IAEA-TECDOC-1986

IAEA TECDOC SERIES

IAEA-TECDOC-1986

Radiation Protection of Wildlife: Modelling the Exposure and Effects

Joint Summary Report of Working Groups 8 and 9 (MODARIA I) and Working Group 5 (MODARIA II)

Modelling and Data for Radiological Impact Assessments (MODARIA) Programme

IAEA

International Atomic Energy Agency

IAEA SAFETY STANDARDS AND RELATED PUBLICATIONS

IAEA SAFETY STANDARDS

Under the terms of Article III of its Statute, the IAEA is authorized to establish or adopt standards of safety for protection of health and minimization of danger to life and property, and to provide for the application of these standards.

The publications by means of which the IAEA establishes standards are issued in the **IAEA Safety Standards Series**. This series covers nuclear safety, radiation safety, transport safety and waste safety. The publication categories in the series are **Safety Fundamentals**, **Safety Requirements** and **Safety Guides**.

Information on the IAEA's safety standards programme is available on the IAEA Internet site

http://www-ns.iaea.org/standards/

The site provides the texts in English of published and draft safety standards. The texts of safety standards issued in Arabic, Chinese, French, Russian and Spanish, the IAEA Safety Glossary and a status report for safety standards under development are also available. For further information, please contact the IAEA at: Vienna International Centre, PO Box 100, 1400 Vienna, Austria.

All users of IAEA safety standards are invited to inform the IAEA of experience in their use (e.g. as a basis for national regulations, for safety reviews and for training courses) for the purpose of ensuring that they continue to meet users' needs. Information may be provided via the IAEA Internet site or by post, as above, or by email to Official.Mail@iaea.org.

RELATED PUBLICATIONS

The IAEA provides for the application of the standards and, under the terms of Articles III and VIII.C of its Statute, makes available and fosters the exchange of information relating to peaceful nuclear activities and serves as an intermediary among its Member States for this purpose.

Reports on safety in nuclear activities are issued as **Safety Reports**, which provide practical examples and detailed methods that can be used in support of the safety standards.

Other safety related IAEA publications are issued as **Emergency Preparedness and Response** publications, **Radiological Assessment Reports**, the International Nuclear Safety Group's **INSAG Reports**, **Technical Reports** and **TECDOCs**. The IAEA also issues reports on radiological accidents, training manuals and practical manuals, and other special safety related publications.

Security related publications are issued in the **IAEA Nuclear Security Series**.

The **IAEA Nuclear Energy Series** comprises informational publications to encourage and assist research on, and the development and practical application of, nuclear energy for peaceful purposes. It includes reports and guides on the status of and advances in technology, and on experience, good practices and practical examples in the areas of nuclear power, the nuclear fuel cycle, radioactive waste management and decommissioning.

RADIATION PROTECTION OF WILDLIFE: MODELLING THE EXPOSURE AND EFFECTS

The following States are Members of the International Atomic Energy Agency:

AFGHANISTAN
ALBANIA
ALGERIA
ANGOLA
ANTIGUA AND BARBUDA
ARGENTINA
ARMENIA
AUSTRALIA
AUSTRIA
AZERBAIJAN
BAHAMAS
BAHRAIN
BANGLADESH
BARBADOS
BELARUS
BELGIUM
BELIZE
BENIN
BOLIVIA, PLURINATIONAL STATE OF
BOSNIA AND HERZEGOVINA
BOTSWANA
BRAZIL
BRUNEI DARUSSALAM
BULGARIA
BURKINA FASO
BURUNDI
CAMBODIA
CAMEROON
CANADA
CENTRAL AFRICAN REPUBLIC
CHAD
CHILE
CHINA
COLOMBIA
COMOROS
CONGO
COSTA RICA
CÔTE D'IVOIRE
CROATIA
CUBA
CYPRUS
CZECH REPUBLIC
DEMOCRATIC REPUBLIC OF THE CONGO
DENMARK
DJIBOUTI
DOMINICA
DOMINICAN REPUBLIC
ECUADOR
EGYPT
EL SALVADOR
ERITREA
ESTONIA
ESWATINI
ETHIOPIA
FIJI
FINLAND
FRANCE
GABON
GEORGIA
GERMANY
GHANA
GREECE
GRENADA
GUATEMALA
GUYANA
HAITI
HOLY SEE
HONDURAS
HUNGARY
ICELAND
INDIA
INDONESIA
IRAN, ISLAMIC REPUBLIC OF
IRAQ
IRELAND
ISRAEL
ITALY
JAMAICA
JAPAN
JORDAN
KAZAKHSTAN
KENYA
KOREA, REPUBLIC OF
KUWAIT
KYRGYZSTAN
LAO PEOPLE'S DEMOCRATIC REPUBLIC
LATVIA
LEBANON
LESOTHO
LIBERIA
LIBYA
LIECHTENSTEIN
LITHUANIA
LUXEMBOURG
MADAGASCAR
MALAWI
MALAYSIA
MALI
MALTA
MARSHALL ISLANDS
MAURITANIA
MAURITIUS
MEXICO
MONACO
MONGOLIA
MONTENEGRO
MOROCCO
MOZAMBIQUE
MYANMAR
NAMIBIA
NEPAL
NETHERLANDS
NEW ZEALAND
NICARAGUA
NIGER
NIGERIA
NORTH MACEDONIA
NORWAY
OMAN
PAKISTAN
PALAU
PANAMA
PAPUA NEW GUINEA
PARAGUAY
PERU
PHILIPPINES
POLAND
PORTUGAL
QATAR
REPUBLIC OF MOLDOVA
ROMANIA
RUSSIAN FEDERATION
RWANDA
SAINT LUCIA
SAINT VINCENT AND THE GRENADINES
SAMOA
SAN MARINO
SAUDI ARABIA
SENEGAL
SERBIA
SEYCHELLES
SIERRA LEONE
SINGAPORE
SLOVAKIA
SLOVENIA
SOUTH AFRICA
SPAIN
SRI LANKA
SUDAN
SWEDEN
SWITZERLAND
SYRIAN ARAB REPUBLIC
TAJIKISTAN
THAILAND
TOGO
TRINIDAD AND TOBAGO
TUNISIA
TURKEY
TURKMENISTAN
UGANDA
UKRAINE
UNITED ARAB EMIRATES
UNITED KINGDOM OF GREAT BRITAIN AND NORTHERN IRELAND
UNITED REPUBLIC OF TANZANIA
UNITED STATES OF AMERICA
URUGUAY
UZBEKISTAN
VANUATU
VENEZUELA, BOLIVARIAN REPUBLIC OF
VIET NAM
YEMEN
ZAMBIA
ZIMBABWE

The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world".

IAEA-TECDOC-1986

RADIATION PROTECTION OF WILDLIFE: MODELLING THE EXPOSURE AND EFFECTS

JOINT SUMMARY REPORT OF WORKING GROUPS 8 AND 9 (MODARIA I) AND WORKING GROUP 5 (MODARIA II)

MODELLING AND DATA FOR RADIOLOGICAL IMPACT ASSESSMENTS (MODARIA) PROGRAMME

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2021

For further information on this publication, please contact:

Radiation Safety and Monitoring Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna, Austria
Email: Official.Mail@iaea.org

Printed by the IAEA in Austria
December 2021

IAEA Library Cataloguing in Publication Data

Names: International Atomic Energy Agency.
Title: Radiation protection of wildlife : modelling the exposure and effects / International Atomic Energy Agency.
Description: Vienna : International Atomic Energy Agency, 2021. | Series: IAEA TECDOC series, ISSN 1011–4289 ; no. 1986 | Includes bibliographical references.
Identifiers: IAEAL 21-01460 | ISBN 978-92-0-138121-7 (paperback : alk. paper) | ISBN 978-92-0-138021-0 (pdf)
Subjects: LCSH: Radiation — Safety measures. | Wildlife management — Effect of radiation on. | Wildlife conservation.

FOREWORD

The IAEA has been organizing international model testing programmes for the transfer of radionuclides in the environment and the estimation of radiation exposures since the 1980s. These programmes have contributed to a general improvement in such models, both in the transfer of data and in the capabilities of modellers in Member States. IAEA publications on this subject over the past three decades demonstrate the comprehensive nature of the programmes and record the associated advances which have been made.

From 2012 to 2015 the IAEA organized a programme entitled Modelling and Data for Radiological Impact Assessments (MODARIA). The first phase of the programme (MODARIA I) focused on testing the performance of models, developing and improving models for particular environments, reaching consensus on data sets that are generally applicable in environmental transfer models and providing an international forum for the exchange of experience, ideas and research information.

Different aspects were addressed by ten working groups within MODARIA I covering four thematic areas: (i) remediation of contaminated areas, (ii) uncertainties and variability, (iii) exposures and effects on wildlife and (iv) marine modelling. This publication describes the work carried out under thematic area (iii) within working groups 8 and 9.

From 2016 to 2019 the IAEA organized the second phase of the programme, MODARIA II, where seven working groups continued much of the work of MODARIA I. This publication describes the ongoing work on exposures and effects on wildlife that began in MODARIA I and continued during MODARIA II within working group 5.

The IAEA wishes to express its gratitude to all those who participated in working groups 8 and 9 of the MODARIA I programme and working group 5 of the MODARIA II programme. The IAEA gratefully acknowledges the valuable contributions of N. Beresford (United Kingdom) and J. Vives i Batlle (Belgium) both as leaders of the working groups and to this publication. The IAEA officers responsible for this publication were D. Telleria and J. Brown of the Division of Radiation, Transport and Waste Safety.

CONTENTS

SUMMARY

In recent years there has been a rapid development in models and approaches to assess whether the environment (or wildlife) is protected from releases of radioactive material. Through the Environmental Modelling for Radiation Safety (EMRAS and EMRAS II) and Modelling and Data for Radiological Impact Assessments (MODARIA I and MODARIA II) programmes, the IAEA has facilitated knowledge sharing on this topic, including through model intercomparison, testing and development.

In this publication, a summary of the activities of the MODARIA I Working Group 8 (WG8) and Working Group 9 (WG9), along with MODARIA II Working Group 5 (WG5) is presented considering:

— The estimation of the radiation exposure of wildlife;
— Population effects modelling.

During both MODARIA programmes, the fitness for purpose of available models and tools for estimating wildlife exposures have been assessed. On the basis of the evaluations carried out, a number of the models and tools can be proposed for use by assessors, all of which are freely available to users. Some of these tools facilitate increasingly complex tiered (or graded) assessments, whilst others offer increased functionality for specific assessment aspects. Whilst there are many assumptions and simplifications in the available models, and large uncertainties with respect to radionuclide transfer to organisms, it can be concluded that the commonly used models are generally fit for purpose for screening level assessments. In this publication the many lessons from the IAEA programmes to assist regulatory bodies and assessors in protecting the environment from ionizing radiation are summarized.

The aim of the system of radiological protection for the environment is to protect populations from the deterministic effects of radiation in order to maintain biodiversity. However, most methods and tools are developed for estimating exposure to individuals of flora and fauna. In this publication, modelling approaches for estimating population dynamics and radiation dose effects to populations of wildlife are also addressed. The main output of this activity is an ecologically relevant conceptual model of a population of voles in Chornobyl’s Red Forest. Whilst the model is not yet experimentally validated with field information for multiple scenarios (which would require long term studies), it has now been sufficiently developed to produce guidance on, *inter alia*, the evaluation of risk criteria (benchmarks) used in regulation for biota populations in an ecological context. Factors considered include spatial influences (e.g. migration, heterogeneity of contamination) and historical doses (higher exposure of previous generations).

The area of wildlife radiological assessment is still developing, with underlying databases continuing to be improved, new approaches being generated and existing models and tools being revised.

In conclusion, the IAEA has a key role to continue to promote and support the facilitation and sharing of new knowledge and approaches, model development, testing and intercomparison, as well as training for its Member States, many of whom have only just begun to adapt to revised international recommendations to ensure that the environment and wildlife is protected from releases of radioactivity into the environment.

1. INTRODUCTION

1.1. BACKGROUND OF THE MODARIA I AND II PROGRAMMES

The IAEA organized a programme from 2012 to 2015, entitled Modelling and Data for Radiological Impact Assessments (MODARIA[2]), which had the general aim of improving capabilities in the field of environmental radiation dose assessment by means of acquisition of improved data for model testing, model testing and comparison, reaching consensus on modelling philosophies, approaches and parameter values, development of improved methods and exchange of information.

The following topics were addressed in ten working groups:

Remediation of Contaminated Areas

- Working Group 1: Remediation strategies and decision aiding techniques
- Working Group 2: Exposures in contaminated urban environments and the effects of remedial measures
- Working Group 3: Application of models for assessing radiological impacts arising from NORM and radioactively contaminated legacy sites to support the management of remediation

Uncertainties and Variability

- Working Group 4: Analysis of radioecological data in IAEA Technical Reports Series publications to identify key radionuclides and associated parameter values for human and wildlife exposure assessment
- Working Group 5: Uncertainty and variability analysis for assessments of radiological impacts arising from routine discharges of radionuclides
- Working Group 6: Common framework for addressing environmental change in long term safety assessments of radioactive waste disposal facilities
- Working Group 7: Harmonization and intercomparison of models for accidental tritium releases

Exposures and Effects on Biota

- Working Group 8: Biota modelling: Further development of transfer and exposure models and application to scenarios
- Working Group 9: Models for assessing radiation effects on populations of wildlife species

Marine Modelling

- Working Group 10: Modelling of marine dispersion and transfer of radionuclides accidentally released from land-based facilities

The IAEA organized a programme from 2016 to 2019 entitled Modelling and Data for Radiological Impact Assessments (MODARIA II), which had the general aim of enhancing the capabilities of Member States to simulate radionuclide transfer in the environment and, thereby, to assess exposure levels of the public and in the environment in order to ensure an appropriate

[2] Herein after referred to as MODARIA I in order to differentiate between the two phases of the programme.

level of protection from effects of ionizing radiation associated with releases of radionuclides and from existing radionuclides in the environment.

The following topics were addressed in seven working groups:

- Working Group 1: Assessment and Decision Making of Existing Exposure Situations for NORM and Nuclear Legacy Sites
- Working Group 2: Assessment of Exposures and Countermeasures in Urban Environments
- Working Group 3: Assessments and Control of Exposures to the Public and Biota for Planned Releases to the Environment
- Working Group 4: Transfer Processes and Data for Radiological Impact Assessment
- Working Group 5: Exposure and Effects to Biota
- Working Group 6: Biosphere Modelling for Long Term Safety Assessments of High Level Waste Disposal Facilities
- Working Group 7: Assessment of Fate and Transport of Radionuclides Released in the Marine Environment

The activities and results achieved by the Working Groups are described in individual IAEA Technical Documents (IAEA-TECDOCs). This publication describes the work of MODARIA II Working Group 5, in addition to that carried out under MODARIA I in Working Groups 8 and 9.

1.2. BACKGROUND AND OBJECTIVES FOR MODARIA I AND MODARIA II WORKING GROUPS

In the early 1990s, protection of the environment from radiation was still based on a statement issued by the International Commission on Radiological Protection (ICRP) which stated that:

> "The Commission believes that the standard of environmental control needed to protect man to the degree currently thought desirable will ensure that other species are not put at risk. Occasionally, individual members of non-human species might be harmed, but not to the extent of endangering whole species or creating imbalance between species. At the present time, the Commission concerns itself with mankind's environment only with regard to the transfer of radionuclides through the environment, since this directly affects the radiological protection of man" [1].

Consequently, there was no international guidance on how to conduct assessments of the impacts of radiation on wildlife, or non-human biota, and no commonly used models for conducting radiological environmental impact assessments.

However, since the 2000s, requirements and guidelines for the protection of wildlife have been developed in some countries, e.g. Canada [2], Sweden [3], England and Wales [4] and the USA [5], with international organizations beginning to reconsider their position on the issue [6]. At the same time, coordinated multinational programmes to develop assessment tools were beginning in Europe [7–9].

Subsequently ICRP, in its Publication 103 [10], recommended the explicit consideration of radiological protection of the environment with the objective:

> “to maintain biological diversity, conservation of species, protection of the health and status of natural habitats, communities and ecosystems, with targets related to populations or higher organisational levels rather than individual organisms”.

As a first step to developing a framework for the protection of the environment, the ICRP introduced the concept and use of Reference Animals and Plants (RAPs[3]) [11].

The IAEA has a role in transforming the ICRP’s recommendations into practical guidance applicable in regulatory frameworks. Principle 7 of the IAEA Safety Fundamentals [12] states that **“People and the environment, present and in the future, must be protected against radiation risks.”** The IAEA elaborated a generic screening methodology based on ICRP Publications 108 and 124 [11, 13] to assess protection of populations of non-human biota within the framework of prospective radiological impact assessment for nuclear facilities, which was in turn included in a safety guide published in 2018 and co-sponsored by the United Nations Environmental Programme (UNEP) [14].

Recognizing that assessment models and approaches were being developed, the IAEA also established the ‘Biota Working Group’, Working Group 1 under Theme 3 of its EMRAS (Environmental Modelling for Radiation Safety) programme in 2004 [15, 16]. This provided a forum to begin to compare the various elements of the models being developed [17, 18], and where model predictions were compared with data from contaminated sites [18, 19] and suggestions for future developments agreed [20]. This led to further work during the EMRAS II, MODARIA I and MODARIA II programmes that comprised:

(1) The ‘Biota Modelling Group’ (EMRAS Working Group 4);
(2) Additional activities being initiated on radiation effects [21] and subsequently population modelling, starting with the ‘Biota Dose Effects Modelling’ Working Group’ (Working Group 6) within the EMRAS II programme;
(3) Continuation of the work in EMRAS II Working Group 6 in MODARIA I under Working Group 9 and MODARIA II under Working Group 5;
(4) EMRAS II Working Group 5 being established to compile radionuclide transfer parameters for wildlife [21];
(5) Continuation of the work in EMRAS II Working Group 5 in MODARIA I under Working Group 8 and MODARIA II under Working Group 5.

As part of the work, a cohort of scientists was established who have continued to collaborate outside of the IAEA programmes [22–27].

This publication presents a summary of the activities of the MODARIA I Working Groups 8 and 9, and the MODARIA II Working Group 5. These Working Groups considered different aspects of non-human biota, taking into consideration: (i) the estimation of the radiation exposure of wildlife (see Section 2 of this publication) and (ii) population effects modelling (Section 3 below). This publication concludes with a discussion and suggestions for further work on these topics (see Section 4).

---

[3] The RAP is defined as:

> “a hypothetical entity, with the assumed basic characteristics of a specific type of animal or plant, as described to the generality of the taxonomic level of Family, with precisely defined anatomical, physiological, and life-history properties that can be used for the purposes of relating exposure to dose, and dose to effects, for that type of living organism”.

2. ESTIMATING THE EXPOSURE OF WILDLIFE

This element of the work programme builds upon and continues activities initiated during the EMRAS I programme [15, 16]. The majority of these studies have now been published in various peer reviewed Journals; Appendix I provides a listing of papers published by participants of the Working Groups during the EMRAS and MODARIA programmes.

An overall aim of the work programmes was to evaluate whether currently used models are fit for purpose and to test their (often simplistic) assumptions to determine if the approaches used are generally protective.

2.1. ESTIMATING EXPOSURE IN CONTAMINATED ENVIRONMENTS: ANIMAL–ENVIRONMENT INTERACTIONS

Over the period that models, tools and radiological environmental assessment frameworks have been developed, there have been evaluations of the fitness for purpose of various model components (see Section 2.2 below for a summary of activities by the relevant working groups from the EMRAS and MODARIA programmes). An element of the assessment approach which had previously been overlooked was how animals interact with their environment and how this influences the radiation dose they receive. Currently in assessments dose rates to animals may be predicted using point of capture/assessment media activity concentrations, or averaged media activity concentration across an assessment site [14] or, alternatively, an assumed home range for a species. Some field studies may simply relate observations of purported radiation effects to ambient dose rate measurements using handheld detectors [27]. The use of animal movement models to assess non-radiological contamination had previously been proposed [28, 29].

At the outset of the MODARIA I working group activities on this topic, there was only one study that the group was aware of which considered this issue, a Chornobyl small mammal study [30], in which thermoluminescent dosimeters (TLDs) were attached to mice and voles at three sites in the Chornobyl Exclusion Zone. The results suggested that assuming the average ^{137}Cs activity concentration in soil across the assumed home range gave adequate external dose rate predictions (compared to results from the TLDs).

During MODARIA I, two activities were initiated to test the fitness for purpose of current approaches to estimating exposure of free ranging animals in the field using field studies involving reindeer in Norway (Section 2.1.1) and Elk in Sweden (Section 2.1.2).

2.1.1. Reindeer, Norway

Collars with dosimeters and GPS units were fitted to free ranging reindeer (*Rangifer tarandus tarandus*) in an upland area of Norway which received comparatively high deposition of ^{137}Cs from the 1986 Chornobyl accident, as detailed in a published study [31]. The dosimeters were recovered from 12 animals approximately 11 months after being fitted. Live monitoring data were available for the animals as was a spatial dataset of soil ^{137}Cs contamination. External dose rates were estimated using the ERICA Tool [32] from:

— ^{137}Cs soil activity concentrations averaged over the whole ranging area of the herd;
— ^{137}Cs soil activity concentrations for areas where the reindeer were known to visit based on the GPS tracking data.

The average ^{137}Cs dose rate to the 12 study animals was estimated to be approximately twice that estimated for the entire range area; collared reindeer mostly occupied areas with the highest ^{137}Cs soil concentrations as these were correlated with their favoured habitats. The external dose estimated using the GPS tracking data were in reasonable agreement with doses estimated from the collar mounted dosimeters. External exposure was the focus of this study; however, internal dose could be estimated from the available live monitoring data and this was approximately one order of magnitude higher than the external dose.

2.1.2. Elk, Sweden

Data were available for an area of Sweden in which long term studies of the behaviour of Eurasian elk (*Alces alces*) had been conducted [33, 34]. The data included GPS tracking locations for elk between 2006–2007, a ^{137}Cs deposition surface from post-Chornobyl aerial surveys, habitat and topography spatial datasets. The study, described in detail elsewhere (e.g. in Ref. [35]), compared different approaches to modelling exposure. The approaches were:

- *Conventional approach:* an appropriate spatial distribution of soil activity concentration for ^{137}Cs within the assessment area was generated. Estimations of exposure were made using a spatially adjusted mean soil activity concentration for the entire assessment area, 'suitable' locations within the assessment area (defined by habitat and terrain), and 'preferred' locations where habitat and terrain were ranked most highly.
- *Mass balanced foodweb approach:* a mass balanced food web model [36] was applied in a spatial context. Habitats were defined as 'unsuitable', 'suitable' and 'preferred'. Areas with a slope >10° was also defined as unsuitable.
- *Individual based movement approach:* spatially variable exposures to individual elk were modelled using a simplistic stochastic Lagrangian approach in which elk random walking movement was biased by known habitat and terrain slope preferences (defined as for the mass balance food web approach). The model was implemented in Goldsim Dynamic Monte Carlo Simulation Software[4].

Although the initial focus of this study was consideration of external exposure, the conventional and individual based movement approaches were both used to also estimate internal exposure. The conventional approach simply used an elk specific $CR_{wo\text{-}soil}$ (see Section 2.2.1 for general definition for $CR_{wo\text{-}media}$) value extracted from the Wildlife Transfer Database [37][5] to estimate the ^{137}Cs activity concentration of elk. The individual based movement approach used a simplified intake retention model in which the internal dose over time related to the soil–vegetation–elk uptake of ^{137}Cs along a 'foraging pathway' across the variably contaminated landscape was applied.

The main conclusion drawn from this study was that for screening tier assessments the conventional approach is sufficient for external exposure estimation. External exposure estimates were broadly comparable for the three approaches and the conventional approach was the simplest to apply and could be adapted to readily take into account habitat/terrain preferences. However, the individual based movement approach has the potential to estimate variability within a population and therefore may be useful for higher tier assessments and to inform the interpretations of field studies on radiation effects.

---

[4] Goldsim™; https://www.goldsim.com/web/home/
[5] See also http://www.wildlifetransferdatabase.org/

Internal dose was estimated to be 20–30 times higher than the dose due to external exposure with habitat/terrain preferences being important for the modelling of internal, as well as external, exposure. Predictions from the individual based movement approach demonstrated that internal dose rate will respond to spatial changes in soil contamination more slowly than external dose rate, which responds instantaneously. The slower response of internal dose rate is the consequence of organism uptake and loss rates of radionuclides being influenced by the radionuclide's biological half-life for the organism under consideration.

2.1.3. Discussion

From the studies summarized in Sections 2.1.1 and 2.1.2, it can be concluded that the 'conventional approach' of averaging soil activity concentrations over an appropriate area is suitable for initial screening level assessments.

The two studies outlined in Sections 2.1.1 and 2.1.2, and others published for wolves [38] and wild hogs [39], demonstrate that beyond basic screening level assessments that are based on maximum media activity concentrations, the application of organism specific knowledge of habitat/terrain preferences needs to be considered when estimating exposure. This may mean using different spatial extents (and hence media activity concentrations) for different organisms within an assessment area. The importance of spatial behaviour may vary between different organisms. For instance, it was found [30] that modelling dose rate assuming the average ^{137}Cs activity concentration in soil across the assumed home range gave adequate predictions of external exposure compared to the results of TLDs attached to small mammals (mice and vole species) at sites in the Chornobyl Exclusion Zone. The difference in conclusions reached between the small mammal study [30] and the findings of the elk and reindeer studies described above may be due to the limited spatial variation in soil contamination over smaller ranging areas.

