Journal of Radiological Protection

Official journal of the Society for Radiological Protection

PAPER • OPEN ACCESS

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To cite this article: Tobias Lindborg *et al* 2022 *J. Radiol. Prot.* **42** 020503

IOP Publishing J. Radiol. Prot. 42 (2022) 020503 https://doi.org/10.1088/1361-6498/ac563c

Journal of Radiological Protection

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OPEN ACCESS

RECEIVED
20 December 2021

REVISED
1 February 2022

ACCEPTED FOR PUBLICATION
16 February 2022

PUBLISHED
9 March 2022

PAPER

Safety assessments undertaken using the BIOMASS methodology: lessons learnt and methodological enhancements

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Keywords: safety assessment, biosphere, dose modelling, system understanding, radiological waste management

Abstract

The International Atomic Energy Agency has coordinated an international project addressing enhancements of methods for modelling in post-closure safety assessments of solid radioactive waste disposal. The project used earlier published work from the IAEA biosphere modelling and assessment (BIOMASS) project to further develop methods and techniques. The task was supported by a parallel on-going project within the BIOPROTA forum. The output from the project is described in detail in a forthcoming IAEA report. Here an overview of the work is given to provide researchers in the broader fields of radioecology and radioactive waste disposal with a summarised review of the enhanced BIOMASS methodology and the work that has been undertaken during the project. It is hoped that such dissemination will support and promote integrated understanding and coherent treatment of the biosphere component within the overall assessment process. The key activities undertaken in the project were: review and identification of those parts of the original BIOMASS methodology that needed enhancement, discussions on lessons learned from applying the BIOMASS method, using real examples to assess the methodology and its usefulness, and writing of those parts of the methodology that were considered could benefit from refinement or for which new guidance was required to take account of scientific developments. The work has shown that the overall approach in the original BIOMASS methodology has proven sound. However, the enhanced version clarifies the need for an iterative and holistic approach with system understanding central to the approach. Specifically, experience, especially in site-specific contexts, has emphasised that adequate system understanding is essential in underpinning safety assessments for radioactive waste disposal. The integral role of the biosphere within safety assessment is also emphasised in the enhanced methodology.

1. Introduction

Methodological development of safety assessments has always been an important part of radioactive waste management programmes. During the 1950s discussions started on issues related to the disposal of radioactive waste and the need to assess site conditions in relation to the properties of the waste and its possible future behaviour, see e.g. NRC (1957). Subsequently, the Stripa project (1980–1992) was an example of international cooperation to develop techniques of site evaluation and design of engineered barriers

(Fairhurst *et al* 1993). International guidance on biosphere modelling for radiological assessments was first developed at an international level in the European collaborative project PAGIS, Performance Assessment of Geological Isolation Systems in the 1980s (Lawson and Smith 1985). This was followed up within phase II of the biosphere modelling and validation study (BIOMOVS II) that ran from 1991 to 1996 (Davis *et al* 1999, van Dorp *et al* 1999). The BIOMOVS II study included a working group on 'reference biospheres', the mandate of which was to consider the potential to develop internationally accepted standardised biosphere models for use in long-term safety assessments related to solid radioactive waste disposal. The working group concluded that standardised models would be difficult to apply in practice, due to the need for biosphere models to reflect the context specific to each assessment. Instead of focusing on 'reference biosphere' models, the working group sought to encourage transparency, consensus, and harmonisation in biosphere modelling through the development of a reference methodology. The BIOMOVS II study concluded by recommending that further refinement of the methodology was needed. The IAEA biosphere modelling and assessment (BIOMASS) project that ran from 1996 to 2001 further developed and refined the reference biosphere methodology set out in BIOMOVS II, drawing on experience of its application and through development of several illustrative examples (IAEA 2003).

Since then (2000–2020) several programmes have produced and reported safety assessments for both generic and specific sites for disposal of solid radioactive waste, see e.g. ANDRA (2005, 2015), US DOE (2008), SKB (2011, 2015), Posiva (2012c), NDA (2016), and NWMO (2017, 2018). In parallel with these developments, IAEA has initiated development programmes aiming to harmonise and further enhance methods for evaluating the safety of radioactive waste disposal facility designs and sites. This work within IAEA has resulted in a series of publications including safety standards and guides on assessment practice, see e.g. IAEA (2011a, 2011b, 2012, 2014a, 2014b, 2016).

During this successional development, the biosphere has increasingly been shown to be an important part of the system to assess and is not solely related to dose modelling (Kautsky *et al* 2013). Historically a biosphere model and its associated input parameters were seen as a 'measuring stick' with the sole purpose of converting radionuclide fluxes or concentrations to a common measure of radiation dose that could be used for evaluating compliance with standards. However, it has since been recognised that biosphere modelling needs to be integrated into the general process of developing a site description and enhancing system understanding. Therefore, in some recent radioactive waste disposal programmes, biosphere dose modelling has been integrated into an overall procedure for developing site understanding (Lindborg *et al* 2010, Posiva 2012a, 2013a, 2014a, Andersson *et al* 2013, Kautsky *et al* 2013). This approach arises from the recognition that for many types of disposal facilities and sites, the biosphere is tightly coupled to the geosphere and to other processes that have the potential to influence the long-term safety of the facility, particularly when account is taken of projections of environmental and climate change. This has been emphasised in recent decades, as there has been an increasing emphasis on accounting for site-specific effects of anthropogenic global warming in assessments of long-term safety after repository closure, e.g. BIOCLIM (2004), IAEA (2016), Lindborg *et al* (2018), IAEA (2020). Also, the need for a science-based site understanding that is continually updated on the basis of data on the geosphere and biosphere (and the linkage between them) from the disciplines of ecology, soils, hydrology, hydrogeology, biogeochemistry and hydro-geochemistry has been emphasised in various assessments, see e.g. SKB (2011), Posiva (2012a, 2013a), ANDRA (2015), RMW (2016) and Andersson (2020). BIOPROTA, an international forum to support investigations of key issues related to biosphere aspects in radioactive waste management, has emphasised the importance of, and the requirement for, structured methods of handling the linkage between biosphere safety assessments and site understanding, e.g. BIOPROTA (2014a, 2014b). Therefore, a need for a coherent and scientifically supported understanding of the entire disposal system (biosphere, geosphere and near field) from today and into the future, taking all aspects into account that may have effects on long term safety, has been one main driver in recent development of safety assessments.

The step by step and iterative process needed to site, assess, authorise, construct, operate and close a disposal facility is emphasised in IAEA safety standards (IAEA 2011a, 2011b). This recognises that assessments typically progress from generic studies used in support of programme development and methods evaluations to site-specific assessments with adaptations to features, events, and processes (FEPs). The construction and operational stages can help in optimisation of some repository designs, with implications for the way in which knowledge (including monitoring) of the system is enhanced, design of the facility is adapted, and safety assessments are integrated into the overall process of development. A strategy with a constantly updated site understanding and iterative safety assessments, fed by ongoing detailed site characterisation during the whole construction and operational phase is therefore needed. One example of such repository design is the KBS-3 type for spent-fuel disposal that forms the basis for ongoing applications for construction and eventually start of operations in Sweden and Finland (SKB 2010a, Posiva 2012c). Another example is the ongoing Cigéo repository programme in France (ANDRA 2015). The staged process with inherent iterations within and between repository design, site understanding, safety assessments and applications to move forward in a repository programme is therefore a key aspect of strategy that must be taken into account in the biosphere part of safety assessments.

Ongoing national programmes have shown that, depending on the stage of the repository development programme, needs and expectations change over time and typically an increased level of ambition between programme stages or a shift in focus is needed to address questions raised and to support simplifications and/or assumptions made in the safety assessment.

Therefore, a need to enhance, clarify and further develop the BIOMASS methodology was identified by several IAEA member states delegates during phase I of the modelling and data for radiological impact assessments (MODARIA) program[11] and members of the BIOPROTA forum[12]. New techniques, scientific findings and developments made in national programmes during the last two decades were considered fundamental to further developing the BIOMASS methodology. A working group within phase II of the MODARIA programme was therefore assigned the task, and in this paper, we describe the results and the scientific background to the work done in the MODARIA II programme working group 6 (WG6) as well as work undertaken in parallel, and in collaboration with WG6, within the BIOPPROTA project. This paper describes the overall enhanced BIOMASS methodology steps, reviews the BIOMASS method in the light of its implementation in national programmes, and discusses the resulting enhanced BIOMASS method presented by WG6 and to be reported by IAEA. We believe that this paper can help to transfer the understanding gained in biosphere safety assessment issues to the broader scientific community, as well as trigger discussions and further enhancements in the science of environmental radioactivity.

2. Methods

The IAEA organised MODARIA II programme ran from 2016 to 2019 and had the general aim of enhancing the capabilities of Member States to simulate contaminant/radionuclide transfer in the environment and, thereby, to assess radiation exposures of the public and other biota in order to ensure an appropriate level of protection from the effects of ionising radiation associated with radionuclide releases and from existing radionuclides in the environment. As part of the MODARIA II programme, a work plan to review and enhance the BIOMASS methodology was developed and executed through WG6. In short, WG6 identified aspects of the BIOMASS methodology that could be further enhanced or clarified, or for which new scientific developments warranted the development of new guidance during eight workshops and through the production of several versions of a report that was closely scrutinised by members of the working group and other interested parties. The steps of the methodology and the interactions between steps were discussed. Text and illustrations relating to specific parts of the BIOMASS methodology were adjusted, omitted, added, or rewritten as a result of these discussions and in the light of presentations made by WG6 participants. The new and enhanced BIOMASS report was developed using the original BIOMASS report as a template, because the original methodology had proved useful in various national contexts and it was considered important to preserve much of the structure of that methodology while enhancing those aspects where clearer, updated or new guidance was considered to be desirable. All parts of the method were scrutinised and discussed, and suggested changes took into account experience from application of the existing methodology in assessments, from regulatory reviews, lessons learned in ongoing national programmes and last but not least, insights gained from questions and presentations made by representatives from nations and organisations in early national repository programme stages.

