used as input data. Direct discharge points or atmospheric deposition source terms can be taken into account. STERNE calculates Eulerian radionuclide dispersion using advection and diffusion equations established offline from hydrodynamic calculations. A radioecological model based on dynamic transfer equations is implemented to evaluate activity concentrations in aquatic organisms. Essential radioecological parameters (concentration factors and single or multicomponent biological half-lives) have been compiled for main radionuclides and generic marine species (fish, molluscs, crustaceans and algae). Dispersion and transfer calculations are performed simultaneously on a 3D grid. Results can be plotted on maps, with possible tracking of spatio-temporal evolution.

How the foreground might be exploited, when and by whom: To be exploited by the research and crisis IRSN teams.

IPR exploitable measures taken or intended: Intended as research for scientific publication and operational tool in the IRSN Crisis Centre.

Further research necessary, if any: This model is to be adapted to support hydrodynamic inputs from different models. The biological transfer parametrisation has to be improved.

Potential/expected impact (quantify where possible): In accidental situations, provide a first assessment of radionuclide dispersion, and related activity time and space evolution in seawater and biota.

MSc in Radioecology

The only MSc in Radioecology in Europe is presently organized at NMBU. The education is estimated to 2 yrs (120 ECTS), 60 ECTS education (6 course modules and 10 ECTS each) and usually 60 ECTS (1 yr) for the research project. According to the plan, four of six ECTS credited courses (10 ECTS each) can be fulfilled at NMBU, while 2 (10 ECTS each) are optional (at NMBU or elsewhere) and should fit for purpose of the MSc student (related to the research project). Thus, the students can choose course modules being relevant for their future interest of work (fig. 2). The MSc courses, PhD courses and training courses are given intensively and open to students from all over the world. Detailed information on the MSc in radioecology is included in the Education and Training pages on the COMET Radioecology Exchange website.

Course in Experimental Radioecology

The COMET flagship on Experimental Radioecology organised annually in January, is an intensive 3 weeks course module and covers radioactivity in terrestrial and aquatic environments. A series of international experts are giving the lectures. In addition, laboratory exercises and a semester thesis on a subject selected by the student (part of their MSc or PhD). The course module follows the Bologna model (10 ESTC), and is implemented in the formal MSC education program.

Chernobyl Field Course

A COMET Chernobyl field course, organised first time September 2016 with almost 30 mostly international students, is an intensive 14 days course and will be organized biannually. The course offers expert lectures related to the Chernobyl accident, and on underlying processes influencing the behaviour of radionuclides in different contaminated ecosystems, including the influence of radioactive particles. The intention of the course is also to allow students to initiate research work (sampling, analysis) within the Chernobyl exclusion zone. The work can be implemented in their MSc Research project or in their PhD thesis.

4.3 Report on societal implications

Replies to the following questions will assist the Commission to obtain statistics and indicators on societal and socio-economic issues addressed by projects. The questions are arranged in a number of key themes. As well as producing certain statistics, the replies will also help identify those projects that have shown a real engagement with wider societal issues, and thereby identify interesting approaches to these issues and best practices. The replies for individual projects will not be made public.

A General Information *(completed automatically when **Grant Agreement number** is entered.*	
Grant Agreement Number:	604974
Title of Project:	COordination and iMplementation of a pan-European instrumenT for radioecology
Name and Title of Coordinator:	Dr. Ir Hildegarde Vandenhove, Director Institute EHS, SCK•CEN

B Ethics	
1. Did your project undergo an Ethics Review (and/or Screening)? • If Yes: have you described the progress of compliance with the relevant Ethics Review/Screening Requirements in the frame of the periodic/final project reports? Special Reminder: the progress of compliance with the Ethics Review/Screening Requirements should be described in the Period/Final Project Reports under the Section 3.2.2 *'Work Progress and Achievements'*	***No***
2. Please indicate whether your project involved any of the following issues :	
RESEARCH ON HUMANS	
• Did the project involve children?	No
• Did the project involve patients?	No
• Did the project involve persons not able to give consent?	No
• Did the project involve adult healthy volunteers?	No
• Did the project involve Human genetic material?	No
• Did the project involve Human biological samples?	No
• Did the project involve Human data collection?	No
RESEARCH ON HUMAN EMBRYO/FOETUS	
• Did the project involve Human Embryos?	No
• Did the project involve Human Foetal Tissue / Cells?	No
• Did the project involve Human Embryonic Stem Cells (hESCs)?	No
• Did the project on human Embryonic Stem Cells involve cells in culture?	No
• Did the project on human Embryonic Stem Cells involve the derivation of cells from Embryos?	No
PRIVACY	
• Did the project involve processing of genetic information or personal data (eg. health, sexual lifestyle, ethnicity, political opinion, religious or philosophical conviction)?	No

• Did the project involve tracking the location or observation of people?	No
RESEARCH ON ANIMALS	
• Did the project involve research on animals?	Yes
• Were those animals transgenic small laboratory animals?	No
• Were those animals transgenic farm animals?	No
• Were those animals cloned farm animals?	No
• Were those animals non-human primates?	No
RESEARCH INVOLVING DEVELOPING COUNTRIES	
• Did the project involve the use of local resources (genetic, animal, plant etc)?	No
• Was the project of benefit to local community (capacity building, access to healthcare, education etc)?	No
DUAL USE	
• Research having direct military use	No
• Research having the potential for terrorist abuse	No

C Workforce Statistics

3. Workforce statistics for the project: Please indicate in the table below the number of people who worked on the project (on a headcount basis).