A number of studies are now available in which modelled estimates of external dose can be compared to results from dosimeters attached to study animals, e.g. reindeer [31], snakes [40] and small mammals [30]. These studies all showed reasonable agreement between dosimeter estimates and model predictions.

The focus of the studies described above, along with other published studies [30, 38, 40], was to consider the estimation of external exposure. However, it needs to be noted that habitat/terrain utilization will also impact on internal exposure. Depending upon how animals utilize their habitats, the areas contributing most to internal dose may not be the same as those contributing to external dose (e.g. foxes may feed in areas relatively distant from their burrows). In the reindeer and elk examples, internal dose dominated total exposure. However, the relative contributions of external and internal exposure to total dose will depend upon ecosystem characteristics determining radionuclide transfer, and on the animal species and radionuclide.

The application of individual movement-based approaches could be used to consider variability in doses within populations in higher tier assessments and field studies on radiation effects.

Moreover, it is important to acknowledge that consideration of the importance of animal environment interaction on animal exposure has to date been restricted to terrestrial ecosystems and needs also be given to aquatic environments (e.g. spatial heterogeneity in sediment activity concentrations would impact on dose rates to mobile benthic organisms).

2.2. LESSONS LEARNT FROM THE IAEA PROGRAMMES

Within the EMRAS and MODARIA programmes, many model intercomparison exercises (model–model and model–data) and evaluations of the fitness for purpose of available models for use in regulatory assessments (see Appendix I) have been conducted. Throughout both phases of the MODARIA programmes, Working Group 8 (MODARIA I) and Working Group 5 (MODARIA II) brought together the many lessons from these activities in order to assist regulatory bodies and assessors. These 'lessons' have now been incorporated in a refereed paper [41] and are summarized in the following subsections.

2.2.1. Model selection

The majority of models developed for regulatory assessments over the last 20 years have common features:

- They contain a set of hypothetical organisms which do not represent any actual species but are representative of broad wildlife groups (e.g. mollusc, bird, tree);
- Organisms are represented as simple geometries (e.g. ellipsoids) to facilitate dose calculations;
- Precalculated dose coefficients (DCs) are used to estimate unweighted internal and external dose rates from organism and media activity concentrations respectively (e.g. μGy h^{-1} per Bq L^{-1} water for the external dose in the water column of aquatic ecosystems);
- They consider simplified ecosystems (e.g. freshwater, marine, terrestrial);
- Simple exposure geometries are used (e.g. on water, in the water column, at the sediment water interface, in sediment);
- Some form of 'occupancy factor' is used to describe the fraction of time an organism spends in the different exposure geometries;
- Equilibrium concentration ratios ($CR_{wo\text{-}media}$) relating the whole organism radionuclide activity concentration to those in media (where media is typically soil, water or air);
- For aquatic ecosystems equilibrium water–sediment distribution coefficients (K_d) are used;
- Radiation weighting factors are used for α, low β and high β and γ radiations to estimate weighted absorbed dose rates.

The more comprehensive models are structured to enable tiered assessments, beginning with simple conservative screening assessments and progressing to more refined assessments as necessary.

However, whilst the models have these common features, their default parameter values, namely for $CR_{wo\text{-}media}$, K_d and radiation weighting factors, can differ substantially [18]. The effects of this on model predictions are summarized below.

An overview of some freely available models based upon the activities of the working groups from the EMRAS and MODARIA programmes is provided in Table 1, and key advantages of each model are highlighted.

TABLE 1. FREELY AVAILABLE TOOLS FOR ASSESSMENT OF THE RADIOLOGICAL RISK TO WILDLIFE BASED ON THE FINDINGS OF THE WORKING GROUPS FORMED WITHIN THE IAEA EMRAS AND MODARIA PROGRAMMES

Model	Comment	Availability/Documentation
ERICA Tool	Supports tiered assessment approach. Allows additional radionuclides and organisms to be added	Software available from: http://www.erica-tool.eu/ Underlying reports: https://wiki.ceh.ac.uk/display/rpemain/ERICA+reports Special issue of Journal of Environmental Radioactivity: https://www.sciencedirect.com/journal/journal-of-environmental-radioactivity/vol/99/issue/9 Comprehensive integral Help file
RESRAD BIOTA	Supports tiered (or graded) assessment approach. Simple food chain models can be created and contaminated water as a source of intake by terrestrial animals can be modelled	Software available from: https://resrad.evs.anl.gov/codes/resrad-biota/ User guide and other publications: https://resrad.evs.anl.gov/documents/ Special issue of Journal of Environmental Radioactivity: https://www.sciencedirect.com/journal/journal-of-environmental-radioactivity/vol/66/issue/1
Radon dose calculator	Enables doses from ^{222}Rn and short lived daughter products to be estimated (a functionality missing from current versions of the ERICA Tool and RESRAD BIOTA)	Version (15/4/20): https://radioecology-exchange.org/content/radioecology-models Paper describing methodology: https://doi.org/10.1016/j.scitotenv.2017.06.154
Ar – Kr – Xe dose calculator	Enables estimation of doses from noble gases (important components of releases from nuclear reactors) to be estimated (a functionality missing from current versions of the ERICA Tool and RESRAD BIOTA)	Download via: https://radioecology-exchange.org/content/radioecology-models Paper describing methodology: https://doi.org/10.1016/j.jenvrad.2015.03.004
BiotaDC	Tool enabling dose coefficient to be calculated for the ICRP Reference Animals and Plants according to methodology used in ICRP Publication 136	On-line tool: http://biotadc.icrp.org/ ICRP Publication 136: https://doi.org/10.1177/0146645317728022
EDEN	Estimates exposure from Bq per unit mass or volume. Enables greater flexibility than default approaches in tiered assessment tools (e.g. heterogeneous soil/sediment contamination profiles)	Code can be requested via: http://www.irsn.fr/EN/Research/Scientific-tools/Computer-codes/Pages/The-EDEN-computer-code-Elementary-Dose-Evaluation-for-Natural-environment-2368.aspx Paper presenting the approach: https://doi.org/10.1097/01.hp.0000182192.91169.ed
D-DAT	A dynamic tool for the assessment of radiation doses to marine biota	Download via: https://radioecology-exchange.org/content/radioecology-models Paper describing methodology: https://doi.org/10.1016/j.jenvrad.2007.11.002

The ERICA Tool [32, 42] and RESRAD BIOTA [43] are the two most widely used assessment tools worldwide and both of these models support the implementation of tiered assessment approaches. However, these models currently lack some functionality which may be necessary for some assessment situations. For instance, noble gases are often significant components of releases from nuclear power plants [44], but, neither the ERICA Tool or RESRAD BIOTA currently have the ability to model noble gas releases. Whilst it might be expected, based upon assessments for humans [45], that doses to wildlife from noble gases will be low, ignoring significant components of radioactive releases from assessments is unlikely to be acceptable to stakeholders and regulatory bodies. A model has been developed for estimating the exposure of wildlife to ^{41}Ar, ^{85,88}Kr and ^{131m,133}Xe [46] and a similar methodology for estimating exposure from ^{222}Rn [47, 48], which can dominate the total exposure of wildlife due to natural background sources [49] is also available. Moreover, the latest version of the method also considers thoron exposures [48].

Models such as RESRAD BIOTA and the ERICA Tool use equilibrium concentration ratios ($CR_{wo\text{-}media}$) as collated elsewhere [21] to estimate radionuclide activity concentrations in organisms from those in soil, water or air. Such an approach is likely to be sufficient for the assessment of contaminated sites (i.e. existing contamination scenarios) and long term planned releases. However, for unplanned release scenarios involving abrupt changes in discharges, dynamic models may be necessary. This is especially true for organisms that respond slowly to a change in ambient radioactivity concentration [50]. The Fukushima accident elicited a desire to be able to predict the potential exposure of wildlife following accidental releases [51–53]. Whilst the working groups of the EMRAS and MODARIA programmes identified a number of dynamic models, most of these are unfortunately not freely available. However, an exception is the D-DAT model for marine ecosystems [54].

Under MODARIA I, Working Group 8, in collaboration with Working Group 10, compared the predictions of a range of dynamic marine models with those made using concentration ratios from the ERICA Tool for a location situated offshore from the Fukushima Daiichi site [55]. Figure 1 compares predicted ^{137}Cs and ^{131}I activity concentrations in benthic fish using the ERICA Tool with those predicted using the D-DAT dynamic model. The equilibrium model predicts that activity concentration will rise and subsequently decline more rapidly than the dynamic model. This is a consequence of the latter incorporating biological half-lives which result in a reduced rate of uptake and loss compared to the instantaneous equilibrium of the $CR_{wo\text{-}water}$ model. For ^{131}I, the rate of loss is dominated by the physical decay of the isotope ($T_{1/2} \approx 8$ d) and there is less difference between the two sets of predictions than for ^{137}Cs. After 100 days, the two models give more comparable results with much of the residual variability likely being differences in the $CR_{wo\text{-}water}$ values used in D-DAT compared to the ERICA Tool. To support the development of dynamic models, Working Group 8 published a collation of biological half-life values for terrestrial, marine and freshwater organisms [56].

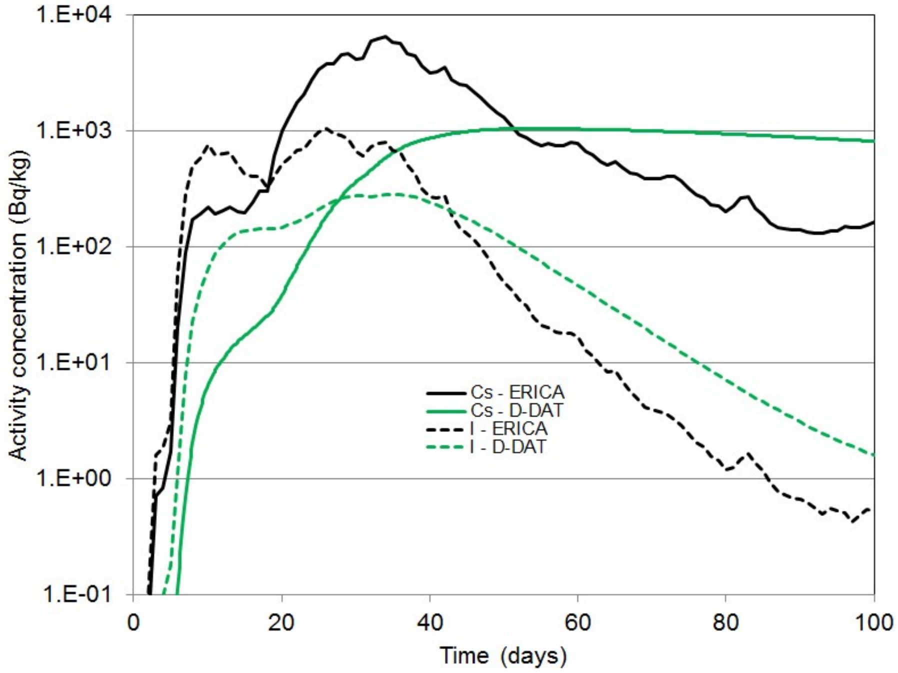

FIG. 1. Predicted changes in ^{131}I and ^{137}Cs activity concentrations in benthic fish (whole body). The predictions used modelled water concentrations with time '0' being 11 March 2011; the assessment site was assumed to be located 30 m north of the Daiichi drainage channels (adapted from Ref. [55]).

2.2.2. Radionuclide transfer

Model–model comparisons [18, 57] and the application of participating models in scenario applications (i.e. model–data comparisons) [19, 58–60] demonstrated that differences in $CR_{wo\text{-}media}$ values between models contributed most to variability in predicted estimated dose rates. For a given radionuclide–organism combination $CR_{wo\text{-}media}$ values may vary over four orders of magnitude. Such large variation is seen over all ecosystem and organism types and most radionuclides. The uncertainty potentially added to assessments by $CR_{wo\text{-}media}$ values led to a coordinated effort to collate values [21, 37] and improve the derivation of recommended $CR_{wo\text{-}media}$ values for different organism–radionuclide combinations [61]; these $CR_{wo\text{-}media}$ values have subsequently been used to (re-)parameterize models. These efforts also prompted studies to increase the range and depth of data available for models in specific environments such as tropical systems [62], arid systems [63] and pre- versus post-accident data for the Fukushima marine area [64]. Some organisms have life stages which utilize different environments (e.g. some insects, amphibians) and data are often lacking with regard to radionuclide transfer to non-adult life stages [21]. Recognizing the paucity of $CR_{wo\text{-}media}$ data for non-adult life stages, MODARIA II Working Group 5 undertook further studies to begin addressing these data gaps (e.g. [65]).

For aquatic ecosystems, K_d values may be equally as variable as $CR_{wo\text{-}media}$ values. However, until relatively recently, there has been less consideration given to the improvement of datasets. This situation has improved for freshwater systems with the publication of a compilation of K_d values [66, 67] in collaboration with participants of MODARIA I Working Group 4 who were working on K_d values.

2.2.3. Dosimetry – what matters and what does not

The dosimetric components of participating models have been compared in two intercomparison exercises considering predicted unweighted dose rates [17, 68]; the exercises made predictions of internal and external dose rate under the assumption of unit organism and media concentrations, respectively. Internal dose rates predicted by the various models were generally similar with 70% of predictions being within ± 20% [68]. Although external dose rate estimates were generally within an order of magnitude of each other, they were more variable than internal dose predictions. These differences were usually easily explainable, being related to: assumed media densities; the number of daughter radionuclides included in the parent radionuclide dose coefficients; differences in source target geometry (e.g. accounting for feather/fur shielding); source of data on radionuclides (e.g. energy, yield). Whilst explainable, the differences could lead to some systematic differences between models [69]. For external exposure, variation in estimates was generally greatest for α- and low energy β-emitting radionuclides. Where variation was considerable, the DC values tended to be low, for instance, the 'on soil' external ^{14}C DC for the ICRP Reference Rat geometry [11] ranged from 0 to 6×10^{-7} µGy h^{-1} per Bq kg^{-1} soil [17]. Therefore, it is highly unlikely that the variation in DC, although large, will actually add much to the overall variation in total estimated dose rates to any meaningful degree (because the DCs are relatively low and hence the external dose rates will be low whichever model is used). Application of the models to various case study scenarios [19, 57–60] demonstrated that differences in the dosimetry components of models contributed little to the overall variation in total dose estimates; differences in total dose are dominated by variation in predicted organism activity concentrations leading to variation in internal dose estimates.

2.2.3.1. *Uncertainty in wildlife dosimetry*

Organism size

The available models contain a relatively limited range of different default organism geometries. This can give rise to concerns that it is difficult for users to model specific organisms of relevance to them. However, in reality whilst there is an impact of mass on DC this is not that great [17, 41, 68] as can be seen from Table 2 which presents predicted external and internal dose rates using the ERICA Tool for organisms ranging over eight orders of magnitude in mass. Hence, in the mass range of most organisms, differences between default organism geometries and the actual geometry of any local organisms of interest will add little uncertainty to the overall dose rate estimation.

TABLE 2. A COMPARISON OF INTERNAL AND EXTERNAL DOSE RATES TO ORGANISMS OF DIFFERENT SIZES ASSUMING ORGANISM AND WATER ACTIVITY CONCENTRATIONS OF 1 Bq kg^{-1} FM AND USING THE ERICA TOOL [32]

Isotope	Fish egg mass 4×10^{-6} kg	Fish mass 1.5 kg	Seal mass 200 kg
External dose rate (µGy h^{-1})			
H-3	9.5×10^{-11}	3.7×10^{-13}	3.2×10^{-14}
Co-60	1.5×10^{-3}	1.2×10^{-3}	7.2×10^{-4}
Pu-240	9.6×10^{-7}	1.2×10^{-7}	2.6×10^{-8}
Sr-90	4.9×10^{-4}	1.9×10^{-5}	4.1×10^{-6}
Internal dose rate (µGy h^{-1})			
H-3	8.2×10^{-6}	8.2×10^{-6}	8.2×10^{-6}
Co-60	5×10^{-5}	2.6×10^{-4}	2.8×10^{-4}
Pu-240	3×10^{-2}	3×10^{-2}	3×10^{-2}
Sr-90	1.6×10^{-4}	6.3×10^{-4}	6.5×10^{-4}

Voxel phantoms

In estimating the dose rate to humans, voxel modelling is used. In contrast to the simplistic assumptions included in wildlife assessment tools (e.g. simplified geometry, homogenous distribution of radionuclides within organisms) voxel modelling utilizes advanced imaging technologies to generate realistic and detailed dosimetric phantoms to calculate radiation dose to individual organs via the Monte Carlo modelling method. A number of voxel models have now been proposed for wildlife species, such as crab [70], frog [71], small mammals [23, 72] and trout [73]. The voxel models are not proposed for application in regulatory assessment, however, they have been used as a mechanism of assessing whether the assumptions used in regulatory models are fit for purpose [23, 41, 73]. In summary, the findings of these evaluations were as follows:

- Dose rates calculated assuming a simple homogenous geometry generally agree with those calculated by organism specific voxel models within a factor of two to three;
- Variations in assumptions with regard to tissue composition and density will add little uncertainty to dose estimates;
- Highly heterogeneous distribution of radionuclides (e.g. ^{90}Sr in bone, ^{131}I in thyroid) will lead to organ specific dose rates that are considerably higher than estimated dose rates for the simple homogenous geometry.

Based on these evaluations, it can be concluded that the simplified homogenous geometries used within tools utilized for regulatory assessment are fit for purpose. Exceptions may be the few cases where a radionuclide accumulates in a relatively small organ (radioiodine accumulation in the thyroid is likely the most extreme example of this). Complex voxel models may have a role in aiding the interpretation of wildlife dose effect studies.

Soil water

For terrestrial ecosystems estimates of soil activity concentrations are needed to estimate external dose rates and possibly organism activity concentrations. To estimate external dose rates, DC values are in theory applied to fresh mass soil activity concentrations, whereas to estimate organism activity concentrations $CR_{wo\text{-}soil}$ values are applied to dry mass soil activity concentrations. External DC values were estimated to vary by a factor of approximately 1.5 over realistic ranges of soil moisture (dry to saturated) [74]. Compared to $CR_{wo\text{-}soil}$ values this adds little uncertainty to the estimation of exposure.

It is likely that assessors will input dry matter soil activity concentrations into their assessment. This is appropriate for conservative screening assessments as it will maximize the estimated external dose rate. However, for ecosystems with high soil moisture content (e.g. wetlands) fresh mass soil activity concentrations need to be used to estimate external dose rates. For instance, it has been demonstrated [59] that external dose rates using a reported soil dry matter content of 10% were an order of magnitude lower than those calculated using soil dry mass activity concentrations; converting to a fresh mass soil activity concentration resulted in an order of magnitude decrease in the soil activity concentration in effect by dilution.

Inhomogeneous radionuclide distribution on soil/sediment profiles

While radionuclide activity concentrations are likely to vary with depth in soils and sediments, assessment models typically assume homogeneous distributions. It has been demonstrated [75] that external dose rates could vary over three orders of magnitude when considering realistic soil dwelling organism locations and radionuclide profiles and that an assumption of homogenous distribution was not necessarily conservative. However, for conservative screening assessments, assuming homogenous radionuclide distribution in soils and sediments will be conservative if the maximum soil activity concentration (from any soil layer) is the method used.

Radioactive decay and daughter products

'Short lived' radionuclides generated by radioactive decay are included within the DC for the parent radionuclide in many models with secular equilibrium between the parent and daughter radionuclides being assumed [17]. The rules defining which radionuclides are included within the parent DC varies between models. For instance, in the current ERICA Tool version (v1.3) [32] the parent DC includes daughter products with decay half-lives of ≤ 10 days while in the initial assessment levels of RESRAD BIOTA [43] the half-life cut-off is 100 years. Users need to understand these rules and ensure that they do not double account by considering the daughter radionuclide separately from the parent in the assessment (e.g. RESRAD BIOTA includes ^{234}Th (half-life approximately 24 days) in the DC of ^{238}U). An implicit assumption on including daughter radionuclides in the parent DC is that the transfer of the daughter to organisms is the same as that of the parent, which is not always the case.

The validity, and conservatism, of this assumption has not been investigated. Ideally daughter radionuclides would be modelled separately and the approach for the assessment of the impact of radioactive discharges to the environment to wildlife[6] would adopt this approach which is based upon ICRP Publication 136 [77]. However, this approach requires $CR_{wo\text{-}media}$ values for daughter radionuclides, some of which are elements for which there are few $CR_{wo\text{-}media}$ values available. This requirement for additional $CR_{wo\text{-}media}$ values may add uncertainty to the assessment.

2.2.4. Using the models in assessments

The available models have limitations with respect to, for instance, the default ecosystems, organisms considered, exposure geometries and input requirements. However, as discussed below, it is possible to use the models in ways which circumnavigate some of these limitations.

2.2.4.1. Ecosystems

Models consider generic ecosystems, for example terrestrial, marine and freshwater in the ERICA Tool and terrestrial, freshwater and riparian in RESRAD BIOTA. However, assessors may need to consider different ecosystems, migratory species or organisms spending time in more than one ecosystem type.

In some instances it may be possible to re-parameterize the $CR_{wo\text{-}media}$ values to be representative of the ecosystem under consideration. For example, the Wildlife Transfer Database contains data for estuarine ecosystems [37]. If an organism which inhabits more than one ecosystem type (e.g. duck species) requires assessment then, for a conservative screening assessment, risk quotients for each radionuclide could be estimated separately for the different ecosystem types with the overall risk quotient being the sum of the most conservative radionuclide specific values regardless of the ecosystem. For a more refined assessment, estimates of the time spent in the different ecosystems could be used together with consideration of which ecosystem(s) is used for food.

[6] A new approach is under development and will replace that used in Ref. [76].

Assessor choice when considering organisms which may inhabit different ecosystems can result in considerably different dose estimates. In a published example [59], assessment predictions for wetland ecosystems were compared and it was found that dose estimates varied by up to three orders of magnitude depending on the choices made by the assessor.

2.2.4.2. Exposure geometries

There are limitations in most assessment models on the organism and exposure geometries that can be considered. In the terrestrial ecosystem for example, the ERICA Tool allows birds to be on soil or in the air whereas mammals can be on the soil surface or in soil. However, assessments might be necessary for birds that burrow (e.g. *Fratercula arctica*) or flying mammals (e.g. bats). While it may appear that the ERICA Tool could not model these organisms, the bat could potentially be modelled as a bird (organism density assumptions in the model are the same for both mammals and birds) if an external dose rate in air is needed, and a dose rate for *F. arctica* in burrows could be estimated by modelling it as a burrowing mammal. A model intercomparison exercise for an area containing contaminated waste trenches [57] gives examples of how non-standard organism exposure geometries can be modelled.

The appropriateness of default geometries for plants in some approaches requires consideration. In some approaches (e.g. Refs [11, 77, 78]) the geometry for plants represents above ground parts (e.g. tree trunk) whereas in many situations plant roots may be the most exposed plant parts. Although some approaches allow users to create geometries representing roots, as discussed previously [57], it may be appropriate to have plant root as a default geometry.

2.2.4.3. Model inputs ^{3}H and ^{14}C

In some approaches specific activity models are used to predict ^{3}H and ^{14}C activity concentrations in terrestrial organisms. These approaches relate organism activity concentrations to air concentrations, not soil activity concentrations as is the case for most radionuclides [18]; this is similar to some approaches for estimating ^{3}H and ^{14}C transfer to human foodstuffs [79]. However, in some instances assessors will have soil but not air concentrations available (see the example given in Ref. [59]). Therefore, guidance on how to estimate an air activity concentration from a soil concentration is needed.

The underlying assumption of a simple specific activity model is that the ratio of the concentrations of radioactive and stable isotopes is the same in all environmental compartments. Therefore, in the case of ^{14}C, if the soil activity concentration is known, ^{14}C air concentrations can be approximated as follows:

$$^{14}C_{air} = \frac{^{14}C_{soil} \times 0.2}{Soil\ Carbon} \qquad (1)$$

where:

$^{14}C_{soil}$ is the activity concentration of ^{14}C in soil (Bq kg^{-1});
$^{14}C_{air}$ is the activity concentration of ^{14}C in air (Bq m^{-3});
Soil Carbon is the concentration of stable carbon in soil (g kg^{-1});
0.2 is the typical stable carbon content of air (g/m^{3}) [21].

For ^{3}H, the assumption can be made that the activity concentration in air moisture (C_{AM}, Bq m^{-3}) will be equal to that in soil water (C_{SW}, Bq m^{-3}). The concentration of ^{3}H in air (C_{air}, Bq m^{-3}) can then be estimated as follows:

$$C_{air} = C_{AM} \times H_A \tag{2}$$

where:

H_A is the absolute humidity (kg m^{-3}).

Typical H_A values for different climates are presented in Ref. [80], which also presents a methodology for estimating H_A from relative humidity if already known. This approach will give an approximation of the ^{3}H concentration in air which can be input into models. However, it needs to be noted that root uptake may be the dominant source of ^{3}H in plants at sites with contaminated soil and/or groundwater [81, 82].