In the following, the description of and discussion on the enhanced BIOMASS methodology presented here follows the steps as set out in the report prepared for the IAEA. This paper uses the term 'biosphere assessment' to include all aspects of the safety assessment that handle biosphere issues. This is to harmonise with earlier publications on BIOMASS methodology (IAEA 2003) and the common usage of the term in national programmes and international forums.

3. Resulting enhanced BIOMASS methodology

Although the need for an updated BIOMASS methodology was identified, taking new experience and scientific developments into account, it is important to emphasise that the overall structure of the original BIOMASS methodology has proved sound (BIOPROTA 2016). The enhanced BIOMASS methodology described here and shown in a cyclical form in figure 1 is, therefore, to a large extent, consistent with the original methodology. However, the enhanced version clarifies the need for an iterative and holistic approach

[11] www-ns.iaea.org/projects/modaria/.
[12] www.bioprota.org.

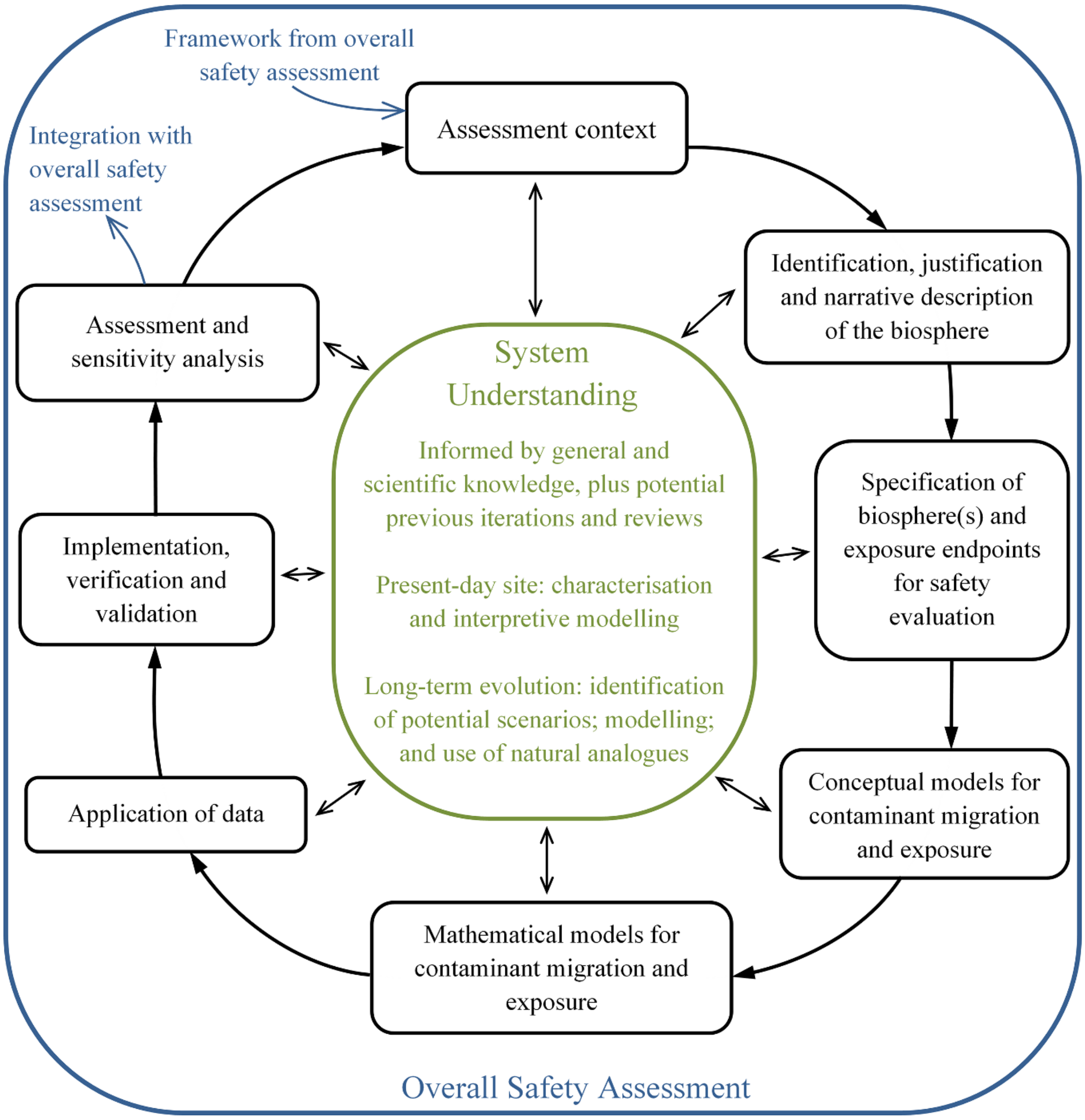

Figure 1. Schematic illustration of the enhanced BIOMASS methodology (in black) showing integration with the overall safety assessment (in blue) and the central role that is played by understanding of the disposal system (in green).

where the biosphere part of the safety assessment is embedded in a system understanding with constant feedback loops to the rest of the safety assessment, site characterisation, facility design and the overall safety case. Also experience, especially in site-specific contexts, has emphasised that system understanding plays a central role in safety assessments for radioactive waste disposal. The integral role of the biosphere within the overall safety assessment is also emphasised.

The methodology highlights and calls for an approach with flexibility to incorporate new information into biosphere assessments in an iterative manner during the development of the repository programme. This means that each assessment cycle should take account of experience from earlier iterations. Assimilation of experience gained by using data, models and interpreting interim results, changes in assumptions and needs, new scientific understanding and changes in regulatory expectations are emphasised as an important and constantly evolving assessment task, see e.g. ASN (2008), ONR (2011), Code de l'Environment (2015a, 2015b), SSM (2018), STUK (2018). Also, the importance of keeping comprehensive records of each assessment stage is emphasised where multiple assessment cycles are undertaken at different stages of development of a disposal facility. Reference to these records should facilitate the maintenance of continuity in the assessment process, while ensuring that the significance of moving to the next stage of development and of incorporating new information and understanding is properly evaluated through a comparison of assessment results.

In the following sections 3.1–3.4, the resulting enhanced methodology is summarised with experience and lessons learned from recent applications of the BIOMASS methodology referenced as specific examples.

For a full description of the methodology, reference should be made to the upcoming IAEA report on the enhanced BIOMASS methodology.

3.1. Assessment context

The context for the biosphere in the safety assessment is set by that for the overall safety assessment of which it is a part. Both the overall and biosphere assessment contexts address the fundamental questions that define the objectives and scope of the post-closure safety assessment, in particular, what issues you are trying to assess and why. These issues reflect the need to present the reasons as to why it is appropriate to consider specific FEPs central to the disposal system as well as societal expectations (IAEA 2003, and appendix IV of IAEA 2016). The assessment context also sets out aspects of how the objectives of the assessment can be met, e.g. the specific assessment end-points—what is to be calculated and the timeframe over which they should be assessed? The defined assessment context has implications both for the safety assessment and for other parts of the overall safety case and is therefore a common task for the overall programme. The assessment context is the appropriate place to document constraining assumptions needed in undertaking an assessment and needs to be designed to avoid endless speculation on unknowns such as future human actions. These assumptions can involve strategic, technical, and social value judgements and may require wider consultation to determine their acceptability. They may also need to be updated with each iteration of assessment during a repository development program.

The components described in the assessment context in the enhanced BIOMASS methodology are:

- the purpose of the assessment, e.g. optimisation, guidance, confidence, and support development of or compliance with requirements;
- endpoints of the assessment;
- assessment philosophy and treatment of uncertainty;
- disposal system safety strategy and general site context;
- source term to the biosphere and geosphere-biosphere interface;
- time frames over which the end-points are required to be assessed; and
- societal assumptions, e.g. to support assumptions for future human behaviour.

During the MODARIA II review of earlier work, the value in a clear definition of the assessment context was recognised as being well founded in established science and in experience of conducting safety assessments. However, lessons learned from ongoing national programmes demonstrated the importance of integrating the biosphere context into the overall safety assessment context. This is to make sure that the constraints on the assessment are well defined, that the implications for the system being assessed are understood and that the constraints and implications are used consistently in all aspects of the safety assessment project. One example of this is the climate scenarios adopted, which need to be defined considering the assessment time frame, the site context and type of disposal system. These components are important to the overall safety assessment and may, in some repository types, have an impact on the strategy used in representing the biosphere and the geosphere as well as on the safety function that is set on the design of the natural and engineered barriers. This implies that the decision on what climate scenarios to extract from global, regional, and local understanding is governed by needs from all parts of a safety assessment. It was also recognised that the assessment context often needs adjustment during a safety assessment and between repository programme stages due to new insights gained and results from previous iterations. The implications of these context changes must be assessed in relation to the whole repository system, as dependencies between system parts can mediate chain effects, e.g. changes in the time frame of interest may lead to new climate scenarios that can have an impact on site development models that, in turn, may lead to a need for changes in dose model concepts as well as repository design. This is illustrated by the new considerations that arose when the regulatory timescale relating to disposals of spent fuel and high-level waste at Yucca Mountain, Nevada was increased from 1×10^4 years to 1×10^6 years (Smith and Kozak 2011). Therefore, a total system understanding is needed to represent the various parts of the repository system and the dependencies between them.