Type of Position	Number of Women	Number of Men
Scientific Coordinator	1	0
Work package leaders	5 (4)	0 (1)
Experienced researchers (i.e. PhD holders)	41	46
PhD Students	0	3
Other	1	3

4. How many additional researchers (in companies and universities) were recruited specifically for this project?	
Of which, indicate the number of men:	0

D Gender Aspects

5.	**Did you carry out specific Gender Equality Actions under the project?**	○ ☒	Yes No

6. Which of the following actions did you carry out and how effective were they?

		Not at all effective → Very effective
❑	Design and implement an equal opportunity policy	○ ○ ○ ○ ○
❑	Set targets to achieve a gender balance in the workforce	○ ○ ○ ○ ○
❑	Organise conferences and workshops on gender	○ ○ ○ ○ ○
❑	Actions to improve work-life balance	○ ○ ○ ○ ○
☒	Other:	We have a good gender distribution in radioecology. Expertise is more important than gender sometimes.

7. Was there a gender dimension associated with the research content – i.e. wherever people were the focus of the research as, for example, consumers, users, patients or in trials, was the issue of gender considered and addressed?

○ Yes- please specify

☒ No

E Synergies with Science Education

8. Did your project involve working with students and/or school pupils (e.g. open days, participation in science festivals and events, prizes/competitions or joint projects)?

○ Yes- please specify

☒ No

9. Did the project generate any science education material (e.g. kits, websites, explanatory booklets, DVDs)?

☒ Yes- please specify See WP5 + list with dissemination activities (websites/applications)

○ No

F Interdisciplinarity

10. Which disciplines (see list below) are involved in your project?

1 Main discipline[12]:

○ Associated discipline[12]: ○ Associated discipline[12]:

G Engaging with Civil society and policy makers

11a	**Did your project engage with societal actors beyond the research community?** *(if 'No', go to Question 14)*	☒ ○	Yes No

11b If yes, did you engage with citizens (citizens' panels / juries) or organised civil society (NGOs, patients' groups etc.)?

☒ No
○ Yes- in determining what research should be performed
○ Yes - in implementing the research
○ Yes, in communicating /disseminating / using the results of the project

11c In doing so, did your project involve actors whose role is mainly to organise the dialogue with citizens and organised civil society (e.g. professional mediator; communication company, science museums)?	○ ☒	Yes No

12. Did you engage with government / public bodies or policy makers (including international organisations)

○ No
☒ Yes- in framing the research agenda
☒ Yes - in implementing the research agenda
☒ Yes, in communicating /disseminating / using the results of the project

13a Will the project generate outputs (expertise or scientific advice) which could be used by policy makers?

☒ Yes – as a **primary** objective (please indicate areas below- multiple answers possible)
○ Yes – as a **secondary** objective (please indicate areas below - multiple answer possible)
○ No

13b If Yes, in which fields?

Agriculture Audiovisual and Media Budget Competition Consumers Culture Customs Development Economic and Monetary Affairs Education, Training, Youth Employment and Social Affairs	☒ (Education, Training, Youth)	Energy Enlargement Enterprise Environment External Relations External Trade Fisheries and Maritime Affairs Food Safety Foreign and Security Policy Fraud Humanitarian aid	☒ (Environment)	Human rights Information Society Institutional affairs Internal Market Justice, freedom and security Public Health Regional Policy Research and Innovation Space Taxation Transport	☒ (Research and Innovation)

[12] Insert number from list below (Frascati Manual).

13c If Yes, at which level? ○ Local / regional levels ○ National level ☒ European level ☒ International level	

H Use and dissemination

14. How many Articles were published/accepted for publication in peer-reviewed journals?	**39**
To how many of these is open access[13] provided?	**6**
How many of these are published in open access journals?	**6**
How many of these are published in open repositories?	**0**
To how many of these is open access not provided?	**33**
Please check all applicable reasons for not providing open access:	
☒ publisher's licensing agreement would not permit publishing in a repository ❑ no suitable repository available ❑ no suitable open access journal available ☒ no funds available to publish in an open access journal ❑ lack of time and resources ☒ lack of information on open access ❑ other[14]: ……………	

15. How many new patent applications ('priority filings') have been made? *("Technologically unique": multiple applications for the same invention in different jurisdictions should be counted as just one application of grant).*		/
16. Indicate how many of the following Intellectual Property Rights were applied for (give number in each box).	Trademark	/
	Registered design	/
	Other	/