2.2.5. Best practice approach – coping with missing data and daughter products

During the course of assessing the various scenarios, issues were encountered with respect to dealing with missing data (e.g. for a specific daughter product within a decay chain). This was most notable for the scenarios which considered lakes impacted by uranium mining and processing industries [60, 83]. Some best practice guidance has been suggested to aid future assessors; this is summarized below and can be found in more detail elsewhere [41]:

- If only water activity concentrations are available for an aquatic assessment: to calculate sediment activity concentrations a best estimate K_d value is used, e.g. the mean value for similar sites or a value selected from an up to date comprehensive review [66, 67].
- If only sediment activity concentrations are available for an aquatic assessment: to calculate water activity concentrations a best estimate K_d value is used, e.g. the mean value for similar sites or a value selected from an up to date comprehensive review [66, 67].
- If media activity concentrations are lacking for radionuclides within a decay chain for an aquatic assessment: secular equilibrium in the same media is assumed, preferably with the closest member in the decay chain for which data are available. For the ^{238}U and ^{232}Th decay chains, radon and thoron gas will escape; ^{210}Po and ^{210}Pb activity concentrations in media can be assumed to be 80% of the ^{226}Ra activity concentrations [84].
- If sufficient whole organism activity concentrations are available for organisms of interest, then these are used in the assessment. Moreover, consideration needs to be given to the amount of data available versus the quantity and provenance of $CR_{wo\text{-}media}$ values available in the Wildlife Transfer Database[7] [37].
- If whole organism activity concentrations for a given organism are not available at an assessment, data for the most similar species at the same site are used if available.
- If no measured data for a given organism are available at a site, then the whole organism activity concentration is predicted using $CR_{wo\text{-}media}$ values preferably from measurements made previously at the assessment (or similar) site if sufficient measurements are available; if no relevant $CR_{wo\text{-}media}$ values are available then they can be obtained from the Wildlife Transfer Database.
- If neither $CR_{wo\text{-}media}$ values or whole organism activity concentrations are available for the specific radionuclide–organism combination, then extrapolation approaches as described elsewhere [32, 85] are used.

[7] The database can be accessed: http://www.wildlifetransferdatabase.org/

3. MODELLING AND DATA FOR ASSESSING RADIATION EFFECTS ON POPULATIONS OF WILDLIFE SPECIES

3.1. BACKGROUND

Over the last 20 years, an international system for the protection of wildlife from ionizing radiation has emerged. As part of this, it has been necessary to implement an approach to determine the potential effects of environmental exposures. This approach is based on Environmental Risk Assessment (ERA) methodologies, equivalent to those used for chemical substances [86, 87], and whose aim is also to protect populations and biodiversity. The ERA approach is aimed at estimating environmental risk for exposed non-human biota at different levels of biological organization for many wildlife groups. The risk determines the probability and magnitude of adverse effects that occur (for example in exposed individuals, populations, communities, ecosystems) for different groups of wildlife.

In order to be able to determine the level of risk, the output from an ERA needs to be compared to numeric criteria to determine the level of risk to wildlife. For example, the ERA approach developed in ERICA [32, 42] uses a generic Predicted No Effect Dose Rate (PNEDR) (which is equivalent to Predicted No Effect Concentration (PNEC) for chemicals) for the protection of ecosystems 10 μGy h^{-1}, which is considered incremental to the natural background [88–92]. Other numeric criteria called Derived Consideration Reference Levels (DCRLs[8]) have also been proposed by the ICRP in Publication 108 [11]. DCRLs have been defined for a set of twelve Reference Animals and Plants (RAPs) that have been identified by the ICRP [11], as it is impossible to consider all species of flora and fauna in assessments. These RAPs are the reference deer, rat, duck, frog, trout, flatfish, bee, crab, earthworm, pine tree, wild grass and brown seaweed. For screening prospective assessments in regulatory frameworks for nuclear facilities, the IAEA recommends the use of ICRP RAPs and DCRLs [14] noting that this is also compatible with the use of reference organisms and radiological criteria as recommended in the ERICA approach [32, 42].

There is a degree of discrepancy between traditional chemical ERA methods, most often measured at the individual level in a limited number of test species, and the recommended goal for radiation protection of the environment which is ‘to ensure ecosystem function by protecting the sustainability at the population level, of the vast majority of all species’. It is recognized that special attention needs to be given to ‘keystone, foundation, rare, protected or culturally significant species’ [89, 93].

Furthermore, radiation effects data for actual populations encountered in the field are rather limited, requiring assessors to use laboratory data and make assumptions on their extrapolation, which introduces uncertainties into the assessment. Frequently, this is addressed by incorporating some level of precaution in the ERA by, for example, dividing the PNEDR values derived from individual level radiotoxicity data by a safety factor. A comparative study of radiotoxicity data between laboratory tests and the Chornobyl exclusion zone suggested that

[8] The DCRL is defined as follows (see Ref. [14]:

> “a band of dose rate within which there is likely to be some chance of deleterious effects of ionizing radiation occurring to individuals of that type of reference animal and plant (derived from a knowledge of defined expected biological effects for that type of organism) that, when considered together with other relevant information, can be used as a point of reference to optimize the level of effort expended on environmental protection, dependent upon the overall management objectives and the relevant exposure situation.”

PNEDR values might differ by more than one order of magnitude between controlled experimental and natural field conditions [94].

Within both MODARIA programmes, the IAEA posed the key question: "Which dose rate levels do not affect populations and ecosystems?", thereby framing the question in terms of population modelling and the data available to parameterize them. The objective was to apply population models to different exposure situations, learn from these applications (in particular aspects relating to spatial and ecological issues), identify or conduct new experimental studies or data against which to test models and increase where possible the robustness of model assumptions and hence predictions. Where possible, data and models for species representative of the RAPs were the focus of the work undertaken. The available science was to be examined in relation to the requirements established in the IAEA safety standards in relation to the assessment and regulation of radioactive releases to the environment, taking advantage of the international forum provided by the MODARIA programmes for the exchange of experience, ideas and research information.

3.2. DEVELOPMENT OF THE MODELLING AND DATA FRAMEWORK (MODARIA I)

3.2.1. Introduction and scope

Working Group 9 (WG9) was established as part of the MODARIA I programme and comprised some 20 researchers and regulators with the IAEA as a key stakeholder. It had, as its overall objective, the assessment of radiological effects on populations of various representative wildlife species, with a focus on developing and promoting modelling methods to link effects reported for laboratory or field organisms to their integrated consequences on populations. To fulfil this objective, exposure conditions, dose response relationships for relevant life history traits and life history characteristics of the considered species, over their entire life cycles, needed to be described in a form amenable to the derivation of parameters for modelling. Working Group 9 also identified key endpoints for use in population modelling that could be used as a basis for assessing protection levels for populations. Working Group 9 did not propose that any population models developed are to be used for regulatory purposes, but rather presented a mathematical solution, or conceptual model, for use in determining the robustness of the benchmarks for use in wildlife radiological assessment.

Initial discussions by WG9 focused on answering the question: "How can population models be used to test the robustness of benchmarks such as the DCRLs?" It was concluded that models need to be kept as generic as possible and be applicable to different species, with an adequate degree of realism (region of interest related to the exposure situation, population size, geographical range, survival areas); avoiding models that are too complicated. Population models for radiation protection of wildlife need to focus on basic ecological interactions, such as monospecific population responses of reference species, and then be applied to representative wildlife species (including RAPs) so that they can be used to assess population effects against the relevant DCRL. Comparisons of population outputs with thresholds for effects at the level of individuals in experimentally controlled exposures (such as those provided by studies collated within FREDERICA[9]) are also possible, in order to assess whether a population type assessment is more or less restrictive than the appropriate benchmark that is being applied within an assessment.

[9]www.frederica-online.org

The need for reviewing relevant chronic experimental and field data was underlined, in order to transform them to quality assured models that are applicable to chronic dose rate exposure situations. It was also deemed necessary to establish a conceptual model that takes into account both acute and chronic exposure situations, operating at the community level and integrating ecophysiological factors such as food limitation, density dependence, self-limiting growth and animal mobility. This established the basic philosophy to follow during MODARIA I and MODARIA II.

The following tasks were undertaken within WG9:

- **Task 1:** Identification of sources of population modelling parameter data, involving reviews of laboratory and field studies, leading to life history and ecology data, as well as radiation effects datasets. Of particular importance here are life history parameters for a number of species, i.e. bee and other insects (*Drosophila*); duck; salmon, frog, crab and other benthic crustaceans (lobsters); pine tree, wild grass, brown seaweed and any other species which relate to the ICRP RAPs and have previously well studied radiation effects.
- **Task 2:** Compilation and evaluation of population models, leading to selected practical approaches to radiation dose effect modelling in wildlife. This was to include a comparison of radiation dose effect models developed for EMRAS II Working Group 6 and STAR[10] WP5 (ordinary differential equation (ODE) population models) and physiology based matrix population models (DEBTox applications from STAR).
- **Task 3:** Methodological guidance for population modelling, including the preparation of a definition for 'population' for modelling purposes in the context of radiation protection, formulation of a mathematical solution or conceptual model for specific animals and plants using effects data from both acute and chronic radiation exposures, and focusing on the repair mechanism and its influence on the three effects endpoints; mortality, morbidity and reproduction (fecundity).
- **Task 4:** Conducting an ongoing review of data on historical adaptive responses and hormetic effects of low dose exposure, as part of an effort to identify what data are available for population modelling.

3.2.2. Population modelling life history and radiosensitivity data

A biological description of each representative species identified for potential use in population modelling was performed. It was decided to focus on species that are representative of the taxonomic groups represented by the ICRP RAPs [11] considering their different life stages. For example, the ICRP 'Reference Deer' is representative of a large terrestrial mammal. Deer are important components of ecosystems and have been the subject of various radioecological studies. Likewise, the ICRP 'Reference Rat' is representative of a small terrestrial mammal, and with the exception of humans, there is probably more information on the effects of radiation on rodents than on any other mammal. The ICRP 'Reference Duck', representative of an aquatic bird, can be viewed as a bird that is 'typical' of wetland areas [11]. The ICRP 'Reference Bee' is representative of a terrestrial insect, the ICRP 'Reference Crab' of a marine crustacean, and the ICRP 'Reference Earthworm' of a terrestrial annelid. For all of the RAPs, life history parameters and radiosensitivity data were gathered.

[10] Strategy for Allied Radioecology, the EC-funded Network of Excellence in Radioecology (https://www.ceh.ac.uk/our-science/projects/strategy-allied-radioecology-star)

Some other species were explicitly included if they had been modelled by any of the WG9 participants in the context of population modelling, such as, for example, the European lobster (*Homarus gammarus*) and various fish. In addition, a primary focus was given to species for which at least one chronic gamma effect on survival, fecundity or hatching is described. Overall, the selected species covered several taxonomic groups including aquatic and soil invertebrates (i.e. molluscs, annelids and arthropods) as well as fish and terrestrial mammals. Some additional species for which no relevant chronic effect data were available were also included in the review (i.e. *Lumbricus terrestris* and *Sus scrofa*). The earthworm *L. terrestris* was included in order to explore how the difference in life history characteristics compared to a closely related species (i.e. *Eisenia fetida*) may influence population responses, assuming the same individual radiosensitivity with respect to reproduction endpoints.

The AnAge curated database of ageing and life history in animals[11] provided another accessible and extensive collection of information suitable for population modelling, including average lifespan, average mortality rate, reproduction rate, survivorship of youngling and adults, death rates, biomass (and loss rate); germination rate, flowering rate, carrying capacity, which can be used in models to parameterize standard ecological processes. Radiation effects data linking effects for the relevant endpoints (i.e. mortality, morbidity and reproduction) were identified with the FREDERICA database, a primary information source for this project [95–97] and in a focused article on species radiosensitivity [98]. This allowed the production of a summary of the species and endpoints that have been studied in field experiments.

A collection of relevant life history, ecology parameters and radiation effects datasets for animals and plants was eventually produced. A template was developed to accommodate the relevant data, and this continued to be updated during both the MODARIA I and II programmes. The dataset contains, for example: 300 references for plants e.g. wild grass, and 40 references dealing with *Pinus* (mainly *sylvestris*); data on salmonids, insects (e.g. *Drosophila* and bees); data on Daphnia and 14 other species from the EC STAR project including nematodes, frogs, marine crustaceans (e.g. *Homarus gammarus*) and many other species. The habitats of the different life stages were noted and indicated, with care being taken to avoid unnecessary complexity, yet collecting life stage information at the highest life stage resolution that is possible to avoid missing opportunities for describing critical life stages.

The main conclusion of this part of the work was that there are sufficient data to parameterize population models for most of the ICRP RAPs, mainly for single age class models but also for multiple age class models in some cases, and that the principal sources of information are the AnAge curated database for life history data and the FREDERICA database for radiosensitivity data.

3.2.3. Review of population models

3.2.3.1. Identification of population models

A literature search for existing population models for each representative species was performed in the online databases. Models were selected and listed, along with a description of any particular life cycle format used (if present) along with model applications. Population models were found for amphibians (frogs); fish (flatfish, trout and salmon); insects (bees) and crustaceans (crab and lobsters). Models reviewed belonged to two main categories, namely:

[11] https://genomics.senescence.info/species/

— Stage structured or age structured matrix models often including a density dependent parameter; or
— ODE models, i.e. models based on solving a system of ordinary differential equations representing the population with time as a continuous variable.

Most population models have been applied to non-radiological stressors; few models have been specifically developed for radiation effects. Population modelling has been introduced in the field of radioecology [99–102] and a number of population models have been developed to consider the impact of radiation on mortality, fecundity and radiation damage repair [103, 104]. The concept has been extended to include age structure, such as the four age groups model for the European lobster *Homarus gammarus* combining reproduction, removal by predation, natural death, fishing, ionizing radiation effects and migration [105]. After being identified in the initial review, models of this type were further developed and applied in the modelling activities performed during the MODARIA II programme.

A number of population models were identified for vegetation, as well as an overview of models for plants, summarized in Refs [106, 107]. This included models for pine tree population response to various stressors including climate change. Matrix models have also been used to model the number of trees in each stage or age class [108]. In the case of algae (brown seaweed), structured matrix models exist for predicting general density dynamics, and also ODE models with the population biomass usually expressed as a whole without discriminating between size or life history phases. Another study [109] combined the two model types into a model for macroalgae which modelled biomass and numerical density of predefined size classes simultaneously, as a function of time.

Finally, a mathematical modelling approach to understand the ecological effect of chronic irradiation in a microcosm microbial system was also evaluated [110]. The model is an ODE approach, with a variant of the Lotka-Volterra equation. The system consisted of defined microorganisms, namely, the free living heterotroph protozoa *Tetrahymena thermophila B*, the autotroph algae *Euglena gracilis* and the heterotroph bacteria *Escherichia coli.* This study compared different experimental results with model predictions based on acute experimental data, leading to a new model for chronic exposure. Through this model, it is possible to explore the concept that a real ecosystem is too complex to evaluate the ecological effects of an environmental stressor, so a closed experimental ecosystem (microcosm) which is self-contained and more simplified, is used in conjunction with a mathematical model of the microcosm.

The main conclusions arising from the several hundred studies identified were that:

— Very few studies consider recovery after external stress;
— The models reviewed tended to be based on a limited amount of information, and were specific for very particular sets of conditions;
— Most studies use density independent models with no competition considered;
— Most models are heavily grounded in basic biology, with information on life history that is relatively easy to find.

3.2.3.2. Sourcing of radiosensitivity information and issues identified

Participants of WG9 reviewed the basic radiation effects data for population model parameter estimation. Key data were obtained, such as $LD_{50/30}$, LD_{100}, dose producing sterility, life shortening at different dose rates, recovery rate after non-lethal acute exposure, percentage of reversible damage in tissues and doses producing total depression of immunity. These data were transformed into the modelling parameters needed to run an ODE radiation repair type of population model, set up for two mammal species of different size and lifespan, i.e. mice and wolf.

Modelling studies were identified, whose aim was to test the hypothesis that population level endpoints might be more radiosensitive than individual level endpoints for a wider range of animal species. Some of these studies have suggested applying population models of representative wildlife species to investigate population responses to ionizing radiation [111–113]. Expanding on this aspect, as part of the research conducted during STAR, population modelling was carried out for aquatic invertebrates exposed to chronic gamma radiation [113], using matrix models known as 'Leslie matrices' [114]. The model simulations appear to support the hypothesis that in some species, the endpoints at population level might potentially be more radiosensitive than individual level endpoints (e.g. the response by the modelled population was observed to have resulted from simultaneous effects affecting several individual level modelled endpoints).

Another issue raised by this review was that the small number of population models that consider radiation do not take important factors like radio adaptation into account, and that adaptation effects are not presently included in species sensitivity distributions presently[12]. Overall, the source of information most directly relevant for the work performed during MODARIA I was the deliverable report D5.2 of the EC programme STAR [115]. This report was particularly useful for the modelling work performed during MODARIA I and II as it contained mature examples of both matrix and radiation repair ODE modelling, and thus formed the initial basis of much of the subsequent MODARIA I model development work.

3.2.3.3. Contributions from members of MODARIA I Working Group 9

MODARIA I WG9 work continued in the direction of the aforesaid investigations with a detailed study on population modelling to compare chronic external gamma radiotoxicity between individual and population endpoints in four taxonomic groups, covering 12 laboratory species (including aquatic and soil invertebrates, fish and terrestrial mammals); thereby enabling the transition from individual to species population level effects using Leslie matrices. A successful comparison of the radiosensitivity between individual and population endpoints was made as well as an examination of how protective the internationally proposed benchmarks for environmental radioprotection were against various risks at the population level; this was reported in the first major publication from the Working Group [99]. Matrix models combining life history and chronic radiotoxicity data derived from laboratory experiments were used to simulate changes in population endpoints for a range of dose rates. Model predictions indicate that proposed reference benchmarks for different taxonomic groups are protective of all simulated species against population extinction, and that the ERICA reference benchmark of 10 μGy h^{-1} is adequate as a protection criterion for all simulated species against 10% of the effect causing population extinction.

For vegetation, both a simple working ODE biomass model for grass and a matrix (age structured) population model were proposed. The ODE model included vegetation specific processes such as seasonal variations in germination, flowering and seed production. A comparative analysis of both types of plant model was therefore possible. Spatial coverage of the model, competition between grass species and meta populations (distinct patches coupled by dispersal) were identified as additional processes that might need to be included in future model developments.

[12] This was modelled in detail at a later date during the MODARIA II programme.

Additional work within WG9 also led to a model being developed with distinct compartments for the different individual types of bees (i.e. workers, males and females/queen). This work, in addition to the presentation of a mechanistic toxicity study on *Daphnia magna* [112, 116, 117], shows that it is feasible to use the Leslie matrix approach to test benchmarks for individuals in order to investigate how populations respond to them, and that this approach allows for the incorporation of modes of action and effects; it being possible to fit the DEBTox equation to the available data and to easily adapt it to different species. Matrix modelling was also used to show that community level interactions might play an important role, and such a model could be validated by designing experiments (such as irradiation of beehives) to gain new data based on model predictions. On the other hand, the matrix modelling approach has the limitations that the models reviewed are density independent, do not include seasonality and they are not really designed for forecasts in the long term.

3.2.3.4. Main conclusions of the population modelling review

The main conclusions of the population modelling review were that:

- Both matrix and ODE approaches are applicable for determining the sensitivity of different end points to chronic and acute doses of radiation in wildlife populations;
- Stage based matrix models are more common in the literature;
- Matrix models can be kept relatively simple, assuming density independence and deterministic population dynamics (where vital rates remain constant).

Consequently, these models can be used to predict exponential population growth or decline, determine the age stage distribution throughout the population and the reproductive rates for each class.

Regarding ODE models, several mathematical formulations including the Malthus model, a logistic model, a single age fecundity repair model and dual age class radiation effects modelling were available [103, 104, 118]. ODE models are amenable to the amalgamation of processes in a flexible set of differential equations, which allows testing of process sensitivity and the effect of multiple stressors in a broader ecological context within a mathematical framework. The potential of the ODE approach as a heuristic tool for conceptual development of the approach for radiation dose to populations was therefore highlighted, including its ability to combine, in a relatively simple phenomenological approach, the impact of multiple stressors on populations.

3.2.4. Formulation of a mathematical methodology for population modelling

3.2.4.1. Definition of population for the purposes of population modelling

The first step in the formulation of a mathematical methodology for population modelling is to have a working definition of population for the purposes of modelling. Two complementary definitions were proposed within WG9:

- Population definition 1 (model cohort) from the perspective of dose criteria, the population is defined as a group of individuals exposed to the same level of radiation stress modelled through an ecological approach to simulate the collective response of a group. Population growth rate, carrying capacity and minimum viable population might be the targeted endpoints.
- Population definition 2 (assessment model) based on the operational definition of the assessment population in which individuals with common ecological characteristics (as defined by the ecological parameters of the population) undergo different exposure conditions.

At a given dose level, a population can be considered to be protected if, following a continuous constant level of dose in the presence of all relevant natural stressors, the total size of the different age classes in the population decreases temporarily relative to the control population, but eventually tends towards a new stable level. The problem is that communities change due to many factors so the impact of radiation in this context is hard to prove unless the problem is framed not only in terms of radiation biology but also within an ecological framework.

Consequently, the modelling problem to be solved is how to deduce the dose rate that induces population extinction or (for a matrix model) the reduction in the population growth rate parameter (λ) that causes extinction.

3.2.4.2. Mathematical model formulation

Different approaches can be formulated to predict actual wildlife population dynamics under the effect of radiation. The simplest of all the sufficiently realistic approaches are:

— A first order ODE approach based on logistic growth [119, 120] (see Eq. (3));
— the Leslie matrix approach [121] (see Eq. (4)), which is a discrete population model of finite age classes.

In their simplest conception, both approaches can be described as follows:

$$\frac{dx}{dt} = rx\left(1 - \frac{x}{k}\right) - \alpha x \tag{3}$$

$$\boldsymbol{x}(t+1) = (1-\alpha)\boldsymbol{L}\boldsymbol{x}(t) \tag{4}$$

where:

x denotes the population density;
r denotes the intrinsic growth rate per individual which is equal to the reproduction rate of the female population multiplied by the fraction of females (y^{-1});
α denotes the mortality rate due to the irradiation (y^{-1}) in the logistic model (or the probability of death in the matrix model);
K denotes the carrying capacity;
$\mathbf{x}(t)$ denotes the vector of the population density in each age ($x_0(t)...x_n(t)$);
L denotes the life table (matrix).

It needs to be noted that the matrix model is a discrete time model, whereas the ODE models are continuous time models.

In the Leslie matrix approach, the population is represented as an age structured vector N(t) containing the numbers n_i(t) of individuals in each age class i at time t, with i the individual age ranging from 1 to i_{max} [122]. All existing age classes instantaneously advance one age class at discrete, equidistant time intervals Δ. The number of eggs in $n_1(t)$ depends on the cumulative reproductive investment of individuals in all cohorts over the time interval (t + Δ, t). The population at t + Δ is obtained from the following equation:

$$N(t+\Delta) = A \times N(t) \tag{5}$$

where:

A is the transition matrix of size $i_{max}\times$.

The elements of the matrix, A are the survival rates P_i , or probability that an individual of age class i survives to the next age class over the time interval $t + \Delta$, t) arranged on the subdiagonal of A; and the fecundity rates F_i for each age class i arranged on the first row of A.

In the case of continuous variable ODE population models (in which population and time are not discrete but continuous variables) a system of ordinary differential equations is to be used, as in the following example of dual age class model:

$$\frac{dN_0}{dt} = M_0(t) - sN_0 - d_0N_0 + I_0(t) \tag{6}$$

$$\frac{dN_1}{dt} = sN_0 - d_1N_1 + I_1(t) \tag{7}$$

where:

N_i is the abundance at time t ($i = 0$ for juvenile and 1 for adult);
$M_0(t)$ is the number of offspring generated per unit time;
s is the growth rate from juvenile to adult;
d_i are the intrinsic rates of juvenile or adults loss due to mortality (intrinsic and predation);
$I_i(t)$ represent immigration for each age group of the population.

In this ODE model, the interlife stage rate constants are equivalent to the interstage probabilities of the Leslie matrix; however, in this case the variables are continuous.

This linear model assumes ideal resources (food, shelter, temperature and living space) at the start of the simulation. As the population grows, however, individuals interfere with each other by competing for some critical resource, such as food or living space, as modelled by the logistic equation described above.

MODARIA I WG9 proposed the 'radiation damages recovery and repair' ODE approach [104] as the viable ODE model to adopt. In this type of model, the population consists of healthy and sick individuals, all having a repair mechanism, but in the sick individuals this mechanism is impaired (expressed as a reduction of a 'repair pool'), wherefore some sick individuals can become healthy and some will die. At high radiation doses, the repair pool is totally impaired and the model therefore allows a seamless transition from chronic to acute effects. Only individuals labelled as 'sick' can die from radiation exposure, although healthy individuals can die of natural causes. Radiation repair is based on the concept of the repairing pool operating at a phenomenological rather than molecular level. The repair pool is 100% (expressed in relative units) when there is no radiation exposure and it becomes depleted in proportion to dose, compensated by a natural self-recovery tendency in the form of a logistic function. The model also allows reproductive effects to be considered separately from morbidity and mortality by means of a similarly designed 'fecundity pool'.

This type of approach has been extensively developed [103–105, 118, 122], tested in an intercomparison of population models performed at the end of EMRAS II Working Group 6 activities [101] and shown to be able to reproduce the effects observed at various doses for fish and small mammals reported in the FREDERICA database [122].