3.2. Representation of the biosphere

The assessment context described above sets the overall scope of the assessment and bounds the envelope of cases that need to be evaluated. The next few components of the enhanced BIOMASS methodology relate to developing and documenting an understanding of the biosphere characteristics to be adopted in the assessment and setting out how the biosphere is to be represented, both conceptually and numerically, to be able to assess potential contaminant impacts on human health and the environment. The methodology also

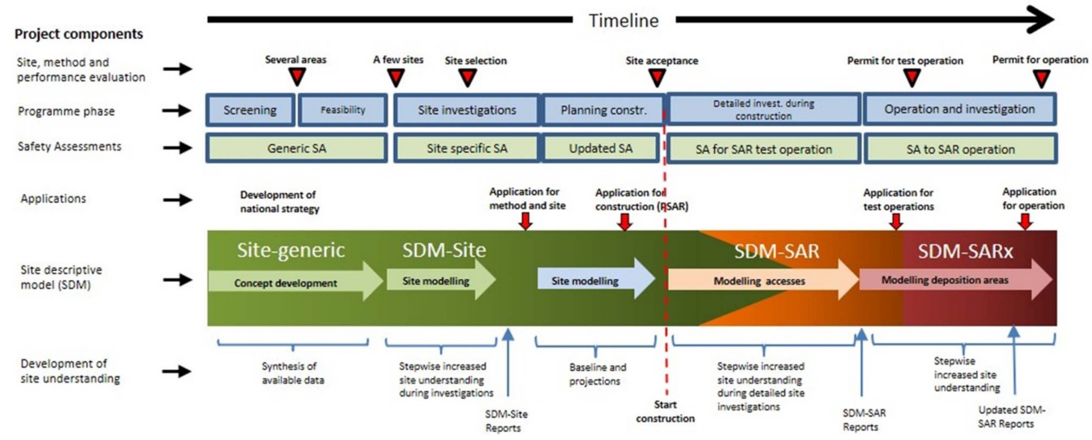

Figure 2. The stepwise enhancement of site understanding and safety assessments during a typical iterative siting programme. The BIOMASS methodology is part of the safety assessment project component and uses the SDMs developed for each step. SA: safety assessment, SDM: site descriptive model, SAR: safety analysis report, SARx: updates of SAR during operation. Modified from SKB internal document SKBdoc 1880 352. With permission courtesy of SKB.

describes how to use biosphere understanding as a support in making assumptions and justifying simplifications implemented in the contaminant transport model.

To undertake the task of biosphere representation, a well-defined understanding of what is meant by the term 'biosphere' is needed. In the enhanced BIOMASS methodology, the term biosphere is used as 'surface systems of particular interest for contaminant retention and potential exposure'. This is a broad definition and can also be described as everything that should be included in, or affects, the conceptual model describing contaminant transport and impact evaluation in relation to both humans and the environment. The biosphere is often, but not always, closely constrained by geosphere properties and processes that influence the transport of contaminants to and within the biosphere part of the system. It is also important to make the distinction between the local biosphere that is discussed here with the global surrounding biosphere with which it interacts.

The methodology adopts a stepwise approach going from identification, justification, and construction of narratives relating to the biosphere to the final biosphere description as a support to assumptions and simplifications made in the dose modelling as well as informing the calculations that need to be undertaken to make appropriate use of site data in the assessment context. A key to appropriately identifying a biosphere system to be used in a contaminant transport and impact model is to make sure that the transport linkage between release scenarios from a repository is understood and justified for the geosphere–biosphere system being represented. This means that the conceptual biosphere used should be a good representation of the environment of when and where potential discharges of contaminants may enter the biosphere in a release scenario. The task of representing the biosphere in safety assessments is therefore strongly linked to, and dependent on, the development of the overall system understanding (see figure 1) and site characterisation.

In figure 2, a typical stepwise repository programme is illustrated with an emphasis on components influencing site understanding. Before potential sites are identified or have been investigated, the biosphere can only be represented by using a generic or semi-generic conceptual model and uses only literature data and commonly accepted conceptual models on biosphere features and processes (e.g. Lindborg and Schüldt 1998, Walke *et al* 2013). This stage is also used to test the repository concept and to evaluate assessment methods, repository designs and site characteristics, see figure 3. As the repository programme develops and a site or sites are identified and become available for characterisation, the representation of the biosphere becomes more site specific and integrated into the overall system understanding (biosphere, geosphere and designed parts of the repository), see e.g. SKB (2011), Posiva (2012a, 2013a), Andersson *et al* (2013), Kautsky *et al* (2013). The task of representing the biosphere described in the enhanced BIOMASS methodology can therefore be seen as part of two iterative cycles, one that follows the stages of the developing repository programme, and an embedded cycle for each repository programme step that follows the enhanced BIOMASS methodology. Lessons learned from ongoing national programmes in more advanced stages show that later iterations can jump between parts of the methodology, run activities in parallel or skip parts already handled after confirmation of validity. One such example could be the reusage of site data and the conceptual understanding of the biosphere system from previous programme steps. Such changes in focus between stages during a repository programme are to be expected and are reflected in the increased emphasis

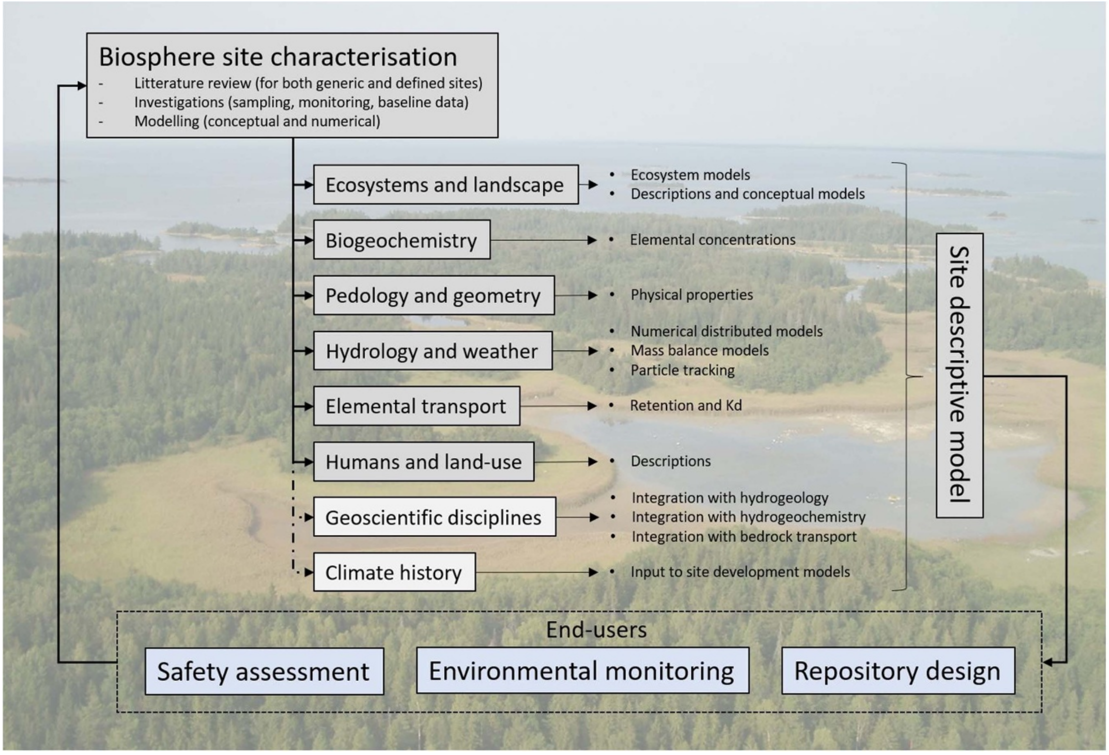

Figure 3. Illustration of a typical biosphere site characterisation setup in recent national radioactive waste repository programmes. Background photograph with permission courtesy of SKB.

on iteration within and between components of the enhanced BIOMASS methodology and other parts of the programme.

To provide an effective representation of the biosphere in a safety assessment, the assessment context needs to be well understood. Apart from a good basic representation of present site conditions together with its historical development, the assessment time frame often leads to a need for long-term future scenarios (or narratives) of biosphere characteristics, see IAEA (2016, 2020). Results from climate modelling (Pimenoff *et al* 2011, 2012, ANDRA 2015, SKB 2019, Lord *et al* 2020), landscape development models (Lindborg *et al* 2013, Posiva 2013c, 2013d, ANDRA 2015) and analogue sites representing possible futures (Haapanen *et al* 2011, Posiva 2013a, Lindborg 2017) may change the conceptual understanding of contaminant release pathways, contaminant transport and possible modes of exposure in the system assessed. Also, the application of data may be affected by consideration of FEPs identified as relevant in future scenarios for a site or discovered by investigations of sites considered to be analogous to potential future characteristics of the site of interest, see e.g. Johansson (2016) and Lindborg *et al* (2020). One example of this would be when going from a temperate to a periglacial climate with permafrost (Lindborg 2017). The extraction of groundwater in a contaminant transport model representing permafrost conditions may need to be set to zero and instead all water used should be taken from surface waters (Johansson *et al* 2015). The opposite may be valid for a very dry, warm arid climate type were the only way to extract water is by using a well. This type of conditions can be illustrated by the Yucca Mountain site in US that is dominated by precipitation and evapotranspiration, with infiltration and runoff representing only small portions of the water balance (USNRC 2014).

