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Approaches for Modelling of Radioecological Data to Identify Key Radionuclides and Associated Parameter Values for Human and Wildlife Exposure Assessments

Report of 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
MODARIA Topical Heading Uncertainties and Variability

Modelling and Data for Radiological Impact Assessments (MODARIA) Programme

IAEA
International Atomic Energy Agency

APPROACHES FOR MODELLING OF RADIOECOLOGICAL DATA TO IDENTIFY KEY RADIONUCLIDES AND ASSOCIATED PARAMETER VALUES FOR HUMAN AND WILDLIFE EXPOSURE ASSESSMENTS

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IAEA-TECDOC-1950

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AND ASSOCIATED PARAMETER
VALUES FOR HUMAN AND
WILDLIFE EXPOSURE ASSESSMENT
MODARIA TOPICAL HEADING
UNCERTAINTIES AND VARIABILITY

MODELLING AND DATA FOR
RADIOLOGICAL IMPACT ASSESSMENTS
(MODARIA) PROGRAMME

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FOREWORD

Models are essential tools for use in the evaluation of radiological impacts within the safety assessment process and regulatory control of nuclear facilities and activities in planned, existing and emergency exposure situations. Modelling the fate and transport of radionuclides in the environment and assessing the resulting radiation doses to people and the environment is needed, for example, in the evaluation of the radiological relevance of routine and accidental releases of radionuclides, to assist in decision making during remediation activities, in the framework of long term safety assessments of nuclear waste disposal facilities, and for clearance and exemption of material with low levels of radioactivity from the need for regulatory control.

The IAEA has been organizing programmes of international model testing since the 1980s. These programmes have contributed to a general improvement in models, both in the transfer of data and 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), which concentrated on testing the performance of models; developing and improving models for particular environments; reaching consensus on datasets that are generally applicable in environmental transfer models; and providing an international forum for the exchange of experience, ideas and information.

Different aspects were addressed by ten working groups within MODARIA covering four thematic areas: remediation of contaminated areas; uncertainties and variability; exposures and effects on biota; and marine modelling. This publication describes the activities of the working group on 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 4).

The IAEA thanks all those who participated in the work of the MODARIA programme and gratefully acknowledges the valuable contributions of B. Howard (United Kingdom), as chair of the working group, and of S. Fesenko (Russian Federation). The IAEA officers responsible for this publication were A. Iurian and M. Phaneuf of the Division of IAEA Environment Laboratories.

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SUMMARY

This publication describes the work undertaken by Working Group 4 (WG4) of the IAEA's MODARIA programme on the prioritization of radionuclides contributing to total dose rates to wildlife and on the revision of goat and cow milk transfer parameters. Three IAEA Technical Reports Series publications (TRS 422, 472, 479) provide datasets of transfer parameter values that may be used in assessments to estimate the effective doses to humans and wildlife. MODARIA WG4 has further explored the development of approaches to evaluate the potential importance of radionuclides in radiological environmental impact assessments for wildlife and methods to prioritize these based on radionuclide contribution to dose rates for different reference organisms and wildlife groups. A collation of data to improve the quality of parameter values for the transfer of radionuclides to cow and goat milk has also been undertaken. The work of WG4 related to the improvement of distribution coefficient (K_d) datasets for soils and freshwater sediments will be reported as part of a separate report that covers the work undertaken under both the MODARIA I and MODARIA II programmes.

Different approaches were developed to rank the potential importance of anthropogenic and naturally occurring radionuclides in contributing to the total dose rates to wildlife. The prioritization analysis for anthropogenic radionuclides released during planned exposure situations showed that the ranking of radionuclides, in terms of their importance in contributing to dose rates to wildlife, differed substantially if the amounts of each radionuclide released were considered, rather than assuming all the radionuclides were released in equal quantities. In a prioritization exercise for naturally occurring radionuclides, the use of parameter values from IAEA Technical Reports Series No. 479, when applied to a specific uranium mining site, was shown, for some radionuclides, to under- or overestimate dose rates to wildlife due mostly (but not always) to differences in the whole organism concentration ratios ($CR_{wo\text{-}media}$) and tissue conversion factors measured at the site. The consideration of both radioecological data and tissue conversion rates in evaluating gaps in the available data is, therefore, important.

A substantial revision of the goat and cow milk transfer parameter dataset published in IAEA Technical Reports Series No. 472 has improved information on both the provenance of the data used and transparency of data selection or rejection. The revised dataset includes a wider range of radionuclides, especially for concentration ratio (CR) values between concentrations in animal feed and concentrations in milk. Overall, there were only minor differences in values for both the CR and the equilibrium transfer coefficient, F_m, reported in the revised dataset compared with the previous dataset published by the IAEA. Comparison of gut absorption values with the transfer parameter values indicates that, in the absence of available data, published gut absorption values for humans can be used to estimate order of magnitude transfer parameter values to milk for different radionuclides.

1. INTRODUCTION

1.1. BACKGROUND OF THE MODARIA PROGRAMME

The IAEA organized a programme from 2012 to 2015, entitled Modelling and Data for Radiological Impact Assessments (MODARIA), 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 effect of remedial measures
- Working Group 3: Application of models for assessing radiological impacts arising from naturally occurring radioactive material (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 activities and results achieved by the Working Groups are described in individual IAEA Technical Documents (IAEA-TECDOCs). This TECDOC describes the work of MODARIA Working Group 4 on the analysis of radioecological data in IAEA Technical Report Series publications to identify key radionuclides and associated parameter values for human and wildlife exposure assessment.

1.2. BACKGROUND FOR MODARIA WORKING GROUP 4

During the two EMRAS (Environmental Modelling for Radiation Safety) programmes, significant progress was made in compiling data on environmental transfer of radionuclides in the environment. These data have been made available in two Technical Reports Series (TRS) publications — one covering the human food chain (TRS 472, Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Terrestrial and Freshwater Environments [1]) and another on transfer to wildlife (TRS 479, Handbook of Parameter Values for the Prediction of Radionuclide Transfer to Wildlife [2]). Both of these publications, along with an earlier one on marine systems (TRS 422, Sediment Distribution Coefficients and Concentration Factors for Biota in the Marine Environment [3]), are now widely used in assessments to estimate effective doses to humans and internal and external dose rates for wildlife groups.

The empirical ratios given in Refs [1–3] cover a range of different approaches to quantify transfer between different environmental compartments. They give ratios of radionuclide activity concentrations:

(1) In the soil or sediment divided by those in the solution;
(2) In a crop divided by those in a specified depth of soil;
(3) In an animal product divided by those in the animal feed (or by the daily intake of radionuclide or by the deposition density in soil to a given depth);
(4) In an aquatic food product divided by that in water;
(5) In the whole organism of different wildlife groups commonly divided by that in the soil or water.

Currently, the various compilations [1–3] exhibit data gaps, raising the issue of how to identify which of these data gaps are important with respect to radiological environmental impact assessment (REIA) and would therefore justify the expenditure of resources to enhance the available datasets by filling the gaps and, conversely, which data gaps are not important. There are many such gaps in most of the tables of data in Refs [1–3] and limited research and financial resources to address these deficiencies. In some cases, the tabulated datasets are more complete, but have used a variety of different extrapolation methods to derive the values reported [4]. Identification and prioritization of the key radionuclides and pathways contributing to the doses received by humans and wildlife groups is an important mechanism to justify further enhancement of the datasets.

Identifying or deriving parameter values for REIA is an iterative process, during which determination of appropriate values can be time consuming. There are many factors which affect the quality of parameter values selected for use in an assessment. If there are few relevant data, then an overly conservative approach may be taken to select parameter values and this may have a significant impact on the assessment results.

Within the MODARIA programme, Working Group 4 (WG4) considered the analysis of radioecological data in Refs [1–3] to identify key radionuclides and associated parameter values for human and wildlife REIA. The Working Group explored the development of approaches to evaluate the importance of parameter values for different radionuclides in contributing to doses to wildlife. The Working Group also collated data to allow an improvement in the data on parameter values for the transfer to cow and goat milk, including providing transparency regarding the quality and quantity of the underpinning data. Milk was selected as it often has a high priority in REIA. The work of MODARIA WG4 builds on, and complements, model based sensitivity analyses performed as part of the work done in Working Group 8 ‘Environmental Sensitivity’ of the EMRAS II programme, published in IAEA-TECDOC-1719, Environmental Sensitivity in Nuclear Emergencies in Rural and Semi-natural Environments [5].

1.3. OBJECTIVES AND SCOPE

The general aim of the MODARIA programme was to improve capabilities in the field of REIA by means of acquisition of improved data for model testing and comparison, reaching consensus on modelling philosophies, approaches and parameter values, and development of improved methods and exchange of information. The work of Working Group 4 was primarily intended:

(1) To develop approaches to prioritize radionuclides contributing to exposure for a range of different sources relevant to radiation protection of the environment, to support the orientation of future research programmes;
(2) To improve the quality and amount of information provided for selected high priority parameter values, namely the transfer parameters for cow and goat milk.

This publication comprises two main sections. The first section considers prioritization approaches to identify the radionuclides and pathways that potentially contribute most to internal and external exposure to organisms in wildlife groups for different sources and exposure situations. The prioritization approaches for the different exposure situations are presented and the outcomes compared with the extent of information on transfer parameter values given in TRS 479 [2]. These approaches consider the benefits and problems associated with the application of internationally compiled sources of transfer parameters compared with site specific data.

The focus of the second section is the improvement of transfer parameter values for animal product data, namely cow and goat milk. The quality, quantity and provenance of transfer parameter data for goat and cow milk presented in TRS 472 [1] have been improved. The newly compiled information addresses the need to enhance the data and to fill gaps in the international compilation [1].

This publication is intended to provide Member States with technical information and data that can be used by their national authorities to develop and improve their models and approaches for REIA for facilities and activities.

1.4. STRUCTURE

Section 2 describes and provides examples of different approaches for prioritizing data that are necessary for estimating internal and external exposure to wildlife for different sources of radionuclides, ecosystems and exposure pathways. Prioritization approaches are described for anthropogenic and naturally occurring sources of radionuclides, initially considering qualitative approaches exploring the radionuclides discharged or present in the environment. Examples of quantitative approaches, where the amounts of radionuclides released or present in the environment are considered, are also presented for exposure situations for anthropogenic and naturally occurring radionuclides. The radionuclide ranking in terms of importance in contributing to doses to wildlife for the two exposure scenarios considered is compared with the amount and quality of transfer parameter data for each radionuclide available in TRS 479 [2].

Section 3 provides the revised collated data and parameter values for transfer to goat and cow milk and describes an extrapolation method to predict transfer to milk from gastrointestinal absorption.

2. PRIORITIZATION OF RADIONUCLIDES ACCORDING TO THEIR CONTRIBUTION TO DOSES TO WILDLIFE

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2.1. INTRODUCTION

The approach used to quantify environmental transfer processes when conducting radiological impact assessments is similar for humans via the human food chain, and for other organisms, here termed wildlife. Concentration ratio ($CR_{wo\text{-}media}$) and distribution coefficient (K_d) are radioecological parameters often used to quantify the transfer between a number of different compartments in the environment. The focus of the work undertaken by Working Group 4 is on radiological impact assessments for wildlife. The $CR_{wo\text{-}media}$ used for wildlife assessments for a whole organism is defined as:

$$\boldsymbol{CR_{wo-media}} = \frac{\boldsymbol{Activity\ concentration\ in\ biota\ whole\ body\ (\frac{Bq}{kg}\ fresh\ mass)}}{\boldsymbol{Activity\ concentration\ media\ (filtered\ water\ \left(\frac{Bq}{kg}\right), soil (Bq/kg\ dry\ mass)}} \quad (1)$$

The $CR_{wo\text{-}media}$ values are defined for steady state equilibrium and are assumed to be the same for different isotopes of the same element.

There is a vast diversity of wildlife and a broad range of radionuclides that are present in the environment. The radionuclides originate from several sources including those of natural origin, from regulated releases from various facilities, from historic atmospheric weapon tests and from unplanned releases as the result of accidents. Considerable recent efforts have been made to fill K_d or $CR_{wo\text{-}media}$ data gaps in the field of radioecology. However, it will never be possible to fully quantify the environmental processes that affect the extent of transfer of radionuclides to every living organism. The solution adopted by the international community has been to define reference organisms [6] or similar concepts such as reference animals and plants (RAPs) [7]. The need for data is reduced, to some extent, by assumptions of equilibrium and that different isotopes of an element behave similarly.

Two complementary approaches can be applied to increase the available knowledge on the transfer of radionuclides to wildlife. The most obvious consists of acquiring new knowledge through experimentation and field measurements. However, the availability of new relevant

data is constrained due to resource limitation, ethical issues and safety concerns. Also, many radionuclides are difficult to measure in the environment and in organisms, especially at low activity concentrations. An alternative approach consists of making best use of the available data by developing appropriate extrapolation methods [4]. Whatever the method adopted, it necessarily involves significant investment of resources, and such efforts need to be focused to optimize resources. Clearly, the best way to utilize the available resources is to focus on the combinations of radionuclides and wildlife that potentially contribute most to the internal and/or external dose received for the exposure situation being considered. When considering the selection of priority wildlife, the 'reference organisms' or RAP approach is generally viewed as an appropriate simplified representation of the biodiversity of ecosystems, at least for screening assessments [6, 7].

An attempt at identifying important and less important radionuclides that contribute to the dose to wildlife has previously been made, but this was limited to terrestrial RAPs specified by the ICRP [8]. To enlarge the scope of such studies, and consider more exposure situations, two approaches have been developed under the framework of MODARIA WG4 and are presented below. One approach attempts the prioritization of radionuclides released as authorized discharges by French nuclear facilities, with an emphasis on planned exposure situations [9]. A complementary study in Australia is included which focused on an existing exposure situation at a uranium mining site in Australia [10].

Using the compilations of $CR_{wo\text{-}media}$ value data for wildlife from TRS 479 [2], the objectives of using the prioritization approaches in this study within MODARIA WG4 were:

(1) To identify radionuclides which are potentially important in contributing to external and/or internal doses to wildlife for different transfer pathways, selected sources and different exposure situations;
(2) To compare the transfer parameter data for the list of identified high priority radionuclides with data provided to the international community [2];
(3) To identify, for selected sources and environments, the data gaps that are potentially important for assessing doses to wildlife and those that are less important.

2.2. RADIONUCLIDE SOURCES FOR DIFFERENT EXPOSURE SITUATIONS

The first step of the prioritization was establishing the list of radionuclides that may be of interest regarding wildlife exposure. Therefore, a review of the radionuclides potentially released to, or already present, in the environment from diverse sources was carried out.

Radiological impact assessments of wildlife exposure to radionuclides of both natural and anthropogenic origin are now being conducted in many countries. The range of radionuclides present varies considerably depending on the sources. It is therefore important to have information on the radionuclides for which $CR_{wo\text{-}media}$ values might be needed to conduct a radiological impact assessment.

Anthropogenic radionuclides in the environment arise from various sources including normal operation of nuclear facilities, nuclear weapons testing and from incidents or accidents. In each case, radionuclides can be released via liquid and/or atmospheric routes of release. The nature of released radionuclides may vary depending on the situation, the facility and the release pathway.

To demonstrate the range of radionuclides that could be present in the environment and be included in an assessment of doses to wildlife, the radionuclides present in releases from various

French nuclear facilities and from two major accidents, at the Chernobyl and Fukushima Daiichi Nuclear Power Plants, are listed in Table 1 for liquid sources and Table 2 for atmospheric sources [9, 11–17]. Data for liquid releases from a French former uranium mining site are also listed in Table 1 [18]. It is expected that these lists cover the majority of radionuclides that could be important in contributing to wildlife exposure from planned, existing and accidental releases to the environment.

Over all types of facilities included, the liquid releases included 130 radionuclides, plus some of their short lived decay products, which corresponds to a total of 61 elements. For atmospheric releases, 106 radionuclides plus some decay products are listed for a total of 52 elements.

A complete prioritization analysis would potentially need to consider all radionuclide entries in Tables 1 and 2. However, no single nuclear release source term would include the entire list and the quantities of each radionuclide released for a given exposure scenario will be different, affecting their significance in contributing to wildlife exposure. Therefore, for the purpose of demonstrating the prioritization approach described in Section 2.3, a more realistic case with a reduced number of radionuclides has been considered. Radionuclides were considered that are actually released from the considered sources, have parent radionuclides with 'long' half-lives or have 'high' branching ratio for decay products. Threshold values were arbitrarily set at 5 days (exclusion of isotopes with lower half-lives) and 0.1 (exclusion of decay products with lower branching ratios), to identify radionuclides that were more likely to be relevant with regard to chronic exposure of wildlife. This consideration also led to the exclusion of inert gases. From the radionuclides identified as released in liquid and/or atmospheric discharges in Tables 1 and 2, a list of prioritized elements based on the selection criteria used is given in Table 3, excluding inert gases.

2.3. APPROACHES TO ANTHROPOGENIC AND TECHNOLOGICALLY ENHANCED NATURAL RADIONUCLIDE PRIORITIZATION FOR WILDLIFE

Collaboration between IRSN, Commissariat à l'énergie atomique et aux énergies alternatives (CEA) and Électricité de France (EDF) from 2011 to 2014 focused on improving methods, tools and associated data necessary to assess the radiological impacts on ecosystems. The analysis was carried out using the Environmental Risk from Ionising Contaminants: Assessment and Management (ERICA) integrated approach [6]. One of the objectives of the study was to identify priority radionuclides of interest that are relevant to radiation protection of the environment, to support the orientation of potential future research programmes.

The study initially focused on situations of chronic exposure of ecosystems to ionising radiation and was subsequently extended to acute exposure situations. It was applied to radionuclides identified as potentially present in freshwater, marine or terrestrial ecosystems. The list of radionuclides considered corresponded to the sources described in Tables 1 and 2 for nuclear power plants (normal operation and decommissioning) and research centres, but excluded the inert gases (Ar, Kr and Xe), which are not included in the ERICA tool (version 1.2) [6]. Default information from the ERICA tool was used as often as possible for reference organisms, radionuclides and the associated parameterization applied for transfer and dosimetry. When necessary, a brief review of the literature was carried out to supplement the available data, sometimes used in combination with extrapolation methods that have been previously applied in the ERICA tool. An example of how this combined approach has been used is given in Ref. [4].

TABLE 1. EXAMPLE RADIONUCLIDES IDENTIFIED AS RELEASED IN LIQUID DISCHARGES FOR VARIOUS NUCLEAR FACILITIES (BASED ON DATA FROM FRANCE) AND MAJOR ACCIDENTS

Isotope	Reprocessing plant [9, 11]	Landfill disposal [12]	Nuclear power plants [13]		Research centres [14]	Former U mining site [18]	Accidental releases	
			Normal operation	Decommissioning			Chernobyl [15]	Fukushima [16, 17]
H-3	X		X	X	X			
Be-10	X							
C-14	X		X	X	X			
Na-22					X			
Na-24			X					
Cl-36	X			X	X			
P-32					X			
P-33					X			
K-40				X				
Ca-41	X			X				
Cr-51			X		X			
Mn-54	X		X		X			
Co-57	X		X		X			
Co-58	X		X		X			X[c]
Co-60	X		X	X	X			
Fe-55	X			X	X			
Fe-59			X					
Ni-59	X			X	X			
Ni-63	X		X	X	X			
Zn-65	X		X		X			
Se-75					X			
Se-79	X							
Sr-85	X				X			
Sr-90+Y-90[a]	X			X	X			X[c]
Rb-87	X							
Y-91	X							
Nb-92				X				
Nb-93m				X				
Nb-94	X				X			
Nb-95	X		X		X			
Zr-93	X							
Zr-95	X		X		X			
Mo-93	X							
Mo-99+Te99m[a]			X					X[c]
Tc-99	X				X			
Tc-99m			X					
Ru-103+Rh-103[a]	X				X			
Ru-105								X[c]
Ru-106+Rh-106[a]	X				X			X[c]
Pd-107	X							
Ag-108m			X		X			
Ag-110m	X		X		X			
Cd-109	X		X		X			
Cd-113								
Sn-113			X					
Sn-117m			X					
Sn-121	X							
Sn-121m	X							
Sn-126	X							

TABLE 1. EXAMPLE RADIONUCLIDES IDENTIFIED AS RELEASED IN LIQUID DISCHARGES FOR VARIOUS NUCLEAR FACILITIES (BASED ON DATA FROM FRANCE) AND MAJOR ACCIDENTS (cont.)

Isotope	Reprocessing plant [9, 11]	Landfill disposal [12]	Nuclear power plants [13]		Research centres [14]	Former U mining site [18]	Accidental releases	
			Normal operation	Decommissioning			Chernobyl [15]	Fukushima [16, 17]
Sb-122			X					
Sb-124	X		X		X			
Sb-125	X		X		X			
Sb-126	X							
Te-123m			X					
Te-125m					X			
Te-127	X							
Te-127m	X							
Te-129m+Te-129a								X[c]
Te-132+I-132[a]								X[c]
I-129	X	X			X			
I-131	X		X		X			X[c]
I-133	X							
Ba-133					X			
Xe-133								
Xe-133m								
Xe-135								
Cs-134	X		X	X	X			X[c]
Cs-135	X	X						
Cs-136								X[c]
Cs-137+Ba-137m[a]	X	X	X	X	X			X[c]
Ba-140+La-140[a]								X[c]
Ce-144+Pr-144[a]	X				X			
Pm-147	X							
Sm-151	X	X			X			
Eu-150				X				
Eu-152	X			X	X			
Eu-154	X				X			
Eu-155	X			X	X			
Gd-152				X				
Hf-178m				X				
W-187								
Pb-202+Tl-202[a]					X			
Hg-203								
Tl-207						X		
Bi-210						X		
Bi-211						X		
Bi-214						X		
Pb-210						X		
Pb-211						X		
Pb-214						X		
Po-210						X		
Po-214						X		
Po-215						X		
Po-218						X		
Rn-219						X		
Rn-222						X		

TABLE 1. EXAMPLE RADIONUCLIDES IDENTIFIED AS RELEASED IN LIQUID DISCHARGES FOR VARIOUS NUCLEAR FACILITIES (BASED ON DATA FROM FRANCE) AND MAJOR ACCIDENTS (cont.)