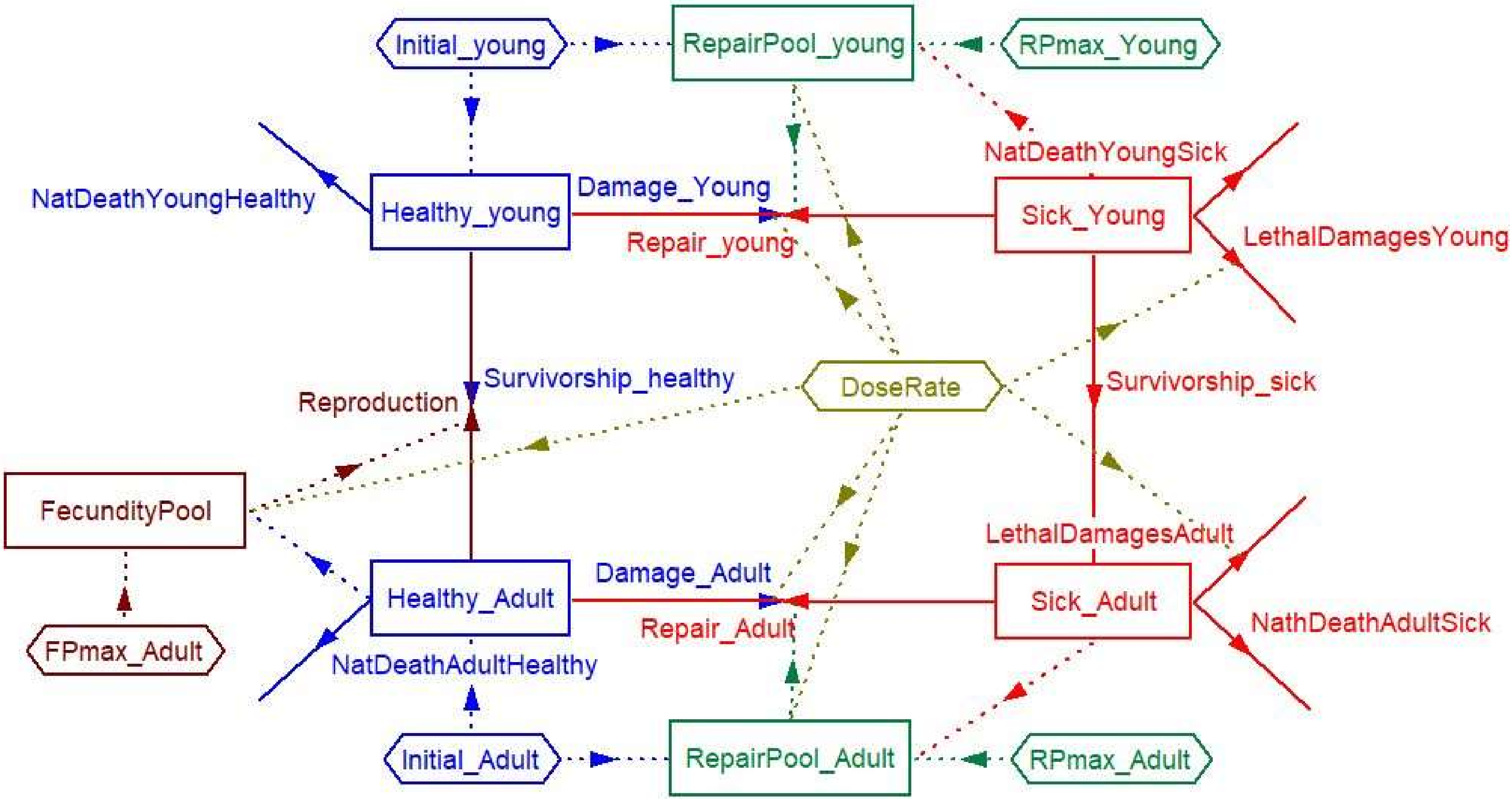

FIG. 2. Illustration of the dual age class ODE radiation damages and repair model (adapted from Ref. [122]).

3.2.4.3. *Example of application: the dual age class ODE population model*

The dual age class model for the simulation of radiation effects in biota was set up for fish and small mammals, i.e. mice, during the preceding work carried out during EMRAS II (see Fig. 2). The mathematical development, including how the previous equations were generalized to various species, exposure situations and age groups, is fully described in the deliverable report D5.2 of the EC STAR project [115], which contains mature examples of both matrix and radiation repair ODE modelling. During the EMRAS II project, using the dual age class ODE model, the following conclusions were obtained:

- The population survival of short lived species is better than that of long lived animals;
- Dose rates of about 10^{-2} Gy d^{-1} for 5 years produce a significant reduction of large mammal populations, while populations of small mammals survive at 80–100% of the control;
- A dose rate of 2×10^{-2} Gy d^{-1} for 5 years produces a considerable reduction of all populations, excepting small mammals, which survived at levels above 70% of the control;
- Higher dose rates result in progressive extinction of the population of all species modelled.

Based on these conclusions, a potential relationship between higher reproduction rates and lower radiation effects at population level can be hypothesized, in that the population survival of species that have a high reproduction capacity seems to be better.

3.2.4.4. *Conclusions on population models and suggestions for further work*

In conclusion, the work of WG9 enabled the exploration of radiation effects in the models in terms of: (i) propagating dose rate response curves from individual to population using population matrices; and (ii) demonstrating the radiation induced lethality versus recovery approach in continuous ODE models for single and multiple age classes.

The final outcome of WG9's work was the formulation of ODE models to simulate population response to ionizing radiation in an ecosystem with a limiting resource. The equations for biomass growth in a limiting environment were combined with the equations for the repairing pool and fecundity autorecovery in the same model.

For the first time, a method to extract analytical solutions from the model was developed, which made it possible to bridge the gap of calibration of chronic effects with acute data or vice versa, and which also allows the analytical calculation of thresholds for population extinction for different animal species while taking into account the compensatory effect of the environment. This model was applied to mice and wolf populations, and it was used to construct a preliminary 'radiation exposure population effects' scale for the two species in order to identify which species was vulnerable to chronic radiation exposure at the population level [123].

WG9 was able to demonstrate that continuous ODE models and Leslie matrix models are equivalent, in the sense that they derive from the same general principles, and that matrix models can be deduced as a discretization limit of continuous models. The working group also developed an approach to bridge the gap between acute and chronic effects within the context of the ODE model.

The work performed suggested the need for future investigations to validate and improve the predictive ability of different population dose effects models. This included principally the need to include ecological effects such as emigration and immigration from the patch occupied by the population or, at a later stage, introducing a more detailed age class structure into the population models.

There have been a number of publications prepared as a consequence of the work carried out on this topic during MODARIA I, and its continuation during MODARIA II building on the work undertaken during EMRAS II. The main work is cited in Refs [99, 101, 102, 104, 105, 115, 118, 122–124]. Appendix II provides a separate list of all papers published by members of the Working Groups on the subject of estimating radiation effects on wildlife.

3.2.5. Ongoing literature review on data on effects and adaptive response

Throughout the duration of the project, an ongoing search for the available adaptive response, non-targeted effects and historical effect data was conducted. Available data on adaptive and hormetic responses in non-human biota databases, and their potential implications for radiation protection, were examined through a modelling application within MODARIA II, WG5.

Environmentally relevant dose rates to wildlife resulting from routine radioactive discharges and existing environmental relevant exposure situations are usually low. Effects caused by low dose rates in any living organism are complex to interpret, a problem often compounded with the fact that radiation effects data derived from field studies of low dose radiation exposure are challenging to interpret because such exposure could potentially result in hormetic effects and adaptive responses, as well as genomic instability and other effects such as hypersensitivity, thought to be adverse.

Adaptive and hormetic responses may need to be taken into account in a regulatory context. Potentially, considering these effects could have an impact on the guidelines and policies used for the protection of biota. For example, not considering studies reporting neutral or beneficial effects of radiation could lead to a more negative perception of radiation. If radiation effects were to produce a positive result, this would mean that the current approach to protection is likely to be conservative. However, the matter is far from resolved, i.e. there is an ongoing need for more exposure testing, as it is not currently possible to prove conclusively that there is a positive response from low levels of radiation exposure in exposed species. The first step to take was therefore to carry out a review the available evidence.

A literature search was performed with the aim of reviewing the data available for adaptive responses and hormetic effects at the organism level on biota. In total, 58 research articles were found for which most data were on mammals (mice); followed by insects and fish. A database of articles was created, in which the articles are cited along with organism name, development stage, radionuclide, experiment type, type of effect observed, summary of findings and a commentary on the findings.

An explanation on the current understanding of non-targeted effects of ionizing radiation is provided in Ref. [125], and an up to date review including non-human biota considerations is provided in Ref. [126]. These show that hormetic effects and adaptive response are not considered in species sensitivity distributions, probably because there is still not enough information on these types of responses in non-human biota at the levels of radiation exposure at which regulation is applied. The majority of the studies identified were published in the last 15 years, which may indicate that interest in this area is beginning to increase.

The main conclusion of this work is that there is excellent research on genomic instability, bystander effects and adaptive responses, but the processes controlling these phenomena and their link to ionizing radiation in the environment are not yet clearly understood. It is too early to incorporate this type of effect into modelling approaches used in an assessment and regulatory context. Reviewing and evaluating new data as it emerges in the future is therefore important and the follow-up programme to MODARIA II could be an appropriate forum to do this. The importance of modelling approaches which include non-targeted effects has been highlighted by WG5, by introducing an adaptation in the ODE conceptual model developed for field voles in the Chornobyl Red Forest.

3.3. THE ECOSYSTEM MODELLING APPROACH AND REGULATORY IMPLICATIONS (WORK UNDER MODARIA II)

3.3.1. Introduction and scope

MODARIA II Working Group 5’s subgroup on effects in non-human biota (WG5 Effects) comprised a core of 15 experts with the aim of continuing with the work started during MODARIA I. By the end of the MODARIA I programme, preparation for population model methodologies and data to analyse the effects of ionizing radiation in non-human biota had been completed. The subsequent problem to be addressed during MODARIA II was how to transition to practical examples of population models. The specific key questions to be addressed were:

— How robust are the existing radiation protection benchmarks for exposure to biota populations?

— Can population modelling provide evidence based arguments to defend the radiation protection benchmarks for wildlife when they are challenged by stakeholders?

In order to achieve a focused breakthrough, and given the participant expertise available, it was decided to pursue an ODE modelling framework in further investigations, focusing on the post-accident situation in Chornobyl and attempting to model the impact of radiation in a population of voles from the Red Forest. The WG5 Effects subgroup established the following tasks around the modelling effort, which eventually converged in the mathematical formulation of a model fully adopting an ecological approach to study the impact of ionizing radiation in wildlife:

— **Task 1.** Review evidence on historical doses and transgenerational effects: evaluating existing data on radiation effects propagation across the generations, and based on data available, adapt the ODE population model formulism to account for inherited effects, including possible beneficial effects of radiation such as adaptation.
— **Task 2.** Model the impact of radiation exposure in a population of voles from the Red Forest, considering an ecosystem approach to study the impact of historical exposures on population dynamics.
— **Task 3:** Review population modelling approaches in the regulation of chemical hazards, establishing how population modelling has influenced benchmarks with regards to chemicals (i.e. pesticides, metals and organic substances).

3.3.2. Review of evidence on historical doses and transgenerational effects (Task 1)

A review of available data was performed on radiation induced inheritable (memory) effects to distant progenies of non-human biota in chronic or acute low dose exposures. The main objective was to identify scientific reports linking current radiation effects to historic dose rates and to subsequently identify potential issues in relation to the interpretation of benchmarks for radiation protection. An additional objective was to identify whether these inheritable effects help to explain current controversies in the literature about whether biota are affected at the lower levels of dose involved in most planned exposures.

The effects and mechanisms induced by low dose exposures are increasingly being recognized as different to high dose/dose rate effects. They include non-targeted effects (NTE) and so called 'memory' effects. The mechanisms underlying these effects are not clearly understood (even in human radiobiology) although they are well documented *in vivo* and *in vitro*. They dominate the radiation response at doses below 0.5Gy acute exposure, contributing 90–100% of the observed total effect.

The outcomes of radiation exposure are still controversial. They range (with acceptable supporting data) from claims of beneficial hormetic effects and adaptive responses to claims of low dose hypersensitivity, bystander effects and genomic instability increasing the relative effects of low doses [127, 128]. It is probable that all these outcomes occur and are driven more by genetic and lifestyle/environmental factors rather than dose. This does not help those trying to reduce uncertainties, but it does support the need to develop community level multistressor modelling approaches in order to move forward.

The present review identified past radiation experiments that could not be carried out today due to financial and sometimes more stringent ethical reasons. Therefore, it is important to ensure that data from these studies are preserved. Specific studies are cited in the European Radiobiological Archives[13], which are thereby highlighted as an important information resource. Moreover, an article on the quantification of thresholds for lifetime health effects in biota was published by the members of the WG5 Effects subgroup [129].

The hypothesis was evaluated that effects reported at the current dose rates documented in the Chornobyl Exclusion Zone (CEZ) could be due to past acute exposure and subsequent transgenerational transfer of genetic damage, i.e. residual from acute exposure, rather than current dose rates. This is considered to be an important issue because it has the potential to clear controversies about the interpretation of field data present in the current published literature [130–136]. These controversies remain open, so there is a need for further evaluation to determine whether there are issues with the methodology (e.g. field dosimetry issues or confounding factors) or other explanations for the reported effects.

Two studies were carried out in association with MODARIA II WG5 that attempted to garner further evidence on this subject. Through a PhD project set up at McMaster University in Canada [137], the yield of mutations in bird populations from the CEZ were compared against a new generation of mutation rates from cellular lines using lethal mutation assay, essentially assessing radiation effects in the progeny of originally irradiated cells. In effect, this is a historic dose reconstruction exercise to the time of the Chornobyl accident. A reasonable assumption was made that birds in the area were descendants of those living there during the original incident. Results suggest a non-targeted type of effect, since there were no signs of increase in effect with increasing dose, but rather a saturated response was seen.

Additionally, during the project, a dose reconstruction was carried out on the Fukushima Daiichi Nuclear Power Plant accident, studying the effects of the initial doses on directly exposed species and their progeny at the time where the radionuclides in the environment were decaying [138] The authors of the papers proposed that 'historic acute exposure and its resulting

[13] https://era.bfs.de

NTEs may be partially involved in the high mortality/abnormality rates seen across generations of pale grass blue butterflies (*Zizeeria maha*) around Fukushima' [138]. It appears that mortality rates of the progeny from irradiated progenitors increased linearly with the increasing historic radiation doses. These results are a possible suggestion of NTEs being involved, but continual accumulation of mutations over generations in their natural contaminated habitats remains a likely contributor to the observed outcome [138].

The WG5 Effects subgroup also evaluated reports on radiation effects for situations in which there was no direct energy deposition in the cells of organisms, yet chemical or biological signals induced a response, including effects through progeny. This issue is currently not considered in radiation protection. Genomic instability and whether this can give a higher level of effects in progeny is also not factored into models at the current time, yet it could potentially help explain laboratory field discrepancies, although whether these impacts are causing significant harm and, therefore, whether they need to be taken into account in risk assessments has not yet been concluded. Another point of interest is the bystander effect, which has long been reported in literature for many decades, and radiation induced genomic instability, which allows for possible change in a population that could lead to a form of adaptation.

The findings and implications of the studies mentioned above are still being considered, so no definitive conclusions can be made at this point. The WG5 Effects subgroup therefore proposes that this remains an important area of work and that the follow-up IAEA programme to MODARIA II would be an appropriate forum to undertake this work.

A practical modelling study was identified on the subject of adaptive response [139], and this found ready application in the modelling of radiation effects in Chornobyl Red Forest vole populations conducted under Task 2 (see Section 3.3.3). This study postulates that an increased radioresistance phase occurs at intermediary doses of radiation (0.5–1 Gy); following a 'priming' low dose phase that somewhat reduces the overall susceptibility of a cell population. The model discussed in Ref. [139] considers both a memory mechanism leading to successful repair/adaptation of radiation-damaged organisms and a communication mechanism under which a damaged organism can induce another organism to adapt. An adapted organism can also induce protection in a healthy organism, but this presumably happens in single cells rather than whole animals.

The overall conclusion from the review of historical effects is that the outcomes of radiation exposures are still controversial, but more quantitative information is continuing to become available. Recent analysis of the contributions of memory and legacy effects to the total effects seen using data sets from Chornobyl and Fukushima (i.e. voles, birds, fruit flies and butterflies), suggest that this type of research may help to reduce uncertainties arising from extrapolations from laboratory studies to field situations [137, 138]. Given the discrepancy between data from measurement in the field and predicted dose effects generated using databases mainly containing data from laboratory based experiments from acute exposures, it is important to continue reviewing the information, in order to develop meaningful models.

3.3.3. Modelling the impact of historical exposures on population dynamics (Task 2)

3.3.3.1. Formulation of the modelling problem

Population models in the context of the work of WG5 were used as a tool to answer questions relevant to regulation (such as how robust the existing benchmarks are for exposure to biota populations) but without suggesting that population models are to be used as a new method as part of regulatory assessments. This is because the IAEA and other international organizations (i.e. ICRP, UNSCEAR, UNEP, IUR, EC, OECD-NEA) convened under the auspices of the

Coordination Group on Radiological Protection of the Environment concluded that, particularly for planned exposure situations, the reference approach provided by the ICRP is sufficiently practical for the assessment and control of the radiological impact related to planned releases to the environment. Therefore, notwithstanding the need for more detailed considerations regarding populations in certain radiological scenarios, it is not the aim to change the structure of the protection system as of now.

The question of how to bring ecological realism into population models for radiation exposure of biota was the first part of the activities carried out by the WG5 Effects subgroup. A previously published nutrient phytoplankton zooplankton model [140] was used as an example of how to consider balances and imbalances between benchmark species for radiation exposure when dealing with the protection of an ecosystem, and to feed into the discussion of what constitutes a population for the purposes of modelling. It was observed that in a predator–prey system, if the predator is more radiosensitive than the prey, then an indirect effect of the radiation exposure is to increase the prey population which could offset the direct impact of exposure. This indicates that population level effects are more complex than effects at the level of the individual, and that a model ought to therefore contain enough realism to cover the most important ecological interactions, especially those that can counterbalance the impact of radiation, such as migration and predation, and that populations and not 'population' is what is present and needs to be protected when looking at the problem.

The WG5 Effects subgroup tested the impact of the acquired knowledge on ecological interactions between species on the radiation protection of an ecosystem by producing a demonstration population model for a vole population inhabiting a contaminated patch of the CEZ, known as the Red Forest. The scenario involved a realistic dose profile to small mammals as a function of time since the beginning of the accident to the present, taking into account the decay of short and long lived components of the contamination from the initial high dose rate to the present. Ecosystem permeability was considered as a factor, i.e. including spatial variability in exposure due to patchy contamination in three adjacent regions, with organisms able to migrate with set migration rates between a high exposure inner to a less exposed outer region, which in turn is open to animals from neighbouring environments to move into the area.

It is necessary that the model can make the connection between historical doses and transgenerational effects, because any transgenerational effect is, by definition, a consequence of a past (historical) dose, so in modelling one cannot really separate the two. As part of this, the model may explicitly consider the probability of radiation induced adaptation as a new mechanism for the model, because, of all the mechanisms considered in the Task 1 review, this was the most amenable to be mathematically conceptualized. The model is an extension of the ODE approach previously studied during MODARIA I (Section 3.2.4), and considers reproduction (fecundity function) and radiation damage repair mechanisms (repairing pool) as a function of dose rate, as well as natural death, in a population comprising of healthy, sick and adapted organisms. For the propagation of historical effects, it is necessary to consider that both healthy and sick organisms can reproduce such inherited effects and could be represented.

WG5 developed a population model and took it through an integrated testing in order to effectively explore the influence of historical doses on current generations by considering radiation exposure, migration, radiation damage and repair and spatial issues at the population level. It is expected to be possible in the future to further develop the model through the introduction of other non-targeted and hormetic effects beyond the proof of concept factorization of adaptation that was carried out here.

3.3.3.2. Model design

The model that was developed considers three spatial zones, i.e. a contaminated inner region, an intermediate partly contaminated zone and a non-contaminated outer zone. Organisms can pass between each zone, but will always pass through the intermediate zone. A carrying capacity determines how much of the population is able to live in each zone, i.e. what is the maximum population density at which further population growth stops according to the Verhulst logistic population model [119, 120]. Migration fluxes were assumed to be proportional to population density differences between adjacent zones, and to interzonal migration rates calculated by means of a stochastic random walk model. Therefore, the model calculates overall population movement in a simplified way, since a more realistic and detailed treatment would require an individual based model (IBM), which is well beyond the scope of the present study.

The mathematical blueprint of the model for all processes considered is given by the following dynamic equations:

$$\frac{dX_i}{dt} = -(\mathrm{d}_i + \alpha_i \mathrm{DR}_i)X_i + \mathrm{p}_i\kappa_i Y_i \mathrm{R}_i + r_i\frac{X_i}{L_i}\mathrm{F}_i\left(1-\frac{L_i}{\mathrm{K}_i}\right) + \eta_i W_i - (\beta_{0i}Y_i + \beta_{1i}W_i)X_i + \frac{M_i}{T_i}X_i \quad (8)$$

$$\frac{dY_i}{dt} = -(\mathrm{d}_i + \varepsilon_i)Y_i + \alpha_i \mathrm{DR}_i X_i - \kappa_i Y_i \mathrm{R}_i + r_i\frac{Y_i}{L_i}\mathrm{F}_i\left(1-\frac{L_i}{\mathrm{K}_i}\right) + \frac{M_i}{T_i}\mathrm{Y}_i \quad (9)$$

$$\frac{dW_i}{dt} = -\mathrm{d}_i W_i + r_i\frac{W_i}{L_i}F_i\left(1-\frac{L_i}{\mathrm{K}_i}\right) - \eta_i W_i + (\beta_{0i}Y_i + \beta_{1i}W_i)X_i + (1-\mathrm{p}_i)\kappa_i Y_i \mathrm{R}_i + \frac{M_i}{T_i}\mathrm{W}_i \quad (10)$$

$$\frac{dZ_i}{dt} = \mathrm{d}_i L_i + \varepsilon_i Y_i \quad (11)$$

$$\frac{dF_i}{dt} = r_i\mathrm{F}_i\left(1-\frac{F_i}{\mathrm{K}_i}\right) - r_i\mathrm{F}_i\left(1-\frac{L_i}{\mathrm{K}_i}\right) - \alpha_{fi}DR_iF_i + M_{Fi} \quad (12)$$

$$\frac{dR_i}{dt} = \mu_{Ri}R_i\left(1-\frac{R_i}{\mathrm{K}_i}\right) - \kappa_{ri}Y_i\mathrm{R}_i - \alpha_{ri}DR_iR_i + M_{Ri} \quad (13)$$

where:

X_i, Y_i, W_i, Z_i are the healthy, sick, radiation adapted and dead individuals at Regions *i*=1, 2 and 3;
$L_i = X_i + Y_i + W_i$ is the total living population in each region *i;*
F_i and R_i are the (dose dependent) fecundity and radiation damage repairing functions;
DR_i is the time dependent dose rate;
r_i is the reproduction rate of the overall population (0.06 days^{-1});
d_i is the natural death rate (combining natural death and predation) of 0.0031 days^{-1}.

The migration fluxes M_i are given by:

$$M_i = \sum_{j=1}^{3}\left(\mu_{ji}\frac{T_j}{S_j} - \mu_{ij}\frac{T_i}{S_i}\right) + \phi_0\delta_{i3} \quad (14)$$

where:

μ_{ij} is the migration matrix which has elements dependent on the surface area of the zone, which conform to a surface migration rate of 3.7×10^5 m^2 d^{-1}. The term $\phi_0\delta_{i3}$ with $\delta_{i3} = 1$ if $i = 3$ and 0 otherwise signifies that Region 3 is an unlimited source of animals with a flux ϕ_0 set to balance loss of animals to inner regions.

In Eqs (8)–(13), the time dependent carrying capacities K_i of the three regions are given by:

$$\frac{dK_i}{dt} = K_i^{max}\sigma_i\left(1 - \frac{K_i}{K_i^{max}}\right) - \nu_i DR_i \quad (15)$$

where:

$\delta_i DR_i$ is a term representing radiation damages to the ecosystem;
K^{max} is the maximum carrying capacity in optimum conditions;
DR_i is the dose rate;
σ_i and ν_i are the parameters (0.0164 and 0.036 days^{-1}, respectively) which are the rates of recovery and damage, respectively, for the understory vegetation that the voles feed upon.

The main parameters of the radiation damage and repair submodel are as follows:

— α, α_r and α_f are parameters for damage to the population, its repairing pool and the fecundity (0.11, 0.4 and 0.45 Gy^{-1}, respectively).
— κ and κ_r are rate constants for the repairing process and the recovery from non-lethal damages (0.2 and 0.21 days^{-1}, respectively).
— ε is the lethality rate for radiation damaged individuals that do not recover (0.015 days^{-1}).
— μ_r is the damaged individuals repair rate (0.032 days^{-1}).
— p_0, p_1 are the two coefficients for the saturation function controlling adaptation probability in the model described in Ref. [139];
— η is the rate for adapted organisms becoming healthy (0.1, 0.032 Gy^{-1} and 0.15 day^{-1}, respectively).

Full details of the derivation of the model equations and parameters are given in Ref. [141].

3.3.3.3. Modelling results and interpretation

An illustration of the type of model simulations run during the present study is given in Fig. 3, which shows an initial fall of healthy animals in Region 1. At this point, there is limited resource available for the voles. Migration from Region 2 into Region 1 takes place, but incoming animals soon become sick. Meanwhile, more voles move into Region 1 from Region 3. A peak of adapted organisms forms at 100 days. The population tend gradually to a stable level as radiation dose decreases.