In the enhanced BIOMASS methodology, interaction matrices, process-influence diagrams and the system understanding that follows from site characterisation are described as useful tools in producing a biosphere representation. The system understanding and site descriptive model (SDM), have in recent safety assessments been the main contributors supporting and justifying the biosphere representation adopted. Examples of site descriptions that describe the biosphere system and emphasise the site understanding as important to support safety assessments can be found in Anderssson (2010), Aquilonius (2010) and Löfgren (2010) that, in detail, describe and synthesise the marine, limnic and terrestrial ecosystems for the Forsmark site in Sweden. Another example is the inland ecosystem description found in ANDRA (2015).
This derivation of the biosphere representation from system understanding followed by a systematic handling of that understanding in process matrices, ecosystem models, and climate and landscape development models (Posiva 2012b, 2013a, 2013b, 2013d, Lindborg *et al* 2013, IAEA 2016) have been shown

to give the biosphere representation a good foundation and the scientific support needed to argue for simplifications and assumptions made in safety evaluations.

During the task of developing a representation of the biosphere of interest for contaminant transport modelling, the relevant human population, and in many cases also other relevant biota, need to be identified for use in the exposure calculations. Recommendations from the ICRP are available and the emphasis, in terms of impacts on humans, is put on small, reasonably homogeneous population groups (e.g. adults in the most exposed group) and lifetime exposures (ICRP 2013). However, the linkage between a specific representation of the biosphere and the selection of a particular human population or land-use associated with that biosphere is not given much attention in ICRP publications. Also, national regulations and praxis differ between programmes, which implies flexibility can be used in the method for identification of the relevant human population and other relevant biota.

A common way to handle the representation of human populations, as described in the enhanced BIOMASS methodology, is to define the habits of potential exposure groups (PEGs) within the context of the adopted biosphere system (as opposed to defining the biosphere system to encompass a pre-defined set of habits selected with a view to maximising the doses received). These habits can be associated with a present lifestyle or with historical combinations of habits and land-use, such as those associated with hunter-gatherer communities or for different climatic contexts (see e.g. ANDRA 2015). In other recent safety assessments, novel methods for defining the most exposed group have emerged. For example, SKB in Sweden have developed an approach that considers the potential for different land uses for specific identified 'biosphere objects' (areas of relevance to the calculation of dose) and the ecosystem production capabilities of those objects i.e. the object ecosystem defines the possible types of food production and the production within the biosphere object defines the population size. This use of biosphere objects sets an overall context for defining the radionuclide source to the object, modes of exposure, routes of exposure, size of the exposed human population and potential land-uses, see SKB (2011, 2015, 2019) and Saetre *et al* (2013). A similar approach has been used also by Posiva (Broed *et al* 2008, Hjerpe *et al* 2010, Posiva 2013b, Hjerpe 2019), extended to address the distribution of the doses to the full population (Hjerpe *et al* 2011).

3.3. Post closure impact modelling

The enhanced methodology addresses the development of conceptual and quantitative models of contaminant migration and potential exposure. A biosphere assessment model needs to be developed in a way that is both practical and transparent. It needs to be flexible to adapt to new challenges and insights gained during the repository siting process, as well as being robust and supported by science and site understanding. The methodology therefore suggests a systematic approach that allows assumptions and simplifications to be recorded and justified in a traceable manner.

The starting point is the description of the biosphere system(s) at the time of contaminant releases (see section above) and in which exposures are assumed to take place, coupled with a description of the contaminant releases into or within that system.

The development and justification of a biosphere assessment model and refinement of the associated description will generally be an iterative process that runs in parallel with SDM and, for each repository programme stage, with the continuous improvements in system understanding. Therefore, the initial model development and subsequent iteration aim to ensure that a practicable and justified modelling approach is achieved and maintained.

The enhanced BIOMASS methodology suggests the following basic steps in model development, building-on the description of biosphere system(s):

- develop a conceptual understanding of contaminant release, migration, accumulation and potential exposure for each of the biosphere system(s) carried through to the assessment.
- Identify those biosphere components that are to be distinguished as separate features in the representation of mass and contaminant transport (i.e. distinct potentially contaminated environmental media).
- Identify and characterise the human PEGs and potentially exposed populations of biota (PEPs) (if required) that need to be explicitly addressed in the assessment (see IAEA 2014c).
- Develop conceptual models identifying the processes that result in contaminant transport between the biosphere components and give rise to potential exposures of the PEGs and PEPs (if required).
- Develop a mathematical representation for the FEPs comprising each of the conceptual models, taking account of the extent and quality of input data that will be available when the model is to be used.
- Collate and justify the input data required by the mathematical models, drawing on the description of the biosphere system(s) and taking account of the approach with respect to the treatment of parameter uncertainties.
- Implement, verify, and validate, to the extent practicable, the models.

Aquifer	Water abstraction	x	x	x	x	x	Decay Groundwater flow
x	Water Storage and Distribution System	Volatilisation Degassing	Irrigation Sediment transfer	Irrigation and interception	Drinking water Sediment consumption	Ingestion Immersion Dermal absorption	Decay
x	x	Atmosphere (external & internal)	Vapour / aerosol deposition	Vapour / aerosol deposition	Vapour / aerosol inhalation	Vapour / aerosol inhalation Immersion	Decay Advection
x	x	Suspension Volatilisation Gas	Cultivated Soil	Root uptake Soil splash	Consumption of soil on fodder crops	External irradiation Ingestion	Decay Leaching / percolation Erosion
x	x	Transpiration Respiration	Weathering Leaf litter Ploughed-in detritus	Food and Fodder Crops	Ingestion of fodder	Ingestion	Decay
x	x	Eructation	Manuring	x	Farm Animals	Ingestion	Decay
x	x	Respiration	x	x	x	Human Community	Decay Excretion
x (Recharge)	x	x	x	x	x	x	Sinks

Figure 4. Interaction matrix illustrating a conceptual model for contaminant transport and exposure arising from agricultural use of potentially contaminated well water. Arrows illustrate the clockwise notation of the interactions. Reproduced with permission from IAEA (2003).

Conceptual model development starts with the task of identifying the components of the area of interest that have impact on contaminant transport and the exposure to humans and other types of biota. Typically, this is done by using both top-down (generic expert judgement, see e.g. IAEA (2003)) or bottom-up techniques (generic or site-specific FEP-lists and site understanding, see e.g. SKB (2010c), Posiva (2012b)). A fundamental requirement in this work is that the model components with their associated properties and processes are justified and coherent with general scientific understanding of natural processes in the biosphere. This to be able to argue that the model used is a useful representation of the actual features, properties and processes present at the site of interest. Using this approach, it follows that the basis of the biosphere assessment model can be validated against best practice in the natural sciences and can be shown to be fit-for-purpose. A first draft of a conceptual model can be outlined by using general understanding in the natural sciences to define principal characteristics and their typical associated FEPs. The main characteristics to consider could be location, topography, lithology, soils/sediments, water bodies, biota and humans and the main processes interacting on elemental transport within and between them, see figure 4. The task to conceptually define the biosphere assessment model will be dependent on the availability of site information. For an early-stage safety assessment with no site-specific data, a generic model can be produced by using general information from a region or using a site analogue. To start model development already at an early stage has proven extremely useful and not only improves biosphere modelling skills and integration with the overall safety assessment but is also needed in the general 'proof of concept' for the safety case (e.g. Lindborg and Schüldt 1998, Walke *et al* 2013). As the repository programme evolves, the site information increases. The conceptual model should therefore continually be reviewed against the latest site understanding and adapted accordingly, see ANDRA (2005), SKB (2006, 2011, 2015), ANDRA (2015).

When a conceptual model for the biosphere system has been specified, the PEGs and, in some cases, PEPs, associated with it should be defined and represented in the biosphere assessment model. This ensures that the PEGs and PEPs are coherent with the conceptual model and hence consistent with understanding from the natural sciences and site characteristics. This task needs to acknowledge that predictions of human behaviour into the far future are not possible, but physical constraints in the biosphere can be argued for and assumptions made on possible land-use can be supported by research models describing the area of interest for dose calculations. One example of this would be site specific hydrological modelling of periglacial conditions that show no groundwater flow and therefore no possibilities for wells or irrigation from groundwater (Lindborg 2017), see also Hjerpe (2019). Also, national regulations may prescribe the output needed and therefore constrain the type of PEGs to be adopted (implicitly constraining the conceptual model of the biosphere within which they are required to be present). In general, the characteristics of PEGs have tended to be treated deterministically, using point values for occupancies of contaminated areas, consumption rates of food, water and other materials, and respiratory characteristics. The food consumption rates may be justified by local, regional or national surveys. This approach tends to be adopted in recognition that the exposures being calculated are indicative and are for a representative individual (ICRP 2013), rather than being measures of the distributions of exposures in a real local population. In addition, uncertainty in PEG definition is typically informed by consideration of a range of different groups with distinct behaviours.

Where the area modelled has the capacity to supply all the resource requirements of a PEG or PEP, this is typically assumed, see e.g. ANDRA (2015). Where the area modelled is not plausibly sufficient to supply the resource requirements needed, consideration needs to be given to the size of the group and local resource fractions are typically used to explicitly account for the proportion of the intake that will come from the contaminated area. Another way to handle the issue of defining the size of PEG is to let the area modelled govern the size of the PEG. This technique uses the area of interest's potential production capacity of food and water to physically constrain the number of people that can be sustained in the biosphere being modelled, see Lindborg (2010), Hjerpe *et al* (2011), Saetre *et al* (2013), Posiva (2013b) for examples on approaches and techniques used in safety assessments from ongoing advanced programmes.