Isotope	Reprocessing plant [9, 11]	Landfill disposal [12]	Nuclear power plants [13]		Research centres [14]	Former U mining site [18]	Accidental releases	
			Normal operation	Decommissioning			Chernobyl [15]	Fukushima [16, 17]
Ra-223						X		
Ra-226		X		X	X	X		
Ra-228		X						
Ac-227						X		
Th-227						X		
Th-230						X		
Th-231						X		
Th-232		X						
Th-234						X		
Pa-231				X		X		
Pa-233					X			
Pa-234m						X		
U-232	X	X			X			
U-233	X	X						
U-234	X	X		X	X	X		
U-235	X	X			X	X		
U-236	X	X						
U-237					X			
U-238	X	X		X	X	X		
Np-237	X	X		X	X			
Pu-236	X							
Pu-238	X	X		X	X			
Pu-239+Pu-240[b]	X	X		X	X			
Pu-241	X	X			X			
Pu-242	X	X			X			
Am-241	X	X		X	X			
Am-242m	X							
Am-242	X				X			
Am-243	X	X		X				
Cm-242	X	X		X	X			
Cm-243	X	X		X	X			
Cm-244	X	X		X	X			
Cm-245	X							
Cm-246	X			X				

[a] Radioactive decay process at secular equilibrium: parent and progeny present the same activity.
[b] Isotopes measured together.
[c] Obtained from IRSN reports, measured in the environment.

TABLE 2. EXAMPLE RADIONUCLIDES IDENTIFIED AS RELEASED IN ATMOSPHERIC DISCHARGES FOR VARIOUS NUCLEAR FACILITIES (BASED ON DATA FROM FRANCE) AND MAJOR ACCIDENTS

Isotope	Reprocessing plant [9, 11]	Nuclear power plants [13]		Research centres [14]	Accidental releases	
		Normal operation	Decommissioning		Chernobyl [15]	Fukushima [16, 17]
H-3	X	X	X	X		
C-14	X	X	X	X		
Cl-36	X		X			
K-40			X			
Ar-37				X		
Ar-41		X		X		
Ca-41			X			
Cr-51		X				
Mn-54		X				
Co-57	X	X				
Co-58	X	X				
Co-60	X	X	X	X		
Fe-55			X			
Fe-59		X				
Ni-59			X			
Ni-63			X			
Se-75	X	X		X		
As-76		X				
Br-82		X		X		
Kr-85m		X				
Kr-85	X	X		X	X	X[c]
Kr-87				X		
Kr-88		X		X		
Sr-89					X	X[c]
Sr-90+Y-90[a]	X		X	X	X	X[c]
Y-91				X		
Mo-93						
Mo-95					X	
Nb-93m			X			
Nb-94			X			
Nb-95	X	X		X		X[c]
Zr-95	X	X		X	X	
Tc-99m		X				
Ru-103+Rh-103[a]	X	X			X	
Ru-106+Rh-106[a]	X			X	X	
Ag-108m			X			
Ag-110m		X	X	X		X[c]
Cd-109			X			
Cd-113m			X			
Sn-113		X				
Sb-122		X				
Sb-124	X	X				
Sb-125	X	X				
Te-123m		X				
Te-125m	X			X		
Te-127						
Te-127m						
Te-129m+Te-129[a]					X	X[c]
Te-132					X	X

TABLE 2. EXAMPLE RADIONUCLIDES IDENTIFIED AS RELEASED IN ATMOSPHERIC DISCHARGES FOR VARIOUS NUCLEAR FACILITIES (BASED ON DATA FROM FRANCE) AND MAJOR ACCIDENTS (cont.)

Isotope	Reprocessing plant [9, 11]	Nuclear power plants [13]		Research centres [14]	Accidental releases	
		Normal operation	Decommissioning		Chernobyl [15]	Fukushima [16, 17]
I-123				X		
I-125				X		
I-129	X			X		
I-131	X	X		X	X	X
I-132		X				X
I-133	X	X			X	X
I-135		X				
Xe-131m		X		X		
Xe-133		X			X	X
Xe-133m		X				
Xe-135		X		X		
Xe-135m		X				
Cs-134	X	X	X	X	X	X
Cs-135	X					
Cs-136					X	X
Cs-137+Ba-137m[a]	X	X	X	X	X	X
Ba-140+La-140[a]					X	X[c]
Ce-141					X	
Ce-144+Pr-144[a]	X			X	X	
Pm-147				X		
Sm-151			X			
Eu-150			X			
Eu-152			X			
Eu-154			X	X		
Eu-155			X	X		
Gd-152			X			
W-187						
Pb-201				X		
Pb-203				X		
Tl-201				X		
Hg-203	X	X		X		
Rn-222				X		
Ra-226						
Ra-228						
Th-232						
U-232						
U-233						
U-234			X			
U-235						
U-236						
U-238			X			
Np-237			X			
Np-239					X	X
Pu-236						
Pu-238	X		X	X	X	X
Pu-239+Pu-240[b]	X		X	X	X	X
Pu-241	X		X	X	X	
Pu-242					X	

TABLE 2. EXAMPLE RADIONUCLIDES IDENTIFIED AS RELEASED IN ATMOSPHERIC DISCHARGES FOR VARIOUS NUCLEAR FACILITIES (BASED ON DATA FROM FRANCE) AND MAJOR ACCIDENTS (cont.)

Isotope	Reprocessing plant [9, 11]	Nuclear power plants [13]		Research centres [14]	Accidental releases	
		Normal operation	Decommissioning		Chernobyl [15]	Fukushima [16, 17]
Am-241	X		X	X		
Am-242m						
Am-242						
Am-243			X	X		
Cm-242	X			X	X	
Cm-243	X			X		
Cm-244	X		X	X		
Cm-245	X					
Cm-246	X					

[a] Radioactive decay process at secular equilibrium: parent and progeny present the same activity.
[b] Isotopes measured together.
[c] Obtained by IRSN estimation (73 radionuclides potentially emitted via the atmospheric releases).

TABLE 3. LIST OF ELEMENTS POTENTIALLY RELEVANT FOR THE RADIATION PROTECTION OF WILDLIFE

Elements			
Ac	Cs	Np	Se
Ag	Eu	P	Sm
Am	Fe	Pa	Sn
As	Gd	Pb	Sr
Ba	H	Pd	Tc
Be	Hf	Pm	Te
Bi	Hg	Po	Th
C	I	Pr	Tl
Ca	K	Pu	U
Cd	La	Ra	W
Ce	Mn	Rb	Y
Cl	Mo	Rh	Zn
Cm	Na	Rn	Zr
Co	Nb	Ru	
Cr	Ni	Sb	

TABLE 4. PARAMETRIC DEPENDENCES OF THE TWO INDEXES DEFINED FOR THE PRIORITIZATION OF RADIONUCLIDES FOR EXPOSURE OF WILDLIFE

	Acute exposure	Chronic exposure
HI	$AHI = f(RO, RN, t) = f(DC, CR_{wo\text{-}media}, K_d, t)$	$CHI = f(RO, RN) = f(DC, CR_{wo\text{-}media}, K_d)$
RI	$ARI = f(RO, RN, t, q) = f(DC, CR_{wo\text{-}media}, K_d, t, q)$	$CRI = f(RO, RN, q) = f(DC, CR_{wo\text{-}media}, K_d, q)$

Notes:
AHI: Acute Hazard Index; *CHI*: Chronic Hazard Index; *ARI*: Acute Risk Index; *CRI*: Chronic Risk Index.
RN: Radionuclide; RO: Reference Organism; DC: Dose Coefficient.
t: Duration of the acute exposure (1 h, 6 h, 24 h).
q: Normalized release quantity.

For $CR_{wo\text{-}media}$ and K_d values, the data for an element are applied to all isotopes of that element under the implicit assumption that isotopic discrimination does not affect environmental transfer [1, 2, 5, 6]. In contrast, the specific radioisotope is considered for dose coefficients as they depend upon the quality and quantity of emitting radiation. Therefore, the analysis needed to be conducted on radionuclides rather than on elements.

The prioritization method developed during the French collaborative study, described in detail elsewhere [19], includes an initial example application for releases from nuclear power plants. An application of the method enlarged to the list of radionuclides characteristic of the releases from different French nuclear facilities (as described in Section 2.2) is presented below, after a brief summary of the underlying principles.

2.3.1. Basics of the proposed prioritization method

The prioritization method adopted was consistent with the REIA approach, as it aimed at identifying the relative importance of radionuclides contributing to exposure to improve the radiation protection of wildlife. It made use of currently viable approaches for assessing dose rates to wildlife for which parameter values are available. Other potentially important factors, such as weighting of species with regard to their radiosensitivity, could not be included due to a lack of relevant data. By considering a set of representative organisms per ecosystem (the reference organisms commonly used in REIA), it was assumed that species sensitivity was implicitly integrated into the prioritization method.

The applied prioritization method relies on two complementary indexes: the hazard index (*HI*) and the risk index (*RI*) [19] that have been introduced to prioritize radionuclides for situations of both chronic and acute exposure of wildlife (see Table 4). The *HI* value corresponds to the total dose rate each reference organism may absorb per unit of activity concentration of a given radionuclide in an environmental medium (soil, water, sediment). The *RI* value uses the *HI* value and the relative quantity of the radionuclide in the actual release to calculate the dose rate from a specific source term.

Each index value is derived by the deterministic application of a given mathematical formula, combining best estimates of the transfer parameters ($CR_{wo\text{-}media}$ and K_d) and deterministic values of dose coefficients. The index calculation is based on the reference organisms defined in the ERICA tool (version 1.2) [6] and uses the default data in the 2011 version available at the time the method was developed. The collation, extrapolation and transformation of any other data needed by the method are described elsewhere [19].

The calculated indexes can be used to rank the relative importance of both radionuclides and/or elements as contributors to exposure. This approach is necessary as, unlike for dose coefficients, transfer parameters are dependent on element. The method allocates a global rank to each radionuclide in a given ecosystem, that takes into account all relevant reference organisms [19]. For elements, the rank is calculated from the number of their radionuclides that have been previously classified as important for radiation protection of the environment, which ensures consistency between the two ranking processes.

A sensitivity analysis of the indexes has been carried out through a probabilistic approach using a simple correlation coefficient between the transfer parameters (inputs) and the prioritization indexes (outputs); simple linear models are applied to calculate these indexes. The sensitivity analysis is only possible if the uncertainty of at least one of the parameters entering the calculation is known. This is the case for $CR_{wo\text{-}media}$ and K_d for which uncertainty is described in the ERICA tool by probability density functions (PDFs) for the default data in the tool [6]. The available PDFs allow an assessment of the sensitivity of radionuclide prioritization to the

range of parameter values, when the distribution is known for combinations of radionuclide and organism. For the additional parameter data used, PDFs can be fitted accordingly to the method applied in the ERICA tool (log-normal distribution when the mean and the standard deviation are known [20], or exponential distribution if not). *HI* and *RI* values also depend on dose coefficients. These coefficients are deterministically fixed values per reference organism, but, as they are radioisotope dependent, they may influence the results of the sensitivity analysis for different isotopes of the same element, to which the same value of $CR_{wo\text{-}media}$ or K_d is applied. Conversely, the released quantities necessary to assess *RI* values do not affect the analysis as they are deterministic and independent of the reference organisms. The sensitivity analysis provides the same results in terms of sensitivity of the radionuclide prioritization to the range of parameter values for both indexes, due to their simple relationship.

As in the ERICA tool, the results of the sensitivity analysis can be presented on tornado plots. A tornado plot is commonly used to depict the sensitivity of a result (here: *HI* or *RI*) to changes in selected variables (here: $CR_{wo\text{-}media}$ and K_d). It shows the effect on the output of varying each input separately, keeping all the other input variables constant. The degree by which inputs and outputs change together is measured by correlation coefficients. If an input and an output have a high correlation coefficient, it means that the input has a significant impact on the output (both through its uncertainty and its model sensitivity). Positive coefficients indicate that an increase in the input is associated with an increase in the output. Negative coefficients imply the opposite situation. The larger the absolute value of the correlation coefficient, the stronger is the relationship. In tornado plots, the correlation coefficient is visualised vertically in order of descending absolute value, corresponding to a decreasing importance of the input variables.

2.3.1.1. Outcome of the first application of the proposed prioritization method

The results of the first application of the prioritization method described above have been reported in Ref. [19]. *HI* is a semiquantitative indicator defined to compare and classify radionuclides by only accounting for their mobility in the environment, their radiotoxicity and their potential effects on reference organisms. It therefore gives a solely qualitative evaluation of the potential importance of a radionuclide in contributing to the dose to a reference organism. However, it does not take account of the quantities of radionuclides released, or present, in the environment. The prioritization based on the *HI* value, as would be expected, highlighted the potential importance of actinides and ^{60}Co, reflecting their well known radiotoxic character [19].

When aiming to prioritize radionuclides with regard to their importance in terms of radiation protection of the environment, the analysis needs to be extended to include the quantities of radionuclides released into the environment, which is more consistent with the REIA concepts. This is the objective of the approach using the *RI* value, which is a quantitative indicator.

The *RI* concept has been developed to be applicable to both chronic and acute exposure situations. Application of the *Acute Risk Index* (*ARI*) could only be implemented on a reduced set of radionuclides because of the low number of available data on biological depuration kinetics necessary for the *ARI* calculation [19]. Furthermore, acute exposure would mainly result from an accidental situation, which is difficult to predict. The nature and the quantities of emitted radionuclides would be highly variable, depending greatly on the installation under consideration and the nature of accident. Acute source terms can only be obtained with a high uncertainty from prospective modelling, which limits their applicability in a prioritization exercise. Consequently, the initial *RI* study focused on calculation of the *Chronic Risk Index* (*CRI*). The *CRI* provides a quantitative measure of the contribution of a radionuclide to the total dose rate to wildlife (represented by reference organisms).

2.3.2. Extended application of the proposed prioritization method to combined releases from different French nuclear facilities

To illustrate the use of the prioritization approach described in Section 2.3.1, it has been applied to exposure scenarios covering releases of radionuclides from French nuclear power plants, using authorized discharges from normal operation and decommissioning activities, for both aquatic (freshwater, marine) and terrestrial ecosystems (i.e. six exposure scenarios). Two additional scenarios were developed on the basis of planned releases from research facilities into freshwater and terrestrial ecosystems. *CRI* values were calculated for all combinations (radionuclide, reference organism) for each ecosystem. The sensitivity of the results to parametric uncertainty was analysed.

2.3.2.1. Prioritization of radionuclides from their chronic risk index for the source term under consideration

The analysis discussed below that has been undertaken within Working Group 4, is for a reduced list of radionuclides extracted from those in Tables 1 and 2, using the criteria described in Section 2.2, and focussing on releases from the selected French nuclear facilities, in normal operation (authorized discharges) or under decommissioning. They do not constitute an exhaustive compilation of all radionuclides likely to be present in the environment, whatever their origin.

The derived *CRI* values showed similarities within a single ecosystem between some reference organisms, mainly from the same taxonomic group (e.g. vertebrates). The similarity is partially due to similar behaviour (same lifestyle leading to similar exposure pathways) but is also a consequence of the need to extrapolate between organisms to provide a full set of transfer parameter values to be able to calculate the index. One of the most frequently adopted approaches for extrapolation is to take advantage of the taxonomic proximity between reference organisms and to use the same parameter values on the assumption that the transfer parameterization will be similar. This is the case for Bi, for example, where fish $CR_{wo\text{-}media}$ values were applied to all vertebrates in aquatic systems. Furthermore, for ^{3}H in any environment, a single value of $CR_{wo\text{-}media}$ was applied to all organisms. Consequently, in these cases, the variation in *RI* was due only to dose coefficients [21–25].

The anaysis provided a priority list of about 30 radionuclides that were considered most relevant for radiation protection of the environment in the situation of chronic exposure due to authorized discharges from the selected French nuclear facilities (see Table 5 below). The entries in Table 5 are listed in element order and not in the priority order in terms of contributing to wildlife exposure. Generally, the most important radionuclides were those contributing most to releases from the considered nuclear facilities (the highest releases are for ^{14}C and ^{3}H, followed by ^{60}Co). However, some other radionuclides were specified in the priority list that are less often considered in assessments, such as ^{241}Am, ^{244}Cm and ^{152}Eu. Some short lived radionuclides also appeared in the list for certain exposure scenarios, for example, ^{201}Pb (half-life 9.4 h) or ^{203}Pb (half-life 2.2 d) released from French research facilities (see Table 2 in Section 2.3). For these very short lived radionuclides, the effective contribution in terms of absorbed dose may have been overestimated due to the application of a single value of $CR_{wo\text{-}media}$ to all isotopes of a given element. Considering their short physical half-lives, it is possible that their transfer to living organisms will not reach an equilibrium that is assumed by the use of the $CR_{wo\text{-}media}$ parameter and they may decay before equilibrium, leading to lower activity concentrations in the reference organisms than that calculated from the application of the $CR_{wo\text{-}media}$. However, the commonly used concentration ratio equilibrium approach does not distinguish between isotopes, and data are consequently not available to deal with this issue. This acknowledged problem of using the $CR_{wo\text{-}media}$ approach for short lived radionuclides may lead to some additional uncertainties associated with the ranking method that have not yet been addressed.

TABLE 5. DERIVED PRIORITY LIST OF RADIONUCLIDES OF INTEREST FOR RADIATION PROTECTION IN THE SITUATION OF CHRONIC EXPOSURE OF WILDLIFE, FOR ILLUSTRATIVE CASE OF RELEASES FROM FRENCH NUCLEAR FACILITIES, WITH THE ASSOCIATED EXTRAPOLATIONS IN TERMS OF $CR_{wo\text{-}media}$ VALUES[a,b]

Element	Isotopes	Organisms grouped based on extrapolation methods and assumed to have the same $CR_{wo\text{-}media}$ value		
		Freshwater	**Marine**	**Terrestrial**
Ag	108m, 110m	– all vertebrates – crustacean, insect larvae	– bird, mammal, reptile – macroalgae, vascular plant	(1) all vertebrates, bird egg (2) shrub, tree (3) detritivorous invertebrate, flying insect, gastropod, soil invertebrate
Am	241	Bird, amphibian, mammal	(1) bird, reptile (2) macroalgae, vascular plant (3) mollusc, polychaete worm	(1) all vertebrates, bird egg (2) grasses and herbs, shrub
C	14	(1) amphibian, bird, mammal (2) mollusc, crustacean, gastropod, insect larvae	(1) bird, mammal, reptile (2) macroalgae, vascular plant	(1) all vertebrates (2) detritivorous invertebrate, flying insect, gastropod, soil invertebrate
Cl	36	(1) all vertebrates (2) mollusc, crustacean, gastropod, insect larvae (3) planktons, vascular plant	(1) bird, mammal, reptile (2) macroalgae, vascular plant (3) planktons	(1) all vertebrates, bird egg (2) detritivorous invertebrate, flying insect
Cm	244	(1) fish, bird, mammal (2) gastropod, mollusc (3) planktons	(1) bird, reptile (2) macroalgae, vascular plant	(1) all vertebrates, bird egg (2) shrub, tree (3) detritivorous invertebrate, flying insect, gastropod, soil invertebrate
Co	57, 58, 60	Fish, bird, mammal	(1) bird, mammal, reptile (2) macroalgae, vascular plant	(1) all vertebrates, bird egg (2) flying insect, gastropod, soil invertebrate
Cs	134, 137	(1) mammal, amphibian (2) insect larvae, crustacean	Bird, reptile	Mammals (rat and deer)
Eu	152, 155	(1) all vertebrates (2) mollusc, gastropod (3) crustacean, insect larvae (4) planktons	(1) all vertebrates (2) macroalgae, vascular plant (3) crustacean, zooplankton (4) mollusc, polychaete worm	(1) all vertebrates, bird egg (2) shrub, tree (3) detritivorous invertebrate, flying insect, gastropod, soil invertebrate
Fe	55, 59	(1) all vertebrates (2) crustacean, mollusc, gastropod, insect larvae, zooplankton	(1) fish, bird, reptile (2) crustacean, polychaete worm, sea anemones or true corals (3) phytoplankton, vascular plant	(1) all vertebrates, bird egg (2) shrub, tree (3) detritivorous invertebrate, flying insect
H	3	All organisms	All organisms	All organisms
I	123, 125, 129, 131, 132, 133, 135	(1) amphibian, bird, mammal (2) gastropod, mollusc	(1) bird, mammal, reptile (2) macroalgae, vascular plant (3) mollusc, polychaete worm	(1) all vertebrates (2) grasses and herbs, shrub, tree (3) detritivorous invertebrate, flying insect
Mn	54	(1) all vertebrates (2) planktons	Bird, mammal, reptile	(1) all vertebrates, bird egg (2) detritivorous invertebrate, flying insect, gastropod
Ni	63	(1) all vertebrates (2) crustacean, insect larvae (3) planktons (4) gastropod, mollusc	(1) all vertebrates (2) macroalgae, vascular plant	(1) all vertebrates, bird egg (2) detritivorous invertebrate, flying insect
Np	237	(1) all vertebrates (2) mollusc, gastropod	(1) bird, reptile (2) macroalgae, vascular plant (3) mollusc, polychaete worm	(1) all vertebrates, bird egg (2) shrub, tree

TABLE 5. DERIVED PRIORITY LIST OF RADIONUCLIDES OF INTEREST FOR RADIATION PROTECTION IN THE SITUATION OF CHRONIC EXPOSURE OF WILDLIFE, FOR ILLUSTRATIVE CASE OF RELEASES FROM FRENCH NUCLEAR FACILITIES, WITH THE ASSOCIATED EXTRAPOLATIONS IN TERMS OF $CR_{wo\text{-}media}$ VALUES[a,b] (cont.)

Element	Isotopes	Organisms grouped based on extrapolation methods and assumed to have the same $CR_{wo\text{-}media}$ value		
		Freshwater	Marine	Terrestrial
Pb	201, 203	(1) all vertebrates (2) crustacean, insect larvae	(1) bird, mammal, reptile (2) macroalgae, vascular plant (3) polychaete worm, crustacean, sea anemones or true corals	(1) mammals (rat and deer) (2) bird, bird egg
Pu	238, 239	(1) amphibian, mammal (2) mollusc, gastropod (3) crustacean, insect larvae	(1) bird, reptile (2) macroalgae, vascular plant	(1) all vertebrates, bird egg (2) shrub, tree
Ru	106	(1) all vertebrates (2) mollusc, crustacean, gastropod, insect larvae	(1) all vertebrates (2) macroalgae, vascular plant (3) mollusc, polychaete worm	(1) all vertebrates, bird egg (2) shrub, tree (3) detritivorous invertebrate, flying insect, gastropod, soil invertebrate
Sb	124, 125	(1) all vertebrates (2) mollusc, crustacean, gastropod, insect larvae	(1) all vertebrates (2) macroalgae, vascular plant (3) polychaete worm, crustacean	(1) all vertebrates, bird egg (2) shrub, tree (3) detritivorous invertebrate, flying insect, gastropod
Sr	90	(1) all vertebrates (2) crustacean, insect larvae (3) mollusc, gastropod	(1) bird, mammal, reptile (2) macroalgae, vascular plant	Mammals (rat and deer)
Te	123m	(1) all vertebrates (2) mollusc, crustacean, gastropod, insect larvae, zooplankton	(1) all vertebrates (2) macroalgae, vascular plant (3) mollusc, polychaete worm, crustacean, sea anemones or true corals	(1) all vertebrates (2) detritivorous invertebrate, flying insect, gastropod, soil invertebrate
U	238	(1) all vertebrates (2) mollusc, gastropod (3) crustacean, insect larvae	(1) bird, mammal, reptile (2) macroalgae, vascular plant (3) mollusc, polychaete worm	(1) mammals (rat and deer) (2) amphibian, reptile (3) bird, bird egg (4) detritivorous invertebrate, flying insect, gastropod, soil invertebrate

[a] Data from the ERICA tool database, accessed on 30 November 2011.
[b] Listed in element order and not priority order of isotopes.