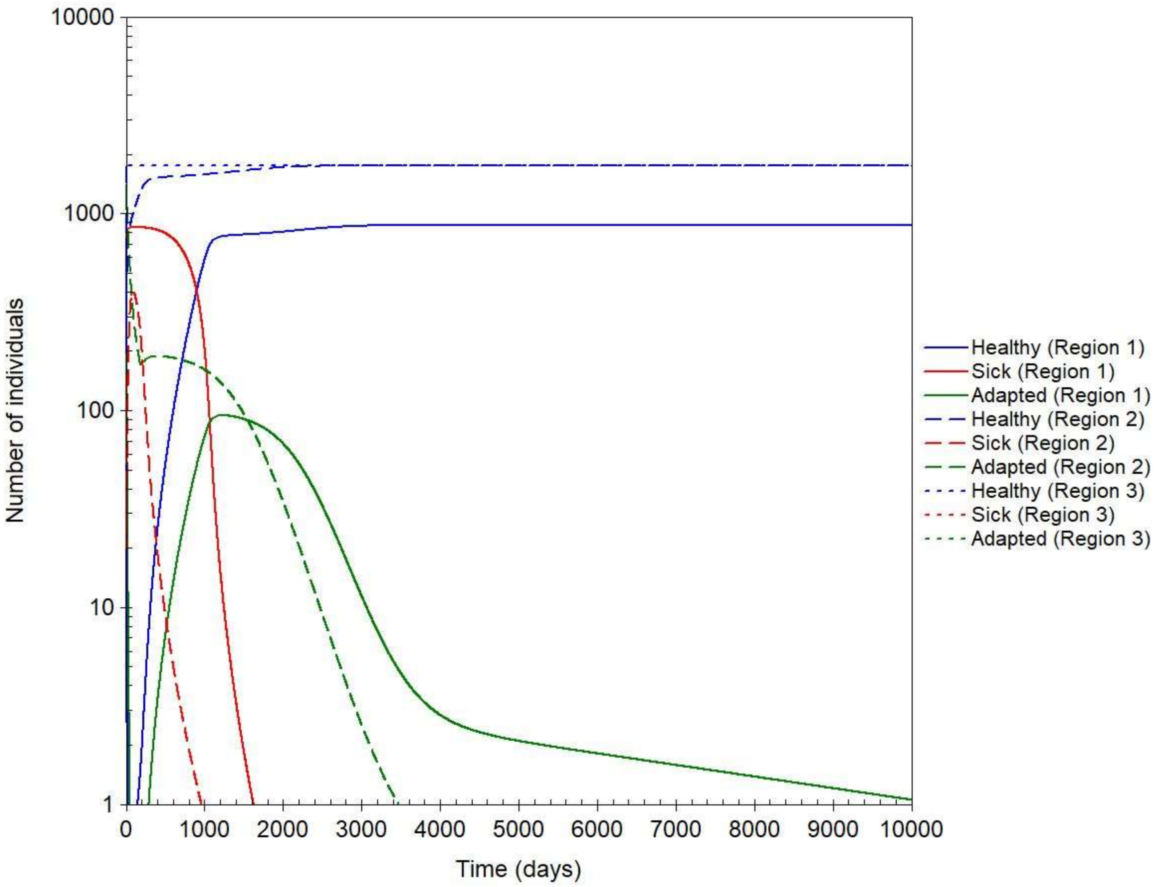

FIG. 3. Model output showing a realistic scenario if response of the field vole population to the decreasing contamination present since the initial accident on 26 April 1986 (adapted from Ref. [141]).

The main conclusions of the modelling exercise were as follows:

— Migration from non-contaminated areas in the early phase of the accident was found to be the main driver to restoring the population lost by the impact of high levels of radiation.
— In a situation such as the Chornobyl Red Forest, newly immigrated individuals became sick but the population of healthy voles recovers steadily over a period of about 3 years, sustained by immigration.
— The ability of the wildlife to self-repair the radiation damages recovers more slowly than the fecundity pool, leading to the propagation of morbidities.
— A migration rate of 255 m^2 s^{-1} at 0.035 Gy d^{-1} acts as a tipping point for population survival for the considered scenario.
— A dose rate of 7–10 Gy d^{-1} is an additional tipping point for vole morbidity.
— The model predicts that a source of healthy voles coming from a relatively uncontaminated area of 20 km^2 can sustain the population as a whole.
— A tipping point for population survival is encountered when the surface area of the most contaminated patch and the total area formed by the three regions exceed a ratio of 1:25.
— Historical effects of radiation are predicted to occur with a time delay of 1 year or more since the highest exposure.
— However, the impact of adaptation seems minor for voles, but it could be stronger in less mobile species where immigration is not such an effective restoring force.

— The population level radiation effects predicted by the model are in reasonable agreement with previous field observations. However, migration of the voles appears to delay the onset of effects appearing at high dose rates by about an order of magnitude.
— The model suggests that, at least for this case study, benchmark values such as the ICRP DCRLs are sufficiently protective at the level of the population, considered in an ecological context.

3.3.4. Chemicals modelling and alternative modelling approaches (Task 3)

There is an emerging trend in the protection of the environment which considers that the demonstration of protection from radioactive substances is integrated into the environmental impact assessment alongside the assessment conducted for chemical substances. Consistency of approach is a desirable goal for a method for explicitly demonstrating that the environment is protected from harmful effects relating both to the presence of radioactive substances and chemical substances. The purpose of this task was not to realize this integration, but to examine population models applied to the chemical domain in order to establish a point of comparison with how far population modelling has gone to assess similar issues in radioecology.

3.3.4.1. Similarities and differences between the regulation of chemicals and radioactive material

At the outset of this work, it was not certain whether the approaches to the regulation of chemicals could be extrapolated or even compared to radiation protection approaches. For wildlife species, at the population level, the potential effects of chemical contaminants are poorly documented. For risk assessment purpose, therefore, extrapolations are made from the observed chemotoxicity in laboratory tests to natural field conditions. Many assumptions and uncertainties arising from this extrapolation have to be taken into account. Moreover, the effects of chemical contaminants on wildlife species are also poorly documented at the population level and this makes it necessary to extrapolate radiotoxicity effects from laboratory tests to natural field conditions.

An increasing number of studies have suggested applying population models of representative wildlife species to investigate population responses to toxic contaminants within a chemical risk assessment. Examples are available for pesticides [142–146]. One of the objectives of these studies was to develop mathematical expressions capable of extrapolating the observed toxic effect (as seen in individuals in some experiments) to the population level, in order to test whether populations can be more sensitive. This challenge is equivalent to that faced when studying the effects of radionuclides, and is addressed in an equivalent way to radionuclides, by incorporating precaution in the ERA. Specifically, the European guidance given in Ref. [147] recommends dividing the PNEC or PNEDR values derived from individual level radiotoxicity data by safety factors. The values for safety factors have a wide range of several orders of magnitude, depending on the quality and quantity of toxicity data (i.e. acute or chronic tests, number of tested species, number of represented trophic levels). Extrapolating environmental risks based on safety factors has been shown in several studies to be a major source of uncertainty in ERA, leading to either under or overestimated risks [148].

There are substantial differences between ERAs for chemical and for radiological assessments (such as a larger number of sources, different modes of action). Hence, the objective of the task was limited to answering the questions: ‘Has population modelling been used (and to what extent) in setting chemical benchmarks?’, and ‘What are the lessons to be learned in radiological benchmark setting?’ For the latter question, a chemical–radiological comparison was previously considered by the EC PROTECT project, and ERICA (and PROTECT) used an approach analogous to that for chemicals to set benchmarks for radiation exposure of wildlife. Therefore, it was thought that there was much to be learned from the use of population models in the regulation of chemicals, for what it represents in terms of consistency of approach with the regulation of the impact of ionizing radiation exposure on biota.

3.3.4.2. Literature review of population models in the regulation of chemicals

The regulation of chemicals invokes ecosystems or foodwebs as protection goals but protection data are largely on individuals, which is similar to the situation for radioactive material. Definitions of protection endpoints for exposure to chemicals appear not to have been elaborated in fine detail as yet. Most chemical protection goals use the threshold principle, based on the most sensitive species. Most regulations require multiple species to be considered (although limited to a small number of taxa) but use of population modelling and food web modelling is rare. For chemicals, there is usually a reliance on standard tests. Whilst population modelling is not legally required in assessments, assessors often consider it as best practice, but this does not influence benchmarking. The radiation protection of biota is actually ahead of this situation, partly due to the drive to prove safety even when the ecosystem is apparently protected.

The main finding of this task was a review of existing chemical toxicity population models [149] which constitutes the key source for which population models are available for chemicals risk assessment. This review refers to 150 publications describing 90 models, with some 27 of these dealing with ecological processes, with most being for the aquatic environment. About a quarter of the models are for the terrestrial environment, with some 81 of the 90 models dealing with extrapolation from individual to population. What is needed in models, such as recovery processes, is stipulated, and how models fit amongst these criteria is generally well defined. The majority of the models are structured population models that take account of different age classes of species.

There have been some initiatives to standardize approaches such as the Marie Curie Initial Training Network project CREAM[14] (Mechanistic Effect Models for Ecological Risk Assessment of Chemicals); the Society of Environmental Toxicology and Chemistry (SETAC) (a learned society rather than an initiative to standardize regulatory approaches); the Guidance on Plant Protection and the European Centre for Ecotoxicology and Toxicology of Chemicals (a consortium of industries that tries to standardize assessment methods at the industry level). This includes ecosystem services. The endpoints of models are similar to population models used in MODARIA I and II for radiation exposure, namely, growth, mortality within population, repairable damages and fecundity.

3.3.4.3. Types of models and data used in ecotoxicology

There seems to be a general tendency towards the application of dynamic energy budget (DEB) modelling to (eco)toxicological problems (DEBTox modelling). DEB modelling is an approach that mathematically follows the energy budget of an individual organism throughout its life cycle. The physical state of the organism e.g. age, size and amount of reserves, and its environment, e.g. food density and temperature, can be characterized. DEB models of individual organisms could be used as a basis for modelling the dynamics of structured populations [150]. Applying DEB modelling to ecotoxicology involves linking toxicant

[14] https://cream-itn.eu/

concentrations to the effects on life history traits over time, in what is known as a toxicokinetic–toxicodynamic modelling approach.

There is abundant information for parameterizing DEBTox, with a particularly relevant resource being the 'Add my Pet' database[15] which is a curated database covering over 1000 species and is readily available. Some DEBTox models that already have a history of chemicals are adapted to deal with radiological exposures in non-human biota [151, 152].

A comprehensive description of DEBTox theory is given elsewhere [151, 152]. Here, only the application of some specific DEBTox models is briefly presented. The DEBTox model for animals has been developed to analyse data from ecotoxicological tests of chemical compounds [153, 154]. Although DEBTox models have been successfully applied to ecotoxicology, ultimately there are not too many examples when it comes to radionuclides. Applying the approach to the case of ionizing radiation implies that a metric is defined for the factor of radiological stress [151, 152]. A DEBTox model for the effects of chronic gamma radiation exposure in the nematode *C. elegans* was recently published [155], whereas other studies [116, 156, 157] have dealt with exposure to depleted uranium.

DEBTox models can be used to test transgenerational changes in effect severity. As formulated, DEBTox modelling has many implications for the interpretation of the links between exposure level and molecular responses and between molecular responses and their consequences for the organism in question. Work carried out by members of WG5 has proven that DEB models can be integrated with bioenergetics models (BEMs); which involve the investigation of energy expenditure, losses, gains and efficiencies of transformations in the body. A BEM-type model is AQUATRIT [158, 159], which was developed for tritium transfer in aquatic food chains, considering both organically bound and dissolved organic tritium.

A particular subset of models used in ecotoxicology are the IBMs; where individuals are modelled and population effects are obtained as emergent properties. Several examples for chemical exposure were found in the literature, specifically models for metals and their effects for invertebrates, copepods and fish [160, 161]. IBMs capture the dynamics of the populations in a realistic way when the environmental parameters are fluctuating. However, this type of model is complex and computationally demanding in comparison with the ODE and matrix models developed during both the MODARIA I and II programmes, where the key processes are captured in a small number of equations that can be solved by a simple iterative integration algorithm and, in some cases, an analytical solution can be found.

Population modelling is not inherently more complex than some of the modelling used in assessments (e.g. geological disposal). There is, however, a general issue with complexity of models in terms of their transparency and openness and communication of the uncertainties built into them. In this regard, an approach that is as practical and simple as possible, involves a less substantial investment to foster the acceptance and understanding among stakeholders and can then be used as a stable base to add new features (such as impact of stressors) onto that base, bridging the gap between science and regulation.

From the argument presented above, it can be concluded that using one of the established IBMs and adding radiation effects might be a good trial approach, in the sense of improving the modelling of effects that can be inherited, such as adaptation and transgenerational effects. However, it is not suggested that this is rushed until an approach is found that is appropriate,

---

[15] https://www.bio.vu.nl/thb/deb/deblab/add_my_pet/index.html

proportional and is robust and fit for purpose. A proof of concept would be a good step and could build on the initial development of individually based population modelling for radiation exposure estimation as described in Section 2.1.2 above. Such a model would allow individuals of different ages coexisting, death due to age to be accounted for individually and differences in males and females to be studied, as well as allowing implementation of non-targeted effects transmitting between exposed and non-exposed organisms. The next IAEA programme following MODARIA could provide an appropriate forum for this work to be carried out.

An additional activity undertaken during the MODARIA II programme was a visit to the University of Gent in Belgium to discuss consistency between the approach in risk assessment within the 'radiological world' and ecotoxicology, examining to what extent one can use or adapt models in (eco)toxicology within the radiological risk assessment. Furthermore, how the gap between research on individuals and assessment at population level is closed by modelling was investigated, as well as whether there are lessons to be learned in the radiological domain. This informed the conclusions outlined below.

3.3.4.4. Main findings of the ecotoxicology and environmental impact assessment review

The situation in the field of ecotoxicology and environmental impact assessment (human or non-human) is that population models are not routinely used because of their perceived complexity and inherent uncertainties. As a result, there is a need to further demonstrate whether the 'simpler' models are robust and fit for purpose. This fits into a broader general mismatch between the speeds at which scientific insights and policy align. The bridging of the individual population gap with models is one of the areas where this mismatch is very pronounced. Nevertheless, the WG5 Effects subgroup advocates that it is important to continue advancing the harmonization of modelling between radioecology and ecotoxicology beyond the MODARIA I and II programmes by fostering interaction with relevant networks of expertise, for example, by holding joint meetings between chemical and radioecological modellers. One such network is the Society of Environmental Toxicology and Chemistry's (SETAC) Mechanistic Models in Chemical Risk Assessment group[16].

Several projects (e.g. as part of the CREAM Network) and workshops have already tried to improve the situation and facilitate the necessary understanding, with some success, i.e. a substantial part of the work carried out during CREAM has been translated into guidance documents for the European Food Safety Agency; notably the guidance for toxicokinetic (TK) models. In this regard, it was noted that IAEA programmes such as MODARIA I and II already help to improve the process and rate at which science is integrated into regulation and guidance in the domain of radiation protection.

Future initiatives to stimulate the exchange between both radioecological and ecotoxicological fields were identified by WG5, and these constitute the basis for the following proposals for future development:

— The facilitation of information exchange, perhaps by way of meetings, to increase the contact between experimentalists and modellers of both chemical and radiological fields (e.g. European Radioecology ALLIANCE workshops could include a specific session on ECOTox models, and SETAC workshops could include a session on radionuclides). Such sessions could explore the parallels and differences between both fields, not only on the scientific side, but also at the level of users such as regulatory bodies and industry.

[16] www.setac.org/group.seigmemorisk

— Stimulation of consistency of approach between environmental impact assessment in ecotoxicology and in radiation protection at a regulatory level. NORM sites and legacies could be a good proof of concept in this regard. Moreover, the EC project RADONORM[17] already includes an initiative to model the impact of ionizing radiation in the context of a chemically contaminated NORM site in Belgium, using a mixed toxicity approach framed in the context of an ODE population model as a proof of concept investigation.
— Produce a prototype IBM model in frame of inheritable effects of ionizing radiation and compare it with the ODE approaches used during the MODARIA II programme.

[17] https://www.radonorm.eu/

4. DISCUSSION AND CONCLUSIONS

4.1. EXPOSURE MODELLING

Over the last 20 years or so, a number of models and tools to assess the radiological risk to wildlife have been developed and some of these are now used worldwide. Through the EMRAS and MODARIA programmes, the fitness for purpose of these various models and tools has been investigated at length. On the basis of evaluations carried out, a number of the models and tools can be proposed for undertaking radiological assessments for wildlife, all of which are freely available to users (see Table 1).

Some of these models are tools which facilitate increasingly complex, tiered (or graded) assessments, while others offer increased functionality for specific aspects of the assessment in question. Whilst there are many simplifications in these models and large uncertainties with respect to radionuclide transfer to organisms, it can be concluded that the commonly used models (e.g. the ERICA Tool [32] and RESRAD BIOTA [43]) are generally fit for purpose for screening level assessments.

The area of wildlife radiological assessment continues to develop. For example, as the parameters within the underlying databases are improved, new approaches are developed and existing models and tools are advanced. For instance, ICRP Publication 136 [77] presents dose coefficients derived using an updated methodology that includes a new approach to assessing the external exposure of terrestrial animals, an extended set of environmental sources of radionuclides in soil and in air, as well as an assessment specific consideration of the contribution of radioactive progeny to the dose coefficient of parent radionuclides.

The forthcoming IAEA approach[18] for the assessment of the impact of radioactive discharges to the environment adopts this revised ICRP methodology for estimating dose coefficients, includes exposure pathways not in the existing screening level models (e.g. land irrigation, application of sewage sludge to land) and includes interception of aerially released radionuclides by vegetation surfaces [162].

In addition to those mentioned above, other novel approaches to estimating the transfer of radionuclides in the environment are being investigated and developed [85, 163, 164].

Continued work in this field has been identified to support the sharing of new knowledge and approaches, further model testing and intercomparisons, and the provision of training for IAEA Member States (many of whom have only just started to adapt to revised international recommendations to ensure that wildlife is protected from releases of radioactivity into the environment).

Furthermore, a number of the exercises carried out during the EMRAS and MODARIA programmes have demonstrated the potential contribution of 'assessor uncertainty' as a contributor to total assessment uncertainty [59, 60, 165].

4.2. POPULATION MODELLING AND EFFECTS

Work carried out on population modelling and effects shows that it is necessary to maintain a stakeholder dialogue on factors influencing wildlife population responses to radiation exposure in the environment and how this affects the validity of the benchmarks used in risk assessments for radiation protection. Evaluating the problem within the context of a population model that

[18] The new approach is under development and will replace that used in Ref. [76].

combines radiological impact with an ecological approach is a viable tool to inform this stakeholder dialogue. With the modelling developed within the MODARIA programmes, it is already possible to do this, but further validation in real field cases is needed. Hence, at present, use of these models in regulatory assessments is not being considered.

Model validation using field data is challenging, due to insufficient long term studies on the response of wildlife to chronic radiation exposure in the presence of ecological factors. Experimental studies using laboratory ecosystems (mesocosms) can provide the necessary knowledge to test and validate the population models. It is also necessary to continue reviewing the evidence for radiation effects including non-targeted effects and adaptation from the level of individuals to populations, reaching a synthesis of the information, in order to develop meaningful model systems for demonstrating the protection of wildlife living in contaminated ecosystems.

Adaptation of biota to chronic exposure to ionizing radiation involves a more detailed consideration in future modelling investigations than has been done previously [141]. This is because phenomena like adaptation may be occurring and involve changes in various biological processes, and the importance these processes have for a wildlife population in a spatially heterogeneous and slowly declining dose profile is not wholly clear. The dose scenario investigated here is an existing exposure situation, whereas most of the models in use are being applied in the context of planned exposure situations and therefore there is a need to expand the work to such exposure scenarios. It is also necessary to seek knowledge on adaptation probability for multicellular animals, given that most of the existing evidence is for laboratory cell cultures. Moreover, what role these factors may play when considering the appropriateness of the benchmarks used in risk assessments still needs to be established.

The reliability of population model predictions depends on the availability of life history information and of robust datasets on biological effects (i.e. morbidity, reproduction and mortality). For chronic lifetime exposures of long lived organisms to radiation, such data are rather limited and extrapolation from acute to chronic effects is fraught with uncertainties. Consequently there is an ongoing need to critically evaluate this information, as has been done during both MODARIA I and II [129].

The population models developed so far [99, 101, 102, 111, 115, 122, 141, 166] need to undergo continual improvement to increase ecological realism, because some of the concerns voiced by stakeholders are about indirect effects. The following areas have therefore been identified for further study:

- Consideration of a more complex connectivity pattern between regions with different levels of contamination;
- Improvement of the representation of habitat restoration in the equations for carrying capacity;
- Inclusion of the differentiation of the sexes (i.e. sex ratio, different home ranges/mobility and behaviour of males and females);
- Incorporation of the Lotka-Volterra predator prey equations [100, 167] in order to better consider ecosystem level effects, given that the death rate is a strong function of predation pressure.

However, it needs to be borne in mind that these developments would tend to cause loss of generality in the model, making it more case specific.

The Chornobyl Field Vole case study [141] clearly demonstrates that morbidity effects in a population are the earliest signs of radiation damage and that a decrease in average population size can be a significant effect at higher doses but also that migration from an uncontaminated area can counteract extinction in such a situations. These results can be used to illustrate that tipping points in terms of dose rate for population survival are higher than the current benchmarks set for the protection of the environment, which seem therefore to be fit for purpose. However, it is necessary to widen the exercise to include additional scenarios and case studies covering different exposure situations, in order to confirm this conclusion. This requires formulating scenarios with different dose rates and basic population parameters (and if possible different but complementary modelling approaches); in order to underpin discussions with stakeholders on what kinds of scenarios and species are more sensitive.

Amongst the set of population recovery strategies considered, migration appears to be the most effective, so this is a key factor to follow up in an assessment, and as part of it, field data on animal mobility would appear to be an important part of an ecological impact assessment. An additional factor is the spatial extent of the contamination, in the sense that if a population is spread over a heterogeneously contaminated zone, there is a point in which the most exposed organisms are sufficiently numerous to be able to consider that the overall population is at risk. It is also clear that if large and/or long lived wildlife are within an assessment, this could be an important factor to consider, because the bigger the size and longevity of an animal implies higher population vulnerability in chronic exposures.

Within both MODARIA I and II, ODE and matrix model approaches were developed, tested and applied successfully to investigate whether current benchmarks are fit for purpose in demonstrating protection at the level of the population. However, the range of case studies has been somewhat limited and other modelling approaches (e.g. DEBTox) are being used in chemicals risk assessment; hence, testing of benchmarks need to be continued under different scenarios in order to understand whether different modelling approaches provide consistent results. The same is true for individual based modelling, since these approaches have proven successful in ecotoxicology.

Effects studies indicating non-targeted effects, genomic instability, hormesis and transgenerational effects as being possible factors for the induction of radiation effects in populations are still being reviewed at the current time, and it is important to maintain an ongoing search for new evidence which is critically evaluated because this could potentially help to explain the controversies between some field studies.

Stimulation of consistency of approach between environmental impact assessment in ecotoxicology and in radiation protection needs to be addressed. NORM and other legacy sites could provide opportunities to explore this because they have a mix of radioactive and chemical contamination. A mixed toxicity approach framed within the context of an ODE population model could be the first step in a proof of concept investigation.

Future initiatives to stimulate the exchange between both radioecological and ecotoxicological ERA fields would be beneficial. Specifically, advantage needs to be taken of opportunities presented at meetings to share and discuss the approaches being developed for risk assessments for chemicals and for radioactive material, allowing for cross pollination of concepts. Consistency of approach needs to be a goal in producing technical and guidance documents as required by the United Nations Environment Programme.

The above conclusions have now been incorporated in a journal article discussing the modelling approach for the assessment of radiological impact on populations of wildlife [168].