The conceptual biosphere assessment model(s), when checked, reviewed, and considered fit for purpose, requires representation in a quantitative assessment model. Typically, a compartmental form is adopted for this model. The model should have the flexibility to handle different time frames and assumptions on equilibrium, complexity in domain types represented and approaches to discretisation of the spatial representation. Process models and spatially distributed numerical models may be needed to support the simplifications and assumptions made in the quantitative biosphere assessment model(s). This requirement can be integrated with the need for such process models as a tool in developing overall site understanding. Site descriptive research models (either generic or site specific) can be used to support quantitative assessment dose model development and provide input parameter values for those models. This engagement from the safety assessment in site modelling activities, and the mutual interest from both site characterisation and safety assessment in the common questions at issue related to system understanding, is a key element in the enhanced BIOMASS methodology. This also addresses the issue of the degree of complexity required in assessment models. The quantitative assessment model should never be more complex than necessary but may rely on research models or site models of higher complexity to justify specific simplifications and/or assumptions made.

3.4. Model application, evaluation of results and communication

A quantitative assessment model is typically applied to a range of scenarios with several calculations for each scenario. In the reviewed safety assessments that have been undertaken, different future site evolution and climate cases and variants of human land use have been chosen to be calculated for several release scenarios derived from the overall safety assessment (SKB 2011, Posiva 2012c). It is therefore of importance that the development and application of the quantitative assessment model for the biosphere is well integrated with other aspects of the work of the overall safety assessment team for a correct setup of model cases. The model application and evaluation of results are thus very dependent on the specific assessment purpose, strategy, and context.

Explorations and evaluations of the assessment results related to the assessment context endpoints quantifying contaminant impact from a radiological protection perspective, may include:

- individual doses and risks to human health,
- collective doses and risks to human health,
- doses or dose rates to non-human biota,
- modifications to the radiation environment, i.e. relating to the distribution of radionuclides derived from a disposal system in the environment and their concentrations, and
- fluxes of radionuclides into or through parts of the biosphere.

One important goal with the evaluation of results is to achieve information relevant to guiding further development within all parts of the repository programme. This is especially important in early repository programme stages when both repository design and site characterisation may still be immature in respect of what is expected for a typical final siting application assessment. Such evaluations are also important steps to test the repository system for different future scenarios and, in later iterative programme stages towards licence applications, to report the long-term potential contaminant impact of the proposed repository system on humans and environment as one of several supportive arguments in the safety case.

To communicate safety assessment results is a difficult task with many different stakeholders involved. Results from safety assessments need to be communicated as part of the overall repository programme and put into context for the specific assessment. The main approach described in the enhanced BIOMASS methodology, with clear tasks, justified and argued dependencies and simplifications, is, therefore, a useful starting point for developing a specific communication plan tailored to address questions and issues that arise for an identified repository programme. Lessons learned from national programmes show that engagement from experts to communicate, both with other experts (regulatory or scientific community), and local community stakeholders, is fruitful and will promote understanding and confidence in the repository programme. In many cases, it is wise for the communication to begin before any results are available. This allows a common understanding to be developed of the role and scope of the assessment and gives stakeholders a chance to influence the assessment strategy. Thus, when results are provided, they should be seen as addressing the needs identified in the assessment context. This may include the waste management organisation, but also regulators and the local population potentially affected by repository development and other potentially affected stakeholders.

4. Discussion and way forward

The overall approach used in the enhanced BIOMASS methodology is a refinement of the original version published in 2003. The methodology has been applied and used for two decades within several safety assessments, e.g. Broed *et al* (2008), Hjerpe *et al* (2010), SKB (2011), Walke *et al* (2013), Posiva (2013b) and ANDRA (2015). The methodology has proven to be sound and has given both assessors and reviewers of the results a tool to define a common agreement on best practice, as well as providing suggestions on the development and implementation of a biosphere model and guidance on ways to show and interpret the results obtained. However, as described in this paper, several radioactive waste disposal programmes have, during the last two decades, when using the methodology, adjusted the approach, developed new techniques, and/or learned important lessons relating to limitations of the methodology. In the following, the main enhancements made to the BIOMASS methodology presented above are described. Also, suggestions for ways to further improve biosphere safety assessments and strengthen the scientific basis for methods used are discussed.

4.1. The biosphere as an integral part of the repository programme

Although the BIOMASS methodology is focused on the biosphere part of a safety assessment, experience shows that a broader viewpoint needs to be taken if the approaches and methods used in BIOMASS are to be correctly handled and linked to the rest of the safety case. Biosphere dose modelling efforts have, in the past, been somewhat detached from other parts of the programme. However, understanding of the process of disposal facility development and what is needed at each step, and when this is needed, is crucial when planning and executing a safety assessment. The level of ambition and the area of focus will change depending on issues not directly related to the biosphere, and the biosphere modelling, methods and results will, in some cases, have an impact on the rest of the programme. Therefore, the planning and execution of biosphere dose modelling needs to be integrated within the wider framework of developing a safety case. A way to further improve this general approach would be to strive for a common safety assessment methodology (as promoted in IAEA 2012) and integrate the methods used in the biosphere with those in the rest of the safety assessment, i.e. through a coherent handling of issues relating to climate and landscape development and their impacts on the biosphere, geosphere and engineered parts of the repository.

4.2. Site understanding and the biosphere

To construct a biosphere model, the site of interest needs to be understood. This can be achieved when going from generic to site-specific assessment with an increased level of ambition and knowledge. Throughout, it should be recognised that the level of ambition is to achieve a description and understanding of the disposal system that is sufficient to move to the next step in the disposal facility development programme. However, to make the right choices in safety assessment, the team in charge of the assessment cannot rely passively on data given by others. An interaction is needed between the site characterisation and safety assessment tasks such that information is synthesised between scientific disciplines and the implications of the biosphere model are assessed and understood. Lessons learned from assessment experience and regulatory review suggest that the planning and follow up on the execution of, and results obtained from, site investigations need to be an integral part of the safety assessment process as an iterative task. A possible way to further integrate the site and system understanding into the biosphere modelling and safety assessment could be to develop and publish possible procedures and examples that guide the user of the enhanced BIOMASS methodology in how to achieve this integration of tasks.

4.3. Climate and site evolution modelling issues

Between the development of the original BIOMASS methodology and the present day, there have been substantial developments in long-term climate modelling and understanding at the global, regional and local scales. These developments have included the incorporation of models of the biogeochemical cycles of carbon and other elements, hybrid techniques in which Earth Models of Intermediate Complexity are used in conjunction with Atmosphere–Ocean General Circulation Models to generate climate projections over timescales of up to 1 million years with a spatial resolution of around 100 km, and downscaling procedures using both mathematical modelling and physical-statistical downscaling techniques (BIOCLIM 2004, IAEA 2020, Lord *et al* 2020). Although large uncertainties in climate projections remain, these techniques allow envelopes of coherent, long-term climate scenarios to be constructed. Also, during this period, there have been substantial developments in quantitative geomorphological modelling that allow projected developments in the landscape under alternative climate scenarios to be made with greater confidence than previously. Thus, for example, river incision and the denudation of arid landscapes are both amenable to quantitative modelling, see ANDRA (2015). The idea to consider changes in climate and landform was already included in the original BIOMASS methodology, but no clear approach or guidance on techniques was put forward. The enhanced BIOMASS methodology links such techniques to the biosphere safety assessment and illustrate their application. Climate and site evolution issues were addressed in work undertaken in MODARIA I (IAEA 2020) that has subsequently been taken further by SKB and Posiva (SKB 2019, Lord *et al* 2020) and in the enhanced version of the BIOCLIM methods (BIOCLIM 2004) developed by and reported in ANDRA (2015). Also, general and common strategies related to site and system understanding have been developed in national programmes and reported in international forums, see e.g. DSA (2020) and Lindborg *et al* (2021). In the next few years, it seems likely that further substantial progress will be made in long-term climate and landscape modelling, e.g. focusing on the shorter timescales of a few thousand years of particular relevance in the near-surface disposal of low-level radioactive wastes and in the management of radioactive legacy sites (IAEA 2014d). These technical developments will not change the overall BIOMASS methodology, but they will strongly influence the tools adopted in applying that methodology in the next generation of safety assessments.

4.4. Defining the area of interest to use in dose calculations

When potential impacts on humans and the environment are to be calculated, information is needed on exposure pathways and concentrations of radionuclides and other types of contaminants in relevant environmental media. Ideally this information is deduced from models that are closely based on knowledge of the site, taking account of the assessment endpoints specified in the assessment context and the consideration of relevant PEGs and PEPs. Many methods to gain this information have been proposed and applied (Lawson and Smith 1985, Commission of the European Communities 1988, JNC 2000, Kautsky *et al* 2013).

One common issue with deriving information applicable to a generic or specific site is to map data obtained from a physical 3D world with time dependent processes into a necessarily simplified dose assessment model. If care is not taken, such a mapping can be incoherent, e.g. physical limitations in possible water supply or food production are not respected, while the lack of area delineation makes it hard to support arguments as to how features and properties of the environment should be represented.

By using site-specific information to define an area with a volume, a physical constraint can be applied for possible parameter variations and dependences. Even though this is not easily done for a generic case, the understanding of the problems for biosphere modelling when not using a specific defined area will help to improve the construction of conceptual models, ensure that consistent assumptions are made, and facilitate the planning of site investigations at meaningful spatial and temporal scales. Examples of ways to handle this issue in site-specific contexts can be found in assessments made in Sweden (Lindborg 2010, Kautsky *et al* 2013), Finland (Posiva 2013b, 2013d) and France (ANDRA 2015). The lessons learned from these programmes show that safety assessments must be integrated with the task of characterising the site, and use the site understanding to inform the biosphere dose modelling.