Assuming that there is no isotopic discrimination, about 20 priority elements were identified with respect to environmental radiation protection for the authorized discharges of the selected French nuclear facilities. The top five priority elements in decreasing order of importance were carbon, hydrogen, caesium, cobalt and americium. The proposed prioritization method, applied to the source terms considered, also ranked silver, strontium, antimony, nickel and curium at the same level, in the upper half of the ranking list.

2.3.2.2. Sensitivity analysis

The sensitivity of results of the prioritization method to the uncertainty of calculation for the elements was explored for each of the ecosystems. Tornado plots were built from the analysis. Figure 1 shows a plot for ^{214}Bi, as an example. For all three ecosystems, Fig. 1 shows the *CRI* values (and ranking of ^{214}Bi) was mainly sensitive to the uncertainty of the $CR_{wo\text{-}media}$ values of some reference organisms. Among the 13 uncertain parameters considered in the freshwater ecosystem, the uncertainty of five $CR_{wo\text{-}media}$ values (for invertebrate reference organisms) mainly influenced the *RI* values calculated. In the marine ecosystem, the ranking of ^{214}Bi was affected by the uncertainty of plant $CR_{wo\text{-}media}$ values. In terrestrial ecosystems, the ranking was influenced by the uncertainty of $CR_{wo\text{-}media}$ values for four reference organisms, namely three invertebrates and lichen and bryophytes.

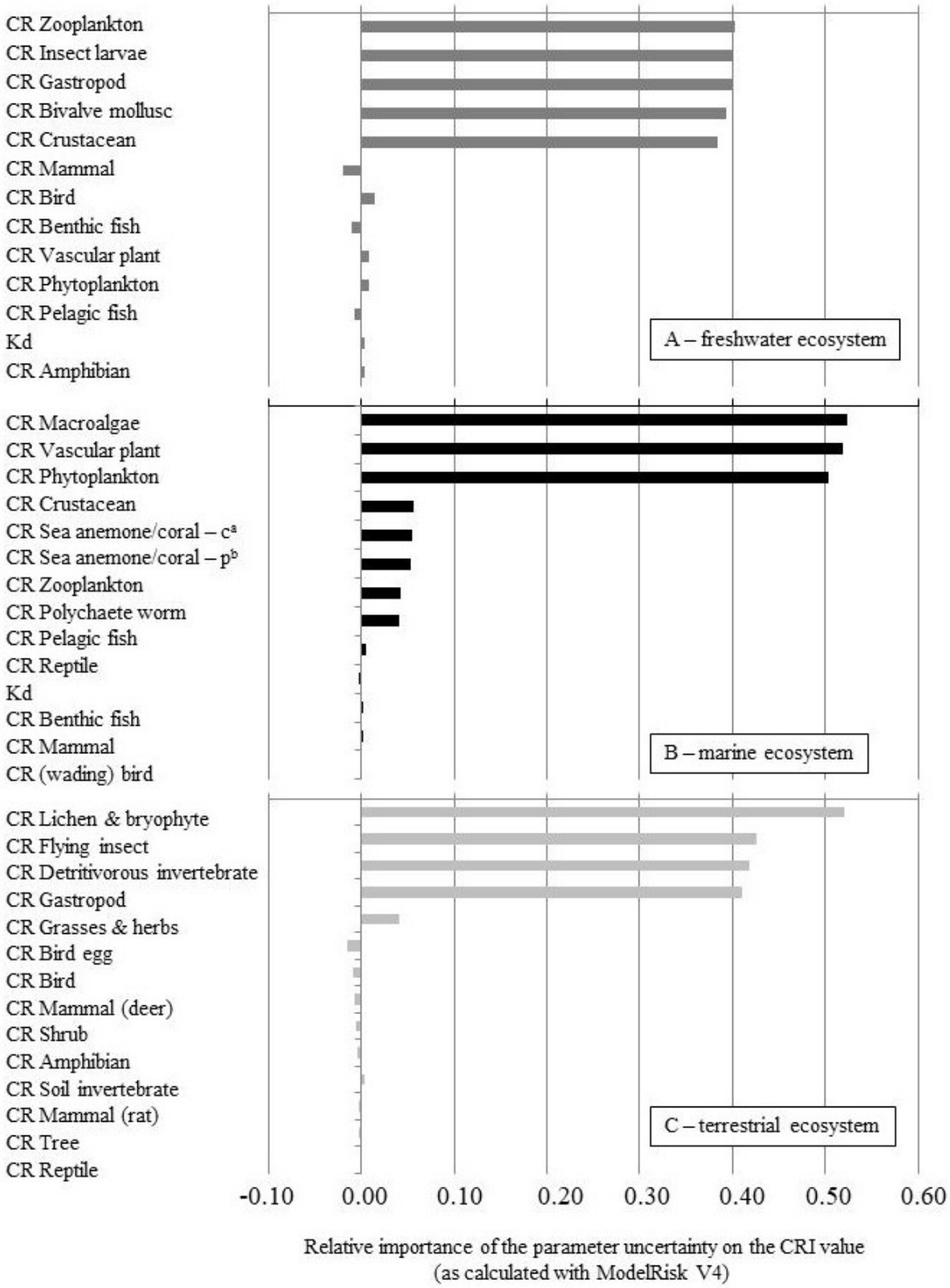

FIG. 1. Example Tornado plot for ^{214}Bi: Sensitivity of the rank to the uncertainty of the transfer parameters used in the calculation.

The contribution of each tested parameter (K_d plus one $CR_{wo\text{-}media}$ per reference organism) varied greatly with the ecosystem and the radionuclide. The rank of a given radionuclide was, in some cases, sensitive to the uncertainty of one single parameter, (e.g. the $CR_{wo\text{-}media}$ for a given reference organism), and, in others, to the combined uncertainty of several variables (e.g. $CR_{wo\text{-}media}$ for several reference organisms and K_d). This was especially evident when the same PDF (same law, same parameters) was used for different reference organisms because of the extrapolations that needed to be conducted to fill data gaps (see Table 5). Sodium-24 in the freshwater ecosystem was the only radionuclide for which K_d is the only key parameter with a negative relationship, whereas the $CR_{wo\text{-}media}$ value uncertainty positively influenced the radionuclide ranking (same variation trend).

The prioritisation analyses identified key reference organisms that may have relatively high exposure to some radionuclides in each ecosystem. The *CRI* values in freshwater were mainly influenced by the plankton $CR_{wo\text{-}media}$ values, with less influence of values for vascular plants and mammals. The analysis gave a ranked order of decreasing importance of key reference organisms in the three ecosystems as follows:

- In **freshwater**: plankton > vascular plants and mammals;
- In **marine**: phytoplankton > anemones and corals > macroalgae > mammals; and
- In **terrestrial**: flying insects > gastropods > birds > lichens and bryophytes > detritivorous invertebrates and mammals.

2.3.2.3. Summary from applying the prioritization method for releases of radionuclides from French nuclear facilities

Lists were compiled of radionuclides present in atmospheric and liquid effluents in discharges during normal operation and decommissioning from both nuclear power plants and research centres in France, which are of potential interest regarding radiation protection of the environment. A prioritization method developed for marine, freshwater and terrestrial ecosystems was initially tested for authorized liquid discharges released during normal operation of French nuclear power plants [19]. This initial application of the proposed method identified the Chronic Risk Index (*CRI*) to be useful for prioritization of radionuclides based on their relative contribution to the total dose rate to wildlife when the quantities of radionuclides released into the environment were taken into account. In the subsequent study carried out by Working Group 4, *CRI* values were calculated for a list of radionuclides established from the authorized discharges from selected French nuclear facilities, including research facilities, which included some radionuclides that are not usually considered in the field of radioecology. The situation of acute exposure, considered for the development and initial testing of the prioritization method [19], has not been used further in the current work due to the current limited availability of biological half-lives at the time of the analysis.

The lack of data also had an impact on the analysis of prioritization of the contribution of radionuclides in chronic situations. The need to apply extrapolation or other methods to fill data gaps [4] meant that it was necessary to use the same transfer data ($CR_{wo\text{-}media}$ values) for many organisms.

The prioritization of radionuclides with respect to dose contribution appears to be most sensitive to the uncertainty of $CR_{wo\text{-}media}$ values for a few reference organisms.

Radionuclides contributing most to releases from the considered nuclear facilities (^{14}C and ^{3}H, and, to a lesser extent, ^{60}Co) are also generally identified as the highest contributors to dose rates to wildlife. However, the list of radionuclides that have relatively high contributions to dose also includes radionuclides that have been much less often considered in assessments, such as ^{241}Am, ^{244}Cm and ^{152}Eu.

2.3.3. Evaluation of the prioritization approach adopted to the combined releases from different French nuclear facilities to identify important data gaps

These studies have demonstrated the feasibility, but not the validity, of prioritization analysis. Various limitations were identified. The classification outcome is highly dependent on the combination of approaches used to rank the radionuclides and the associated assumptions. Such methods are self-contradictory in that they assume that the necessary information is available for each combination (radionuclide, reference organism), when their ultimate objectives are to identify lack of sufficient knowledge and to guide future data provision.

A comparison of required and available data was applied to the chronic exposure situation considered in Section 2.3.2. From Table 5, the ratio between the number of $CR_{wo\text{-}media}$ values available from databases (in the ERICA tool plus additional data) and the total number of $CR_{wo\text{-}media}$ values needed for the *RI* calculation (one value per reference organism in each ecosystem) was estimated for each element in each ecosystem (Table 6). The lower the ratio, the fewer data for $CR_{wo\text{-}media}$ are available and the less robust the ranking. This approach highlighted the extent of data gaps regarding environmental transfer to wildlife of these elements.

The ratio has been determined for the 36 potentially most important radionuclide contributors to doses to wildlife for all three ecosystems and all three radionuclide sources (normal operation and decommissioning of French nuclear power plants and research reactors). This list was made by compiling the top ten radionuclides from each of the eight rankings (three ecosystems, two to three sources per ecosystem) established for the chronic exposure situation. The decision on which radionuclides to include will always be subjective. Furthermore, in practice, other criteria may also be taken into consideration, including stakeholder views (e.g. public perception of risk). As the list is based on radionuclides, a transformation is needed as the ratio ($CR_{wo\text{-}media}$ values available / $CR_{wo\text{-}media}$ values needed) is based on elements (which may be stable or radioactive). The average rank of the corresponding element was calculated for each of the 36 radionuclides. The rank of each radionuclide in the final list was determined based on the number of times it appeared in the eight derived rankings. For example, ^{60}Co is included in all the eight basic rankings, so its overall rank is first, suggesting that it is important for consideration in radiation protection of both fauna and flora under chronic exposure conditions. The other isotopes of cobalt present on the list (^{57}Co and ^{58}Co) ranked 18th and 6th, respectively, within the ranking. Overall, cobalt (the element) ranks 6th, with an average rank of 8.33. Figure 2 illustrates the outcome of this new ranking system for elements; the ranking is based on the average rank of the isotopes for each of the elements, as described above for cobalt.

From this analysis, it is suggested that there is no obvious link between the amount of information available on radionuclide transfer (ratio of available $CR_{wo\text{-}media}$ / $CR_{wo\text{-}media}$ needed) and the final rank of a given element for a chronic exposure situation. Some of the radionuclides with relatively high dose contributions are isotopes of elements for which transfer parameters are among the least well documented (e.g. H in all three ecosystems, Ni in the freshwater ecosystem), whereas parameter values are much more characterized for some radionuclides with a relatively low contributions to doses to wildlife (e.g. Pu).

TABLE 6. RATIO BETWEEN THE NUMBER OF $CR_{wo\text{-}media}$ VALUES FROM DATABASES AND THE TOTAL NUMBER OF $CR_{wo\text{-}media}$ VALUES NEEDED FOR THE INDEX CALCULATION

Element	Freshwater	Terrestrial	Marine
Ag	0.58	0.36	0.79
Am	0.83	0.57	0.79
C	0.58	0.42	0.79
Cl	0.25	0.57	0.57
Cm	0.58	0.36	0.86
Co	0.83	0.50	0.79
Cs	0.83	0.93	0.93
Eu	0.42	0.43	0.50
Fe	0.33	0.57	0.50
H	0.08	0.07	0.07
I	0.75	0.43	0.71
Mn	0.58	0.50	0.86
Ni	0.42	0.57	0.64
Np	0.58	0.57	0.79
Pb	0.58	0.86	0.57
Pu	0.75	0.57	0.86
Ru	0.42	0.36	0.57
Sb	0.42	0.43	0.57
Sr	0.50	0.93	0.79
Te	0.33	0.36	0.36
U	0.50	0.57	0.64

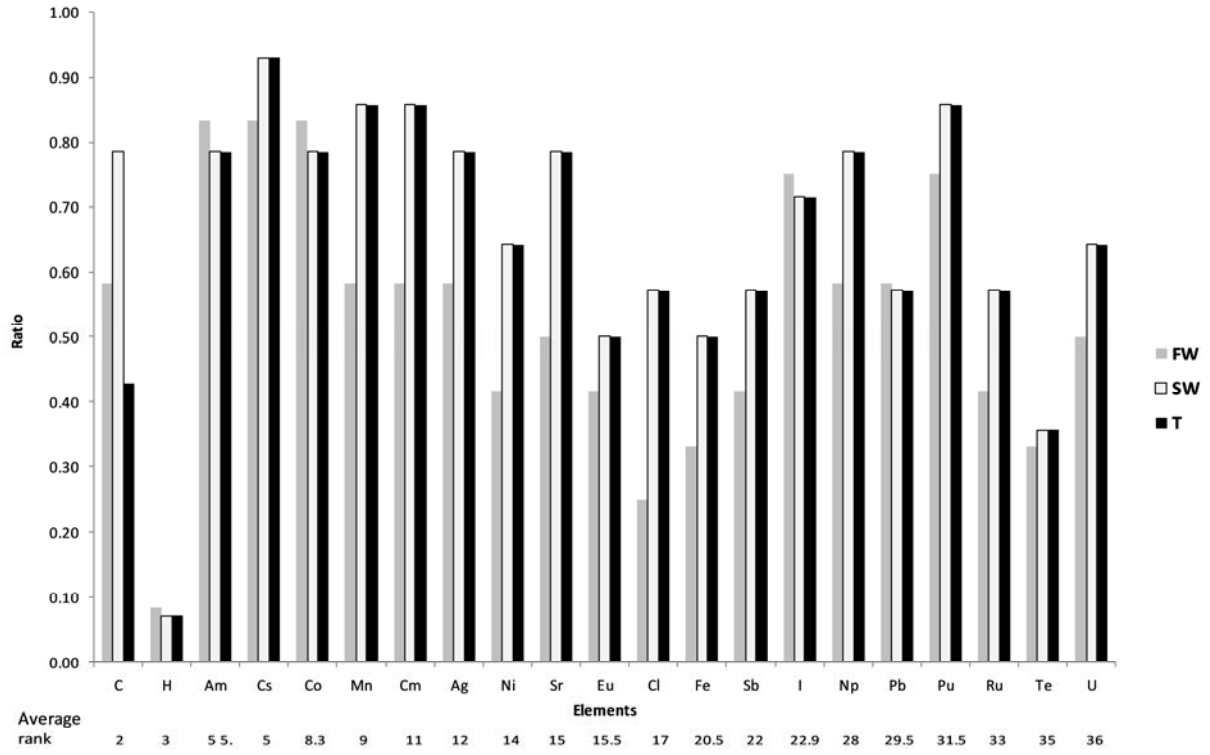

FIG. 2. Ratio (available $CR_{wo\text{-}media}$ / $CR_{wo\text{-}media}$ needed for elements) calculated for the 21 most highly ranked elements with regard to their importance for the three ecosystems (FW: freshwater ecosystem; SW: marine ecosystem; T: terrestrial ecosystem). Elements are ordered based on the average rank of their isotopes in the final global chronic ranking.

2.3.4. Comparison of results of prioritization exercise with data availability for radionuclides in IAEA compilations of transfer data for wildlife

The extent to which the data needs identified above can be met was evaluated by collating information on the number of parameter values available in the compilation of data in TRS 479 [2] for each combination (radionuclide/element, reference organism). The results for the three ecosystems are presented in Table 7 for freshwater, Table 8 for marine and Table 9 for terrestrial, respectively. Reference organisms were matched to the closest appropriate wildlife groups in Ref. [2], based on their category names.

The availability of $CR_{wo\text{-}soil}$ and $CR_{wo\text{-}water}$ values is highly variable depending on the ecosystem, the organism type and the radionuclide. Generally, for the elements considered, less information is available on transfer parameters ($CR_{wo\text{-}media}$) for the freshwater ecosystem than for the terrestrial and marine ecosystems, for which the level of available information is similar. For the list of radionuclides identified as of particular interest in the prioritization exercise presented in this study, there are no data for freshwater birds, marine reptiles, terrestrial flying insects or terrestrial bird eggs in the IAEA compilation of data [2]. There are few data for amphibians, freshwater mammals, marine anemones and corals, marine birds and terrestrial detrivorous invertebrates. In contrast, the $CR_{wo\text{-}media}$ values for some taxonomic groups, such as fish, are significantly better characterized and documented in both freshwater and marine ecosystems, as are plants, except for marine vascular plants.

When considering the priority list based on the prioritization exercise (see Table 5 in Section 2.3.2.1), there are no $CR_{wo\text{-}media}$ values for carbon (C) and hydrogen (H) documented in Ref. [2] for any of the three ecosystems. Also, there are no $CR_{wo\text{-}media}$ values for silver (Ag) and niobium (Nb) in the freshwater ecosystem; iron (Fe) in the marine ecosystem; and neptunium (Np) and tellurium (Te) in the terrestrial ecosystem.

Other elements that were in the full list of elements of potential importance in contributing to doses to wildlife in the prioritization exercise for French nuclear power plants and research reactors (see Table 3 in Section 2.3) for which there are no values for $CR_{wo\text{-}media}$ for any of the three ecosystems are actinium (Ac), bismuth (Bi), protactinium (Pa) and rhodium (Rh). Data are also not available for thallium (Tl) and yttrium (Y) in marine and terrestrial ecosystems; barium (Ba), chromium (Cr) and samarium (Sm) in the marine ecosystem; and promethium (Pm) and praseodymium (Pr) in the terrestrial ecosystem.

Finally, considering the whole set of potentially relevant (radionuclide, reference organism) combinations identified in the prioritization exercise described in this report, the comparison revealed many data gaps for $CR_{wo\text{-}media}$ values for elements (Table 10), with the percentage of missing values varying from 66 to 81% of those needed. For a specific exposure scenario and source term, these gaps can be viewed as more or less significant, depending on the importance of the element with regard to doses to wildlife and radiation protection of the environment.

The results presented in this report illustrate the use of a prioritization approach for releases of radionuclides from French nuclear power plants under operation or decommissioning and research facilities. The outcome shows how such an analysis can usefully provide an input, amongst other complementary criteria, to help inform the choice of future research priorities to support REIA.

TABLE 7. NUMBER OF $CR_{wo\text{-}water}$ VALUES AVAILABLE IN REF. [2] FOR EACH COMBINATION (RADIONUCLIDE, REFERENCE ORGANISM) CONSIDERED APPLICABLE FOR FRESHWATER ECOSYSTEMS (GREY BOX: NO DATA, ORANGE BOX: < 10 VALUES, GREEN BOX: > 10 VALUES)

Element	Amphibian	Benthic fish	Bird	Bivalve mollusc	Crustacean	Gastropod	Insect larvae	Mammal	Pelagic fish	Phytoplankton	Vascular plant	Zooplankton
Ac	0	0	0	0	0	0	0	0	0	0	0	0
Ag	0	0	0	0	0	0	0	0	0	0	0	0
Ba	0	148	0	0	0	0	0	0	340	0	18	0
Bi	0	0	0	0	0	0	0	0	0	0	0	0
C	0	0	0	0	0	0	0	0	0	0	0	0
Ca	9	127	0	3	4	0	4	2	318	20	20	0
Cd	0	39	0	3	0	0	0	0	0	30	3	0
Cl	0	1 (fish)	0	0	0	0	0	0	0	0	6	0
Cm	0	7 (fish forage)	0	0	0	30	15	0	0	0	26	0
Co	0	100	0	3	0	0	0	0	192	35	158	0
Cr	2	105	0	0	0	0	0	0	205	0	44	0
Cs	0	156	0	20	20	50	6	0	439	50	0	0
Eu	0	54 (fish)	0	3	0	0	0	0	43	0	6	0
Fe	0	241	0	3	0	0	0	0	454	10	35	0
H	0	0	0	0	0	0	0	0	0	0	0	0
I	0	135 (fish)	0	0	0	0	0	0	122	0	33	0
K	0	0	0	0	0	0	0	0	0	0	0	0
Mn	0	201	0	3	0	0	0	6	451	0	50	0
Na	0	122	0	3	0	0	0	0	240	0	20	0
Nb	0	0	0	0	0	0	0	0	0	0	0	0
Ni	0	68	0	3	0	0	0	0	116	0	21	0
Np	0	0	0	0	0	0	0	0	0	0	15	0
P	0	45	0	0	0	0	0	0	113	35	0	0
Pa	0	0	0	0	0	0	0	0	0	0	0	0
Pb	2	148	0	32	5	0	0	0	201	0	21	0
Pu	0	73 (fish)	0	0	0	50	15	0	0	0	99	0
Ra	0	88	0	43	5	0	0	45	68	40	73	0
Rh	0	0	0	0	0	0	0	0	0	0	0	0
Ru	0	17 (fish)	0	0	0	0	0	0	0	30	0	0
Sb	0	22	0	0	0	1	14	0	113	0	6	0
Se	0	51	0	0	0	3	9	0	70	0	3	3
Sm	0	0	0	3	0	0	0	0	0	0	6	0
Sr	0	224	0	23	1	60	0	0	491	50	533	10
Tc	0	3 (fish forage)	0	0	0	0	0	0	0	0	0	0
Te	0	0	0	0	0	0	0	0	15	0	0	0
Th	0	64 (fish)	0	0	0	0	0	0	0	30	84	0
Tl	0	0	0	0	0	0	0	0	2	0	0	0
U	0	99	0	3	5	0	0	0	84	40	386	0
Y	0	6 (fish)	0	3	0	0	0	0	0	45	6	0

NOTE: When the organism for which the data in Ref. [2] are stated to be applicable differed from the organism for which the actual data were obtained, this is indicated between brackets in the relevant part of the table.