APPENDIX I. ESTIMATING RADIATION EXPOSURE OF WILDLIFE: REFEREED PUBLICATIONS FROM THE ‘BIOTA MODELLING’ WORKING GROUPS IN THE EMRAS AND MODARIA PROGRAMMES

ARAMRUN. K., BERESFORD, N.A., SKUTERUD, L., HEVROY, T.H., DREFVELIN, J., YUROSKO, C., PHRUKSAROJANAKUN, P., ESOA, J., YONGPRAWAT, M., SIEGENTHALER, A., FAWKES, R., TUMNOI, W., WOOD, M.D., Measuring the radiation exposure of Norwegian reindeer under field conditions, Sci. Total Environ. **687** (2019) 1337–1343. (https://doi.org/10.1016/j.scitotenv.2019.06.177)

BEAUGELIN-SEILLER, K., The assumption of heterogeneous or homogeneous radioactive contamination in soil/sediment: does it matter in terms of the external exposure of fauna? J. Environ. Radioact. **138** (2014) 60–67. (https://doi.org/10.1016/j.jenvrad.2014.07.027)

BEAUGELIN-SEILLER, K., Effects of soil water content on the external exposure of fauna to radioactive isotopes, J. Environ. Radioact. **151** (2016) 204–208. (https://doi.org/10.1016/j.jenvrad.2015.10.005)

BEAUGELIN-SEILLER, K., GOULET, R., MIHOK, S., BERESFORD, N.A., Should we ignore U-235 series contribution to dose? J. Environ. Radioact. **151** (2016) 114–125. (http://dx.doi.org/10.1016/j.jenvrad.2015.09.019)

BERESFORD, N.A., BALONOV, M., BEAUGELIN-SEILLER, K., BROWN, J., COPPLESTONE, D., HINGSTON, J.L., HORYNA, J., HOSSEINI, A., HOWARD, B.J., KAMBOJ, S., NEDVECKAITE, T., OLYSLAEGERS, G., SAZYKINA, T., VIVES I BATLLE, J., YANKOVICH, T.L., YU, C., An international comparison of models and approaches for the estimation of the radiological exposure of non-human biota, Appl. Radiat. Isot. **66** (2008) 1745–1749. (http://dx.doi.org/10.1016/j.apradiso.2008.04.009)

BERESFORD, N.A., BARNETT, C.L., BROWN, J., CHENG, J-J., COPPLESTONE, D., FILISTOVIC, V., HOSSEINI, A., HOWARD, B.J., JONES, S.R., KAMBOJ, S., KRYSHEV, A., NEDVECKAITE, T., OLYSLAEGERS, G., SAXÉN, R., SAZYKINA, T., VIVES I BATLLE, J., VIVES-LYNCH, S., YANKOVICH, T., YU, C., Inter-comparison of models to estimate radionuclide activity concentrations in non-human biota, Radiat. Environ. Biophys. **47** (2008) 491–514. (http://dx.doi.org/10.1007/s00411-008-0186-8)

BERESFORD, N.A., BARNETT, C.L., BEAUGELIN-SEILLER, K., BROWN, J.E., CHENG, J-J., COPPLESTONE, D., GASCHAK, S., HINGSTON, J.L., HORYNA, J., HOSSEINI, A., HOWARD, B.J., KAMBOJ, S., KRYSHEV, A., NEDVECKAITE, T., OLYSLAEGERS, G., SAZYKINA, T., SMITH, J.T., TELLERIA, D., VIVES I BATLLE, J., YANKOVICH, T.L., HELING, R., WOOD, M.D., YU, C., Findings and recommendations from an international comparison of models and approaches for the estimation of radiological exposure to non-human biota, Radioprotection **44** 5 (2009) 565–570. (http://dx.doi.org/10.1051/radiopro/20095104)

BERESFORD, N.A., The transfer of radionuclides to wildlife (Editorial). Radiation Environmental Biophysics **49** (2010) 505–508. (http://dx.doi.org/10.1007/s00411-010-0325-x)

BERESFORD, N.A., BARNETT, C.L., BROWN, J.E., CHENG, J-J., COPPLESTONE, D., GASCHAK, S., HOSSEINI, A., HOWARD, B.J., KAMBOJ, S., NEDVECKAITE, T., OLYSLAEGERS, G., SMITH, J.T., VIVES I BATLLE, J., VIVES-LYNCH, S., YU, C., Predicting the radiation exposure of terrestrial wildlife in the Chernobyl exclusion zone: an international comparison of approaches, J. Radiol. Prot. **30** (2010) 341–373. (http://dx.doi.org/10.1088/0952-4746/30/2/S07)

BERESFORD, N.A., WOOD, M.D., A new simplified allometric approach for predicting the biological half-life of radionuclides in reptiles, J. Environ. Radioact. **138** (2014) 116–121. (http://dx.doi.org/10.1016/j.jenvrad.2014.08.012)

BERESFORD, N.A., BEAUGELIN-SEILLER, K., BURGOS, J., CUJIC, M., FESENKO, S., KRYSHEV, A., PACHAL, N., REAL, A., SU, B.S., TAGAMI, K., VIVES I BATLLE, J., VIVES-LYNCH, S., WELLS, C., WOOD, M.D., Radionuclide biological half-life values for terrestrial and aquatic wildlife, J. Environ. Radioact. **150** (2015) 270–276. (http://dx.doi.org/10.1016/j.jenvrad.2015.08.018)

BERESFORD, N.A., WOOD, M.D., VIVES I BATLLE, J., YANKOVICH, T.L., BRADSHAW, C., WILLEY, N., Making the most of what we have: application of extrapolation approaches in radioecological wildlife transfer models, J. Environ. Radioact. **151** (2016) 373–386. (http://dx.doi.org/10.1016/j.jenvrad.2015.03.022)

BERESFORD, N.A., BEAUGELIN-SEILLER, K., BARNETT, C.L., BROWN, J., DOERING, C., CAFFREY, E., JOHANSEN, M.P., MELINTESCU, A., RUEDIG, H., VANDENHOVE, H., VIVES I BATLLE, J., WOOD, M.D., YANKOVICH, T.L., COPPLESTONE, D., Ensuring robust radiological risk assessment for wildlife: insights from the International Atomic Energy Agency EMRAS and MODARIA programmes. Journal of Radiological Protection (Submitted).

GOULET, R.R., NEWSOME, L., VANDENHOVE, K., KEUM, D.-K., HORYNA, J., KAMBOJ, S., BROWN, J., HOSSEINI, A., JOHANSEN, M.P., TWINING, J., WOOD, M.D., CERNE, M., BEAUGELIN-SEILLER, K., BERESFORD, N.A., International comparisons and best practices for radiological dose model predictions to freshwater food chains: a uranium mining/milling scenario. Journal of Environmental Radioactivity (Submitted).

JOHANSEN, M.P., BARNETT, C.L., BERESFORD, N.A., BROWN, J.E., CERNE, M., HOWARD, B.J., KAMBOJ, S., KEUM, D-K., SMODIŠ, B., TWINING, J.R., VANDENHOVE, H., VIVES I BATLLE, J., WOOD, M.D., YU, C., Assessing doses to terrestrial wildlife at a radioactive waste disposal site: inter-comparison of modelling approaches, Sci. Total Environ. **427–428** (2012) 238–246. (http://dx.doi.org/10.1016/j.scitotenv.2012.04.031)

JOHANSEN, M.P., RUEDIG, E., TAGAMI, K., UCHIDA, S., HIGLEY, K., BERESFORD, N.A., Radiological dose rates to marine fish from the Fukushima Daiichi accident: the first three years across the north Pacific, Environ. Sci. Technol. **49** (2015) 1277–1285. (http://pubs.acs.org/doi/ipdf/10.1021/es505064d)

NEDVECKAITE, T., FILISTOVIC, V., MARCIULIONIENE, D., KIPONAS, D., REMEIKIS, V., BERESFORD, N.A., Exposure of biota in the cooling pond of Ignalina NPP: hydrophytes, J. Environ. Radioact. **97** (2007) 137–147. (http://dx.doi.org/10.1016/j.jenvrad.2007.03.011)

NEDVECKAITE, T., FILISTOVIC, V., MARCIULIONIENE, D., PROKOPTCHUK, N., PLUKIENE, R., GUDELIS, A., REMEIKIS, V., YANKOVICH, T., BERESFORD, N.A., Background and anthropogenic radionuclide derived dose rates to freshwater ecosystem – Nuclear power plant cooling pond – Reference organisms, J. Environ. Radioact. **102** (2011) 788–795. (http://dx.doi.org/10.1016/j.jenvrad.2011.04.012)

STARK, K., ANDERSSON, P., BERESFORD, N.A., YANKOVICH, T.L., WOOD, M.D., JOHANSEN, M.P., VIVES I BATTLE, J., TWINING, J., KEUM, D-K., BOLLHOFER, A., DOERING, C., RYAN, B., GRZECHNIK, M., VANDENHOVE, H., Predicting exposure of wildlife in radionuclide contaminated wetland ecosystems, Environ. Pollut. **196** (2015) 201–213. (http://dx.doi.org/10.1016/j.envpol.2014.10.012)

TAGAMI, K., UCHIDA, S., WOOD, M.D., BERESFORD, N.A., Radiocaesium transfer and radiation exposure of frogs in Fukushima Prefecture, Sci. Rep. **8** (2018) 10662. (https://doi.org/10.1038/s41598-018-28866-0)

VIVES I BATLLE, J., BALONOV, M., BEAUGELIN-SEILLER, K., BERESFORD, N.A., BROWN, J., CHENG, J-J., COPPLESTONE, D., DOI, M., FILISTOVIC, V., GOLIKOV, V., HORYNA, J., HOSSEINI, A., HOWARD, B.J., JONES, S.R., KAMBOJ, S., KRYSHEV, A., NEDVECKAITE, T., OLYSLAEGERS, G., PRÖHL, G., SAZYKINA, T., ULANOVSKY, A., VIVES LYNCH, S., YANKOVICH, T., YU, C., Inter-comparison of absorbed dose rates for non-human biota, Radiat. Environ. Biophys. **46** (2007) 349–373. (http://dx.doi.org/10.1007/s00411-007-0124-1)

VIVES I BATLLE, J., BEAUGELIN-SEILLER, K., BERESFORD, N.A., COPPLESTONE, D., HORYNA, J., HOSSEINI, A., JOHANSEN, M., KAMBOJ, S., KEUM, D-K., KUROSAWA, N., NEWSOME, L., OLYSLAEGERS, G., VANDENHOVE, H., RYUFUKU, S., VIVES LYNCH, S., WOOD, M.D., YU, C., The estimation of absorbed dose rates for non-human biota: an extended intercomparison, Radiat. Environ. Biophys. **50** (2011) 231–251. (http://dx.doi.org/10.1007/s00411-010-0346-5)

VIVES I BATLLE, J., BERESFORD, N.A., BEAUGELIN-SEILLER, K., BEZHENAR, R., BROWN, J., CHENG, J-J., CUJIC, M., DRAGOVIC, S., DUFFA, C., FIEVET, B., HOSSEINI, A., JUNG, K.T., KAMBOJ, S., KEUM, D-K., LEPOIRE, D., MADERICH, V., MIN, B-I., PERIANEZ, R., SAZYKINA, T., SUH, K-S., YU, C., WANG, C., HELING, R., Inter-comparison of dynamic models for radionuclide transfer to marine biota in a Fukushima accident scenario, J. Environ. Radioact. **153** (2016) 31–50. (http://dx.doi.org/10.1016/j.jenvrad.2015.12.006)

WOOD, M.D., BERESFORD, N.A., BRADSHAW, C., HOWARD, D.C., ANDERSSON, P., SINGH, N.J., PALO, R.T., JOHANSEN, M.P., Accounting for animal movement behaviour improves radiation exposure modelling estimates for heterogeneously contaminated environments, Environmental Research (Submitted).

YANKOVICH, T.L., VIVES I BATLLE, J., VIVES-LYNCH, S., BERESFORD, N.A., BARNETT, C.L., BEAUGELIN-SEILLER, K., BROWN, J.E., CHENG, J-J., COPPLESTONE, D., HELING, R., HOSSEINI, A., HOWARD, B.J., KAMBOJ, S., KRYSHEV, A.I., NEDVECKAITE, T., SMITH, J.T., WOOD, M.D., An International model validation exercise on radionuclide transfer and doses to freshwater biota, J. Radiol. Prot. **30** (2010) 299–340. (http://dx.doi.org/10.1088/0952-4746/30/2/S06)

APPENDIX II. ESTIMATING RADIATION EFFECTS ON WILDLIFE: REFERRED PUBLICATIONS FROM THE WORKING GROUPS IN THE EMRAS AND MODARIA PROGRAMMES

ALONZO, F., HERTEL-AAS, T., REAL, A., LANCE, E., GARCIA-SANCHEZ, L., BRADSHAW, C., VIVES I BATLLE, J., GARNIER-LAPLACE, J., Population modelling to compare chronic external gamma radiotoxicity between individual and population endpoints in four taxonomic groups, J. Environ. Radioact. **152** (2016) 46–59. (https://doi.org/10.1016/j.jenvrad.2015.11.001)

HANCOCK, S., VO, N.T.K., OMAR-NAZIR, L., VIVES I BATLLE, J., OTAKI, J.M., HIYAMA, A., HYUN BYUN, S, SEYMOUR, C.B., MOTHERSILL, C., Transgenerational effects of historic radiation dose in pale grass blue butterflies around Fukushima following the Fukushima Dai-ichi Nuclear Power Plant meltdown accident, Environ. Res. **168** (2019) 230–240. (https://doi.org/10.1016/j.envres.2018.09.039)

KRYSHEV, A.I., SAZYKINA, T.G., Modelling the effects of ionizing radiation on survival of animal population: acute versus chronic exposure, Radiat. Environ. Biophys. **54** (2015) 103–109. (https://doi.org/10.1007/s00411-014-0578-x)

SAZYKINA, T., Population sensitivities of animals to chronic ionizing radiation-model predictions from mice to elephant, J. Environ. Radioact. **182** (2018) 177–182. (https://doi.org/10.1016/j.jenvrad.2017.11.013)

SAZYKINA, T., KRYSHEV, A., Simulation of population response to ionizing radiation in an ecosystem with a limiting resource – Model and analytical solutions, J. Environ. Radioact. **151** (2016b) 50–57. (https://doi.org/10.1016/j.jenvrad.2015.09.015)

SAZYKINA, T.G., KRYSHEV, A.I., Radiation effects in generic populations inhabiting a limiting environment, Radiat. Environ. Biophys. **51** (2012) 215–221. (https://doi.org/10.1007/s00411-012-0404-2)

VIVES I BATLLE, J., Dual age class population model to assess radiation dose effects to non-human biota populations, Radiat. Environ. Biophys. (2012a) 225–243. (https://doi.org/10.1007/s00411-012-0420-2)

VIVES I BATLLE, J., BIERMANS, G., COPPLESTONE, D., KRYSHEV, A., MELINTESCU, A., MOTHERSILL, C., SAZYKINA, T., SEYMOUR, C., SMITH, K., WOOD, M.D., Towards an ecological modelling approach for assessing ionising radiation impact on wildlife populations. Journal of Radiological Protection (Submitted).

VIVES I BATLLE, J., SAZYKINA, T., KRYSHEV, A., MONTE, L., KAWAGUCHI, I., Inter-comparison of population models for the calculation of radiation dose effects to wildlife, Radiat. Environ. Biophys. **51** (2012b) 399–410. (https://doi.org/10.1007/s00411-012-0430-0)

VIVES I BATLLE, J., SAZYKINA, T., KRYSHEV, A., WOOD, M.D., SMITH, K., COPPLESTONE, D., BIERMANS, G., Modelling the effects of ionising radiation on a vole population from the Chernobyl Red forest in an ecological context, Ecological Modelling **438** (2020) 109306. (https://doi.org/10.1016/j.ecolmodel.2020.109306)

REFERENCES

[1] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, 1990 Recommendations of the ICRP, Publication 60, Annals of the ICRP, **21** 1–3, Pergamon Press, Oxford (1991).

[2] ENVIRONMENTAL CANADA AND HEALTH CANADA, Canadian Environmental Protection Act 1999, Priority Substances List Assessment Report, Releases of Radionuclides from Nuclear Facilities (Impact on Non-Human Biota), Environmental Canada, Health Canada Report (2003) 117 pp.

[3] HOLM, L.-E., HUBBARD, L., LARSSON, C.-M., SUNDELL-BERGMAN, S., Radiological protection of the environment from the Swedish point of view, J. Radiol. Prot. **22** 3 (2002) 235–47.

[4] COPPLESTONE, D., BIELBY, S., JONES, S.R., PATTON, D., DANIEL, C.P., GIZE, I., Impact Assessment of Ionising Radiation on Wildlife, R&D Publication 128, Environment Agency, Bristol (2001).
https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/290300/sr-dpub-128-e-e.pdf

[5] UNITED STATES DEPARTMENT OF THE ENVIRONMENT, A graded approach for evaluating radiation doses to aquatic and terrestrial biota, USDOE Technical Standard DOE-STD-1153-2002, Washington DC (2002).
https://www.standards.doe.gov/standards-documents/1100/1153-AStd-2002

[6] INTERNATIONAL ATOMIC ENERGY AGENCY, Protection of the Environment from the Effects of Ionizing Radiation, Proceedings of an International Conference Stockholm, Sweden, 6–10 October 2003, IAEA, Vienna (2005).

[7] BROWN, J.E., THØRRING, H., HOSSEINI, A., The “EPIC” impact assessment framework: Towards the protection of the Arctic environment from the effects of ionising radiation, Deliverable D6 for EPIC Environmental Protection from ionising radiation in the Arctic, Project no. ICA2-CT-2000-10032 (2003).
https://wiki.ceh.ac.uk/display/rpemain/EPIC+reports

[8] WILLIAMS, C., (ed.) Special Issue: Framework for assessment of environmental impact (FASSET) of ionising radiation in European ecosystems, J. Radiol. Prot. **24(4A)** (2004).

[9] HOWARD, B.J., LARSSON, C.-M., The ERICA Project, Environmental risk from ionising contaminants: assessment and management, J. Environ. Radioact. **99** (2008) 1361–518.

[10] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, The 2007 Recommendations of the ICRP, Publication 103, Annals of the ICRP 37 (2–4), Pergamon Press, Oxford (2007).

[11] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, The Concept and Use of Reference Animals and Plants for the Purposes of Environmental Protection, J. Valentin (Ed.), Publication 108, Annals of the ICRP 38(4-6), Elsevier, Oxford (2008) 76 pp.

[12] EUROPEAN ATOMIC ENERGY COMMUNITY, FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR ORGANIZATION, INTERNATIONAL MARITIME ORGANIZATION, OECD NUCLEAR ENERGY AGENCY, PAN AMERICAN HEALTH ORGANIZATION, UNITED NATIONS ENVIRONMENT PROGRAMME, WORLD HEALTH ORGANIZATION, Fundamental Safety Principles, IAEA Safety Standards Series No. SF-1, IAEA, Vienna (2006).

[13] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Protection of the Environment under Different Exposure Situations, Publication 124, Annals of the ICRP **43**(1), Pergamon Press, Oxford (2014).

[14] INTERNATIONAL ATOMIC ENERGY AGENCY, Prospective Radiological Environmental Impact Assessment for Facilities and Activities, IAEA Safety Standards Series No. GSG-10, IAEA, Vienna (2018).

[15] INTERNATIONAL ATOMIC ENERGY AGENCY, Modelling Radiation Exposure and Radionuclide Transfer for Non-human Species, Report of the Biota Working Group of EMRAS Theme 3, Environmental Modelling for Radiation Safety (EMRAS) Programme, IAEA, Vienna (2012).
http://www-ns.iaea.org/downloads/rw/projects/emras/final-reports/biota-report.pdf

[16] BERESFORD, N.A., BALONOV, M., BEAUGELIN-SEILLER, K., BROWN, J., COPPLESTONE, D., HINGSTON, J.L., HORYNA, J., HOSSEINI, A., HOWARD, B.J., KAMBOJ, S., NEDVECKAITE, T., OLYSLAEGERS, G., SAZYKINA, T., VIVES I BATLLE, J., YANKOVICH, T., YU, C., An international comparison of models and approaches for the estimation of radiological exposure to non-human biota, Appl. Radiat. Isot. **66** (2008) 1745–9.

[17] VIVES I BATLLE, J., BALONOV, M., BEAUGELIN-SEILLER, K., BERESFORD, N.A., BROWN, J., CHENG, J.-J., COPPLESTONE, D., DOI, M., FILISTOVIC, V., GOLIKOV, V., HORYNA, J., HOSSEINI, A., HOWARD, B.J., JONES, S.R., KAMBOJ, S., KRYSHEV, A., NEDVECKAITE, T., OLYSLAEGERS, G., PRÖHL, G., SAZYKINA, T., ULANOVSKY, A., VIVES-LYNCH, S., YANKOVICH, T., YU, C., Inter-comparison of absorbed dose rates for non-human biota, Radiat. Environ. Biophys. **46** 4 (2007) 349–73.

[18] BERESFORD, N.A., BARNETT, C.L., BROWN, J., CHENG, J.J., COPPLESTONE, D., FILISTOVIC, V., HOSSEINI, A., HOWARD, B.J., JONES, S.R., KAMBOJ, S., KRYSHEV, A., NEDVECKAITE, T., OLYSLAEGERS, G., SAXÉN, R., SAZYKINA, T., VIVES I BATLLE, J., VIVES-LYNCH, S., YANKOVICH, T., YU, C., Inter-comparison of models to estimate radionuclide activity concentrations in non-human biota, Radiat. Environ. Biophys. **47** 4 (2008) 491–514.

[19] YANKOVICH, T.L., VIVES I BATLLE, J., VIVES-LYNCH, S., BERESFORD, N.A., BARNETT, C.L., BEAUGELIN-SEILLER, K., BROWN, J.E., CHENG, J.-J., COPPLESTONE, D., HELING, R., HOSSEINI, A., HOWARD, B.J., KAMBOJ, S., KRYSHEV, T., NEDVECKAITE, T., SMITH, J.T., WOOD, M.D., An international model validation exercise on radionuclide transfer and doses to freshwater biota, J. Radiol. Prot. **30** (2010) 299–340.

[20] BERESFORD, N.A., BARNETT, C.L., BEAUGELIN-SEILLER, K., BROWN, J.E., CHENG, J.-J., COPPLESTONE, D., GASCHAK, S., HINGSTON, J.L., HORYNA, J., HOSSEINI, A., HOWARD, B.J., KAMBOJ, S., KRYSHEV, A., NEDVECKAITE, T., OLYSLAEGERS, G., SAZYKINA, T., SMITH, J.T., TELLERIA, D., VIVES I BATLLE, J., YANKOVICH, T.L., HELING, R., WOOD, M.D., YU, C., Findings and recommendations from an international comparison of models and approaches for the estimation of radiological exposure to non-human biota, Radioprotection **44** 5 (2009) 565–70.

[21] INTERNATIONAL ATOMIC ENERGY AGENCY, Handbook of Parameter Values for the Prediction of Radionuclide Transfer to Wildlife, Technical Reports Series No. 479, IAEA, Vienna (2014).

[22] RUEDIG, E., BERESFORD, N.A., GOMEZ FERNANDEZ, M.E., HIGLEY, K., A comparison of the ellipsoidal and voxelized dosimetric methodologies for internal, heterogeneous radionuclide sources, J. Environ. Radioact. **140** (2015) 70–7.

[23] CAFFREY, E., JOHANSEN, M., HIGLEY, K., Voxel modeling of rabbits for use in radiological dose rate calculations, J. Environ. Radioact. **151** (2016) 480–6.

[24] JOHANSEN, M.P., CHILD, D.P., CAFFREY, E.A., DAVIS, E., HARRISON, J.J., HOTCHKIS, M.A.C., IKEDA-OHNO, A., THIRUVOTH, S., TWINING, J.R., BERESFORD, N.A., Accumulation of plutonium in mammalian wildlife tissues following dispersal by accidental-release tests, J. Environ. Radioact. **151** (2016) 387–94.

[25] YANKOVICH, T., BERESFORD, N.A., WOOD, M.D., SHARP, K.J., BENZ, M.L., CARR, J., KILLEY, R.W.D., Do site-specific radiocarbon measurements reflect localized distributions of 14C in biota inhabiting a wetland with point contamination sources? J. Environ. Radioact. **126** (2013) 352–66.

[26] YANKOVICH, T.L., KING-SHARP, K., CARR, J., ROBERTSON, E., KILLEY, R.W., BERESFORD, N.A., WOOD, M.D., Spatial analysis of carbon-14 dynamics in a wetland ecosystem (Duke Swamp, Chalk River Laboratories, Canada), J. Environ. Radioact. **137** (2014) 173–80.

[27] BEAUGELIN-SEILLER, K., GARNIER-LEPLACE, J., BERESFORD, N.A., Estimating radiological exposure of wildlife in the field, J. Environ. Radioact. **211** (2020) 105830.

[28] CAIRNS, J., NIEDERLEHNER, B.R., Developing a field of landscape ecotoxicology, Ecological Applications (1996) 790–6.

[29] FORBES, V.E., CALOW, P., Promises and problems for the new paradigm for risk assessment and an alternative approach involving predictive systems models, Environ. Toxicol. Chem. **31** (2012) 1663–2671.

[30] BERESFORD, N.A., GASCHAK, S., BARNETT, C.L., HOWARD, B.J., CHIZHEVSKY, I., STRØMMAN, G., OUGHTON, D.H., WRIGHT, S.M., MAKSIMENKO, A., COPPLESTONE, D., Estimating the exposure of small mammals at three sites within the Chernobyl exclusion zone – A test application of the ERICA Tool, J. Environ. Radioact. **99** 9 (2008) 1496–502.

[31] ARAMRUN, K., BERESFORD, N.A., SKUTERUD, L., HEVROY, T., DREFVELIN, J., BENNETT, K., YUROSKO, C., PHRUKSAROJANAKUN, P., ESOA, J., YONGPRAWAT, M., SIEGENTHALER, A., FAWKES, R., TUMNOI, W., WOOD, M.D., Measuring the radiation exposure of Norwegian reindeer under field conditions, Sci. Total Environ. **687** (2019) 1337–43.

[32] BROWN, J., ALFONSO, B., AVILA, R., BERESFORD, N., COPPLESTONE, D., HOSSEINI, A., A new version of the ERICA tool to facilitate impact assessments of radioactivity on wild plants and animals, J. Environ. Radioact. **153** (2016) 141–9.

[33] SINGH, N.J., BÖRGER, L., DETTKI, H., BUNNEFELD, N., ERICSSON, G., From migration to nomadism: movement variability in a northern ungulate across its latitudinal range, Ecological Applications **22** (2012) 2007–20.

[34] ALLEN, A.M.J., MÅNSSON, J., SAND, H., MALMSTEN, J., ERICSSON, G., SINGH, N.J., Scaling up movements: from individual space use to population patterns, Ecosphere **7** (2016) e01524.

[35] WOOD, M.D., BERESFORD, N.A., BRADSHAW, C., HOWARD, D.C., ANDERSSON, P., SINGH, N.J., PALO, R.T., JOHANSEN, M.P., Accounting for animal movement behaviour improves radiation exposure modelling estimates for heterogeneously contaminated environments, Environmental Research (Submitted).

[36] CHRISTENSEN, V., COLL, M., STEENBEEK, J., BUSZOWSKI, J., CHAGARIS, D., WALTERS, C.J., Representing variable habitat quality in a spatial food web model, Ecosystems **17** (2014) 1397–412.

[37] COPPLESTONE, D., BERESFORD, N.A., BROWN, J.E., YANKOVICH, T., An international database of radionuclide concentration ratios for wildlife: development and uses, J. Environ. Radioact. **126** (2013) 288–98.