4.5. Uncertainties

In safety assessments for radioactive waste disposal facilities, timescales typically span from the present-day out to thousands or millions of years, and profound uncertainties are inherent. Therefore, the management of uncertainties is a fundamental component of such assessments, and the selection of an appropriate approach is a key component of the assessment philosophy. Assessment results need to be interpreted in the light of both the explicitly estimated and residual unquantified uncertainties (IAEA 2009, 2011b, 2012, NEA 2012, ICRP 2013, RWM 2017, Nummi 2019).

The assessment philosophy, which needs to be consistent with that of the overall safety case, and the uncertainties need to be transparently identified, characterised and propagated through the safety assessment and finally into the safety case. Pessimistic approaches are often used, aiming to not underestimate potential impacts on humans and the environment. However, it is not always straightforward to identify which assumptions would be pessimistic overall (e.g. enhanced sorption both slows the transport, but also increases the accumulation and potential for in-growth in radiological decay chains). Also, adopting multiple, 'reasonably pessimistic' assumptions may lead to an extremely pessimistic result. Misleading results may also stem from unduly broad parameter distributions used in probabilistic assessments. These kinds of distortions may be particularly relevant if the assessment is intended to support optimisation or selection between options (ICRP 1985). In probabilistic assessments, care is required also to avoid risk dilution through spatial or temporal averaging missing peak risks (Dverstorp *et al* 2005, Wilmot and Robinson 2005).

In the identification of the uncertainties, their various sources should be considered. These include (Nummi 2019) scenario uncertainties (uncertainties in the system evolution and understanding, identification of FEPs and their interactions), modelling uncertainties (system understanding and its representation by the models, uncertainties in model assumptions and simplifications, model limitations), and parameter uncertainties (representativeness of data, lack of data, spatial and temporal variability). Some specific assumptions, for example relating to human habits and behaviour (e.g. STUK 2018), may be prescribed by the regulations and thus a part of the assessment basis. The uncertainties should be appropriately distinguished from the 'natural' variability (often also called epistemic versus aleatory uncertainties) as far as feasible.

The difficulty of modelling the very long timescales relevant here has long been recognised (Hill 1989, Oreskes *et al* 1994). Therefore, the results should not be presented as predictions, but as projections of possible futures (IAEA 2012, ICRP 2013). There are, however, possibilities for partial validation of models, for example with respect to specific processes and contaminants, e.g. Limer *et al* (2017), and by consideration of analogues, e.g. BIOPROTA (2005), and Lindborg (2017). Further support can be gained through verification or benchmarking by independent modelling (e.g. Xu *et al* 2013, Walke *et al* 2015, Dverstorp and Xu 2017). The use of site characterisation data to derive coherent datasets (e.g. SKB 2010b, Posiva 2014a, ANDRA 2015) has also been found useful. However, using such datasets does not necessarily guarantee considering the full range of situations relevant to the assessment.

Since the original BIOMASS methodology was developed, there has been considerable development of, and much more experience gained in, sensitivity and uncertainty analysis methods. These methods can be used for examining the impact of assumptions, degrees of consistency, and the strength of the data and knowledge basis, e.g. Funtowicz and Ravetz (1990), Nagra (2002), SKB (2004), van der Sluijs *et al* (2005), Ikonen (2006), Smith *et al* (2010), Petersen *et al* (2013), NSAI (2015), Bardos *et al* (2016) and Friedlich (2016).

4.6. Biomass methodology communication

The development of the biosphere modelling and safety assessment techniques and approaches described herein was founded in research and applied science undertaken since the 1980s. New people entering into the field of biosphere modelling and safety assessment have an opportunity to draw on experience developed over the past 40 years. Further, the experience gained, and lessons learned from applying the methods in biosphere modelling and safety assessments needs to be communicated. Here we believe that existing international forums have a role to play in arranging development programmes, educational schools and workshops and producing updated publications on best practice, available for, and accessible to, the broad community of radioactive waste management experts.

Acknowledgments

The authors would like to acknowledge IAEA for arranging and to facilitate the MODARIA II programme and its technical support to WG6. In parallel, the BIOPROTA forum was a key contributor to the work performed. All participants in both these groups shared insights in lessons learned using the BIOMASS methodology and contributed to the results synthesised herein. We also would like to acknowledge Swedish Nuclear Fuel and Waste Management Co. (SKB) for support in publishing this work as Open Access. Finally, we would like to acknowledge the IAEA member state organisations who actively supported specific tasks and the work done within WG6 and BIOPROTA, and these are listed below:

Agence Nationale pour la Gestion des Déchets Radioactifs (Andra), France; Aleksandria Sciences, United Kingdom; Blackthorne Science AB, Sweden; Bundesamt für Strahlenschutz (BfS), Germany; Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, (CIEMAT), Spain; CSD Ingenieure AG, Switzerland; EnviroCase Ltd, Finland; Environment Agency, United Kingdom; Dounreay Site Restoration

Ltd, United Kingdom; Environmental Protection Agency, United States of America; Federaal Agentschap voor Nucleaire Control (FANC)/Agence Fédérale de Contrôle Nucléaire (AFCN), Belgium; GMS Abingdon Ltd, United Kingdom; Josef Stefan Institute, Slovenia; Low Level Waste Repository Ltd (LLWR), United Kingdom; Mike Thorne and Associates Ltd, United Kingdom; Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle (Nagra), Switzerland; Nuclaer Waste Management Organisation of Japan (NUMO), JAPAN; Nuclear Waste Management Organisation (NWMO), Canada; Quintessa Ltd, United Kingdom; RadEcol Consulting Ltd, United Kingdom; Radiation and Nuclear Safety Authority (STUK), Finland; Svensk Kärnbränslehantering AB (SKB), Sweden; Radioactive Waste Management Ltd (RWM), United Kingdom; Posiva Oy, Finland; Strålsäkerhetsmyndigheten (SSM), Sweden; Svensk Kärnbränslehantering AB (SKB), Sweden; Xu Environmental Consulting AB, Sweden.

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References

Andersson J 2020 Science underpinning the safety case of deep geological repositories -challenges in the past and in the future and how to maintain knowledge and competence during operation *EPJ Nucl. Sci. Technol.* **6** 24
Andersson J, Skagius K, Winberg A, Lindborg T and Ström A 2013 Site-descriptive modelling for a final repository for spent nuclear fuel in Sweden *Environ. Earth Sci.* **69** 1045
Andersson E (ed) 2010 The limnic ecosystems at Forsmark and Laxemar-Simpevarp SKB report series TR-10-02 Svensk Kärnbränslehantering AB (Stockholm, Sweden) (available at: www.skb.se)
ANDRA 2005 Evaluation de sûreté du stockage géologique Agence Nationale pour les Gestion des Dechets Radioactifs, C RP ADSQ 04.0022—Dossier Argile, ANDRA, Parc de la Croix Blanche, 1/7 rue Jean-Monnet, 92298 (Châtenay-Malabry) (available at: www.andra.fr)
ANDRA 2015 Safety options report—post-closure part (DOS-AF) ANDRA report CG-TE-D-NTE-AMOA-SR2-0000-r555515-0062 Agence nationale pour la gestion des déchets radioactifs (ANDRA) (Paris) (available at: www.andra.fr)
Aquilonius K (ed) 2010 The marine ecosystems at Forsmark and Laxemar-Simpevarp, SR-site biosphere SKB report series TR-10-03 (Stockholm, Sweden: Svensk Kärnbränslehantering AB) (available at: www.skb.se)
ASN 2008 Guide de sûreté relatif au stockage définitif des déchets radioactifs en formation géologique profonde *Autorité de sûreté nucléaire Guide de l'ASN* p 32 (available at: www.asn.fr)
Bardos R P, Bone B D, Boyle R, Evans F, Harries N D, Howard T and Smith J W N 2016 The rationale for simple approaches for sustainability assessment and management in contaminated land practice *Sci. Total Environ.* **563–564** 755–68
BIOCLIM 2004 Deliverable D10-12: development and application of a methodology for taking climate-driven environmental change into account in performance assessments, Andra, Parc de la Croix Blanche, 1/7 rue Jean Monnet, 92298 Châtenay-Malabry, France (available at: www.andra.fr/bioclim/)
BIOPROTA 2005 Application of biotic analogue data Report prepared under the international collaborative BIOPROTA forum (available at: www.bioprota.org)
BIOPROTA 2014a An exploration of approaches to representing the geosphere—biosphere interface in assessment models *Final Report* (available at: www.bioprota.org) (Accessed December 2014)
BIOPROTA 2014b Representation of environmental change in the near-surface environment *Report of an International Workshop* (*London, 21–23 May 2014*) ed K Smith and G Smith (available at: www.bioprota.org)
BIOPROTA 2016 Update and review of the IAEA BIOMASS-6 reference biospheres methodology report of the first programme workshop Report prepared under the international collaborative BIOPRORA forum, Version 2.0 (available at: www.bioprota.org)
Broed R, Avila R, Bergström U, Hjerpe T and Ikonen A T K 2008 Biosphere analysis for selected cases in TILA-99 and in KBS-3H safety evaluation 2007 Working Report 2007-109 (Posiva Oy, Eurajoki, Finland) (available at: www.posiva.fi)
Code de l'environnement 2015a Code de l'environnement. Partie législative, Livre V: prévention des pollutions, des risques et des nuisances. Titre IV: déchets Chapitre II: Dispositions particulières à la gestion durable des matières et des déchets radioactifs (Article L542-1 à L542-14)
Code l'environnement 2015b Code l'environnement. Partie législative. Livre V: prévention des pollutions, des risques et des nuisances. Titre IX: la sécurité nucléaire et les installations nucléaires de base Chapitre III: Installations nucléaires de base (Articles L593-1 à L593-38)
Commission of the European Communities 1988 Performance assessment of geological isolation systems for radioactive waste: Pagis EUR 11775 EN, ECSC-EEC-EAEC (Brussels-Luxembourg)
Davis P A *et al* 1999 BIOMOVS II: an international test of the performance of environmental transfer models *J. Environ. Radioact.* **42** 117–30