TABLE 8. NUMBER OF $CR_{wo\text{-}water}$ VALUES AVAILABLE IN REF. [2] FOR EACH COMBINATION (RADIONUCLIDE, REFERENCE ORGANISM) CONSIDERED APPLICABLE FOR MARINE ECOSYSTEMS (GREY BOX: NO DATA, ORANGE BOX: < 10 VALUES, GREEN BOX: > 10 VALUES)

Element	Benthic fish	(Wading) bird	Benthic mollusc	Crustacean	Macroalgae	Mammal	Pelagic fish	Phytoplankton	Polychaete worm	Reptile	Sea anemones/ true corals	Vascular plant	Zooplankton
Ac	0	0	0	0	0	0	0	0	0	0	0	0	0
Ag	5 (fish)	0	19	0	20	10	0	10	1 (annelid)	0	2	0	3
Ba	0	0	0	0	0	0	0	0	0	0	0	0	0
Bi	0	0	0	0	0	0	0	0	0	0	0	0	0
C	0	0	0	0	0	0	0	0	0	0	0	0	0
Ca	3	0	0	0	0	0	0	0	0	0	0	0	0
Cd	6 (fish)	0	80	5	63	529	0	56	1 (annelid)	0	0	0	2
Cl	1 (fish)	0	1	1	36	0	0	0	0	0	0	0	0
Cm	0	0	10	0	23	0	0	5	0	0	0	0	0
Co	24	0	42	11	130	0	46	22	3 (annelid)	0	4	3	24
Cr	0	0	0	0	0	0	0	0	0	0	0	0	0
Cs	515	66	336	287	654	717	903	15	40 (annelid)	0	9	3	23
Eu	1 (fish forage)	0	1	0	4	0	0	0	0	0	0	0	0
Fe	0	0	0	0	0	0	0	0	0	0	0	0	0
H	0	0	0	0	0	0	0	0	0	0	0	0	0
I	0	0	8	0	61	8	0	1	0	0	0	1	2
K	0	0	0	0	0	0	0	0	0	0	0	0	0
Mn	57 (fish)	0	41	9	44	10	0	6	1 (annelid)	0	1	2	18
Na	3	0	0	0	0	0	0	0	0	0	0	0	0
Nb	0	0	2	1	15	0	0	0	0	0	0	0	0
Ni	16 (fish)	0	12	0	14	0	0	3	1 (annelid)	0	0	0	2
Np	0	0	14	1	53	0	0	12	0	0	0	0	2
P	21 (fish)	0	1	0	3	11	0	2	1 (annelid)	0	0	0	1
Pa	0	0	0	0	0	0	0	0	0	0	0	0	0
Pb	21 (fish)	0	68	10	80	452	0	36	0	0	0	0	12
Pu	34	0	169	14	308	24	19	55	3 (annelid)	0	1	0	5
Ra	24	0	20	14	8	0	21	7	0	0	0	0	5
Rh	0	0	0	0	0	0	0	0	0	0	0	0	0
Ru	8 (fish)	0	9	0	48	0	0	3	0	0	2	0	0
Sb	0	0	7	0	44	0	0	0	0	0	1	0	13
Se	0	0	4	0	36	720	0	94	1 (annelid)	0	1	0	0
Sm	0	0	0	0	0	0	0	0	0	0	0	0	0
Sr	25	0	32	36	385	33	30	30	1 (annelid)	0	6	1	19
Tc	0	0	63	235	174	0	0	10	0	0	0	0	0
Te	0	0	0	0	0	0	0	12	0	0	0	0	0
Th	1 (fish)	0	5	0	7	0	0	25	0	0	0	0	6
Tl	0	0	0	0	0	0	0	0	0	0	0	0	0
U	9 (fish)	0	22	0	47	0	0	10	0	0	38	2	3
Y	0	0	0	0	0	0	0	0	0	0	0	0	0

NOTE: When the organism for which the data in Ref. [2] are stated to be applicable differed from the organism for which the actual data were obtained, this is indicated between brackets in the relevant part of the table.

TABLE 9. NUMBER OF $CR_{wo\text{-}water}$ VALUES AVAILABLE IN REF. [2] FOR EACH COMBINATION (RADIONUCLIDE, REFERENCE ORGANISM) CONSIDERED APPLICABLE FOR TERRESTRIAL ECOSYSTEMS (GREY BOX: NO DATA, ORANGE BOX: < 10 VALUES, GREEN BOX: > 10 VALUES)

Element	Amphibian	Bird	Bird egg	Detritivorous invertebrate	Flying insect	Gastropod	Grasses and herbs	Lichens and bryophytes	Mammal	Reptile	Shrub	Soil invertebrate (worm)	Tree
Ac	0	0	0	0	0	0	0	0	0	0	0	0	0
Ag	0	0	0	0	0	0	13	12	0	0	5	0	0
Am	22	3	0	29 (arthropod: detritivorous)	0	13	65	3	139	16 (reptile: carnivorous)	12	0	0
Bi	0	0	0	0	0	0	0	0	0	0	0	0	0
Br	0	0	0	0	0	0	6	5	0	0	11	0	4
C	0	0	0	0	0	0	0	0	0	0	0	0	0
Ce	0	0	0	0	0	0	6	5	0	0	77	1 (annelid)	2
Cl	0	0	0	26 (arthropod: detritivorous)	0	20	56	1	0	0	79	1 (annelid)	11
Cm	0	0	0	2 (arthropod: detritivorous)	0	0	1	0	0	0	0	0	2
Co	0	0	0	0	0	0	6	37	29	0	128	0	7
Cr	0	0	0	0	0	0	6	17	0	0	23	0	3
Cs	137	180		76 (arthropod: detritivorous)	0	23	2028	142	2463	137	354	19 (annelid)	487
Eu	0	0	0	0	0	0	6	5	0	0	11	1 (annelid)	3
Fe	0	0	0	0	0	0	6	37	0	0	131	0	4
H	0	0	0	0	0	0	0	0	0	0	0	0	0
Hg	0	0	0	0	0	0	0	0	0	0	0	10 (annelid)	0
I	0	0	0	7 (arthropod: detritivorous)	0	12	39	0	0	0	0	3 (annelid)	0
Mn	0	0	0	0	0	7	0	32	4	1	184	5 (annelid)	3
Mo	0	0	0	0	0	0	0	18	0	0	23	0	0
Na	0	0	0	0	0	0	6	5	0	0	11	0	3
Nb	0	0	0	0	0	0	0	0	0	0	0	1 (annelid)	0
Ni	0	0	0	0	0	7	169	108	2	1	301	77 (annelid)	3
Np	0	0	0	0	0	0	0	0	0	0	0	0	0
Pa	0	0	0	0	0	0	0	0	0	0	0	0	0
Pb	24	424		314 (arthropod: detritivorous)	0	47	301	351	515	45	740	647(annelid)	42
Pm	0	0	0	0	0	0	0	0	0	0	0	0	0
Pr	0	0	0	0	0	0	0	0	0	0	0	0	0
Pu	0	26	0	68 (arthropod: detritivorous)	0	16	78	2	219	41	4	16 (annelid)	0
Ra	0	48	0	0	0	0	464	243	10	0	504	0	20
Rh	0	0	0	0	0	0	0	0	0	0	0	0	0
Ru	0	0	0	0	0	0	0	0	0	0	3	0	0

TABLE 9. NUMBER OF $CR_{wo\text{-}water}$ VALUES AVAILABLE IN REF. [2] FOR EACH COMBINATION (RADIONUCLIDE, REFERENCE ORGANISM) CONSIDERED APPLICABLE FOR TERRESTRIAL ECOSYSTEMS (GREY BOX: NO DATA, ORANGE BOX: < 10 VALUES, GREEN BOX: > 10 VALUES) (cont.)

Element	Amphibian	Bird	Bird egg	Detritivorous invertebrate	Flying insect	Gastropod	Grasses and herbs	Lichens and bryophytes	Mammal	Reptile	Shrub	Soil invertebrate (worm)	Tree
Sb	0	0	0	0	0	7	0	4	0	0	3	1 (annelid)	0
Sr	22	91	0	0	0	7	519	104	474	74	307	1 (annelid)	191
Tc	5	2	0	0	0	0	28	0	0	0	8	0	0
Te	0	0	0	0	0	0	0	0	0	0	0	0	0
Th	0	20	0	0	0	0	341	228	36	18	403	0	85
Tl	0	0	0	0	0	0	0	0	0	0	0	0	0
U	0	20	0	0	0	0	439	237	22	21	970	1 (annelid)	521
Y	0	0	0	0	0	0	0	0	0	0	0	0	0
Zn	0	0	0	0	0	0	12	100	0	30	250	383 (annelid)	4
Zr	0	0	0	0	0	0	0	0	0	0	64	0	0

NOTE: When the organism for which the data in Ref. [2] are stated to be applicable differed from the organism for which the actual data were obtained, this is indicated between brackets in the relevant part of the table.

TABLE 10. SUMMARY OF $CR_{wo\text{-}media}$ PARAMETER VALUE AVAILABILITY IN REF. [2] COMPARED WITH POTENTIALLY IMPORTANT RADIONUCLIDES IDENTIFIED DURING THE ILLUSTRATIVE PRIORITIZATION EXERCISE FOR FRENCH NUCLEAR POWER PLANTS WITH REGARD TO RADIATION PROTECTION OF WILDLIFE

Number of available values	Ecosystem		
	Freshwater	Marine	Terrestrial
0	66%	70%	81%
From 1 to 10	11%	10%	9%
At least 10	23%	20%	10%

2.4. QUALITATIVE AND QUANTITATIVE APPROACHES TO NATURALLY OCCURING RADIONUCLIDE PRIORITIZATION FOR DOSE RATES TO WILDLIFE

Activity concentrations of the uranium and thorium decay series in normal rocks and soil are variable, but generally low. However, certain minerals, including those that are commercially exploited, contain radionuclides from the uranium and thorium decay series at significantly elevated concentrations. These elevated concentrations can lead to enhanced exposure of wildlife, for example, in areas of mining and milling of metal ores (in particular uranium ores) or mineral sands, the oil and gas industry, coal production and fertilizer production. Naturally occurring radionuclides can be discharged as liquid or atmospheric effluents or occur at elevated levels at the surface of remediated industrial or legacy sites.

As with anthropogenic radionuclides, the nature of released radionuclides may vary depending on the situation, the facility and the release pathway. During the extraction of minerals from the Earth's crust and subsequent physical and/or chemical industrial processing, the concentrations of radionuclides may be elevated, and the original decay chain equilibrium disrupted (technically enhanced naturally occurring radioactive material, TENORM). Chemical and physical fractionation of the many members of the decay series, once released into the environment, further complicate the assessment of their transfer in the environment and the radiological impact on wildlife.

To facilitate assessments of wildlife exposure from naturally occurring radionuclides and to optimize research and assessment resources, a prioritization approach for identifying the naturally occurring radionuclides of interest for wildlife exposure to radiation is needed. An approach is outlined in this section with the focus on uranium mining and milling sites, and a specific example is presented for an Australian mining site (see Section 2.4.1.2). However, the approach presented is broadly applicable for use for other situations with elevated levels of naturally occurring radionuclides in the environment and could be adopted for prioritization of radionuclides contributing to exposures for the public as well as to wildlife.

Uranium mining sites do exist in many countries worldwide. These sites may be planned, operational, decommissioned, legacy or remediated, and most have elevated levels of natural radionuclides. If not adequately controlled, releases from a uranium mine site to the environment may, therefore, result in elevated radionuclide concentrations in the environment and radiation exposures to wildlife. The extent of such exposures depends on a variety of factors, such as site characteristics, environmental conditions, species present and their interaction with the site and areas with elevated contamination. The radionuclides leading to elevated exposures of wildlife at uranium mining sites are generally those of the uranium decay series (see Fig. 3 below), although radionuclides of the thorium decay series may also be of concern if they are concentrated in the ore or process streams. Radionuclides of the actinium (i.e. uranium-235) decay series may also be present, though occur naturally at only 4.6% the activity of the uranium decay series. The following prioritization analysis focuses on the uranium decay series as the primary source of radioactive contamination at uranium mining sites.

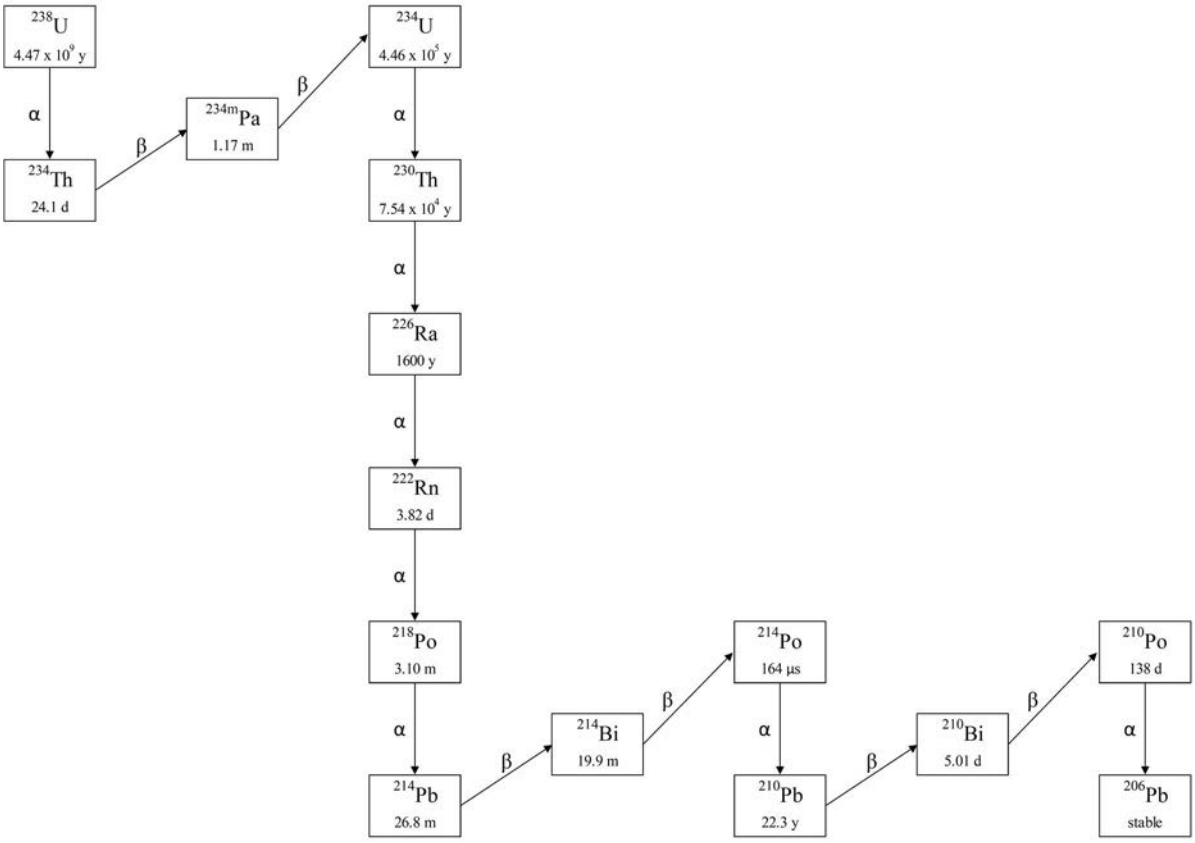

FIG. 3. Uranium decay series showing radionuclide half-lives and decay mechanisms (adapted from Ref. [26]).

2.4.1. Prioritization of radionuclides for wildlife at uranium mining sites

The aim of the quantitative analysis described here is to identify an order of priority of radionuclides in the uranium decay series contributing to wildlife exposures. All of the radionuclides shown in Fig. 3 were considered, except for radon; the contribution due to inhalation of radon and radon progeny in air by burrowing animals was not included. Prioritization has been carried out for chronic exposures and assuming steady state conditions for radionuclides in the environment and their uptake by wildlife. The approach used was to calculate absorbed dose rates to wildlife from activity concentrations of uranium decay series radionuclides in environmental media (soil, sediment and water) and to present the dose rate from each radionuclide as a percentage of the total. Dose rates to wildlife from inhalation of air have not been included, as these are generally very small for naturally occurring radionuclides (excluding radon) compared to other exposure pathways [10].

For this general approach, the radionuclides in the uranium decay series have been assumed to be in secular equilibrium, i.e. equal activity concentrations of each radionuclide were assumed in each of the environmental media that the wildlife are exposed to. Radioactive equilibrium between the radionuclides in soils and sediment was also assumed. Radionuclide concentrations in water were calculated from those in sediment using K_d values.

2.4.1.1. Prioritization of radionuclides for dose rates to wildlife based on IAEA compiled data in TRS 479

In the ERICA tool, a tiered approach is used for the radiological assessment of wildlife in freshwater, marine and terrestrial ecosystems. There are two generic screening tiers and a third site-specific tier. The Tier 2 assessment module in the ERICA tool (version 1.2) [6] was used to calculate dose rates to wildlife from radionuclides in the uranium decay series, excluding radon. Table 11 summarises the input parameter values and Tables 12–15 provide additional details on the calculation of other input data used for determining the parameter values needed for the calculations.

Table 16 provides the percentage contribution of each radionuclide to the total dose rates for each terrestrial wildlife group, assuming that the radionuclides are in secular equilibrium. The order of radionuclide priority for most wildlife groups was ^{226}Ra > ^{210}Po > uranium isotopes > thorium isotopes and ^{210}Pb. Radium-226 contributed >50% to the total dose rates for most wildlife groups and >90% for some.

The contribution of ^{226}Ra to the dose rate for the reptile wildlife group was markedly low, with a value of only 1.9%. The main contributor to the reptile dose rate was ^{210}Po (76.4%). The ^{210}Po $CR_{wo\text{-}soil}$ for the terrestrial reptile group in TRS 479 [2] is 9.5 and appears inconsistently high compared with the transfer value for other radionuclides, as the terrestrial vertebrate $CR_{wo\text{-}soil}$ values for most radionuclides in are generally less than 1. The ^{210}Po $CR_{wo\text{-}soil}$ value [2] for terrestrial reptile is primarily based on a study at the Olympic Dam uranium mine in South Australia, where the data compiled included the collection and analysis of reptile samples from in and around the mine's tailings storage facility [27]. It is possible that the data from the site may not be representative of the environmental transfer of ^{210}Po in undisturbed natural environments because of the physicochemical conditions in the area where the samples were taken or necessarily be consistent with data compiled for other radionuclides where data are derived (in part or wholly) from undisturbed environments. This finding highlights the potential impact of the choice and use of compiled $CR_{wo\text{-}soil}$ values for uranium decay series radionuclides on the potential importance of an individual radionuclide contributing to the dose rate to a specific wildlife group and the care needed with using generically compiled data.

Table 17 gives the percentage contribution of each radionuclide to the total dose rates for each freshwater wildlife group, assuming that the radionuclides are in secular equilibrium. The priority order was generally ^{226}Ra > uranium isotopes > ^{210}Po > thorium isotopes and ^{210}Pb. Radium-226 contributed >50% to the total dose rates for most wildlife groups and >90% for some. The contribution of all other radionuclides to the dose rate was generally very low (i.e. <10%).

One exception has been identified for the mammal wildlife group for which >90% of the dose rate was from uranium isotopes and <1% was from ^{226}Ra. The ^{226}Ra $CR_{wo\text{-}water}$ for mammals in TRS 479 [2] was derived from a study of Canadian beavers [28]. A review of this study and an accompanying research report [29] suggests that the ^{226}Ra $CR_{wo\text{-}water}$ value for mammals adopted in Ref. [2] is around three orders of magnitude too low.

The percentage contributions of radionuclides to the total dose rates for wildlife groups in Tables 16 and 17 provide a general indication of radionuclide priority at uranium mining sites. However, the results are sensitive to the uncertainty in the data and associated assumptions on gap filling and also the degree of the disequilibrium of activity concentrations of the uranium series radionuclides in soil, sediment and water.

TABLE 11. SUMMARY OF INPUT PARAMETER VALUES USED IN THE TIER 2 ASSESSMENT MODULE OF THE ERICA TOOL (VERSION 1.2) [6] TO CALCULATE DOSE RATES TO WILDLIFE

Parameter	Value
Radionuclides[a]	U-238, Th-234 (Pa-234m), U-234, Th-230, Ra-226 (Rn-222, Po-218, Pb-214, Bi-214, Po-214), Pb-210 (Bi-210), Po-210
Organisms	Wildlife groups from TRS 479 [2] mapped to closest matching reference organism in the ERICA tool (version 1.2) (see Table 12)
$CR_{wo\text{-}media}$	Arithmetic Mean (AM) values from TRS 479 [2] with gaps filled using surrogate organism and biogeochemical analogue approaches (see Tables 13 and 14)
K_d	AM values from Table 15, derived from data being collated by MODARIA WG4 [b]
Occupancy factors	Default occupancies for reference organisms in different types of habitats in the ERICA tool (version 1.2) (see Table 12)
Radiation weighting factors	10 for alpha, 1 for gamma/beta and 3 for low energy beta [6]
Environmental media activity concentrations	Secular equilibrium assumed in soils and sediments; water activity concentrations, calculated from sediment activity concentrations using K_d values

[a] The ERICA tool (version 1.2) [6] includes progeny radionuclides in the dose coefficient of the parent if their half-life is less than 10 days, as indicated by those radionuclides given in parentheses.
[b] The K_d data used for the prioritization were compiled under MODARIA WG4. The follow-up MODARIA II Programme (2016–2019) continued the work of MODARIA on K_d compilation, but the final IAEA TECDOC report is not yet available.