[38] HINTON, T.G., BYRNE, M.E., WEBSTER, S.C., LOVE, C.N., BROGGIO, D., TROMPIER, F., SHAMOVICH, D., HORLOOGIN, S., LANCE, S.L., BROWN, J., DOWDALL, M., BEASLEY, J.C., GPS-coupled contaminant monitors on free-ranging Chernobyl wolves challenge a fundamental assumption in exposure assessments, Environ. Int. **133** (2019) 105152.

[39] GAINES, K.F., PORTER, D.E., PUNSHON, T., BRISBIN JR, I.L., A Spatially Explicit Model of the Wild Hog for Ecological Risk Assessment Activities at the Department of Energy's Savannah River Site, Human and Ecological Risk Assessment: An International Journal **11** (2005) 567–89.

[40] GERKE, H.C., HINTON, T.G., TAKASE, T., ANDERSON, D., NANBA, K., BEASLEY, J.C., Radiocesium concentrations and GPS-coupled dosimetry in Fukushima snakes, Sci. Total Environ. **734** (2020) 139389.

[41] BERESFORD, N.A., BEAUGELIN-SEILLER, K., BARNETT, C.L., BROWN, J., DOERING, C., CAFFREY, E., JOHANSEN, M.P., MELINTESCU, A., RUEDIG, H., VANDENHOVE, H., VIVES I BATLLE, J., WOOD, M.D., YANKOVICH, T.L., COPPLESTONE, D., Ensuring robust radiological risk assessment for wildlife: insights from the International Atomic Energy Agency EMRAS and MODARIA programmes, J. Radiol. Prot. (Submitted).

[42] BROWN, J.E., ALFONSO, B., AVILA, R., BERESFORD, N.A., COPPLESTONE, D., PRÖHL, G., ULANOVSKY, A., The ERICA Tool, J. Environ. Radioact. **99** 9 (2008) 1371–83.

[43] UNITED STATES DEPARTMENT OF ENERGY, RESRAD-BIOTA: A Tool for Implementing a Graded Approach to Biota Dose Evaluation, User's Guide, Version 1, U.S. Department of Commerce, Technology Administration, National Technical Information Service, Springfield VA (2004). https://resrad.evs.anl.gov/docs/RESRAD-BIOTA_Manual_Version_1.pdf

[44] COPPLESTONE, D., BROWN, J.E., BERESFORD, N.A., Considerations for the integration of human and wildlife radiological assessments, J. Radiol. Prot. **30** (2010) 283–97.

[45] SMITH, C., Environmental monitoring program report, Bruce Power report B-REP-07000-00005 R000 (2013).

[46] VIVES I BATLLE, J., JONES, S.R., COPPLESTONE, D., A method for estimating ^{41}Ar, ^{85,88}Kr and ^{131m,133}Xe doses to non-human biota, J. Environ. Radioact. **144** (2015) 152–61.

[47] VIVES I BATLLE, J., COPPLESTONE, D., JONES, S.R., WILLIAMS, C., Allometric methodology for the assessment of radon exposures to wildlife, Sci. Total Environ. **427-428** (2012) 50–9.

[48] VIVES I BATLLE, J., ULANOVSKY, A.V., COPPLESTONE, D., A method for assessing exposure of terrestrial wildlife to environmental radon (^{222}Rn) and thoron (^{220}Rn), Sci. Total Environ. **605–606** (2017) 569–77.

[49] BERESFORD, N., BARNETT, C., VIVES I BATLLE, J., POTTER, E.D., IBRAHIMI, Z.-F., BARLOW, T.S., SCHIEB, C., JONES, D.G., COPPLESTONE, D., Exposure of burrowing mammals to ^{222}Rn, Sci. Total Environ. **431** (2012) 252–61.

[50] VIVES I BATLLE, J., Radioactivity in the Marine Environment, In: Meyers, R.A. (Ed.), Encyclopaedia of Sustainability Science and Technology, Springer Science & Business Media, LLC (2012) 8387–8425.

[51] STRAND, P., AONO, T., BROWN, J., GARNIER-LAPLACE, J., HOSSEINI, A., SAZYKINA, T., STEENHUISEN, F., VIVES I BATLLE, J., First international assessment of Fukushima-derived radiation doses and effects on wildlife in Japan, Environ. Sci. Technol. Viewpoint **2014** 1 (2014) 198−203.

[52] GARNIER-LAPLACE, J., BEAUGELIN-SEILLER, K., HINTON, T.G., Fukushima Wildlife Dose Reconstruction Signals Ecological Consequences, Environ. Sci. Technol. **45** (2011) 5077–8.

[53] VIVES I BATLLE, J., AOYAMA, M., BRADSHAW, C., BROWN, J., BUESSELER, K.O., CASACUBERTA, N., CHRISTL, M., DUFFA, C., IMPENS, N., IOSJPE, M., MASQUÉ, P., NISHIKAWA, J., Marine radioecology after the Fukushima Dai-ichi nuclear accident: Are we better positioned to understand the impact of radionuclides in marine ecosystems? Sci. Total Environ. **618** (2018) 80–92.

[54] VIVES I BATLLE, J., WILSON, R.C., WATTS, S.J., JONES, S.R., MCDONALD, P., VIVES-LYNCH, S., Dynamic model for the assessment of radiological exposure to marine biota, J. Environ. Radioact. **99** (2008) 1711–30.

[55] VIVES I BATLLE, J., BERESFORD, N.A., BEAUGELIN-SEILLER, K., BEZHENAR, R., BROWN, J., CHENG, J.J., ĆUJIĆ, M., DRAGOVIĆ, S., DUFFA, C., FIÉVET, B., HOSSEINI, A., JUNG, K.T., KAMBOJ, S., KEUM, D.-K., KRYSHEV, A., LEPOIRE, D., MADERICH, V., MIN, B.-I., PERIÁÑEZ, R., SAZYKINA, T., SUH, K.-S., YU, C., WANG, C., HELING, R., Inter-comparison of dynamic models for radionuclide transfer to marine biota in a Fukushima accident scenario, J. Environ. Radioact. **153** (2016) 31–50.

[56] BERESFORD, N.A., BEAUGELIN-SEILLER, K., BURGOS, J., M., C., FESENKO, S., KRYSHEV, A., PACHAL, N., REAL, A., SU, B.S., TAGAMI, K., VIVES I BATLLE, J., VIVES-LYNCH, S., WELLS, C., WOOD, M.D., Radionuclide biological half-life values for terrestrial and aquatic wildlife, J. Environ. Radioact. **150** (2015) 270–6.

[57] JOHANSEN, M.P., BARNETT, C.L., BERESFORD, N.A., BROWN, J.E., ČERNE, M., HOWARD, B.J., KAMBOJ, S., KEUM, D.-K., SMODIŠ, B., TWINING, J.R., VANDENHOVE, H., VIVES I BATLLE, J., WOOD, M.D., YU, C., Assessing doses to terrestrial wildlife at a radioactive waste disposal site: Inter-comparison of modelling approaches, Sci. Total Environ. **427–428** (2012) 238–46.

[58] BERESFORD, N.A., BARNETT, C.L., BROWN, J.E., CHENG, J.J., COPPLESTONE, D., GASCHAK, S., HOSSEINI, A., HOWARD, B.J., KAMBOJ, S., NEDVECKAITE, T., SMITH, J.T., VIVES I BATLLE, J., VIVES-LYNCH, S., YU, C., Predicting the radiation exposure of terrestrial wildlife in the Chernobyl exclusion zone: an international comparison of approaches, J. Radiol. Prot. **30** (2010) 341–73.

[59] STARK, K., ANDERSSON, P., BERESFORD, N.A., YANKOVICH, T.L., WOOD, M.D., JOHANSEN, M.P., VIVES I BATLLE, J., TWINING, J., KEUM, D.-K., BOLLHOFER, A., DOERING, C., RYAN, B., GRZECHNIK, M., VANDENHOVE, H., Predicting exposure of wildlife in radionuclide contaminated wetland ecosystems, Environ. Pollut. **196** (2015) 201–13.

[60] GOULET, R.R., NEWSOME, L., VANDENHOVE, K., KEUM, D.-K., HORYNA, J., KAMBOJ, S., BROWN, J., HOSSEINI, A., JOHANSEN, M.P., TWINING, J., WOOD, M.D., CERNE, M., BEAUGELIN-SEILLER, K., BERESFORD, N.A., International comparisons and best practices for radiological dose model predictions to freshwater food chains: a uranium mining/milling scenario, J. Environ. Radioact. (Submitted).

[61] WOOD, M.D., BERESFORD, N.A., HOWARD, B., J., COPPLESTONE, D., Evaluating summarised radionuclide concentration ratio datasets for wildlife, J. Environ. Radioact. **126** (2013) 314–25.

[62] DOERING, C., MEDLEY, P., ORR, B., URBAN, D., Whole organism to tissue concentration ratios derived from an Australian tropical dataset, J. Environ. Radioact. **189** (2018) 31–9.

[63] HIRTH, G.A., JOHANSEN, M.P., CARPENTER, J.G., BOLLHÖFER, A., BERESFORD, N.A., Whole-organism concentration ratios in wildlife inhabiting Australian uranium mining environments, J. Environ. Radioact. **178–179** (2017) 385–93.

[64] TAKATA, H., JOHANSEN, M.P., KUSAKABE, M., IKENOUE, T., YOKOTA, M., TAKAKU, H., A 30-year record reveals re-equilibration rates of ^{137}Cs in marine biota after the Fukushima Dai-ichi nuclear power plant accident: Concentration ratios in pre- and post-event conditions, Sci. Total Environ. **675** (2019) 694–704.

[65] TAGAMI, K., UCHIDA, S., WOOD, M.D., BERESFORD, N.A., Radiocaesium transfer and radiation exposure of frogs in Fukushima Prefecture, Scientific Reports **8** 1 (2018) 10662.

[66] TOMCZAK, W., BOYER, P., KRIMISSA, M., RADAKOVITCH, O., Kd distributions in freshwater systems as a function of material type, mass-volume ratio, dissolved organic carbon and pH, Appl. Geochem. **105** (2019) 68–77.

[67] BOYER, P., WELLS, C., HOWARD, B., Extended Kd distributions for freshwater environment, J. Environ. Radioact. **192** (2018) 128–42.

[68] VIVES I BATLLE, J., BEAUGELIN-SEILLER, K., BERESFORD, N.A., COPPLESTONE, D., HORYNA, J., HOSSEINI, A., JOHANSEN, M., KAMBOJ, S., KEUM, D.-K., KUROSAWA, N., NEWSOME, L., OLYSLAEGERS, G., VANDENHOVE, H., RYUFUKU, S., VIVES LYNCH, S., WOOD, M.D., YU, C., The estimation of absorbed dose rates for non-human biota: an extended intercomparison, Radiat. Environ. Biophys. **50** (2011) 231–51.

[69] VIVES I BATLLE, J., BARNETT, C.L., BEAUGELIN-SEILLER, K., BERESFORD, N.A., COPPLESTONE, D., HORYNA, J., HOSSEINI, A., JOHANSEN, M., KAMBOJ, S., KEUM, D.-K., NEWSOME, L., OLYSLAEGERS, G., VANDENHOVE, H., VIVES LYNCH, S., WOOD, M., Absorbed dose conversion coefficients for non-human biota: an extended inter-comparison of data, Radiat. Environm. Biophys. **50** 2 (2011) 231–51.

[70] CAFFREY, E.A., HIGLEY, K.A., Creation of a voxel phantom of the ICRP reference crab, J. Environ. Radioact. **120** (2013) 14–8.

[71] KINASE, S., Voxel-based frog phantom for internal dose evaluation, J. Nucl. Sci. Technol. **45** (2008) 1049–52.

[72] MOHAMMADI, A., KINASE, S., SAITO, K., Evaluation of absorbed doses in voxel based and simplified models for small animals, Radiat. Prot. Dosim. **150** (2012) 283–91.

[73] RUEDIG, E., HESS, C., CAFFREY, E.A., HIGLEY, K.A., Monte Carlo derived absorbed fractions for a voxelized model of Oncorhynchus mykiss, a rainbow trout, Radiat. Environ. Biophys. **53** (2014) 581–7.

[74] BEAUGELIN-SEILLER, K., Effects of soil water content on the external exposure of fauna to radioactive isotopes, J. Environ. Radioact. **151** (2016) 204–8.

[75] BEAUGELIN-SEILLER, K., The assumption of heterogeneous or homogeneous radioactive contamination in soil/sediment: does it matter in terms of the external exposure of fauna? J. Environ. Radioact. **138** (2014) 60–7.

[76] INTERNATIONAL ATOMIC ENERGY AGENCY, Generic Models for Use in Assessing the Impact of Discharges of Radioactive Substances to the Environment, Safety Reports Series No. 19, IAEA, Vienna (2001).

[77] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Dose Coefficients for Non-human Biota Environmentally Exposed to Radiation, Publication 136, Annals of the ICRP **46** 2 (2017) 1–136.

[78] ERICA, Environmental Risk from Ionising Contaminants: Assessment and Management (ERICA) Assessment Tool, Help Documentation, ERICA Tool Version 1.3 (2019).

[79] INTERNATIONAL ATOMIC ENERGY AGENCY, Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Terrestrial and Freshwater Environments, Technical Reports Series No. 472, IAEA, Vienna (2010).

[80] INTERNATIONAL ATOMIC ENERGY AGENCY, Quantification of Radionuclide Transfer in Terrestrial and Freshwater Environments for Radiological Assessments, IAEA-TECDOC-1616, IAEA, Vienna (2009).

[81] EVENDEN, W.G., SHEPPARD, S.C., KILLEY, R.W.D., Carbon-14 and tritium in plants of a wetland containing contaminated groundwater, Appl. Geochem. **13** (1998) 17–21.

[82] YIM, M.-S., CARON, F., Life cycle and management of carbon-14 from nuclear power generation, Prog. Nucl. Energy **48** (2006) 2–36.

[83] BEAUGELIN-SEILLER, K., GOULET, R., MIHOK, S., BERESFORD, N.A., Should we ignore U-235 series contribution to dose? J. Environ. Radioact. **151** (2016) 114–25.

[84] UNITED NATIONS SCIENTIFIC COMMITTEE ON THE EFFECTS OF ATOMIC RADIATION, Sources and effects of ionizing radiation, UNSCEAR 2000 Report to the General Assembly with Scientific Annexes, Volume I: Sources, Annex B: Exposures from natural radiation source. United Nations, New York (2000).

[85] BERESFORD, N.A., WOOD, M.D., VIVES I BATLLE, J., YANKOVICH, T.L., BRADSHAW, C., WILLEY, N., Making the most of what we have: application of extrapolation approaches in radioecological wildlife transfer models, J. Environ. Radioact. **151** 2 (2016) 373–86.

[86] EUROPEAN COMMISSION, Technical Guidance Document in Support of Commission Directive 93/67/EEC on Risk Assessment for New Notified Substances and Commission Regulation (EC) No. 1488/94 on Risk Assessment for Existing Substances and Directive 98/8/EC of the European Parliament and of the Council concerning the placing of biocidal products on the market, Part II, European Commission – Joint Research Centre Institute for Health and Consumer Protection European Chemicals Bureau (ECB) (2003) 328 pp.

[87] EUROPEAN COMMISSION, Technical Guidance Document in Support of Commission Directive 93/67/EEC on Risk Assessment for New Notified Substances, Commission Regulation (EC) No. 1488/94 on Risk Assessment for Existing Substances and Directive 98/8/EC of the European Parliament and of the Council concerning the placing of biocidal products on the market, Part III, European Commission – Joint Research Centre Institute for Health and Consumer Protection European Chemicals Bureau (ECB) (2003) 104 pp.

[88] ANDERSSON, P., BEAUGELIN-SEILLER, K., BERESFORD, N.A., COPPLESTONE, D., DELLA VEDOVA, C., GARNIER-LAPLACE, J., HOWARD, B.J., HOWE, P., OUGHTON, D.H., WELLS, C., WHITEHOUSE, P., PROTECT – Protection of the Environment from Ionising Radiation in a Regulatory Context, Deliverable 5 for EC-project N° FI6R-036425 – Numerical benchmarks for protecting biota from radiation in the environment: Proposed levels, underlying reasoning and recommendations (2008) 72 pp.

[89] ANDERSSON, P., GARNIER-LAPLACE, J., BERESFORD, N., COPPLESTONE, D., HOWARD, B., HOWE, P., OUGHTON, D., WHITEHOUSE, P., Protection of the environment from ionising radiation in a regulatory context (PROTECT): Proposed numerical benchmark values, J. Environ. Radioact. **100** (2009) 1100–8.

[90] GARNIER-LAPLACE, J., DELLA-VEDOVA, C., ANDERSSON, P., COPPLESTONE, D., CAILES, C., BERESFORD, N.A., HOWARD, B.J., HOWE, P., WHITEHOUSE, P., A multi-criteria weight of evidence approach for deriving ecological benchmarks for radioactive substances, J. Radiol. Prot. **30** 2 (2010) 215–33.

[91] HOSSEINI, A., BERESFORD, N.A., BROWN, J.E., JONES, D.G., PHANEUF, M., THØRRING, H., YANKOVICH, T., Background dose-rates to reference animals and plants arising from exposure to naturally occurring radionuclides in aquatic environments, J. Radiol. Prot. **30** 2 (2010) 235–64.

[92] BERESFORD, N.A., BARNETT, C.L., WOOD, C.M., Background exposure rates of terrestrial wildlife in England and Wales, J. Environ. Radioact. **99** 9 (2008) 1430–9.

[93] BRADSHAW, C., KAPUSTKA, L., BARNTHOUSE, L., BROWN, J., CIFFROY, P., FORBES, V., GERASKIN, S., KAUTSKY, U., BREECHIGNAC, F., Using an ecosystem approach to complement protection schemes based on organism-level endpoints, J. Environ. Radioact. **136** (2014) 98–104.

[94] GARNIER-LAPLACE, J., GERAS'KIN, S., DELLA-VEDOVA, C., BEAUGELIN-SEILLER, K., HINTON, T.G., REAL, A., OUDALOVA, A., Are radiosensitivity data derived from natural field conditions consistent with data from controlled exposures? A case study of Chernobyl wildlife chronically exposed to low dose rates, J. Environ. Radioact. **121** (2013) 12–21.

[95] FREDERICA, FREDERICA Radiation Effects Database (2006). https://www.frederica-online.org/mainpage.asp

[96] REAL, A., SUNDELL-BERGMAN, S., KNOWLES, J.F., WOODHEAD, D.S., ZINGER, I., Effects of ionising radiation exposure on plants, fish and mammals: relevant data for environmental radiation protection, J. Radiol. Prot. **24** (2004) A123–A37.

[97] COPPLESTONE, D., HINGSTON, J.L., REAL, A., The development and purpose of the FREDERICA radiation effects database, J. Environ. Radioact. **99** 9 (2008) 1456–63.

[98] GARNIER-LAPLACE, J., GERAS'KIN, S., DELLA-VEDOVA, C., BEAUGELIN-SEILLER, K., HINTON, T.G., REAL, A., OUDALOVA, A., Are radiosensitivity data derived from natural field conditions consistent with data from controlled exposures? A case study of Chernobyl wildlife chronically exposed to low dose rates, J. Environ. Radioact. **121** (2012) 12–21.

[99] ALONZO, F., HERTEL-AAS, T., REAL, A., LANCE, E., GARCIA-SANCHEZ, L., BRADSHAW, C., VIVES I BATLLE, J., GARNIER-LAPLACE, J., Population modelling to compare chronic external gamma radiotoxicity between individual and population endpoints in four taxonomic groups, J. Environ. Radioact. **152** (2016) 46–59.

[100] MONTE, L., Predicting the effects of ionising radiation on ecosystems by a generic model based on the Lotka-Volterra equations, J. Environ. Radioact. **100** 6 (2009) 477–83.

[101] VIVES I BATLLE, J., SAZYKINA, T., KRYSHEV, A., MONTE, L., KAWAGUCHI, I., Inter-comparison of population models for the calculation of radiation dose effects to wildlife, Radiat. Environ. Biophys. **51** 4 (2012) 399–410.

[102] SAZYKINA, T., Population sensitivities of animals to chronic ionizing radiation-model predictions from mice to elephant, J. Environ. Radioact. **182** (2018) 177–82.

[103] KRYSHEV, A.I., SAZYKINA, T.G., BADALIAN, K.D., Mathematical simulation of dose-effect relationships for fish eggs exposed chronically to ionizing radiation, Radiat. Environ. Biophys. **45** 3 (2006) 195–201.

[104] KRYSHEV, A.I., SAZYKINA, T.G., SANINA, K.D., Modelling of effects due to chronic exposure of a fish population to ionizing radiation, Radiat. Environ. Biophys. **47** 1 (2008) 121–9.

[105] VIVES I BATLLE, J., WILSON, R.C., WATTS, S.J., MCDONALD, P., JONES, S.R., VIVES-LYNCH, S.M., CRAZE, A., Approach to the assessment of risk from chronic radiation to populations of European lobster, *Homarus gammarus (L.)*, Radiat. Environ. Biophys. **49** 1 (2009) 67–85.

[106] CRONE, E.E., MENGES, E.S., ELLIS, M.M., BELL, T., BIERZYCHUDEK, P., EHRLE, J., KAYE, T.N., KNIGHT, T.M., LESICA, P., MORRIS, W.F., OOSTERMEIJER, G., QUINTANA-ASCENCIO, P.F., STANLEY, A., TICKTIN, T., VALVERDE, T., WILLIAMS, J.L., How do plant ecologists use matrix population models? Ecology Letters **14** 1 (2011) 1–8.

[107] CRONE, E., ELLIS, M., MORRIS, W., STANLEY, A., BELL, T., BIERZYCHUDEK, P., EHRLÉN, J., KAYE, T., KNIGHT, T., LESICA, P., OOSTERMEIJER, J., QUINTANA-ASCENCIO, P., TICKTIN, T., VALVERDE, T., WILLIAMS, J., DOAK, D., GANESAN, R., MCEACHERN, K., THORPE, A., MENGES, E., Ability of Matrix Models to Explain the Past and Predict the Future of Plant Populations, Conservation Biology **27** 5 (2013) 968–78.

[108] RALSTON, R., BUONGIORNO, J., SCHULTE, B., FRIED, J., Non-linear matrix modeling of forest growth with permanent plot data: The case of uneven-aged Douglas-fir stands, International Transactions in Operational Research **10** 5 (2003) 461–82.

[109] DUARTE, P., FERREIRA, J.G., A model for the simulation of macroalgal population dynamics and productivity, Ecological Modelling **98** 2–3 (1997) 199–214.

[110] DOI, M., KAWAGUCHI, I., TANAKA, N., FUMA, S., ISHII, N., MIYAMOTO, K., TAKEDA, H., KAWABATA, Z., Model ecosystem approach to estimate community level effects of radiation, Radioprotection **40** 1 (2005) S913–S9.

[111] ALONZO, F., HERTEL-AAS, T., GILEK, M., GILBIN, R., OUGHTON, D.H., GARNIER-LAPLACE, J., Modelling the propagation of effects of chronic exposure to ionising radiation from individuals to populations, J. Environ. Radioact. **99** (2008) 1464–73.

[112] BIRON, P.A., MASSARIN, S., ALONZO, F., GARCIA-SANCHEZ, L., CHARLES, S., BILLOIR, E., Population-level modelling to account for multigeneration effects of uranium in Daphnia magna, Environ. Sci. Technol. **46** (2012) 1136–43.

[113] LANCE, E., ALONZO, F., GARCIA-SANCHEZ, L., BEAUGELIN-SEILLER, K., GARNIER-LAPLACE, J., Modelling population-level consequences of chronic external gamma irradiation in aquatic invertebrates under laboratory conditions, Sci. Total Environ. **429** (2012) 206–14.

[114] CASWELL, N., Matrix Population Models: Construction, Analysis, and Interpretation, Sinauer Associates (2001) 772 pp.

[115] ALONZO, F., VIVES I BATLLE, J., HERTEL-AAS, T., BRADSHAW, C., VANDENHOVE, H., GARNIER-LAPLACE, J., Life history traits, radiosensitivity and population modeling: methods to extrapolate from individual endpoints to population dynamics, STAR Deliverable D-N°5.2, Seventh Euratom Framework Programme for Nuclear Research and Training Activities Contract Fission-2010-3.5.1-269672, 31/07/2012 (2012) 125 pp.

[116] MASSARIN, S., BEAUDOUIN, R., ZEMAN, F., FLORIANI, M., GILBIN, R., ALONZO, F., PERY, A.R.R., Biology-based modeling to analyze uranium toxicity data on Daphnia magna in a multigeneration study, Environ. Sci. Technol. **45** 9 (2011) 4151–8.

[117] MASSARIN, S., ALONZO, F., GARCIA-SANCHEZ, L., GILBIN, R., GARNIER-LAPLACE, J., POGGIALE, J.-C., Effects of chronic uranium exposure on life history and physiology of Daphnia magna over three successive generations, Aquatic Toxicology **99** (2010) 309–19.

[118] KRYSHEV, A.I., SAZYKINA, T.G., Modelling the effects of ionizing radiation on survival of animal population: acute versus chronic exposure, Radiat. Environ. Biophys. **54** 1 (2015) 103–9.

[119] VERHULST, P.-F., Notice sur la loi que la population poursuit dans son accroissement, Correspondance Mathématique et Physique **10** (1838) 113–121 (in French).

[120] VERHULST, P.-F., Recherches mathématiques sur la loi d'accroissement de la population, Nouveaux Mémoires de l'Académie Royale des Sciences et Belles-Lettres de Bruxelles **18** (1845) 1–42 (in French).

[121] LESLIE, P.H., The use of matrices in certain population mathematics, Biometrika **33** 3 (1945) 183–212.

[122] VIVES I BATLLE, J., Dual age class population model to assess radiation dose effects to non-human biota populations, Radiat. Environ. Biophys. 51 (2012) 225-43.