DSA 2020 Regulatory framework of decommissioning, legacy sites and wastes from recognition to resolution: building optimization into the process report of an international workshop, held in Tromsø, November 2019 (Norwegian Radiation and Nuclear Safety Authority and the Nuclear Energy Agency) published as DSA 2020 5 (available at: www.dsa.no/filer/a0c711843a.pdf))

Dverstorp B, van Luik A, Umeki H, Voinis S and Wilmot R 2005 Management of uncertainty in safety cases and the role of risk. NEA updates *NEA News* **23** 14–17

Dverstorp B and Xu S 2017 A method for independent modelling in support of regulatory review of dose assessments *J. Environ. Radioact.* **178–179** 446–52

Fairhurst C, Gera F, Gnirk P, Gray M and Stillborg B 1993 The international stripa project: an overview *Tunn. Undergr. Space Technol.* **8** 315–43

Friedrich C M 2016 A model qualification method for mechanistic physiological QSP models to support model-informed drug development *CPT Pharmacometrics Syst. Pharmacol.* **5** 43–53

Funtowicz S O and Ravetz J R 1990 Mapping uncertainties of radiological hazards *Uncertainty and Quality in Science for Policy* (*Theory and Decision Library Series A* vol 15), ed S O Funtowicz and J R Ravetz (Dordrecht, The Netherlands: Kluwer Academic) pp 172–91

Haapanen R, Aro L, Koivunen S, Lahdenperä A-M, Kirkkala T, Hakala A, Helin J and Ikonen A T K 2011 Selection of real-life analogues for future lakes and mires at a repository site *Radioprotection* **46** S647–51

Hill M D 1989 Verification and validation of NRPB models for calculating rates of radionuclide transfer through the environment Report NRPB-R223 National Radiological Protection Board (NRPB), Chilton, UK.IAEA 2003, International Atomic Energy AGency 'Reference Biospheres' for Solid Radioactive Waste Disposal, Report of BIOMASS Theme 1 of the BIOsphere Modelling and Assessment Programme, IAEA BIOMASS-6 (Vienna: IAEA) (available at: www.iaea.org)

Hjerpe T 2019 Exposure pathway analysis for a disposal facility for radioactive waste at the Olkiluoto site Working report 2018–08 (Posiva OY, Eurajoki, Finland) (available at: www.Posiva.fi)

Hjerpe T, Ikonen A T K and Broed R 2010 Biosphere assessment report 2009 Report POSIVA 2010–03 (Posiva Oy, Eurajoki, Finland) (available at: www.posiva.fi)

Hjerpe T, Ikonen A T K and Broed R 2011 Assessing doses to humans in the Posiva safety case *Radioprotection* **46** S235–41

IAEA 2003 'Reference biospheres' for solid radioactive waste disposal Report of BIOMASS Theme 1 of the biosphere modelling and assessment programme, IAEA BIOMASS-6 (Vienna: International Atomic Energy Agency) (available at: www.iaea.org)

IAEA 2009 Safety assessments for facilities and activities. General safety requirements part 4, No. GSR, part 4 (Vienna: International Atomic Energy Agency (IAEA)) (available at: www.iaea.org)

IAEA 2011a Disposal of radioactive waste Specific Safety Requirements, No. SSR-5 (Vienna: International Atomic Energy Agency) (available at: www.iaea.org)

IAEA 2011b Geological disposal facilities for radioactive waste *Specific Safety Guide* IAEA safety standards series, No. SSG-14 (Vienna: International Atomic Energy Agency) (available at: www.iaea.org)

IAEA 2012 The safety case and safety assessment for the disposal of radioactive waste *Specific Safety Guide* IAEA safety standards series No. SSG-23 (Vienna: International Atomic Energy Agency) (available at: www.iaea.org)

IAEA 2014a *Planning and Design Considerations for Geological Repository Programmes of Radioactive Waste* IAEA-TECDOC series No. 1755 (Vienna: International Atomic Energy Agency) (available at: www.iaea.org)

IAEA 2014b *Monitoring and Surveillance of Radioactive Waste Disposal Facilities* IAEA safety standards series No. SSG-31 (Vienna: International Atomic Energy Agency) (available at: www.iaea.org)

IAEA 2014c *Modelling of Biota Dose Effects: Report of Working Group 6, Biota Dose Effects Modelling of EMRAS II Topical Heading, Reference Approaches for Biota Dose Assessment* IAEA-TECDOC-1737 (Vienna: IAEA) (available at: www.iaea.org)

IAEA 2014d Modelling approaches for management and remediation at NORM and nuclear legacy sites, final report of EMRAS II working group 2—reference approaches to modelling for management and remediation at 'NORM and legacy sites' (Vienna: International Atomic Energy Agency) (available at: www.iaea.org)

IAEA 2016 Environmental change in post-closure safety assessment of solid radioactive waste repositories IAEA-TECDOC-1799 (Vienna: International Atomic Energy Agency) (available at: www.iaea.org)

IAEA 2020 Development of a common framework for addressing climate and environmental change in post-closure radiological assessment of solid radioactive waste disposal IAEA-TECDOC-1904 (Vienna: International Atomic Energy Agency) (available at: www.iaea.org)

ICRP 1985 Principles for the disposal of solid radioactive waste. ICRP Publication 46 *46 Ann. ICRP* **15** 4 Pergamon Press

ICRP 2013 Radiological protection ingeological disposal of long-lived solid radioactive waste. ICRP Publication 122 **42**

Ikonen A T K 2006 Posiva biosphere assessment: revised structure and status 2006 Report POSIVA 2006–07 (Posiva Oy, Olkiluoto, Finland) (available at: www.posiva.fi)

JNC 2000 H12: project to establish the scientific and technical basis for hlw disposal in Japan. Supporting report 3. Safety assessment of the geological disposal system (Nuclear Cycle Development Institute, JNC TN1410 2000–004: Japan)

Johansson E 2016 The influence of climate and permafrost on catchment hydrology *Diss* Department of Physical Geography, Stockholm University, Stockholm, Sweden

Johansson E, Gustafsson L-G, Berglund S, Lindborg T, Selroos J-O, Claesson Liljedahl L and Destouni G 2015 Data evaluation and numerical modeling of hydrological interactions between active layer, lake and talik in a permafrost catchment, Western Greenland *J. Hydrol.* **527** 688–703

Kautsky U, Lindborg T and Valentin J (eds) 2013 Humans and ecosystems over the coming millennia: a biosphere assessment of radioactive waste disposal in Sweden *Ambio* **42** 381–526

Lawson G L and Smith G M 1985 BIOS: a model to predict radionuclide transfer and doses to man following releases from geological repositories for radioactive wastes NRPB-R169 (EUR-9755 EN) (London: Her Majesty's Stationary Office)

Limer L M C, Ota M, Tanaka T, Thorne M C and Walke R C 2017 C-14 terrestrial model-data comparisons, final report Report prepared under the international collaborative BIOPROTA forum, version 1.0 (available at: www.bioprota.org)

Lindborg T (ed) 2010 Landscape Forsmark—data, methodology and results for SR-Site SKB report series TR-10-05 (Stockholm, Sweden: Svensk Kärnbränslehantering AB) (available at: www.skb.se)

Lindborg T 2017 Climate-driven landscape development: physical and biogeochemical long-term processes in temperate and periglacial environments *Doctoral thesis* Swedish University of Agricultural Sciences, Umeå

Lindborg T *et al* 2018 Climate change and landscape development in post-closure safety assessment of solid radioactive waste disposal: results of an initiative of the IAEA *J. Environ. Radioact.* **183** 41–53

Lindborg T, Brydsten L, Sohlenius G, Strömgren M, Andersson E and Löfgren A 2013 Landscape development during a glacial cycle: modeling ecosystems from the past into the future *AMBIO* **42** 402–13