TABLE 12. MAPPING OF WILDLIFE GROUPS IN TRS 479 [2] TO REFERENCE ORGANISMS IN THE ERICA TOOL (VERSION 1.2) [6] AND SELECTION OF HABITAT OCCUPANCY FACTORS

TRS 479 wildlife group	ERICA reference organism	Occupancy factor
Terrestrial ecosystem		
Amphibian	Amphibian	In soil: 1
Annelid	Annelid	In soil: 1
Arachnid	Arthropod – detritivorous	In soil: 1
Arthropod	Arthropod – detritivorous	In soil: 1
Bird	Bird	On soil: 1
Fern	Grasses and Herbs	On soil: 1
Fungi	Lichens and Bryophytes	On soil: 1
Grasses and Herbs	Grasses and Herbs	On soil: 1
Lichens and Bryophytes	Lichens and Bryophytes	On soil: 1
Mammal	Mammal – large, Mammal – small burrowing	On soil: 1
Mollusc	Mollusc – gastropod	On soil: 1
Reptile	Reptile	On soil: 1
Shrub	Shrub	On soil: 1
Tree	Tree	On soil: 1
Freshwater ecosystem		
Algae	Phytoplankton	Water: 1
Amphibian	Amphibian	Water: 1
Bird	Bird	Water: 1
Crustacean	Crustacean	Sediment surface: 1
Fish	Benthic fish, Pelagic fish	Sediment surface: 1 (benthic); Water: 1 (pelagic)
Insect	Zooplankton	Water: 1
Insect larvae	Insect larvae	Sediment: 1
Mammal	Mammal	Water: 1
Mollusc	Mollusc bivalve, Mollusc gastropod	Sediment surface: 1
Phytoplankton	Phytoplankton	Water: 1
Reptile	Reptile	Water: 0.5; Sediment: 0.5
Vascular plant	Vascular plant	Sediment surface: 1
Zooplankton	Zooplankton	Water: 1

TABLE 13. GAPS IN TRS 479 [2] CONCENTRATION RATIOS ($CR_{wo\text{-}soil}$) FOR TERRESTRIAL WILDLIFE GROUPS FOR WHICH THE SURROGATE ORGANISM EXTRAPOLATION METHOD WAS USED

Element	Wildlife group	Surrogate organism
Pb	Fern	Grasses and Herbs
	Fungi	Lichens and Bryophytes
Po	Amphibian	Mammal
	Arachnid	Annelid
	Arthropod	Annelid
	Fern	Grasses and Herbs
	Fungi	Lichen and Bryophytes
	Mollusc	Annelid
Ra	Amphibian	Mammal
	Annelid	Arthropod
	Arachnid	Arthropod
	Fern	Grasses and Herbs
	Fungi	Lichens and Bryophytes
	Reptile	Mammal
Th	Amphibian	Mammal
	Annelid	Mammal
	Arachnid	Mammal
	Arthropod	Mammal
	Fern	Grasses and Herbs
	Fungi	Lichens and Bryophytes
	Mollusc	Mammal
U	Amphibian	Mammal
	Arachnid	Arthropod
	Fern	Grasses and Herbs
	Fungi	Lichens and Bryophytes
	Mollusc	Annelid

TABLE 14. GAPS IN TRS 479 [2] CONCENTRATION RATIOS ($CR_{wo\text{-}water}$) FOR FRESHWATER WILDLIFE GROUPS AND EXTRAPOLATION APPROACHES USED

Element	Wildlife group	Extrapolation method	Organism/analogue
Pb	Algae	Surrogate organism	Vascular plant
	Bird	Surrogate organism	Reptile
	Insect	Surrogate organism	Crustacean
	Insect larvae	Surrogate organism	Crustacean
	Mammal	Surrogate organism	Reptile
	Phytoplankton	Surrogate organism	Vascular plant
	Zooplankton	Surrogate organism	Crustacean
Po	Algae	Surrogate organism	Vascular plant
	Amphibian	Surrogate organism	Reptile
	Bird	Surrogate organism	Reptile
	Insect	Surrogate organism	Crustacean
	Insect larvae	Surrogate organism	Crustacean
	Mammal	Surrogate organism	Reptile
	Phytoplankton	Surrogate organism	Vascular plant
	Zooplankton	Surrogate organism	Crustacean
Ra	Algae	Surrogate organism	Phytoplankton
	Amphibian	Surrogate organism	Reptile
	Bird	Surrogate organism	Reptile
	Insect	Surrogate organism	Crustacean
	Insect larvae	Surrogate organism	Crustacean
	Zooplankton	Surrogate organism	Crustacean

TABLE 14. GAPS IN TRS 479 [2] CONCENTRATION RATIOS ($CR_{wo\text{-}water}$) FOR FRESHWATER WILDLIFE GROUPS AND EXTRAPOLATION APPROACHES USED (cont.)

Element	Wildlife group	Extrapolation method	Organism/analogue
Th	Algae	Surrogate organism	Phytoplankton
	Amphibian	Surrogate organism	Reptile
	Bird	Surrogate organism	Reptile
	Crustacean	Surrogate organism/ biogeochemical analogue	Crustacean/U
	Insect	Surrogate organism/ biogeochemical analogue	Crustacean/U
	Insect larvae	Surrogate organism/ biogeochemical analogue	Crustacean/U
	Mammal	Surrogate organism	Reptile
	Mollusc	Surrogate organism/ biogeochemical analogue	Mollusc/U
	Zooplankton	Surrogate organism/ biogeochemical analogue	Crustacean/U
U	Algae	Surrogate organism	Phytoplankton
	Amphibian	Surrogate organism	Reptile
	Bird	Surrogate organism	Reptile
	Insect	Surrogate organism	Crustacean
	Insect larvae	Surrogate organism	Crustacean
	Mammal	Surrogate organism	Reptile
	Zooplankton	Surrogate organism	Crustacean

TABLE 15. *IN SITU* SEDIMENT-WATER DISTRIBUTION COEFFICIENT (K_d) VALUES DERIVED FROM DATA COLLATED BY THE MODARIA WORKING GROUP 4[a]

Element	GM	GSD	AM	ASD	Min	Max	n
Pb	4.2×10^4	4.2×10^0	1.2×10^5	3.2×10^5	3.3×10^1	5.6×10^6	29
Po	8.2×10^4	2.8×10^0	1.4×10^5	1.8×10^5	2.2×10^4	6.1×10^6	10
Ra	3.7×10^2	3.4×10^0	7.7×10^2	1.4×10^3	8.2×10^1	1.7×10^5	15
Th	7.3×10^4	2.0×10^0	9.3×10^4	7.4×10^4	3.6×10^2	4.7×10^5	9
U	4.4×10^2	1.5×10^0	4.8×10^2	2.0×10^2	9.1×10^1	8.0×10^4	14

[a] The K_d data used for the prioritization were compiled under MODARIA WG4. The follow-up MODARIA II Programme (2016 – 2019) continued the work of MODARIA on K_d compilation, but the final IAEA TECDOC report is not yet available. GM = Geometric Mean; AM = Arithmetic Mean; GSD = Geometric Standard Deviation; ASD = Arithmetic Standard Deviation.

TABLE 16. PERCENTAGE CONTRIBUTIONS OF RADIONUCLIDES TO DOSE RATE FOR TERRESTRIAL WILDLIFE GROUPS[a]

Wildlife group	U-238	Th-234	U-234	Th-230	Ra-226	Pb-210	Po-210
Amphibian	1.4	0.1	1.6	0.0	70.6	0.3	26.0
Annelid	0.0	0.0	0.1	0.0	99.2	0.0	0.7
Arachnid	0.1	0.0	0.1	0.0	99.1	0.0	0.7
Arthropod	0.1	0.0	0.1	0.0	99.1	0.0	0.7
Bird	0.2	0.1	0.2	0.2	93.7	0.3	5.3
Fern	6.8	0.2	7.9	13.0	52.8	0.0	19.3
Fungi	10.1	0.0	11.5	4.4	39.5	0.1	34.3
Grasses and Herbs	6.8	0.2	7.9	13.0	52.8	0.0	19.3
Lichens and Bryophytes	10.1	0.0	11.5	4.4	39.5	0.1	34.3
Mammal (large)	1.4	0.0	1.7	0.0	69.3	0.1	27.5
Mammal (small)	1.4	0.1	1.6	0.0	70.6	0.1	26.2
Mollusc	2.0	0.0	2.4	0.0	65.9	0.0	29.6
Reptile	9.3	0.0	10.9	1.4	1.9	0.0	76.4
Shrub	2.8	0.1	3.3	3.4	69.7	0.1	20.6
Tree	8.4	0.2	9.8	1.5	18.7	1.0	60.4

[a] Assumes a unit activity concentration of each radionuclide in the environmental media each wildlife group is exposed to, i.e. the radionuclides are in secular equilibrium.

TABLE 17. PERCENTAGE CONTRIBUTIONS OF RADIONUCLIDES TO DOSE RATE FOR FRESHWATER WILDLIFE GROUPS[a]

Wildlife group	U-238	Th-234	U-234	Th-230	Ra-226	Pb-210	Po-210
Algae	3.2	0.0	3.6	3.0	89.7	0.0	0.4
Amphibian	3.8	0.0	4.5	0.2	91.0	0.0	0.5
Bird	3.6	0.0	4.2	0.2	91.5	0.0	0.5
Crustacean	13.7	0.3	15.9	0.1	67.6	0.0	2.5
Fish benthic	4.2	0.0	5.0	0.5	89.0	0.0	1.2
Fish pelagic	4.3	0.0	5.0	0.5	88.9	0.0	1.2
Insect	13.7	0.3	15.9	0.1	67.6	0.0	2.5
Insect larvae	13.5	0.5	15.7	0.1	67.6	0.1	2.5
Mammal	42.5	0.0	49.6	2.0	0.3	0.0	5.6
Mollusc bivalve	0.6	0.0	0.8	0.0	98.0	0.0	0.6
Mollusc gastropod	0.6	0.0	0.8	0.0	98.0	0.0	0.6
Phytoplankton	3.2	0.0	3.6	3.0	89.7	0.0	0.4
Reptile	3.8	0.0	4.3	0.2	91.3	0.0	0.5
Vascular plant	3.9	0.1	4.6	6.6	84.7	0.0	0.1
Zooplankton	13.8	0.0	16.1	0.1	67.5	0.0	2.5

[a] Assumes a unit activity concentration of each radionuclide in the environmental media each wildlife group is exposed to, i.e. the radionuclides are in secular equilibrium.

The $CR_{wo\text{-}media}$ values in TRS 479 [2] and the K_d values in Table 15 are average values derived from global data compilations with standard deviations giving a broad measure of uncertainty. The $CR_{wo\text{-}media}$ values also contain other uncertainties because of transformations applied to some of the data to ensure a standard format. Generic conversion factors are listed to enable transformation of data from tissue to whole organism values and from a dry or ash mass basis to fresh mass basis where such information was missing from source publications [2]. The extent of such transformations in deriving $CR_{wo\text{-}media}$ values is not documented for the wildlife groups in the compilation.

The IAEA compilation in TRS 479 [2] does not include all combinations of $CR_{wo\text{-}media}$ needed for an assessment of the dose rates to wildlife at uranium mining sites. Data availability is 63% for terrestrial wildlife groups and 43% for freshwater groups, measured in terms of radionuclide and wildlife group combinations for which data are available. Filling the existing gaps (Tables 13 and 14) introduced uncertainties into the assessment because it involved extrapolation, which assumes that $CR_{wo\text{-}media}$ values can be used interchangeably for surrogate organisms and/or biogeochemical analogues. Further uncertainties are associated with the assumption of steady state conditions which may not be the case for radionuclides in some terrestrial and freshwater ecosystems [4].

The influence of statistical uncertainties in $CR_{wo\text{-}media}$ and K_d on the predicted dose rates was evaluated using sensitivity analysis. The Tier 3 assessment module in the ERICA tool (version 1.2) [6] was used with probability distribution functions of $CR_{wo\text{-}media}$ and K_d values, which were assumed to be log-normal if the value had a standard deviation and to be exponential if they did not. This is the same general approach as used in the ERICA tool for defining distribution functions [6]. Figure 4 shows the average correlation between the probabilistic inputs and estimated dose rates for the terrestrial ecosystem and Fig. 5 for the freshwater ecosystem. On average, dose rates were most sensitive to the ^{226}Ra $CR_{wo\text{-}media}$ in both ecosystems.

The sensitivity analysis results (Figs 4 and 5) and percentage contributions of radionuclides to the total dose rates (Tables 16 and 17) indicate that characterization of ^{226}Ra $CR_{wo\text{-}media}$ is likely to be the most important focus for research for radiation protection of the environment at uranium mining sites for both terrestrial and freshwater wildlife.

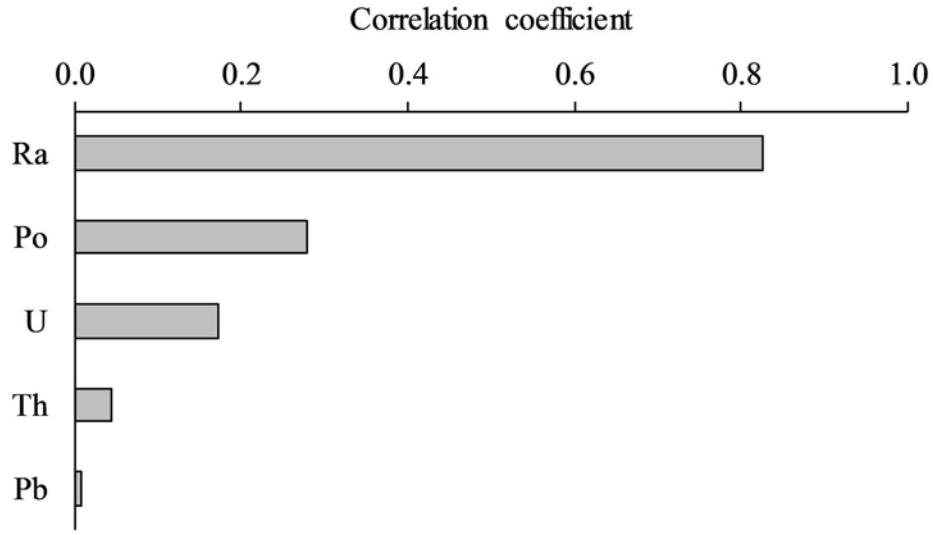

FIG. 4. Average correlation coefficient between dose rates and the uncertainty in concentration ratio ($CR_{wo\text{-}soil}$) values for terrestrial wildlife.

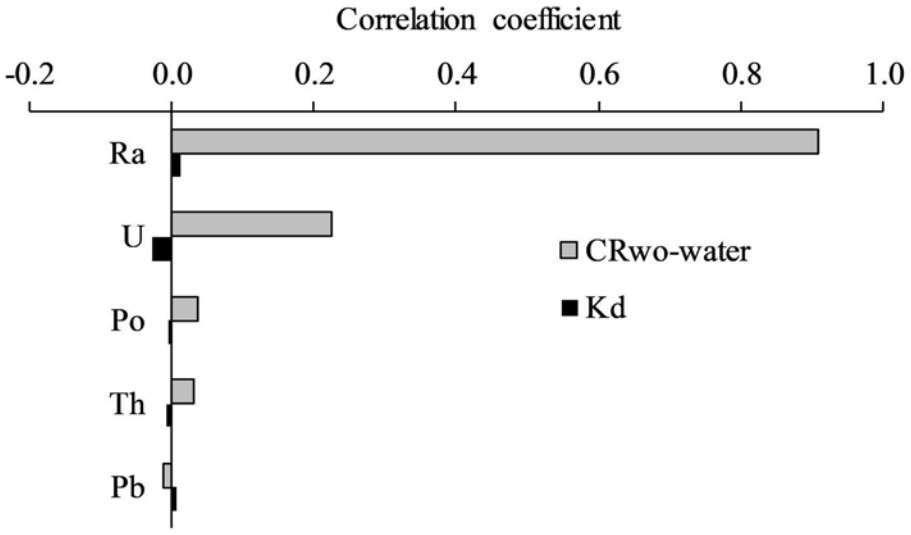

FIG. 5. Average correlation coefficient between dose rates and uncertainty in the concentration ratio ($CR_{wo\text{-}water}$) and distribution coefficient (K_d) values for freshwater wildlife.

2.4.1.2. Example of the prioritization approach for an Australian uranium mining site

The prioritization of the contribution of radionuclides in the uranium decay series to the dose rates to wildlife has been considered for a uranium mining site in Australia [10]. The results of this study are summarized here along with further evaluation of the data using the prioritization approach described in Section 2.4.1. The Ranger uranium mine is an open cut mine with on-site ore processing facilities and has been producing uranium oxide (U_3O_8) via acid leach extraction since 1981. It is located in the Alligator Rivers Region in the wet-dry tropics of northern Australia and is surrounded by the world heritage listed Kakadu National Park and its Ramsar listed wetlands. The current authorisation for the mine requires that all operations must cease by 2021 and that the decommissioning and remediation works on site must be completed by 2026. The remediation plan for the site includes burying uranium mill tailings in the pit voids and building and constructing a landform covered by low uranium grade waste rock which will then be revegetated [30]. No additional clean cover is planned to be applied above the waste rock layer due to restrictions on bringing outside material into a world heritage area.

After remediation, the presence of radionuclides in the proposed waste rock substrate used for the landform may lead to elevated radiation exposures to wildlife. This includes exposures to terrestrial wildlife utilizing the landform as a habitat and also to freshwater wildlife from runoff and seepage into adjacent creeks and transport to surface waters downstream of the site during the wet season. A remediation standard for environmental radiation protection has been developed for the site [31] based on international guidance (ICRP, UNSCEAR).

Radionuclide activity concentration data [32] have been used to derive site specific $CR_{wo\text{-}media}$ values for two terrestrial wildlife groups (Table 18) and six freshwater groups (Table 19). The values were derived by calculating $CR_{muscle\text{-}media}$ and then converting to $CR_{wo\text{-}media}$ using tissue conversion factors for most wildlife groups [2]. However, for ^{226}Ra in the terrestrial mammal and reptile groups, tissue conversion factors were derived from the available site specific data [10] instead of using the internationally compiled values [2]. Data for paired bed sediment and filtered water samples collected from Mudginberri Billabong, located approximately 12 km downstream of the mine [32], were used to derive sediment–water K_d values (Table 20).

The same prioritization approach as that used for the analysis using data from TRS 479 [2] (see Section 2.4.1.1) has been applied. The difference was that site specific AM for $CR_{wo\text{-}media}$ values from Tables 18 and 19 and bed sediment–water K_d values from Table 20 have been used. Secular equilibrium of the radionuclides in each of the environmental media considered was assumed.

The results of the analysis showed that ^{226}Ra was again the radionuclide that gave the highest contribution to dose rate for the two terrestrial wildlife groups considered (mammal and reptile), with a percentage contribution to the total dose rate of >90% (Table 21). Polonium-210 was the only other radionuclide contributing more than 1% to the total dose rate.

The order of priority for the six freshwater wildlife groups was generally ^{226}Ra > ^{210}Po > thorium isotopes and uranium isotopes > ^{210}Pb (Table 22). Radium-226 contributed >50% to all freshwater wildlife groups and >90% to some. The contribution from ^{210}Po was up to about 11%.

TABLE 18. CONCENTRATION RATIOS ($CR_{wo\text{-}soil}$) FOR TERRESTRIAL WILDLIFE GROUPS FROM THE ALLIGATOR RIVERS REGION [32]

Element	Wildlife group	N	GM	GSD	AM	ASD	Min	Max
Pb	Mammal	1	n.a.	n.a.	1.7×10^{-3}	n.a.	n.a.	n.a.
	Reptile	3	1.9×10^{-2}	2.0×10^{0}	2.4×10^{-2}	1.9×10^{-2}	6.1×10^{-3}	4.5×10^{-2}
Po	Mammal	2	n.a.	n.a.	7.5×10^{-2}	n.a.	6.6×10^{-3}	1.4×10^{-1}
	Reptile	2	n.a.	n.a.	1.1×10^{-1}	n.a.	6.7×10^{-2}	1.5×10^{-1}
Ra	Mammal	6	1.5×10^{-1}	2.3×10^{0}	2.1×10^{-1}	2.0×10^{-1}	4.1×10^{-2}	4.6×10^{-1}
	Reptile	5	3.8×10^{-1}	1.8×10^{0}	4.6×10^{-1}	3.0×10^{-1}	1.2×10^{-1}	9.2×10^{-1}
Th	Mammal	2	n.a.	n.a.	3.5×10^{-3}	n.a.	2.3×10^{-3}	4.8×10^{-3}
	Reptile	3	7.5×10^{-4}	2.3×10^{0}	1.1×10^{-3}	1.1×10^{-3}	3.5×10^{-4}	2.4×10^{-3}
U	Mammal	2	n.a.	n.a.	2.0×10^{-3}	n.a.	1.6×10^{-3}	2.4×10^{-3}
	Reptile	4	2.2×10^{-3}	1.6×10^{0}	2.4×10^{-3}	1.2×10^{-3}	1.1×10^{-3}	3.8×10^{-3}

N: Sample size; GM: Geometric Mean; GSD: Geometric Standard Deviation; AM: Arithmetic Mean; ASD: Arithmetic Standard Deviation; Min: Minimum; Max: Maximum; n.a.: Not applicable.