[123] SAZYKINA, T., KRYSHEV, A., Simulation of population response to ionizing radiation in an ecosystem with a limiting resource e Model and analytical solutions, J. Environ. Radioact. **151** (2016) 50–7.

[124] SAZYKINA, T.G., KRYSHEV, A.I., Radiation effects in generic populations inhabiting a limiting environment, Radiat. Enviro. Biophys. **51** 2 (2012) 215–21.

[125] KADHIM, M., SALOMAA, S., WRIGHT, E., HILDEBRANDT, G., BELYAKOV, O.V., PRISE, K.M., LITTLE, M.P.N., Non-targeted effects of ionizing radiation—implications for low dose risk, Mutat. Res. **752** 1 (2013) 84–98.

[126] MOTHERSILL, C., RUSIN, A., SEYMOUR, C., Low doses and non-targeted effects in environmental radiation protection; where are we now and where should we go? Environ. Res. **159** (2017) 484–90.

[127] MOTHERSILL, C., SEYMOUR, C., Targets, pools, shoulders, and communication — A reflection on the evolution of low-dose radiobiology, Int. J. Radiat. Biol. **95** 7 (2019) 851–60.

[128] MOTHERSILL, C., RUSIN, A., SEYMOUR, C., Towards a new concept of low dose, Health Phys. **117** 3 (2019) 330–6.

[129] SAZYKINA, T., KRYSHEV, A., Lower thresholds for lifetime health effects in mammals from high-LET radiation — Comparison with chronic low-LET radiation, J. Environ. Radioact. **165** (2016) 227–42.

[130] BERESFORD, N.A., HOREMANS, N., COPPLESTONE, D., RAINES, K.E., ORIZAOLA, G., WOOD, M.D., LAANEN, P., WHITEHEAD, H.C., BURROWS, J.E., TINSLEY, M.C., SMITH, J.T., BONZOM, J.-M., GAGNAIRE, B., ADAM-GUILLERMIN, C., GASHCHAK, S., JHA, A.N., DE MENEZES, A., WILLEY, N., SPURGEON, D., Towards solving a scientific controversy — The effects of ionising radiation on the environment, J. Environ. Radioact. (2020) 106033.

[131] MØLLER, A.P., MOUSSEAU, T.A., Reduced abundance of insects and spiders linked to radiation at Chernobyl 20 years after the accident, Biology Letters **5** (2009) 356–9.

[132] MØLLER, A.P., MOUSSEAU, T.A., Assessing effects of radiation on abundance of mammals and predator–prey interactions in Chernobyl using tracks in the snow, Ecological Indicators **26** (2013) 112–6.

[133] MØLLER, A.P., MOUSSEAU, T.A., Are organisms adapting to ionizing radiation at Chernobyl? Trends in Ecology and Evolution **31** (2016) 281–9.

[134] MØLLER, A.P., MOUSSEAU, T.A., Reduced colonization by soil invertebrates to irradiated decomposing wood in Chernobyl, Sci. Total Environ. **645** (2018) 773–9.

[135] BERESFORD, N.A., COPPLESTONE, D., Effects of ionizing radiation on wildlife: What knowledge have we gained between the Chernobyl and Fukushima accidents? Integ. Environ. Assess. Manag. **7** 3 (2011) 371–3.

[136] MOTHERSILL, C.E., OUGHTON, D.H., SCHOFIELD, P.N., MICHAEL ABEND, M., ADAM-GUILLERMIN, C., ARIYOSHI, K., BERESFORD, N.A., BONISOLI-ALQUATI, A., COHEN, J., DUBROVA, Y., GERAS'KIN, S.A., HEVRØY, T.H., HIGLEY, K.A., HOREMANS, N., JHA, A.N., KAPUSTKA, L.A., KIANG, J.G., MADAS, B.G., POWATHIL, G., SARAPULTSEVA, E.I., SEYMOUR, C.B., VO, N.T.K., WOOD, M.D., From tangled banks to toxic bunnies; a reflection on the issues involved in developing an ecosystem approach for environmental radiation protection, Int. J. Radiat. Biol. (2020). 10.1080/09553002.2020.1793022.

[137] OMAR-NAZIR, L., XIAOPEI, S., MOLLER, A., MOUSSEAU, T., BYUN, S., HANCOCK, S., SEYMOUR, C., MOTHERSILL, C., Long-term effects of ionizing radiation after the Chernobyl accident: possible contribution of historic dose, Environmental Research **165** (2018) 55–62.

[138] HANCOCK, S., VO, N.T.K., L., O.-N., VIVES I BATLLE, J., OTAKI, J.M., HIYAMA, A., HYUN BYUN, S., SEYMOUR, C.B., MOTHERSILL, C., Transgenerational effects of historic radiation dose in pale grass blue butterflies around Fukushima following the Fukushima Dai-ichi Nuclear Power Plant meltdown accident, Environmental Research **168** (2019) 230–40.

[139] WODARZ, D., SORACE, R., KOMAROVA, N.L., Dynamics of Cellular Responses to Radiation, PLOS Computational Biology **10** 4 (2014) 1–11.

[140] WILSON, R.C., VIVES I BATLLE, J., WATTS, S.J., MCDONALD, P., JONES, S.R., VIVES-LYNCH, S.M., CRAZE, A., Approach to the assessment of risk from chronic radiation to populations of phytoplankton and zooplankton, Radiat. Environ. Biophys. **49** 1 (2010) 87–95.

[141] VIVES I BATLLE, J., SAZYKINA, T., KRYSHEV, A., WOOD, M.D., SMITH, K., COPPLESTONE, D., BIERMANS, G., Modelling the effects of ionising radiation on a vole population from the Chernobyl Red forest in an ecological context, Ecological Modelling **438** (2020) 109306.

[142] FORBES, V.E., CALOW, P., Population growth rate as a basis for ecological risk assessment of toxic chemicals, Philos. Trans. R. Soc. Lond. B. Biol. Sci. **357** (2002) 1299–306.

[143] STARK, J.D., BANKS, J.E., VARGAS, R., How risky is risk assessment? The role that life history strategies play in susceptibility of species to pesticides and other toxicants, Proceedings of the National Academy of Sciences of the United States of America 101 (2004) 732–6.

[144] HANSON, N., STARK, J.D., Utility of population models to reduce uncertainty and increase value relevance in ecological risk assessments of pesticides: an example based on acute mortality data for daphnids, Integ. Environ. Assess. Manage. **8** (2011) 262–70.

[145] IBRAHIM, L., PREUSS, T.G., SCHAEFFER, A., HOMMEN, U., A contribution to the identification of representative vulnerable fish species for pesticide risk assessment in Europe e a comparison of population resilience using matrix models, Ecological Modelling **280** (2014) 65–75.

[146] HANSON, N., STARK, J.D., An approach for developing simple generic models for ecological risk assessments of fish populations, Environ. Toxicol. Chem. **30** 10 (2011) 2372–83.

[147] EUROPEAN COMMISSION, Technical Guidance For Deriving Environmental Quality Standards, Guidance Document No. 27, Common Implementation Strategy for the Water Framework Directive (2000/60/EC), Technical Report, 2011-0552011 (2011).

[148] FORBES, V.E., CALOW, P., SIBLY, R.M., Are current species extrapolation models a good basis for ecological risk assessment? Environ. Toxicol. Chem. **202** 2 (2011) 442–7.

[149] GALIC, N., HOMMEN, U., BAVECO, J.M.H., VAN DEN BRINK, P.J., Potential application of population models in the European ecological risk assessment of chemicals II: Review of models and their potential to address environmental protection aims, Integ. Environ. Assess. Manage. **6** 3 (2010) 338–60.

[150] METZ, J.A.J., DIEKMANN, O., The Dynamics of Physiologically Structured Populations, Vol. 68, Springer-Verlag, Berlin (1986).

[151] ALONZO, F., ZIMMER, E., PLAIRE, D., BUISSET-GOUSSEN, A., ADAM-GUILLERMIN, C., LECOMTE-PRADINES, C., HOREMANS, N., HINTON, T., STAR Deliverable (D-N°5.4). Understanding the “metabolic” mode of actions of two different types of radiation using biokinetics/DEBtox models. European Comission, 7th Framework, Contract N (Fission-2010-3.5.1-269672) (2014) 69 pp.

[152] ALONZO, F., HOREMANS, N., OUGHTON, D., ADAM-GUILLERMIN, C., LECOMTE-PRADINES, C., PARISOT, F., BUISSET-GOUSSEN, A., ZIMMER, E., REAL, A., GARNIER-LAPLACE, J., STAR Deliverable (D-N°5.5). Protection criteria: Integrating radiation protection from molecules to populations and evaluation of group specific criteria. European Commission, 7th Framework, Contract N (Fission-2010-3.5.1-269672) (2015). 69 pp.

[153] JAGER, T., ZIMMER, E.I., Simplified Dynamic Energy Budget model for analysing ecotoxicity data, Ecological Modelling **225** (2012) 74–81.

[154] KOOIJMAN, S.A.L.M., BEDAUX, J.J.M., Analysis of toxicity tests on Daphnia survival and reproduction, Water Research **30** 7 (1996) 1711–23.

[155] LECOMTE-PRADINES, C., HERTEL-AAS, T., CUTRIS, C., GILBIN, R., OUGHTON, D., ALONZO, F., A dynamic energy-based model to analyze sublethal effects of chronic gamma irradiation in the nematode Caenorhabditis elegans, J.Toxicol. Environ. Health – Part A **80** 16-18 (2017) 830–44.

[156] AUGUSTINE, S., GAGNAIRE, B., ADAM-GUILLERMIN, C., KOOIJMAN, S., Effects of uranium on the metabolism of zebrafish, *Danio rerio*, Aquatic Toxicology **119** (2012) 9–26.

[157] GOUSSEN, B., PERY, A.R.R., BONZOM, J.-M., BEAUDOUIN, R., Transgenerational adaptation to pollution changes energy allocation in populations of nematodes, Environ. Sci. Technol. **49** 20 (2015) 12500–8.

[158] MELINTESCU, A., GALERIU, D., Dynamic model for tritium transfer in an aquatic food chain, Radiat. Environ. Biophys. **50** (2011) 459–73.

[159] MELINTESCU, A., GALERIU, D., KIM, S.B., Tritium dynamics in large fish – a model test., Radioprotection **46** (2011) S431–S6.

[160] NYS, C., VLAEMINCK, K., VAN SPRANG, P., DE SCHAMPHELAERE, K., A generalized bioavailability model (gBAM) for predicting chronic copper toxicity to freshwater fish, Environ. Toxicol. Chem. **39** 12 (2020) 2424–2436.

[161] MEBANE, C.A., CHOWDHURY, M.J., DE SCHAMPHELAERE, K., LOFTS, S., PAQUIN, P.R., SANTORE, R.C., WOOD, C.M., Metal bioavailability models: current status, lessons learned, considerations for regulatory use, and the path forward, Environ. Toxicol. Chem. **39** (2020) 60–84.

[162] BERESFORD, N.A., BROWN, J., BONCHUK, Y., PHILLIPS, H., THIESSEN, K., ULANOWSKI, A., YANKOVICH, T., Quantifying exposure of plants and animals to radiation: a new methodology, In: 3rd European Radiological Protection Research Week, Rovinj, Croatia, 1–5 October 2018, Book of Abstracts (2018) p. 109.

[163] BROWN, J.E., BERESFORD, N.A., HEVRØY, T., Exploring taxonomic and phylogenetic relationships to predict radiocaesium transfer to marine biota, Sci. Total Environ. **649** (2019) 916–28.

[164] BERESFORD, N.A., WILLEY, N., Moving radiation protection on from the limitations of empirical concentration ratios, J. Environ. Radioact. **208-209** (2019) 106020.

[165] JOHANSEN, M.P., RUEDIG, E., TAGAMI, K., UCHIDA, S., HIGLEY, K., BERESFORD, N.A., Radiological Dose Rates to Marine Fish from the Fukushima Daiichi Accident: The First Three Years Across the North Pacific, Environ. Sci. Technol. **49** 3 (2015) 1277–85.

[166] SAZYKINA, T., KRYSHEV, A., Simulation of population response to ionizing radiation in an ecosystem with a limiting resource – Model and analytical solutions, J. Environ. Radioact. **151** (2016) 50–7.

[167] VOLTERRA, V., Theorie mathematique de la lutte pour la vie, Gauthier-Villars, Paris (1931) 214 pp (in French).

[168] VIVES I BATLLE, J., BIERMANS, G., COPPLESTONE, D., KRYSHEV, A., MELINTESCU, A., MOTHERSILL, C., SAZYKINA, T., SEYMOUR, C., SMITH, K., WOOD, M.D., Towards an ecological modelling approach for assessing ionising radiation impact on wildlife populations, J. Radiol. Prot. (Submitted).

LIST OF ABREVIATIONS

BEM	bioenergetics model
CEZ	Chornobyl Exclusion Zone
CREAM	mechanistic effect models for ecological risk assessment of chemicals
DC	dose coefficient
DCRL	derived consideration reference level
DEB	dynamic energy budget
DEBTox	DEB modelling to (eco)toxicological problems
ERA	environmental risk assessment
IBM	individual based model
ICRP	International Commission on Radiological Protection
NTE	non-targeted effects
ODE	ordinary differential equation
PNEC	predicted no effect concentration
PNEDR	predicted no effect dose rate
RAPs	reference animals and plants
SETAC	Society of Environmental Toxicology and Chemistry
TLD	thermoluminescent dosimeter

CONTRIBUTORS TO DRAFTING AND REVIEW

Alonzo, F.	Institut de Radioprotection et de Sûreté Nucléaire, France
Barnett, C.L.	UK Centre for Ecology and Hydrology, United Kingdom
Beaugelin-Seiller, K.	Institut de Radioprotection et de Sûreté Nucléaire, France
Beresford, N.A.	UK Centre for Ecology and Hydrology, United Kingdom
Biermans, G.	Federal Agency for Nuclear Control/Agence Fédérale de Controle Nucléaire, Belgium
Bradshaw, C.	Stockholm University, Sweden
Brown, J.	International Atomic Energy Agency
Caffrey, E.	Oregon State University, United States of America
Copplestone, D.	University of Stirling, United Kingdom
Halsall, C.	International Atomic Energy Agency
Howard, D.C.	UK Centre for Ecology and Hydrology, United Kingdom
Johansen, M.	Australian Nuclear Science and Technology Organisation, Australia
Kryshev, A.	Research and Production Association "Typhoon", Russian Federation
Melintescu, M.A.	"Horia Hulubei" National Institute of Physics and Nuclear Engineering, Romania
Mothersill, C.	McMaster University, Canada
Ruedig, E.	Los Alamos National Laboratory, United States of America
Sazykina, T.	Research and Production Association "Typhoon", Russian Federation
Seymour, C.	McMaster University, Canada
Smith, K.	RadEcol Consulting Limited, United Kingdom
Vives i Batlle, J.	Belgian Nuclear Research Centre (SCK CEN), Belgium
Wood, M.	University of Salford, United Kingdom

LIST OF PARTICIPANTS

Al Neaimi, A.	Emirates Nuclear Energy Corporation, United Arab Emirates
Alonzo, F.	Institut de Radioprotection et de Sûreté Nucléaire, France
Andersson, E.	Swedish Nuclear Fuel and Waste Management Company, Sweden
Andersson, P.	Swedish Radiation Safety Authority, Sweden
Aramrun, P.	Ministry of Sciences and Technology, Thailand
Barnett, C.L.	UK Centre for Ecology and Hydrology, United Kingdom
Bartie, P.	University of Stirling, United Kingdom
Bartusková, M.	National Radiation Protection Institute, Czech Republic
Beaugelin-Seiller, K.	Institut de Radioprotection et de Sûreté Nucléaire, France
Beresford, N.A.	UK Centre for Ecology and Hydrology, United Kingdom
Bezhenar, R.	Institute of Mathematical Machines and System Problems, Ukraine
Biermans, G.	Federal Agency for Nuclear Control/Agence Fédérale de Controle Nucléaire, Belgium
Bollhöfer, A.	Department of the Environment and Energy, Australia
Bonchuk, Y.	Ukrainian Radiation Protection Institute, Ukraine
Bradshaw, C.	Stockholm University, Sweden
Brinkmann, L.	Canadian Nuclear Laboratories, Canada
Brittain, J.	University of Oslo, Norway
Brown, J.	International Atomic Energy Agency
Brown, J.	Norwegian Radiation and Nuclear Safety Authority, Norway
Burbidge, C.	Environmental Protection Agency, Republic of Ireland
Burgos Gallego, J.	Consultant, Spain
Caffrey, E.	Oregon State University, United States of America
Charrasse, B.	Commissariat á l'Energie Atomique, France

Condon, C.	Oregon State University, United States of America
Copplestone, D.	University of Stirling, United Kingdom
Cujic, M.	University of Belgrade, Serbia
De Sanctis, J.	SOGIN S.p.A, Italy
Doering, C.	Department of the Environment and Energy, Australia
Dragovic, S.	University of Belgrade, Serbia
Fernandes, S.	Canada North Environmental Services Limited Partnership, Canada
Fesenko, S.	Russian Institute of Agricultural Radiology and Agroecology, Russian Federation
Florou, H.	National Center for Scientific Research “Demokritos”, Greece
Galeriu, D.[†]	“Horia Hulubei” National Institute of Physics and Nuclear Engineering, Romania
Geras'kin, S.	Russian Institute of Agricultural Radiology and Agroecology, Russian Federation
Goulet, R.	Canadian Nuclear Safety Commission, Canada
Grzechnik, M.	Australian Radiation Protection and Nuclear Safety Agency, Australia
Gu, Z.	China Institute for Radiation Protection, People’s Republic of China
Gudkov, D.	Institute of Hydrobiology of the National Academy of Sciences of the Ukraine, Ukraine
Hansen, V.	Aarhus University, Denmark
Hashimoto, S.	Forestry and Forest Products Research Institute, Japan
Heling, R.[†]	Nuclear Research and Consultancy Group, Netherlands
Higley, K.	Oregon State University, United States of America
Hinton, T.	Fukushima University, Japan

[†] Deceased.

Hosseini, A.	Norwegian Radiation and Nuclear Safety Authority, Norway
Howard, B.J.	School of Bioscience, University of Nottingham and Fellow of UK Centre for Ecology and Hydrology, United Kingdom
Howard, D.C.	UK Centre for Ecology and Hydrology, United Kingdom
Huutoniemi, T.	Vattenfall AB, Sweden
Ikonen, A.	EnviroCase Limited, Finland
Iosjpe, M.	Norwegian Radiation and Nuclear Safety Authority, Norway
Ishii, N.	National Institute of Radiological Sciences, Japan
Jaeschke, B.	ÅF Pöyry AB, Sweden
Jeong, H.	Korea Atomic Energy Research Institute, Republic of Korea
Johansen, M.	Australian Nuclear Science and Technology Organisation, Australia
Kamboj, S.	Argonne National Laboratory, United States of America
Kangasniemi, V.	EnviroCase Limited, Finland
Kautsky, U.	Swedish Nuclear Fuel and Waste Management Company, Sweden
Kawaguchi, I.	National Institute of Radiological Sciences, Japan
Kennedy, P.	Food Standards Agency, United Kingdom
Keum, D-K.	Korea Atomic Energy Research Institute, Republic of Korea
Kim, S.B.	Canadian Nuclear Laboratories, Canada
Kim, S-Y.	Khalifa University of Science, Technology and Research, United Arab Emirates
Kobayashi, T.	Japan Atomic Energy Agency, Japan
Kryshev, A.	Research and Production Association “Typhoon”, Russian Federation
Lamego Simões Filho, F.	Instituto de Engenharia Nuclear, Brazil
Leclerc, E.	Agence Nationale pour la Gestion des Déchets Radioactifs, France
Libert, M.	Commissariat á l'Energie Atomique, France

Lintott, R.	University of Stirling, United Kingdom
Maderych, V.	Institute of Mathematical Machines and System Problems, Ukraine
Martinez, N.	Clemson University, United States of America
McGuire, C.	Scottish Environment Protection Agency, United Kingdom
McLaren, D.	University of Stirling, United Kingdom
McLellan, K.	United States Department of Energy, United States of America
Melintescu, M.A.	“Horia Hulubei” National Institute of Physics and Nuclear Engineering, Romania
Mihalik, J.	National Radiation Protection Institute, Czech Republic
Monte, L.	Agenzia nazionale per le nuove tecnologie, l’energia e lo sviluppo economico sostenibile, Italy
Mothersill, C.	McMaster University, Canada
Mustonen, J.	EnviroCase Limited, Finland
Nordén, M.	Swedish Radiation Safety Authority, Sweden
Nordén, S.	Swedish Nuclear Fuel and Waste Management Company, Sweden
Outola, I.	Radiation and Nuclear Safety Authority, Finland
Palo, T.	Swedish University of Agricultural Science, Sweden
Pastor, L.	Electricité de France, France
Periáñez, R.	University of Seville, Spain
Phaneuf, M.	Canadian Nuclear Safety Commission, Canada
Pröhl, G.	Consultant, Germany
Proverbio, A.	Dounreay Site Restoration Limited, United Kingdom
Psaltaki, M.	National Technical University of Athens, Greece
Punt, A.	RadEcol Consulting Limited, United Kingdom

Ramadan Ahmed, A.B.[†]	Egyptian Nuclear and Radiological Regulatory Authority, Egypt
Real, A.	CIEMAT, Spain
Riekki, K.	Posiva Oy, Finland
Rowan, D.	Canadian Nuclear Laboratories, Canada
Ruedig, E.	Los Alamos National Laboratory, United States of America
Saito, M.	Kyoto University, Japan
Sazykina, T.	Research and Production Association “Typhoon”, Russian Federation
Seymour, C.	McMaster University, Canada
Singh, N.	Swedish University of Agricultural Science, Sweden
Skuterud, L.	Norwegian Radiation and Nuclear Safety Authority, Norway
Smith, K.	RadEcol Consulting Limited, United Kingdom
Smodis, B.	Jozef Stefan Institute, Slovenia
Sotiropoulou, M.	CERN, European Organization for Nuclear Research, Switzerland
Stark, K.	Swedish Radiation Safety Authority, Sweden
Tagami, K.	National Institutes for Quantum and Radiological Science and Technology, Japan
Tanaka, T.	Laboratoire National d'Hydraulique et Environnement, France
Telleria, D.	International Atomic Energy Agency
Twining, J.	Austral Radioecology, Australia
Uchida, S.	National Institutes for Quantum and Radiological Science and Technology, Japan
Udomsomporn, S.	Office of Atoms for Peace, Thailand
Vilimaite Silobritiene, B.	Ministry of Environment of the Republic of Lithuania, Lithuania
Vandenhove, H.	Studiezentrum für Kernenergie, Belgium

[†] Deceased.

Varga, B.	National Foodchain Safety Office, Food and Feed Safety Directorate, Hungary
Vives i Batlle, J.	Belgian Nuclear Research Centre (SCK CEN), Belgium
Willemsen, S.	Nuclear Research and Consultancy Group, Netherlands
Willrodt, C.	Bundesamt für Strahlenschutz, Germany
Wood, M.	University of Salford, United Kingdom
Wu, Q.	Tsinghua University, People's Republic of China
Yankovich, T.	International Atomic Energy Agency
Yoo, S-J.	Korea Institute of Nuclear Safety, Republic of Korea
Yu, C.	Argonne National Laboratory, United States of America

MODARIA I Technical Meetings, IAEA Headquarters, Vienna

19–22 November 2012, 11–15 November 2013, 10–14 November 2014,
9–13 November 2015

Interim Working Group Meetings, MODARIA I Working Group 8, Vienna

27–28 May 2013, 24–25 June 2014, 20–23 April 2015

Interim Working Group Meetings, MODARIA I Working Group 9, Vienna

29–31 May 2013, 25–27 June 2014, 30 June – 2 July 2015

MODARIA II Technical Meetings, IAEA Headquarters, Vienna

31 October – 4 November 2016, 30 October – 3 November 2017, 22–25 October 2018,
21–24 October 2019

Interim Working Group Meetings, MODARIA II Working Group 5

Brussels, Belgium, 27–29 June 2017,
Vienna, Austria, 18–22 June 2018, 3–5 July 2019

IAEA
International Atomic Energy Agency

No. 26

ORDERING LOCALLY

IAEA priced publications may be purchased from the sources listed below or from major local booksellers.

Orders for unpriced publications should be made directly to the IAEA. The contact details are given at the end of this list.

NORTH AMERICA

Bernan / Rowman & Littlefield

15250 NBN Way, Blue Ridge Summit, PA 17214, USA
Telephone: +1 800 462 6420 • Fax: +1 800 338 4550

Email: orders@rowman.com • Web site: www.rowman.com/bernan

REST OF WORLD

Please contact your preferred local supplier, or our lead distributor:

Eurospan Group

Gray's Inn House
127 Clerkenwell Road
London EC1R 5DB
United Kingdom

Trade orders and enquiries:

Telephone: +44 (0)176 760 4972 • Fax: +44 (0)176 760 1640
Email: eurospan@turpin-distribution.com

Individual orders:

www.eurospanbookstore.com/iaea

For further information:

Telephone: +44 (0)207 240 0856 • Fax: +44 (0)207 379 0609
Email: info@eurospangroup.com • Web site: www.eurospangroup.com

Orders for both priced and unpriced publications may be addressed directly to:

Marketing and Sales Unit
International Atomic Energy Agency
Vienna International Centre, PO Box 100, 1400 Vienna, Austria
Telephone: +43 1 2600 22529 or 22530 • Fax: +43 1 26007 22529
Email: sales.publications@iaea.org • Web site: www.iaea.org/publications

International Atomic Energy Agency
Vienna