Lindborg T, Ikonen A T K, Kautsky U and Smith G 2021 System understanding as a scientific foundation in radioactive waste disposal, legacy site and decommissioning programmes *J. Radiol. Prot.* **41** S9–S23
Lindborg T, Rydberg J, Andersson E, Löfgren A, Lindborg E, Saetre P, Sohlenius G, Berglund S, Kautsky U and Laudon H 2020 A carbon mass-balance budget for a periglacial catchment in West Greenland – Linking the terrestrial and aquatic systems *Sci. Total Environ.* **711** 134561
Lindborg T and Schüldt R 1998 The biosphere at Aberg, Beberg and Ceberg—a description based on literature concerning climate, physical geography, ecology, land use and environment SKB Report series TR-98-20 (Stockholm, Sweden: Svensk Kärnbränslehantering AB) (available at: www.skb.se)
Löfgren A (ed) 2010 The terrestrial ecosystems at Forsmark and Laxemar-Simpevarp, SR-site biosphere SKB Report series TR-10-01 (Stockholm, Sweden: Svensk Kärnbränslehantering AB) (available at: www.skb.se)
Lord N S, Lunt D and Thorne M 2020 Modelling changes in climate over the next 1 million years POSIVA OY report 2019-04 (Olkiluoto, Finland) ISSN 2343-4740 (available at: www.posiva.fi)
Nagra 2002 Project opalinus clay: models, codes and data for safety assessment NTB-02-06 (Wettingen, Switzerland: Nagra)
NDA 2016 Geological disposal. Generic post-closure safety assessment. Radioactive waste management limited. NDA report No. DSSC/321/01 Nuclear Decommissioning Authority
NEA 2012 Methods for safety assessment of geological disposal facilities for radioactive waste: outcomes of the NEA MeSA initiative Report No. 6923 (Paris: Nuclear Energy Agency (NEA))
NRC 1957 The disposal of radioactive waste on land. Report of the committee on waste disposal of the division of earth sciences. Publ 519 (Washington, DC: National Academy of Science, National Research Council) (Accessed September 1957)
NSAI 2015 Standard documentation of chemical exposure models. S R CWA 16938: 2015 (The National Standards Authority of Ireland)
Nummi O 2019 Plan for uncertainty assessment in the safety case for the operating licence application Report POSIVA 2018-02 (Posiva Oy, Eurajoki, Finland) (available at: www.posiva.fi)
NWMO 2017 Postclosure safety assessment of a used fuel repository in crystalline rock NWMO-TR-2017-02 (Toronto, Canada: Nuclear Waste Management Organization)
NWMO 2018 Postclosure safety assessment of a used fuel repository in sedimentary rock NWMO-TR-2018-08 (Toronto, Canada: Nuclear Waste Management Organization)
ONR 2011 Joint regulatory scrutiny of RWM's work relating to geological disposal of higher activity radioactive waste: regulatory review of the generic disposal system safety case Environment agency and office for nuclear regulation. Environment Agency report GENW1211BVDX-E-E (Accessed 1 December 2011)
Oreskes N, Shrader Frechette K and Belitz K 1994 Verification, validation and confirmation of numerical models in the earth sciences *Science* **263** 641–6
Petersen A C, Janssen P H M, van der Sluijs J P, Risbey J S, Ravetz J R, Wardekker J A and Martinson Hughes H 2013 *Guidance for Uncertainty Assessment and Communication* 2nd edn (The Hague: PBL Netherlands Environmental Assessment Agency)
Pimenoff N, Venäläinen A and Järvinen H 2011 Climate scenarios for Olkiluoto on a time-scale of 120 000 years Report POSIVA 2011–04 (Posiva Oy, Eurajoki, Finland) (available at: www.posiva.fi)
Pimenoff N, Venäläinen A and Järvinen H 2012 Climate and sea level scenarios for Olkiluoto for the next 10 000 years Report POSIVA 2012–26 (Posiva Oy, Eurajoki, Finland) (available at: www.posiva.fi)
Posiva 2012a Olkiluoto site description Report POSIVA 2011–02 (Posiva Oy, Eurajoki, Finland) (available at: www.posiva.fi)
Posiva 2012b Safety case for the disposal of spent nuclear fuel at Olkiluoto: features, events and processes 2012 Report POSIVA 2012-07 (Posiva Oy, Eurajoki, Finland) (available at: www.posiva.fi)
Posiva 2012c Safety case for the disposal of spent nuclear fuel at Olkiluoto: synthesis 2012 Report POSIVA 2012-12 (Posiva Oy, Eurajoki, Finland) (available at: www.posiva.fi)
Posiva 2013a Olkiluoto biosphere description Report POSIVA 2012-06 (Posiva Oy, Eurajoki, Finland) (available at: www.posiva.fi)
Posiva 2013b Safety case for the disposal of spent nuclear fuel at Olkiluoto: biosphere assessment 2012 Report POSIVA 2012-10 (Posiva Oy, Eurajoki, Finland) (available at: www.posiva.fi)
Posiva 2013c Safety case for the disposal of spent nuclear fuel at Olkiluoto: surface and near-surface hydrological modelling in the biosphere assessment BSA-2012 Report POSIVA 2012-30 (Posiva Oy, Eurajoki, Finland) (available at: www.posiva.fi)
Posiva 2013d Safety case for the disposal of spent nuclear fuel at Olkiluoto: terrain and ecosystems development modelling in the biosphere assessment BSA-2012 Report POSIVA 2012-29 (Posiva Oy, Eurajoki, Finland) (available at: www.posiva.fi)
Posiva 2014a Safety case for the disposal of spent nuclear fuel at Olkiluoto: data basis for the biosphere assessment BSA-2012 Report POSIVA 2012–28 (Posiva Oy, Eurajoki, Finland) (available at: www.posiva.fi)
RWM 2016 Geological disposal: biosphere status report Radioactive waste management report DSSC/454/01 (Harwell, UK: Radioactive Waste Management Limited (RWM))
RWM 2017 Geological disposal: methods for management and quantification of uncertainty Report NDA/RWM/153 (Harwell, UK: Radioactive Waste Management Limited (RWM))
Saetre P, Valentin J, Lagerås P, Avila R and Kautsky U 2013 Land use and food intake of future inhabitants: outlining a representative individual of the most exposed group for dose assessment *Ambio* **42** 488–96
SKB 2004 Preliminary site description of the forsmark area (version 1.1) SKB report series R-04-15 (Stockholm, Sweden: Svensk Kärnbränslehantering AB) (available at: www.skb.se)
SKB 2006 Site descriptive modelling Forsmark stage 2.1. Feedback for completion of the site investigation including input from safety assessment and repository engineering SKB report series R-06-38 (Stockholm, Sweden: Svensk Kärnbränslehantering AB)
SKB 2010a Spent nuclear fuel for disposal in the KBS-3 repository SKB report series TR-10-13 (Stockholm, Sweden: Svensk Kärnbränslehantering AB)
SKB 2010b Biosphere analysis for the safety assessment SR-site—synthesis and summary of results SKB report series TR-10-09 (Stockholm, Sweden: Svensk Kärnbränslehantering AB) (available at: www.skb.se)
SKB 2010c Components, processes and interactions in the biosphere SKB report series R-10-37 (Stockholm, Sweden: Svensk Kärnbränslehantering AB) (available at: www.skb.se)
SKB 2011 Long-term safety for the final repository for spent nuclear fuel at forsmark. Main report of the SR-Site project SKB report series TR-11–01 (Stockholm, Sweden: Svensk Kärnbränslehantering AB) (available at: www.skb.se)
SKB 2015 Safety analysis for SFR long-term safety. Main report for the safety assessment SR-PSU Revised edn SKB report series TR-14-01 (Stockholm, Sweden: Svensk Kärnbränslehantering AB) (Updated 4 2017)
SKB 2019 Climate and climate-related issues for the safety evaluation SE-SFL SKB report series TR-19-04 (Solna, Sweden: Svensk Kärnbränslehantering AB) (available at: www.skb.se)

Smith G and Kozak M 2011 Historical development and evolution of EPRI's post-closure dose assessment of potential releases to the biosphere from the proposed HLW repository at Yucca Mountain *J. Health Phys.* **101** 709–21

Smith K, Robinson C, Jackson D, de la Cruz I, Zinger I and Avila R 2010 Non-human biota dose assessment: sensitivity analysis and knowledge quality assessment Working report 2010-69 (Posiva Oy, Eurajoki, Finland) (available at: www.posiva.fi)

SSM 2018 Strålsäkerhet efter slutförvarets förslutning. Beredning inför regeringens prövning Slutförvaring av använt kärnbränsle Strålsäkerhetsmyndigheten (in Swedish)

STUK 2018 Disposal of nuclear waste. Regulatory guide YVL D.5 (Helsinki, Finland: Radiation and Nuclear Safety Authority (STUK) (available at: www.stuklex.fi/en/ohje/YVLD-5) (Accessed 13 February 2018)

US DOE 2008 Yucca mountain repository license application *Safety Analysis Report* Repository Safety after Permanent Closure, DOE/RW-0573, Rev. 1 (Las Vegas, Nevada: United States Department of Energy, Office of Civilian Radioactive Waste Management) ch 2

USNRC 2014 Safety evaluation report related to disposal of high-level radioactive wastes in a geologic repository at Yucca Mountain, Nevada Volume 3: Repository Safety After Permanent Closure. NUREG-1949

van der Sluijs J P, Craye M, Funtowicz S, Kloprogge P, Ravetz J and Risbey J 2005 Combining quantitative and qualitative measures of uncertainty in model-based environmental assessment: the NUSAP system *Risk Anal.* **25** 481–92

van Dorp F *et al* 1999 Biosphere modelling for the assessment of radioactive waste repositories; the development of a common basis by the BIOMOVS II reference biosphere working group *J. Environ. Radioact.* **42** 225–36

Walke R C, Kirchner G, Xu S and Dverstorp B 2015 Post-closure biosphere assessment modelling: comparison of complex and more stylised approaches *J. Environ. Radioact.* **148** 50–58

Walke R C, Thorne M C and Limer L M C 2013 RWMD biosphere assessment model: terrestrial component, Quintessa and AMEC report to NDA RWM QRS-1628A-2 (Henley-on-Thames)

Wilmot R and Robinson P, 2005 The issue of risk dilution in risk assessments *Management of Uncertainty in Safety Cases Andthe Role of Risks: Workshop Proc.* (*Stockholm, Sweden*, *2–4 February 2004*) Report No. 5302 (Paris: Organisation for Economic Co-operation and Development (OECD), Nuclear Energy Agency (NEA)) pp 197–206

Xu S, Dverstorp B and Nordén M 2013 Independent modelling in SSM's licensing review of a spent fuel repository *Proc. a Nuclear Energy Agency Symp. on 'The Safety Case for Deep Geological Disposal of Radioactive Waste: 2013 State of the Art* (*Paris*, *7–9 October 2013*)