TABLE 19. CONCENTRATION RATIOS ($CR_{wo\text{-}water}$) FOR FRESHWATER WILDLIFE GROUPS FROM THE ALLIGATOR RIVERS REGION [32]

Element	Wildlife group	N	GM	GSD	AM	ASD	Min	Max
Pb	Bird	3	3.8×10^{1}	1.2×10^{0}	3.8×10^{1}	7.4×10^{0}	3.2×10^{1}	4.6×10^{1}
	Crustacean	3	5.0×10^{1}	2.2×10^{0}	6.7×10^{1}	6.3×10^{1}	2.3×10^{1}	1.4×10^{2}
	Fish	75	1.3×10^{2}	5.1×10^{0}	6.2×10^{2}	2.2×10^{3}	1.2×10^{0}	1.8×10^{4}
	Mollusc	156	1.8×10^{4}	3.1×10^{0}	6.2×10^{4}	1.0×10^{5}	1.3×10^{2}	5.1×10^{5}
	Reptile	7	1.7×10^{2}	2.0×10^{0}	2.7×10^{2}	2.1×10^{2}	1.2×10^{1}	5.3×10^{2}
	Vascular plant	6	3.5×10^{2}	1.6×10^{0}	3.9×10^{2}	1.9×10^{2}	1.9×10^{2}	6.8×10^{2}
Po	Bird	3	4.9×10^{2}	1.6×10^{0}	5.2×10^{2}	2.4×10^{2}	3.0×10^{2}	7.8×10^{2}
	Crustacean	4	5.2×10^{2}	1.2×10^{0}	5.3×10^{2}	1.1×10^{2}	3.8×10^{2}	6.0×10^{2}
	Fish	102	4.8×10^{2}	3.3×10^{0}	1.1×10^{3}	2.0×10^{3}	2.7×10^{1}	1.6×10^{4}
	Mollusc	37	5.5×10^{4}	1.7×10^{0}	6.8×10^{4}	4.1×10^{4}	1.2×10^{4}	1.7×10^{5}
	Reptile	8	1.1×10^{3}	1.6×10^{0}	1.3×10^{3}	6.6×10^{2}	2.4×10^{2}	2.1×10^{3}
	Vascular plant	8	4.6×10^{2}	1.5×10^{0}	5.0×10^{2}	2.0×10^{2}	2.5×10^{2}	8.5×10^{2}
Ra	Bird	4	6.9×10^{2}	1.8×10^{0}	2.3×10^{3}	1.5×10^{3}	7.9×10^{0}	3.1×10^{3}
	Crustacean	5	1.1×10^{2}	2.0×10^{0}	1.4×10^{2}	1.1×10^{2}	6.2×10^{1}	3.4×10^{2}
	Fish	139	2.7×10^{2}	3.6×10^{0}	1.2×10^{3}	2.4×10^{3}	7.4×10^{0}	1.7×10^{4}
	Mollusc	367	5.7×10^{4}	2.7×10^{0}	9.8×10^{4}	1.3×10^{5}	1.7×10^{3}	8.4×10^{5}
	Reptile	11	3.1×10^{3}	2.9×10^{0}	7.2×10^{3}	1.0×10^{4}	2.6×10^{2}	3.5×10^{4}
	Vascular plant	31	2.6×10^{2}	2.8×10^{0}	4.6×10^{2}	6.2×10^{2}	3.0×10^{1}	2.8×10^{3}
Th	Bird	5	2.1×10^{2}	1.3×10^{0}	2.2×10^{2}	5.6×10^{1}	1.4×10^{2}	2.9×10^{2}
	Crustacean	3	1.0×10^{2}	2.1×10^{0}	1.4×10^{2}	1.2×10^{2}	4.5×10^{1}	2.7×10^{2}
	Fish	31	1.8×10^{2}	3.2×10^{0}	5.6×10^{2}	9.5×10^{2}	1.6×10^{1}	4.5×10^{3}
	Mollusc	58	3.8×10^{2}	1.8×10^{0}	4.7×10^{2}	3.1×10^{2}	8.0×10^{1}	1.3×10^{3}
	Reptile	12	2.8×10^{2}	2.1×10^{0}	4.7×10^{2}	3.8×10^{2}	3.3×10^{1}	1.0×10^{3}
	Vascular plant	12	4.1×10^{2}	1.9×10^{0}	4.8×10^{2}	3.5×10^{2}	1.9×10^{2}	1.5×10^{3}
U	Bird	4	6.7×10^{1}	1.4×10^{0}	6.9×10^{1}	2.3×10^{1}	5.4×10^{1}	1.0×10^{2}
	Crustacean	4	5.0×10^{1}	2.2×10^{0}	8.4×10^{1}	7.8×10^{1}	1.4×10^{1}	1.6×10^{2}
	Fish	153	1.3×10^{2}	4.6×10^{0}	6.7×10^{2}	2.0×10^{1}	1.4×10^{0}	1.6×10^{4}
	Mollusc	43	5.4×10^{2}	1.8×10^{0}	6.7×10^{2}	4.2×10^{2}	1.5×10^{2}	1.8×10^{3}
	Reptile	14	8.3×10^{1}	1.9×10^{0}	1.2×10^{2}	8.5×10^{1}	1.0×10^{1}	3.1×10^{2}
	Vascular plant	18	2.2×10^{2}	1.4×10^{0}	2.4×10^{2}	8.8×10^{1}	1.2×10^{2}	3.8×10^{2}

N: Sample size; GM: Geometric Mean; GSD: Geometric Standard Deviation; AM: Arithmetic Mean; ASD: Arithmetic Standard Deviation; Min: Minimum; Max: Maximum.

TABLE 20. *IN SITU* BED SEDIMENT–WATER DISTRIBUTION COEFFICIENTS (K_d) FOR MUDGINBERRI BILLABONG

Element	N	GM	GSD	AM	ASD	Min	Max
Pb	2	n.a.	n.a.	1.3×10^{5}	n.a.	1.2×10^{5}	1.4×10^{5}
Po	2	n.a.	n.a.	1.2×10^{5}	n.a.	7.5×10^{4}	1.7×10^{5}
Ra	17	4.8×10^{4}	2.8×10^{0}	9.1×10^{4}	1.3×10^{5}	3.8×10^{5}	5.3×10^{5}
Th	1	1.0×10^{5}	n.a.	1.0×10^{5}	n.a.	n.a.	n.a.
U	8	8.5×10^{4}	2.3×10^{0}	1.3×10^{5}	1.3×10^{5}	1.5×10^{4}	4.1×10^{5}

N: Sample size; GM: Geometric Mean; GSD: Geometric Standard Deviation; AM: Arithmetic Mean; ASD: Arithmetic Standard Deviation; Min: Minimum; Max: Maximum; n.a.: Not applicable.

TABLE 21. PERCENTAGE CONTRIBUTION OF RADIONUCLIDES TO THE DOSE RATE FOR TERRESTRIAL WILDLIFE GROUPS USING SITE SPECIFIC DATA FROM THE ALLIGATOR RIVERS REGION

Wildlife group	Percentage dose rate (%)						
	U-238	Th-234	U-234	Th-230	Ra-226	Pb-210	Po-210
Mammal	0.2	0.0	0.2	0.3	92.2	0.0	7.2
Reptile	0.1	0.0	0.1	0.0	94.6	0.0	5.1

TABLE 22. PERCENTAGE CONTRIBUTION OF RADIONUCLIDES TO THE DOSE RATE FOR FRESHWATER WILDLIFE GROUPS USING SITE SPECIFIC DATA FROM THE ALLIGATOR RIVERS REGION

Wildlife group	Percentage dose rate (%)						
	U-238	Th-234	U-234	Th-230	Ra-226	Pb-210	Po-210
Bird	0.3	0.0	0.4	1.5	94.3	0.0	3.4
Crustacean	1.2	14.8	1.4	3.0	67.6	1.4	10.6
Fish benthic	4.0	0.6	4.6	4.9	76.7	0.1	9.1
Fish pelagic	4.7	0.1	5.5	5.8	73.1	0.0	10.8
Mollusc bivalve	0.1	0.0	0.1	0.1	89.1	0.1	10.6
Reptile	0.2	0.1	0.2	1.1	95.7	0.0	2.7
Vascular plant	2.3	7.9	2.7	6.8	71.0	2.5	6.7

TABLE 23. COMPARISON OF IAEA TRS 479 [2] AND SITE SPECIFIC TISSUE CONVERSION FACTORS FOR RADIUM (MUSCLE WHOLE ORGANISM)

Wildlife group	IAEA TRS 479 [2]	Site specific
Mammal	38 (n=2)	960 (n=1)
Reptile	– [a]	220 (n=2)

[a] Data not available.

2.4.2. Comparison of prioritization for naturally occurring radionuclides using data from IAEA TRS 479 and site specific data for an Australian mining site

Two terrestrial wildlife groups and six freshwater groups were common to both the prioritization analysis using data from TRS 479 [2] and that using Alligator Rivers Region site specific data [10, 32]. Figure 6 compares the results obtained for the terrestrial groups in common and Fig. 7 for the six freshwater groups in common.

For most radionuclides, there was reasonable agreement between the two sets of analysis results. However, there was a substantial difference between the results for the terrestrial reptile wildlife group (Fig. 6). For the analysis using the data from TRS 479 [2], ^{210}Po was identified as the highest priority radionuclide, whereas for the analysis using the Alligator Rivers Region data, ^{226}Ra was identified as giving the highest contributor to the total dose rate. The data underpinning the reptile $CR_{wo\text{-}soil}$ for ^{210}Po [2] comes primarily from an area with environmental conditions that have been impacted by acidic, radioactive tailings on a uranium mining site [27] (as discussed in Section 2.4.1.1). The data underpinning the reptile $CR_{wo\text{-}soil}$ values for the Alligator Rivers Region comes from natural undisturbed environments. Differences in the results for reptiles may at least partially reflect these differences in environmental conditions. Another identified source of difference for ^{226}Ra was the tissue conversion factors used. For ^{226}Ra in terrestrial mammals and reptiles, tissue conversion factors were derived from the site specific data [32], instead of using the compiled data values from TRS 479 (Table 23). The

value for mammals [2] was around a factor of 25 times lower than the site specific value, which was derived from data for wallaby. The dataset in Ref. [2] does not include a ^{226}Ra tissue conversion factor for reptiles. The site specific tissue conversion factor for reptiles was derived from data for goanna.

The comparison of the prioritization analysis carried out to estimate the total dose rate for mammals and reptiles using radium tissue conversion factors from TRS 479 [2] versus the site specific tissue conversion factors in the Alligator Rivers Region is shown in Fig. 8. In using the TRS 479 dataset [2], a tissue conversion factor for mammals was assumed for reptiles. Total dose rates estimated using the tissue conversion factor for radium [2] were approximately one order of magnitude lower than those estimated using the site specific values for both mammals and reptiles.

The prioritization approach using both the data from TRS 479 [2] and the Alligator Rivers Region data was based on the relative contribution of each radionuclide to the total dose rates assuming secular equilibrium between the radionuclides in the environment. The results do not show whether there would be a difference in the estimated dose rates to wildlife using the two different datasets. To address this point, Fig. 9 shows the ratio of the total dose rates predicted from the Alligator Rivers Region prioritization analysis to those from the prioritization using data from TRS 479 [2]. With the exception of terrestrial reptiles and freshwater vascular plants, the predicted total dose rates were higher (i.e. had a ratio greater than one) for the Alligator Rivers Region analysis compared to the analysis using data from TRS 479, primarily due to higher $CR_{wo\text{-}media}$ values for ^{226}Ra being used in the Australian site specific study. However, higher total dose rates for terrestrial reptiles and freshwater vascular plants were predicted using the data from TRS 479 due to differences in the ^{210}Po $CR_{wo\text{-}soil}$ value for reptiles and the ^{230}Th $CR_{wo\text{-}water}$ value for vascular plants.

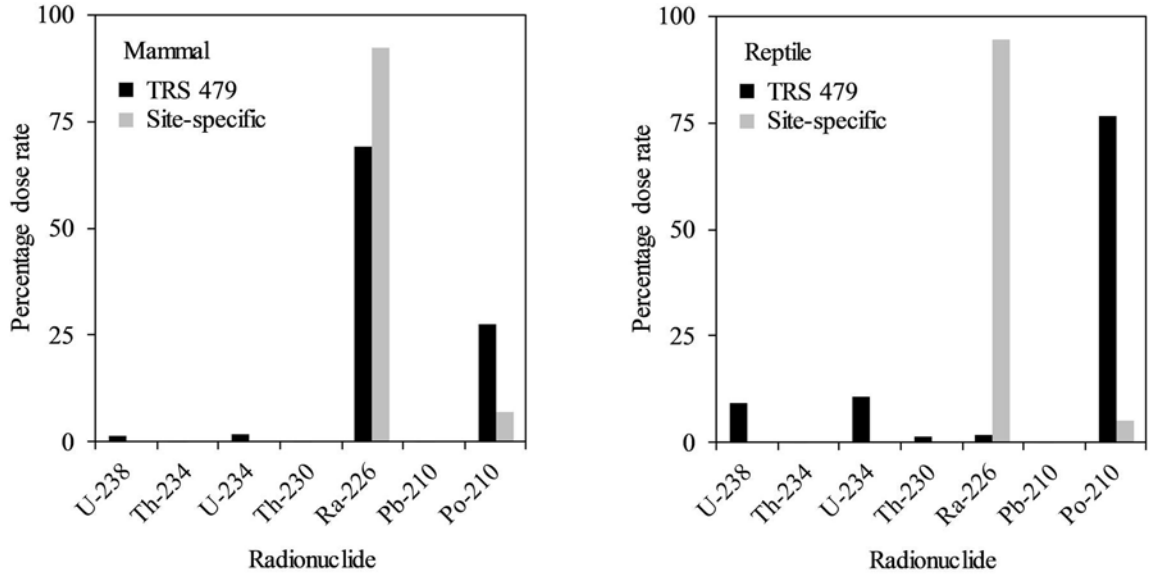

FIG. 6. Comparison of percentage contribution of radionuclides to total dose rates obtained for terrestrial wildlife groups using data from TRS-479 [2] and site specific data for the Alligator Rivers Region from Ref. [32].

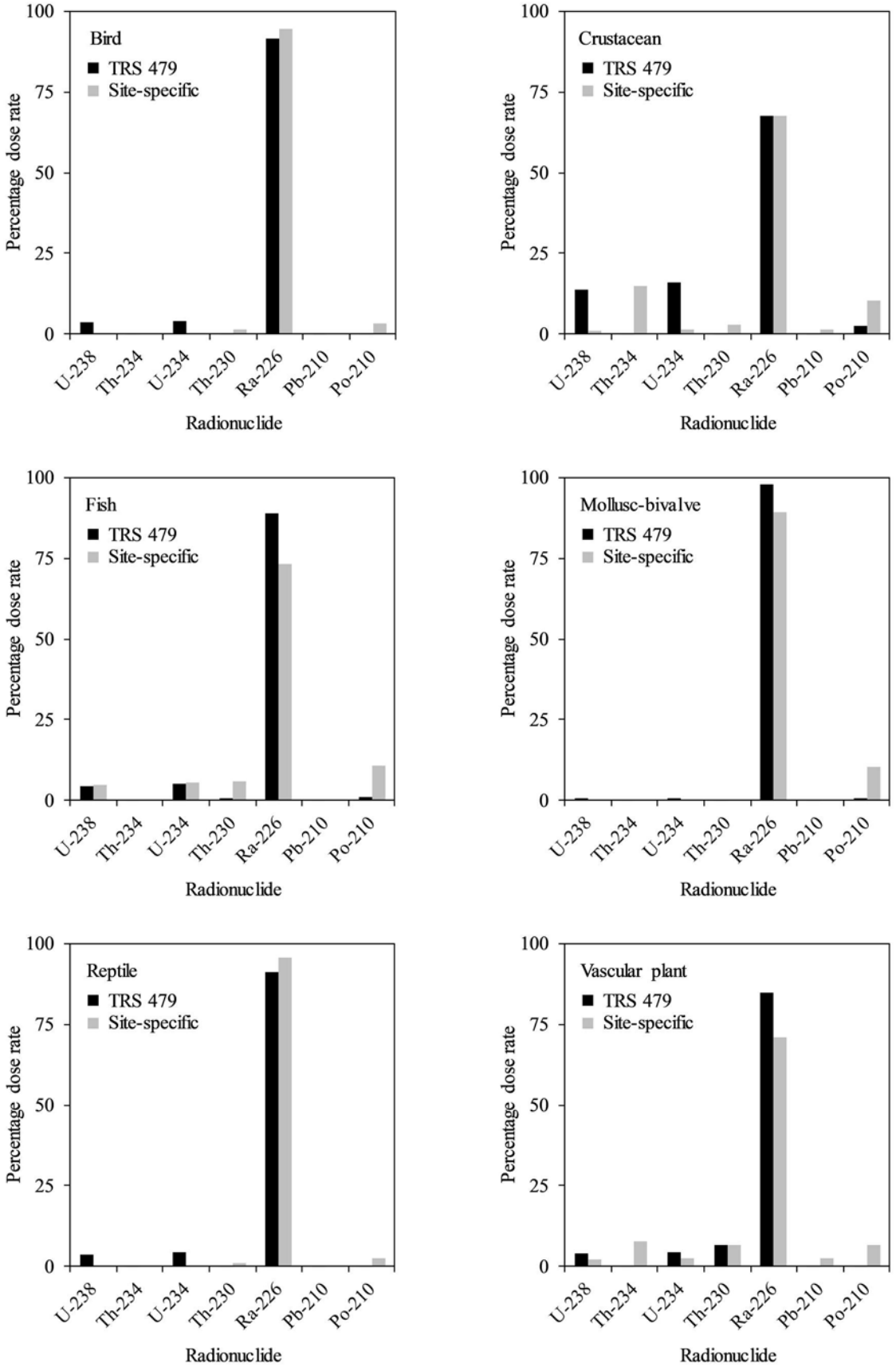

FIG. 7. Comparison of percentage contribution of radionuclides to total dose rates obtained for freshwater wildlife groups using data from TRS 479 [2] and site specific data for the Alligator Rivers Region from Ref. [32].

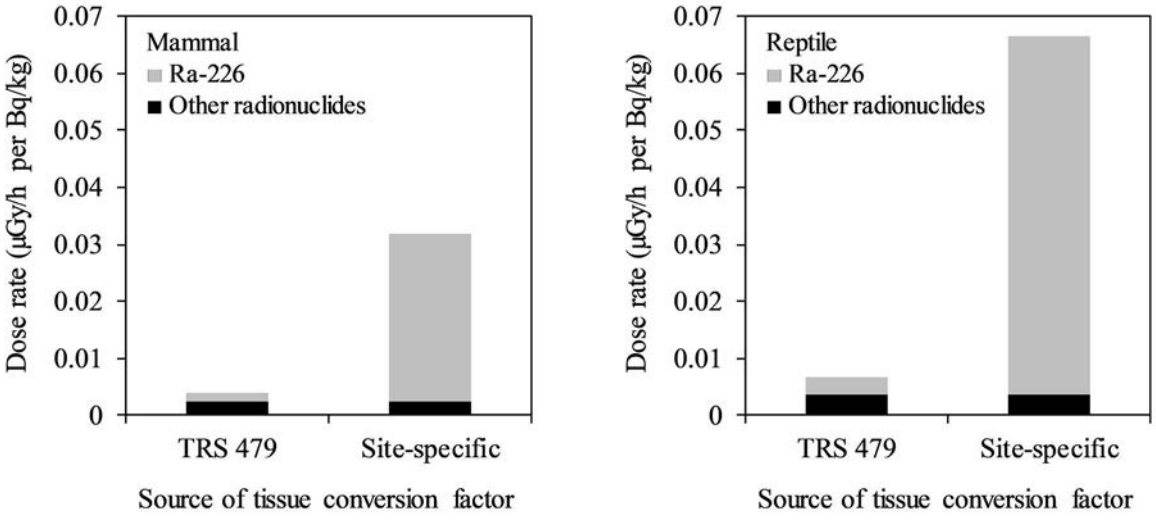

FIG. 8. Comparison of total dose rates for mammals and reptiles using tissue conversion factors for radium from TRS 479 [2] (left) versus values derived from site specific data for the Alligator Rivers Region [32] (right).

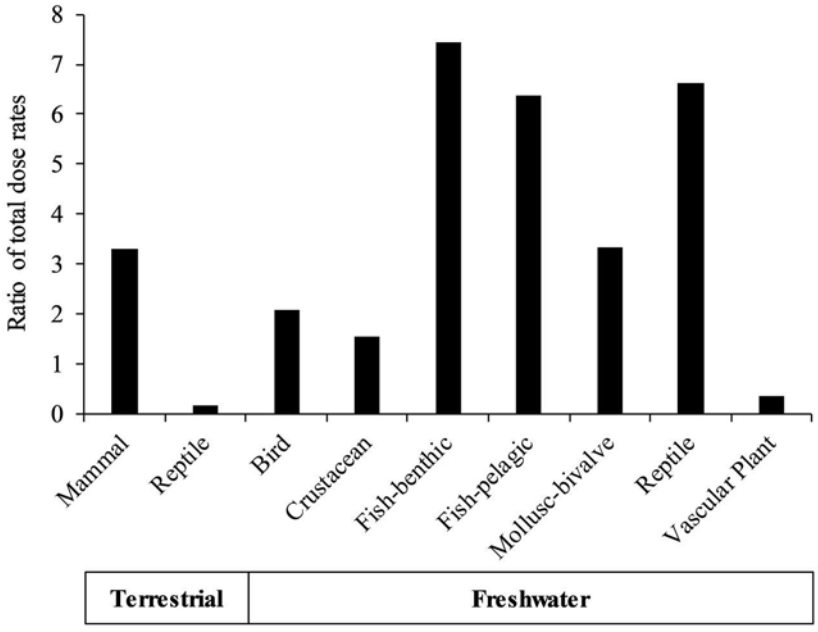

FIG. 9. Ratio of total dose rates to wildlife from the Alligator Rivers Region analysis to those calculated using data from TRS 479 [2].

2.4.3. Summary of using the prioritization approach for naturally occurring radionuclides at uranium mine sites

Prioritization analysis using both data from the IAEA compilation [2] and site specific data for the Alligator Rivers Region in Australia identifies the general priority order of radionuclides for environmental exposure of wildlife at uranium mine sites as ^{226}Ra > ^{210}Po and uranium isotopes > ^{210}Pb and thorium isotopes. Based on a comparison with data for the Alligator Rivers Region in Australia, the analysis also indicates that use of data from the TRS 479 compilation could under- or overestimate dose rates to wildlife at a specific uranium mine site due mostly (but not always) to differences between site specific values and the generic values for the $CR_{wo\text{-}media}$ and tissue conversion factors in the IAEA compilation. The implication is that care is needed when using the generic values of $CR_{wo\text{-}media}$ compiled by the IAEA for assessments for specific uranium mine sites, particularly if the purpose is to demonstrate compliance with regulatory requirements.

2.5. KEY OUTCOMES OF THE RADIONUCLIDE PRIORITIZATION ANALYSES

Different approaches were developed to rank the importance of anthropogenic and naturally occurring radionuclides in terms of their contribution to dose rates to wildlife. This prioritization study highlights that:

- It is possible to develop prioritization methods for a variety of ecosystems and exposure situations;
- The prioritization methods are dependent on the underlying data and are influenced by the data gaps and extrapolation approaches adopted;
- The outcome of the prioritization analysis is highly dependent on the amount of each radionuclide present in the source term. For naturally occurring radionuclides evaluated for uranium mine sites, it was assumed that all radionuclides are present and in secular equilibrium. This is likely to be a reasonably robust assumption for undisturbed environments [10] but disequilibrium between radionuclides may need to be investigated for specific sites. For planned releases from nuclear facilities as discussed in Section 2.3, it is very important to consider both the radionuclides discharged and the quantites of each radionuclide discharged, which has been done;
- Prioritization depends on a complex interaction between environmental, physical and biological factors and wildlife groups considered, as well as the relative amounts of each radionuclide in the source term or the environmental medium to which the wildlife are exposed. Some of the radionuclides identified as ranking highly with respect to dose rates to wildlife, had few if any $CR_{wo\text{-}soil}$ values, whereas some ranking less highly had many;
- The contribution of ^{226}Ra and ^{210}Po to total dose rate is likely to be the most important for terrestrial and freshwater wildlife groups for situations where wildlife groups are exposed to naturally occurring radionuclides from the uranium decay series, for example for uranium mine sites;
- It is likely to be useful to revisit the prioritization exercises as new data (from experiments, field studies or validation of an extrapolation method) become available, particularly for elements for which currently there are few data, to help focus ongoing research and measurement programmes.