17. How many spin-off companies were created / are planned as a direct result of the project?	/
Indicate the approximate number of additional jobs in these companies:	/

18. Please indicate whether your project has a potential impact on employment, in comparison with the situation before your project:

❑ Increase in employment, or	❑ In small & medium-sized enterprises
❑ Safeguard employment, or	❑ In large companies
❑ Decrease in employment,	☒ None of the above / not relevant to the project
☒ Difficult to estimate / not possible to quantify	

19. For your project partnership please estimate the employment effect resulting directly from your participation in Full Time Equivalent (*FTE = one person working fulltime for a year*) jobs:	*Indicate figure:*
Difficult to estimate / not possible to quantify	☒

I Media and Communication to the general public

20. As part of the project, were any of the beneficiaries professionals in communication or media relations?

○ Yes ☒ No

21. As part of the project, have any beneficiaries received professional media / communication training / advice to improve communication with the general public?

○ Yes ☒ No

22 Which of the following have been used to communicate information about your project to the general public, or have resulted from your project?

☒	Press Release	☒	Coverage in specialist press
☒	Media briefing	☒	Coverage in general (non-specialist) press
❑	TV coverage / report	☒	Coverage in national press
❑	Radio coverage / report	☒	Coverage in international press
☒	Brochures /posters / flyers	☒	Website for the general public / internet
❑	DVD /Film /Multimedia	☒	Event targeting general public (festival, conference, exhibition, science café)

23 In which languages are the information products for the general public produced?

❑	Language of the coordinator	☒	English
☒	Other language(s)		

Question F-10: Classification of Scientific Disciplines according to the Frascati Manual 2002 (Proposed Standard Practice for Surveys on Research and Experimental Development, OECD 2002):

FIELDS OF SCIENCE AND TECHNOLOGY

1. NATURAL SCIENCES

1.1 Mathematics and computer sciences [mathematics and other allied fields: computer sciences and other allied subjects (software development only; hardware development should be classified in the engineering fields)]

1.2 Physical sciences (astronomy and space sciences, physics and other allied subjects)

1.3 Chemical sciences (chemistry, other allied subjects)

[13] Open Access is defined as free of charge access for anyone via Internet.

[14] For instance: classification for security project.

1.4 Earth and related environmental sciences (geology, geophysics, mineralogy, physical geography and other geosciences, meteorology and other atmospheric sciences including climatic research, oceanography, vulcanology, palaeoecology, other allied sciences)
1.5 Biological sciences (biology, botany, bacteriology, microbiology, zoology, entomology, genetics, biochemistry, biophysics, other allied sciences, excluding clinical and veterinary sciences)

2 ENGINEERING AND TECHNOLOGY
2.1 Civil engineering (architecture engineering, building science and engineering, construction engineering, municipal and structural engineering and other allied subjects)
2.2 Electrical engineering, electronics [electrical engineering, electronics, communication engineering and systems, computer engineering (hardware only) and other allied subjects]
2.3. Other engineering sciences (such as chemical, aeronautical and space, mechanical, metallurgical and materials engineering, and their specialised subdivisions; forest products; applied sciences such as geodesy, industrial chemistry, etc.; the science and technology of food production; specialised technologies of interdisciplinary fields, e.g. systems analysis, metallurgy, mining, textile technology and other applied subjects)

3. MEDICAL SCIENCES
3.1 Basic medicine (anatomy, cytology, physiology, genetics, pharmacy, pharmacology, toxicology, immunology and immunohaematology, clinical chemistry, clinical microbiology, pathology)
3.2 Clinical medicine (anaesthesiology, paediatrics, obstetrics and gynaecology, internal medicine, surgery, dentistry, neurology, psychiatry, radiology, therapeutics, otorhinolaryngology, ophthalmology)
3.3 Health sciences (public health services, social medicine, hygiene, nursing, epidemiology)

4. AGRICULTURAL SCIENCES
4.1 Agriculture, forestry, fisheries and allied sciences (agronomy, animal husbandry, fisheries, forestry, horticulture, other allied subjects)
4.2 Veterinary medicine

5. SOCIAL SCIENCES
5.1 Psychology
5.2 Economics
5.3 Educational sciences (education and training and other allied subjects)
5.4 Other social sciences [anthropology (social and cultural) and ethnology, demography, geography (human, economic and social), town and country planning, management, law, linguistics, political sciences, sociology, organisation and methods, miscellaneous social sciences and interdisciplinary , methodological and historical S1T activities relating to subjects in this group. Physical anthropology, physical geography and psychophysiology should normally be classified with the natural sciences].

6. HUMANITIES
6.1 History (history, prehistory and history, together with auxiliary historical disciplines such as archaeology, numismatics, palaeography, genealogy, etc.)
6.2 Languages and literature (ancient and modern)
6.3 Other humanities [philosophy (including the history of science and technology) arts, history of art, art criticism, painting, sculpture, musicology, dramatic art excluding artistic "research" of any kind, religion, theology, other fields and subjects pertaining to the humanities, methodological, historical and other S1T activities relating to the subjects in this group]