The need to address data gaps is often focused on radioecological data. However, in the study on natural radionuclides, site specific measurements for the conversion factor from measured tissues to whole organism were used in some cases rather than the value compiled by the IAEA [2]. The outcome was a large change in the dose contribution from ^{226}Ra and nearly one order of magnitude difference in the estimated total dose rate to some wildlife groups. This difference emphasizes the importance of reliable ancillary information, such as tissue to whole organism conversion factors, in addition to radionuclide transfer data and the need for site specific data for complex assessments. Consideration of important data gaps needs to consider both radioecological transfer data and ancillary information, including tissue conversion factors.

The need for data specific to different organisms may be less critical than expected. In a recent, separate, evaluation of some $CR_{wo\text{-}media}$ values in TRS 479 [2], only a few values differed significantly (e.g. when mammals were categorized by feeding strategy) amongst specific taxonomic groups [33]. The observations argue in favour of the use of the same transfer parameter values for different organisms within a taxonomic group and deserve to be more deeply investigated to determine their impact with regard to the ranking of radionuclides as outlined here.

The update and enhancement of available transfer parameter data as discussed in Section 3 partly addresses the need to improve available data underlined by the process of prioritization. It also facilitates improved sensitivity analysis by providing probability distributions for some transfer parameters.

3. UPDATING ANIMAL PRODUCT TRANSFER PARAMETER VALUES FOR COW AND GOAT MILK

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3.1. INTRODUCTION

This section covers work undertaken within the Working Group to revise and extend the datasets in IAEA publications [1, 2, 34, 35] for transfer of radionuclides to animal products, focusing on cow and goat milk. The IAEA has compiled transfer parameter values for animal products in TRS 364, Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Temperate Environments, published in 1994 [34] and has revised them in TRS 472 published in 2010 [1] supported by IAEA-TECDOC-1616, Quantification of Radionuclide Transfer in Terrestrial and Freshwater Environments for Radiological Assessments [35]. The tables in these publications provide animal transfer parameter values for milk (cow, goat and sheep) and meat products (beef, goat meat, mutton, poultry and pork), and for eggs. In addition, aggregated transfer values are reported in TRS 479 [2] for seminatural animal food products.

The transfer coefficient, defined as the equilibrium ratio of the activity concentration in milk or meat (on a fresh mass basis) to the daily dietary radionuclide intake, has been widely adopted as the basis for quantifying transfer to milk (F_m, d/L or d/kg) and meat (F_f, d/kg) and eggs for all radionuclides [36, 37].

For many years, it was generally accepted that transfer coefficients for smaller animals were higher than those for larger animals, so those for adults are lower than those for younger livestock. Reports have suggested that much of this difference was because transfer coefficients incorporate daily dry matter intake (*DMI*, kg/d), which increases with animal size [38, 39]. An alternative approach to quantifying transfer is to remove the dietary intake used in the estimation of F_m or F_f, and simply calculate the concentration ratio, *CR*, defined as the equilibrium ratio between the radionuclide activity concentration in the animal food product (Bq/kg fresh mass) divided by the radionuclide activity concentration in the feedstuff ingested (Bq/kg dry mass). Values for *CR* were first provided in TRS 472 [1] and are now often reported for animal products.

The widespread use of compiled values from large reviews of data, for example as published by the IAEA in TRS 364 [34], can lead to a situation where new and valuable data are not incorporated into models at regular intervals when they become available. Instead, updating of such compiled values tends to follow that of the IAEA review cycle which has been at long intervals, often exceeding a decade. Within the MODARIA programme, it was recognized that mechanisms to produce more frequent revisions of transfer parameter tables need to be explored. Any revision of the datasets needs to be in a formal published format, such as in a TRS publication or a TECDOC, so that the version of the data used can be appropriately referenced in assessments.

Current problems encountered in using the compiled datasets published by the IAEA include the provenance of the data reviewed and compiled, transparency of changes made between compilations, how the source data were evaluated and the available documentation and consistency of data quality checks. When carrying out assessments, or using the parameter

values in models, clear information on how and why the recommended values have changed is needed. Therefore, such ancillary information needs to be made available.

One of the aims of MODARIA WG4 was to substantially enhance some of the animal product datasets and associated tables for both F_m and CR for cow and goat milk. The details of the procedures adopted for the evaluation and compilation of the data described here are published elsewhere [40, 41].

3.2. THE SERIES OF IAEA COMPILATIONS ON ANIMAL PRODUCT TRANSFER FACTORS

3.2.1. IAEA Technical Reports Series 364

The animal product tables for F_f and F_m [34] were compiled by the end of 1992 and published in 1994. Some studies conducted in the former Union of Soviet Socialist Republics were also included from a limited number of translated monographs and reviews. The compilation included values that were reported as 'unassociated' transfer coefficients [42], i.e. derived using separate data sources for element concentrations in animal products and feed. The animal product tables given in Ref. [34] provided 'Expected F_f and F_m' values and ranges. 'Less than' values were included (i.e. values below detection limits) and the type of experimental or source data was given in footnotes to the tables. Many of the data values compiled were derived from other literature reviews [42–47].

3.2.2. IAEA Technical Reports Series 472

The F_f, F_m and CR values [1] were compiled up to 2007 under the EMRAS programme and published in Refs [1, 35]. The dataset incorporates data for both radionuclides and stable elements. The sources of information used are given in Figure 6.1 of TECDOC 1616 [35]; they include data published since the early 1990s and an extensive review of Russian language publications reporting studies conducted in the former Union of Soviet Socialist Republics [48–51]. Detailed information on the approach taken to derive the tables and supplementary information can be found in the accompanying TECDOC [35] and other publications [36, 37].

CR values were included in cases where they were also reported in the source data used to generate the F_m or F_f values. These CR values were supplemented with values based on stable element concentrations in animal products and feed. Values from the literature for stable element concentrations were collated for each of the animal product. For concentrations in animal feed, a limited amount of data was collated from key agricultural compilations [51–55]. The arithmetic mean (AM) of the collated values of concentrations of a given element in animal products from the literature was then divided by the AM of concentrations of the element in animal feed to derive a CR value.

3.2.3. Revision of transfer factor tables

The revision of animal product datasets was prioritised based on the available resources. The first two revised animal product datasets that have been completed are for dairy goat milk and dairy cow milk. The detailed procedures used for the review and evaluation of data are published elsewhere [40, 41] and a summary is given here.

3.3. APPROACHES USED FOR THE GOAT AND COW MILK PRODUCT TRANSFER FACTOR TABLES

An approach was adopted that reviewed and evaluated the provenance and quality of the data in the literature on transfer to cow and goat milk. The procedures used are described in full

elsewhere [40, 41]. Firstly, various quality control procedures were implemented for the compilation of the goat and cow milk datasets. A quality check was performed on all original data used in TRS 472 [1], tracing the F_m and *CR* values back to their original sources. Discrepancies and outliers were further examined. Values were removed if the data could not be verified, if values used were not consistent with compiled values from reported Russian language studies [48], or if the stable element intake exceeded the maximum tolerable mineral levels[1] in feed advised for goats or cows [53]. Some duplication of data was removed, as were a few 'less than' values. Other values were removed due to possible cross-contamination issues (for a complete list of reasons for data removal, see Refs [40, 41]).

A further literature search was then conducted. Additional values were included in both the goat and cow milk datasets if they reported an F_m or *CR* values, or if these could be calculated from the raw data. Both datasets were further enhanced with stable element 'agricultural review' values, which enabled a *CR* value to be calculated from concentrations of stable elements in goat or cow milk and animal feed (pasture grass, forage grass or mixed herbage) for many elements. An F_m value for an element was only included in the dataset when more than five independent measurements of stable element concentrations in cow or goat milk were available.

There is a positive linear relationship between the body mass of an animal and the daily dry matter intake (*DMI*) [56]. The adoption of assumptions for changes in liveweight for cows and goats over several decades, for which relevant data have been reported, enabled *DMI* values to be estimated where they were not explicitly reported in individual studies. This has enabled the conversion of previously reported F_m values to *CR* values, which has increased the number of *CR* values in the goat and cow milk datasets compared with those reported in TRS 472. The approaches used to estimate the *DMI* values for dairy goats and dairy cows are described in Refs [40, 41].

A number of changes have been made in the criteria adopted for accepting data into the dataset presented here compared to the approach used in TRS 472 [1]. These criteria are more rigorous and consistent than those used previously and details are provided in Refs [40, 41].

For each element for which transfer parameters are reported in Tables 24–27, the AM and arithmetic standard deviation (ASD) have been calculated. Where the sample size is N≥3, the geometric mean (GM) and geometric standard deviation (GSD) have also been calculated.

3.4. GOAT MILK DATASET

The goat milk dataset includes data for an increased number of elements, compared with that in TRS 472 [1]; in the case of F_m, the number of elements has increased from 28 to 33, and for *CR*, it has increased from 21 to 34. The goat milk dataset values are given in Tables 24 and 25 for F_m and *CR*, respectively.

In TRS 472 [1], the F_m for Co was based upon a single value from Ref. [57]; this value has been removed as part of the quality control procedures followed during the construction of the goat milk dataset. No further *CR* values have been identified for Co. Within the goat milk dataset, other data gaps remain for radionuclides potentially relevant for radiological impact assessment (e.g. many naturally occurring radionuclides, plutonium and americium).

[1] The maximum tolerable level of a mineral is defined as the dietary level that, when fed for a defined period of time, will not impair animal health ot performance. For some minerals (e.g. silica, iron and aluminium), the maximum tolerable level may very by several orders of magnitude depending upon the chemical form of the mineral [53].

TABLE 24. TRANSFER COEFFICIENTS (F_m, d/kg) FOR GOAT MILK

Element	N	AM	ASD	GM	GSD	Min	Max
As	1	1.5×10^{-2}	n.a.	n.a.	n.a.		
Am	2	2.8×10^{-5}	n.a.	n.a.	n.a.	3.7×10^{-6}	5.2×10^{-5}
Ba	2	3.3×10^{-3}	n.a.	n.a.	n.a.	2.1×10^{-3}	4.6×10^{-3}
Ca	11	1.5×10^{-1}	2.1×10^{-1}	9.3×10^{-2}	2.7	1.2×10^{-2}	7.6×10^{-1}
Cd	4	2.1×10^{-3}	2.4×10^{-3}	9.6×10^{-4}	4.9	1.7×10^{-4}	5.4×10^{-3}
Ce	1	4.0×10^{-5}	n.a.	n.a.	n.a.	n.a.	n.a.
Cr	1	2.9×10^{-3}	n.a.	n.a.	n.a.	n.a.	n.a.
Cs	27	1.4×10^{-1}	7.9×10^{-2}	1.1×10^{-1}	2.1	9.0×10^{-3}	3.3×10^{-1}
Cu	5	3.1×10^{-2}	2.8×10^{-2}	2.3×10^{-2}	2.3	9.7×10^{-3}	7.8×10^{-2}
Fe	1	4.0×10^{-2}	n.a.	n.a.	n.a.	n.a.	n.a.
Hg	4	2.3×10^{-2}	4.6×10^{-2}	4.8×10^{-4}	38.6	2.2×10^{-5}	9.3×10^{-2}
I	23	3.2×10^{-1}	2.3×10^{-1}	2.1×10^{-1}	3.0	2.7×10^{-2}	7.7×10^{-1}
Li	1	3.0×10^{-2}	n.a.	n.a.	n.a.	n.a.	n.a.
Mg	2	3.8×10^{-2}	n.a.	n.a.	n.a.	2.9×10^{-2}	4.7×10^{-2}
Mn	2	3.4×10^{-2}	n.a.	n.a.	n.a.	1.5×10^{-3}	6.6×10^{-2}
Mo	5	1.1×10^{-2}	5.1×10^{-3}	1.1×10^{-2}	1.6	5.4×10^{-3}	1.9×10^{-2}
Na	3	2.4×10^{-1}	2.4×10^{-1}	1.8×10^{-1}	2.5	1.0×10^{-1}	5.1×10^{-1}
Nb	1	6.4×10^{-6}	n.a.	n.a.	n.a.	n.a.	n.a.
Ni	1	3.2×10^{-3}	n.a.	n.a.	n.a.	n.a.	n.a.
Np	1	5.3×10^{-5}	n.a.	n.a.	n.a.	n.a.	n.a.
P	2	1.6×10^{-1}	n.a.	n.a.	n.a.	5.5×10^{-2}	2.6×10^{-1}
Pb	1	3.7×10^{-2}	n.a.	n.a.	n.a.	n.a.	n.a.
Pm	1	2.7×10^{-5}	n.a.	n.a.	n.a.	n.a.	n.a.
Po	2	2.3×10^{-3}	n.a.	n.a.	n.a.	1.8×10^{-3}	2.7×10^{-3}
S	12	4.7×10^{-2}	1.9×10^{-2}	3.8×10^{-2}	1.7	1.6×10^{-2}	6.8×10^{-2}
Se	4	7.2×10^{-2}	2.9×10^{-2}	6.8×10^{-2}	1.5	4.1×10^{-2}	1.1×10^{-1}
Sr	21	2.0×10^{-2}	1.9×10^{-2}	1.5×10^{-2}	2.0	5.8×10^{-3}	8.1×10^{-2}
Te	1	4.4×10^{-3}	n.a.	n.a.	n.a.	n.a.	n.a.
Ti	1	1.5×10^{-4}	n.a.	n.a.	n.a.	n.a.	n.a.
U	1	1.4×10^{-3}	n.a.	n.a.	n.a.	n.a.	n.a.
Y	1	2.0×10^{-5}	n.a.	n.a.	n.a.	n.a.	n.a.
Zn	7	4.8×10^{-2}	2.3×10^{-2}	4.3×10^{-2}	1.6	2.6×10^{-2}	8.6×10^{-2}
Zr	1	5.5×10^{-6}	n.a.	n.a.	n.a.	n.a.	n.a.

N: Sample size; AM: Arithmetic Mean; ASD: Arithmetic Standard Deviation; GM: Geometric Mean; GSD: Geometric Standard Deviation; Min: Minimum; Max: Maximum; n.a.: Not applicable.

TABLE 25. CONCENTRATION RATIOS (*CR*) FOR GOAT MILK DATASET

Element	N	AM	ASD	GM	GSD	Min	Max
As	1	9.6×10^{-3}	n.a.	n.a.	n.a.	n.a.	n.a.
Am	2	4.4×10^{-5}	n.a.	n.a.	n.a.	4.4×10^{-6}	8.4×10^{-5}
Ba	2	8.5×10^{-3}	n.a.	n.a.	n.a.	3.3×10^{-3}	1.4×10^{-2}
Ca	11	2.6×10^{-1}	3.3×10^{-1}	1.7×10^{-1}	2.6	1.9×10^{-2}	1.2×10^{0}
Cd	4	4.0×10^{-3}	4.8×10^{-3}	1.9×10^{-3}	4.4	3.9×10^{-4}	1.1×10^{-2}
Ce	1	6.4×10^{-5}	n.a.	n.a.	n.a.	n.a.	n.a.
Cr	1	4.6×10^{-3}	n.a.	n.a.	n.a.	n.a.	n.a.
Cs	26	2.2×10^{-2}	9.8×10^{-2}	2.0×10^{-1}	1.7	4.9×10^{-2}	4.3×10^{-1}
Cu	5	4.6×10^{-2}	4.7×10^{-2}	3.2×10^{-2}	2.6	1.2×10^{-2}	1.3×10^{-1}
Fe	1	7.8×10^{-2}	n.a.	n.a.	n.a.	n.a.	n.a.
Hg	4	4.7×10^{-2}	9.3×10^{-2}	7.3×10^{-4}	45.8	3.0×10^{-5}	1.9×10^{-1}
I	21	5.3×10^{-1}	4.0×10^{-1}	3.2×10^{-1}	3.1	4.4×10^{-2}	1.2×10^{0}
Li	1	4.8×10^{-2}	n.a.	n.a.	n.a.	n.a.	n.a.
Mg	2	6.1×10^{-2}	n.a.	n.a.	n.a.	4.6×10^{-2}	7.5×10^{-2}
Mn	2	5.4×10^{-2}	n.a.	n.a.	n.a.	2.3×10^{-3}	1.1×10^{-1}
Mo	5	2.0×10^{-2}	9.0×10^{-3}	1.8×10^{-2}	1.7	8.6×10^{-3}	3.0×10^{-2}
Na	3	3.9×10^{-1}	3.8×10^{-1}	2.9×10^{-1}	2.5	1.6×10^{-1}	8.2×10^{-1}
Nb	1	1.9×10^{-5}	n.a.	n.a.	n.a.	n.a.	n.a.
Ni	1	5.2×10^{-3}	n.a.	n.a.	n.a.	n.a.	n.a.
Np	1	8.4×10^{-5}	n.a.	n.a.	n.a.	n.a.	n.a.
P	2	2.2×10^{-1}	n.a.	n.a.	n.a.	2.1×10^{-2}	4.2×10^{-1}
Pb	1	4.8×10^{-2}	n.a.	n.a.	n.a.	n.a.	n.a.
Pm	1	4.3×10^{-5}	n.a.	n.a.	n.a.	n.a.	n.a.

TABLE 25. CONCENTRATION RATIOS (*CR*) FOR GOAT MILK DATASET (cont.)

Element	N	AM	ASD	GM	GSD	Min	Max
Po	2	3.6×10^{-3}	n.a.	n.a.	n.a.	2.9×10^{-3}	4.3×10^{-3}
S	12	8.3×10^{-2}	3.9×10^{-2}	7.3×10^{-2}	1.7	3.4×10^{-2}	1.3×10^{-1}
Se	4	1.1×10^{-1}	3.8×10^{-2}	1.0×10^{-1}	1.4	6.6×10^{-2}	1.5×10^{-1}
Sr	21	3.4×10^{-2}	3.2×10^{-2}	2.6×10^{-2}	2.1	9.3×10^{-3}	1.3×10^{-1}
Tc	1	1.0×10^{-1}	n.a.	n.a.	n.a.	n.a.	n.a.
Te	1	1.3×10^{-2}	n.a.	n.a.	n.a.	n.a.	n.a.
Ti	1	2.3×10^{-4}	n.a.	n.a.	n.a.	n.a.	n.a.
U	1	4.8×10^{-4}	n.a.	n.a.	n.a.	n.a.	n.a.
Y	1	3.2×10^{-5}	n.a.	n.a.	n.a.	n.a.	n.a.
Zn	7	7.4×10^{-2}	3.9×10^{-2}	6.5×10^{-2}	1.8	2.9×10^{-2}	1.4×10^{-1}
Zr	1	1.7×10^{-5}	n.a.	n.a.	n.a.	n.a.	n.a.

N: Sample size; AM: Arithmetic Mean; ASD: Arithmetic Standard Deviation; GM: Geometric Mean; GSD: Geometric Standard Deviation; Min: Minimum; Max: Maximum; n.a.: Not applicable.

3.5. COW MILK DATASET

In TRS 364 [34], a suggested value of 16.1 kg/d was given for daily *DMI* for dairy cows (range 10–25 kg/d), but it was recommended that location specific information is to be used, where possible. In TRS 472 [1], a suggested value was not provided, but the associated, more detailed TECDOC 1616 [35] quoted 16 kg/d, which was used in TRS 472 [1] to derive cow milk F_m values from *CR* values for some stable elements. The approach used to derive daily *DMI* for different ages of animals (specified in decades) and liveweights for the data provided by MODARIA WG4 are described in the Average UK Milk Yields reports of the UK Agriculture and Horticulture Development Board[2]. Variation in the estimated daily *DMI* used is unlikely to change derived F_m values by more than a factor of 2–3.

Some reported F_m values in TRS 472 [1] exceed 5.0×10^{-2} d/kg, which implies that 5% of the daily intake was secreted in each litre of milk. If a dairy cow is producing more than 20 L of milk a day, this value is clearly not possible. Each value of F_m in the dataset was re-examined, considering the milk production, and values that could not be justified were excluded from the dataset.

The revised cow milk dataset produced under MODARIA WG4 provides 43 F_m values compared with 31 in TRS 472 [1] and *CR* values for 43 elements compared with the 26 reported in TRS 472 [1]. The additional *CR* values have increased the number of data, underpinning the *CR* values from 254 to 824. The resulting AM values for *CR* for these elements are within an order of magnitude of those reported in TRS 472 [1], with the exception of those for Co. The F_m and *CR* parameter values for cow milk that were generated are listed in Tables 26 and 27, respectively.

Table 28 shows the 5th and 95th percentile and coefficient of variation (CV) for all elements in cow milk considered in the dataset produced under MODARIA WG4 that have at least 10 values included in the dataset.

For the elements for which there are more than 100 *CR* and F_m values in the cow milk dataset (Cs, I and Sr), the data have been transformed using a natural logarithm and the frequency distributions plotted (Figs 10–12). The histograms show that both F_m and *CR* have log-normal distributions.

[2] https://ahdb.org.uk/dairy/uk-milk-yield

TABLE 26. TRANSFER COEFFICIENTS (F_m, d/kg) FOR COW MILK

Element	N	AM	ASD	GM	GSD	Min	Max
Al	1	3.3×10^{-4}	n.a.	n.a.	n.a.	n.a.	n.a.
Am	3	1.0×10^{-5}	1.7×10^{-5}	1.6×10^{-6}	12.6	3.0×10^{-7}	3.0×10^{-5}
As	8	1.8×10^{-4}	1.2×10^{-4}	1.4×10^{-4}	2.2	4.3×10^{-5}	3.5×10^{-4}
Ba	17	2.7×10^{-4}	2.3×10^{-4}	1.8×10^{-4}	2.7	3.8×10^{-5}	7.3×10^{-4}
Ca	15	1.1×10^{-2}	4.7×10^{-3}	9.9×10^{-3}	1.6	4.0×10^{-3}	2.1×10^{-2}
Cd	13	2.2×10^{-3}	3.0×10^{-3}	2.6×10^{-4}	16.2	1.8×10^{-6}	7.9×10^{-3}
Ce	8	4.2×10^{-5}	4.5×10^{-5}	1.5×10^{-5}	6.7	1.0×10^{-6}	1.3×10^{-4}
Cl	3	2.4×10^{-2}	1.7×10^{-2}	1.8×10^{-2}	2.9	5.4×10^{-3}	3.9×10^{-2}
Co	16	1.9×10^{-3}	3.0×10^{-3}	3.2×10^{-4}	9.2	2.2×10^{-5}	1.0×10^{-2}
Cr	3	1.3×10^{-3}	1.1×10^{-3}	3.4×10^{-4}	21.0	1.0×10^{-5}	2.1×10^{-3}
Cs	289	6.7×10^{-3}	7.7×10^{-3}	4.9×10^{-3}	2.1	6.0×10^{-4}	5.7×10^{-2}
Cu	16	3.0×10^{-4}	2.3×10^{-4}	2.0×10^{-4}	2.8	3.8×10^{-5}	8.0×10^{-4}
Fe	13	8.8×10^{-3}	1.4×10^{-4}	3.7×10^{-5}	3.8	4.9×10^{-6}	4.5×10^{-4}
Ga	1	6.5×10^{-3}	n.a.	n.a.	n.a.	n.a.	n.a.
Hf	1	3.3×10^{-3}	n.a.	n.a.	n.a.	n.a.	n.a.
Hg	5	2.8×10^{-3}	4.9×10^{-3}	8.3×10^{-4}	5.6	1.0×10^{-4}	1.2×10^{-2}
I	105	9.2×10^{-3}	8.3×10^{-3}	6.0×10^{-3}	2.7	4.0×10^{-4}	4.4×10^{-2}
K	2	4.4×10^{-3}	n.a.	n.a.	n.a.	2.9×10^{-3}	5.9×10^{-3}
Mg	3	2.6×10^{-3}	9.1×10^{-4}	2.6×10^{-3}	1.4	1.7×10^{-3}	3.5×10^{-3}
Mn	16	3.9×10^{-5}	8.0×10^{-5}	1.3×10^{-5}	4.9	5.2×10^{-7}	3.3×10^{-4}
Mo	13	1.8×10^{-3}	1.8×10^{-3}	1.2×10^{-3}	2.6	2.8×10^{-4}	5.9×10^{-3}
N	1	1.2×10^{-2}	n.a.	n.a.	n.a.	n.a.	n.a.
Na	9	1.9×10^{-2}	1.3×10^{-2}	1.6×10^{-2}	1.7	9.8×10^{-3}	5.0×10^{-2}
Nb	1	4.1×10^{-7}	n.a.	n.a.	n.a.	n.a.	n.a.
Ni	5	4.7×10^{-3}	5.3×10^{-3}	2.5×10^{-3}	3.8	6.1×10^{-4}	1.4×10^{-2}
P	4	7.1×10^{-3}	6.7×10^{-3}	4.1×10^{-3}	3.7	1.1×10^{-3}	1.5×10^{-2}
Pb	22	4.2×10^{-4}	4.2×10^{-4}	2.3×10^{-4}	3.7	1.1×10^{-5}	1.7×10^{-3}
Po	4	2.5×10^{-4}	8.9×10^{-4}	2.4×10^{-4}	1.6	1.2×10^{-4}	3.0×10^{-4}
Pu	3	1.7×10^{-4}	2.8×10^{-4}	3.6×10^{-5}	9.8	7.5×10^{-6}	5.0×10^{-4}
Ra	15	6.9×10^{-4}	5.2×10^{-4}	4.6×10^{-4}	2.5	1.1×10^{-4}	1.8×10^{-3}
Rb	1	6.5×10^{-3}	n.a.	n.a.	n.a.	n.a.	n.a.
Ru	6	3.6×10^{-5}	5.4×10^{-5}	9.4×10^{-6}	8.5	6.7×10^{-7}	1.4×10^{-4}
S	2	8.4×10^{-3}	n.a.	n.a.	n.a.	7.9×10^{-3}	8.9×10^{-3}
Sb	3	5.2×10^{-5}	5.1×10^{-5}	3.8×10^{-5}	2.5	2.0×10^{-5}	1.1×10^{-4}
Se	27	4.8×10^{-3}	3.2×10^{-3}	3.8×10^{-3}	2.1	6.7×10^{-4}	1.3×10^{-2}
Sr	118	1.5×10^{-3}	8.3×10^{-4}	1.3×10^{-3}	2.1	1.5×10^{-5}	4.3×10^{-3}
Te	11	4.2×10^{-4}	2.6×10^{-4}	3.2×10^{-4}	2.3	7.8×10^{-5}	1.0×10^{-3}
Th	3	3.7×10^{-3}	4.6×10^{-3}	1.4×10^{-3}	7.8	1.5×10^{-4}	8.9×10^{-3}
Ti	1	1.6×10^{-2}	n.a.	n.a.	n.a.	n.a.	n.a.
U	7	3.1×10^{-3}	1.7×10^{-3}	2.5×10^{-3}	2.2	5.0×10^{-4}	6.1×10^{-3}
W	7	3.3×10^{-4}	2.1×10^{-4}	2.6×10^{-4}	2.4	5.0×10^{-5}	6.8×10^{-4}
Zn	18	3.6×10^{-3}	1.8×10^{-3}	2.8×10^{-3}	2.5	1.3×10^{-4}	6.9×10^{-3}
Zr	6	7.1×10^{-6}	6.9×10^{-6}	3.6×10^{-6}	4.3	5.5×10^{-5}	1.7×10^{-5}

N: Sample size; AM: Arithmetic Mean; ASD: Arithmetic Standard Deviation; GM: Geometric Mean; GSD: Geometric Standard Deviation; Min: Minimum; Max: Maximum; n.a.: Not applicable.

TABLE 27. CONCENTRATION RATIOS (*CR*) FOR COW MILK

Element	N	AM	ASD	GM	GSD	Min	Max
Al	1	5.7×10^{-3}	n.a.	n.a.	n.a.	n.a.	n.a.
Am	3	2.1×10^{-4}	3.6×10^{-4}	7.7×10^{-6}	1.4	6.2×10^{-6}	6.2×10^{-4}
As	8	3.7×10^{-3}	2.6×10^{-3}	2.8×10^{-3}	2.2	9.0×10^{-4}	7.4×10^{-3}
Ba	17	7.7×10^{-3}	1.5×10^{-2}	3.2×10^{-3}	3.7	3.8×10^{-4}	6.2×10^{-2}
Ca	15	1.7×10^{-1}	8.1×10^{-2}	1.5×10^{-1}	1.7	5.2×10^{-2}	3.6×10^{-1}
Cd	13	4.5×10^{-2}	6.2×10^{-2}	5.1×10^{-3}	17	2.7×10^{-5}	1.6×10^{-1}
Ce	8	7.3×10^{-4}	1.1×10^{-3}	1.9×10^{-4}	8.4	1.0×10^{-5}	3.2×10^{-3}
Cl	3	2.1×10^{-1}	2.1×10^{-1}	1.5×10^{-1}	2.6	7.4×10^{-2}	4.5×10^{-1}
Co	16	4.7×10^{-2}	7.3×10^{-2}	6.1×10^{-3}	11.3	4.5×10^{-4}	2.4×10^{-1}
Cr	3	2.7×10^{-2}	2.3×10^{-2}	6.1×10^{-3}	25.5	1.5×10^{-2}	4.3×10^{-2}
Cs	289	1.1×10^{-1}	1.1×10^{-1}	8.4×10^{-2}	2.1	3.6×10^{-3}	9×10^{-1}
Cu	16	6.1×10^{-3}	4.7×10^{-3}	3.8×10^{-3}	3.2	5.3×10^{-4}	1.6×10^{-2}

TABLE 27. CONCENTRATION RATIOS (*CR*) FOR COW MILK (cont.)

Element	N	AM	ASD	GM	GSD	Min	Max
Fe	13	1.8×10^{-3}	3.0×10^{-3}	5.9×10^{-4}	4.4	1.0×10^{-4}	9.7×10^{-3}
Ga	1	1.3×10^{-1}	n.a.	n.a.	n.a.	n.a.	n.a.
Hf	1	6.6×10^{-2}	n.a.	n.a.	n.a.	n.a.	n.a.
Hg	5	5.1×10^{-2}	8.8×10^{-2}	2.6×10^{-2}	5.8	1.8×10^{-3}	2.1×10^{-1}
I	105	2.0×10^{-1}	2.3×10^{-1}	1.1×10^{-1}	3.1	3.0×10^{-3}	1.1×10^{-1}
K	2	8.2×10^{-2}	n.a.	n.a.	n.a.	6.2×10^{-2}	1.0×10^{-1}
Mg	3	5.3×10^{-2}	2.1×10^{-2}	5.0×10^{-2}	1.5	3.5×10^{-2}	7.6×10^{-2}
Mn	16	8.9×10^{-4}	2.0×10^{-3}	2.7×10^{-4}	4.7	1.9×10^{-5}	8.2×10^{-3}
Mo	13	3.1×10^{-2}	2.8×10^{-2}	2.2×10^{-2}	2.6	3.9×10^{-3}	1.0×10^{-1}
N	1	2.0×10^{-1}	n.a.	n.a.	n.a.	n.a.	n.a.
Na	9	2.7×10^{-1}	1.6×10^{-1}	2.3×10^{-1}	1.9	9.8×10^{-2}	5.0×10^{-1}
Nb	1	9.0×10^{-6}	n.a.	n.a.	n.a.	n.a.	n.a.
Ni	5	1.4×10^{-1}	1.6×10^{-1}	6.2×10^{-2}	4.7	1.3×10^{-2}	4.0×10^{-1}
P	4	1.5×10^{-1}	1.3×10^{-1}	1.0×10^{-1}	2.7	4.1×10^{-2}	3.1×10^{-1}
Pb	22	9.1×10^{-3}	1.0×10^{-2}	5.0×10^{-3}	3.4	4.1×10^{-4}	4.0×10^{-2}
Po	4	4.0×10^{-3}	1.5×10^{-3}	3.8×10^{-3}	1.6	2.4×10^{-3}	5.4×10^{-3}
Pu	3	1.8×10^{-3}	2.8×10^{-3}	4.3×10^{-4}	9.6	5.8×10^{-5}	5.0×10^{-3}
Ra	15	1.3×10^{-2}	1.1×10^{-2}	8.9×10^{-3}	2.6	1.9×10^{-3}	4.0×10^{-2}
Rb	1	1.3×10^{-1}	n.a.	n.a.	n.a.	n.a.	n.a.
Ru	6	3.6×10^{-4}	5.3×10^{-4}	1.0×10^{-4}	7.4	1.0×10^{-5}	1.4×10^{-3}
S	2	1.5×10^{-1}	n.a.	n.a.	n.a.	1.4×10^{-1}	1.5×10^{-1}
Sb	3	1.1×10^{-3}	1.4×10^{-3}	5.9×10^{-4}	3.9	2.0×10^{-4}	2.7×10^{-3}
Se	27	9.6×10^{-2}	6.4×10^{-2}	6.3×10^{-2}	2.3	1.3×10^{-2}	2.3×10^{-1}
Sr	118	2.1×10^{-2}	1.5×10^{-2}	1.7×10^{-2}	1.9	5.6×10^{-4}	1.4×10^{-1}
Te	11	7.2×10^{-3}	3.2×10^{-3}	6.1×10^{-3}	2.0	1.4×10^{-3}	1.1×10^{-2}
Th	3	3.7×10^{-2}	4.5×10^{-2}	1.8×10^{-2}	5.4	3.1×10^{-3}	8.9×10^{-2}
Ti	1	3.2×10^{-1}	n.a.	n.a.	n.a.	n.a.	n.a.
U	7	3.1×10^{-2}	1.7×10^{-2}	2.5×10^{-2}	2.2	5.0×10^{-3}	6.1×10^{-2}
W	7	5.9×10^{-3}	3.9×10^{-3}	4.3×10^{-3}	2.9	5.0×10^{-4}	1.2×10^{-2}
Zn	18	6.9×10^{-2}	2.6×10^{-2}	6.1×10^{-2}	1.5	2.9×10^{-2}	1.2×10^{-1}
Zr	6	7.2×10^{-5}	6.8×10^{-5}	4.1×10^{-5}	3.6	1.0×10^{-5}	1.7×10^{-4}

N: Sample size; AM: Arithmetic Mean; ASD: Arithmetic Standard Deviation; GM: Geometric Mean; GSD: Geometric Standard Deviation; Min: Minimum; Max: Maximum; n.a.: Not applicable.

TABLE 28. COMPILATION OF TRANSFER COEFFICIENT (F_m, d/kg) AND CONCENTRATION RATIO (*CR*) STATISTICS, SHOWING 5TH AND 95TH PERCENTILES AND COEFFICIENT OF VARIATION (%) FOR ELEMENTS FOR WHICH N ≥10 IN THE COW MILK DATASET

Element	N	F_m			*CR*		
		5th	95th	CV %	5th	95th	CV %
Ba	17	4.8×10^{-5}	6.4×10^{-4}	11	4.8×10^{-4}	2.4×10^{-2}	23
Ca	15	4.8×10^{-3}	1.9×10^{-2}	10	6.5×10^{-2}	2.9×10^{-1}	27
Cd	13	2.1×10^{-5}	7.2×10^{-3}	33	4.3×10^{-4}	1.5×10^{-1}	56
Co	16	2.4×10^{-5}	1.1×10^{-2}	30	4.5×10^{-4}	1.7×10^{-1}	47
Cs	288	1.6×10^{-3}	1.8×10^{-2}	14	1.8×10^{-2}	2.7×10^{-1}	30
Cu	16	2.2×10^{-5}	6.5×10^{-4}	12	7.2×10^{-4}	1.3×10^{-2}	21
Fe	13	6.6×10^{-6}	3.9×10^{-4}	13	1.0×10^{-4}	8.1×10^{-3}	20
I	105	1.1×10^{-3}	2.4×10^{-2}	19	2.0×10^{-2}	7.2×10^{-1}	53
Mn	16	2.5×10^{-6}	4.3×10^{-4}	13	3.8×10^{-5}	2.5×10^{-3}	19
Mo	13	3.4×10^{-4}	5.5×10^{-3}	14	6.3×10^{-3}	8.0×10^{-2}	25
Pb	22	1.7×10^{-5}	1.2×10^{-3}	14	4.9×10^{-4}	3.5×10^{-2}	23
Ra	15	1.3×10^{-4}	1.5×10^{-3}	12	2.2×10^{-3}	3.3×10^{-2}	20
Se	27	9.9×10^{-4}	1.1×10^{-2}	14	1.5×10^{-2}	2.2×10^{-1}	32
Sr	118	4.5×10^{-4}	2.9×10^{-3}	10	7.2×10^{-3}	4.2×10^{-2}	16
Te	11	9.3×10^{-5}	8.0×10^{-4}	10	1.7×10^{-3}	1.0×10^{-2}	13
Zn	18	1.2×10^{-3}	6.1×10^{-3}	15	3.5×10^{-2}	1.1×10^{-1}	14

N: Sample size; CV: Coefficient of Variation; 5th: 5th percentile; 95th: 95th percentile.

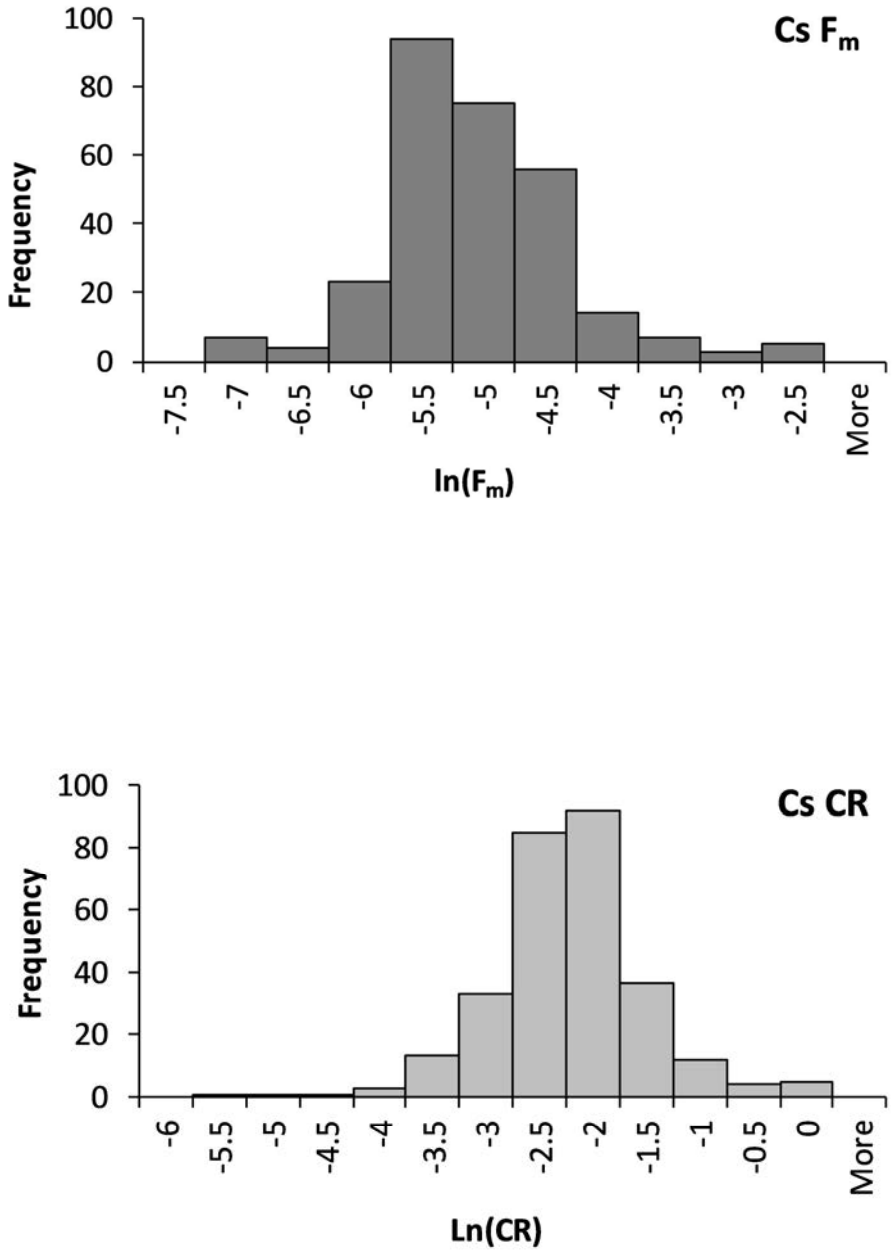

FIG. 10. Histogram for transfer coefficient (F_m, d/kg) and concentration ratio (CR) for Cs data entries in the cow milk dataset.

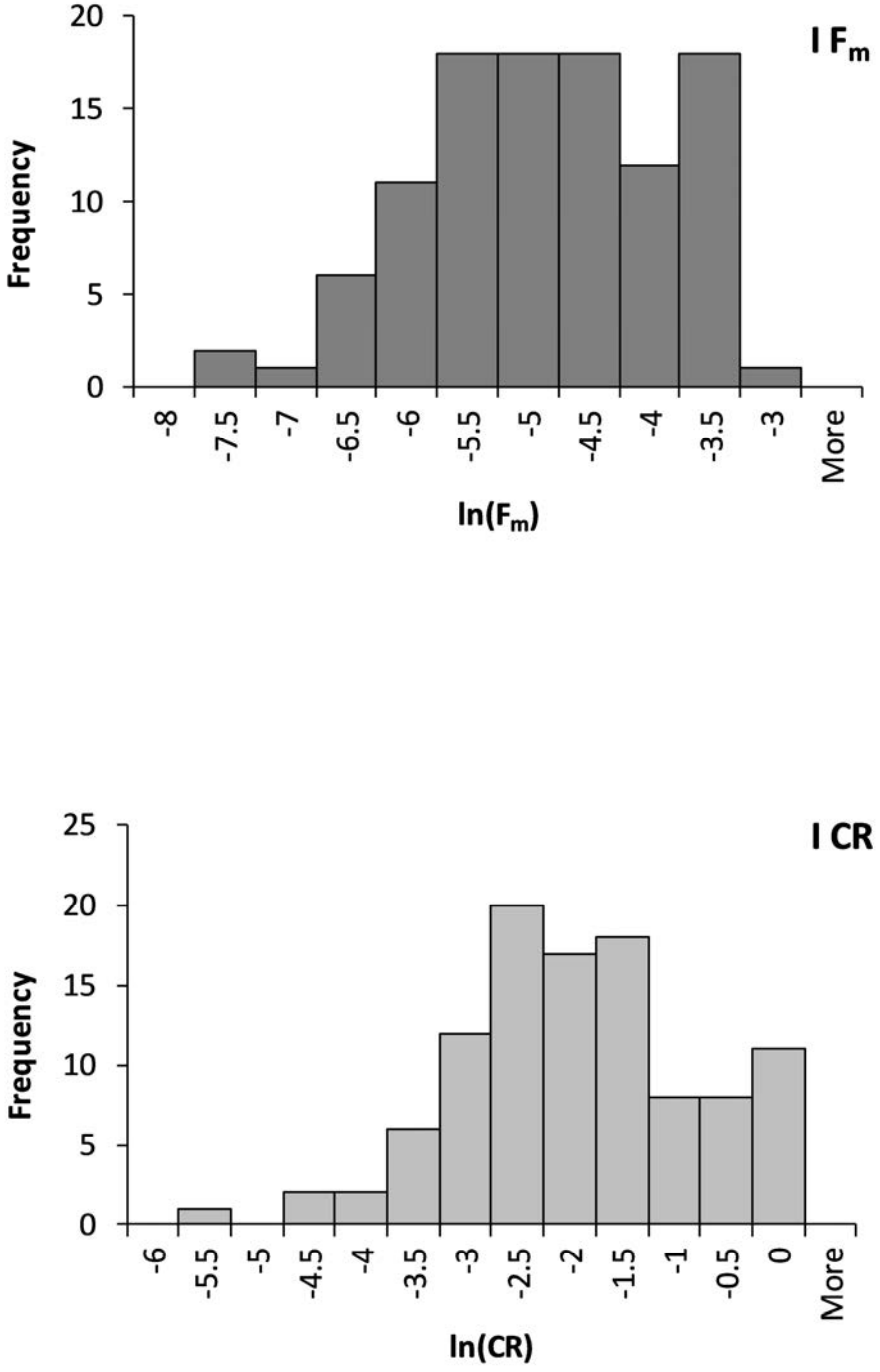

FIG. 11. Histogram for transfer coefficient (F_m, d/kg) and concentration ratio (CR) for I data entries in the cow milk dataset.

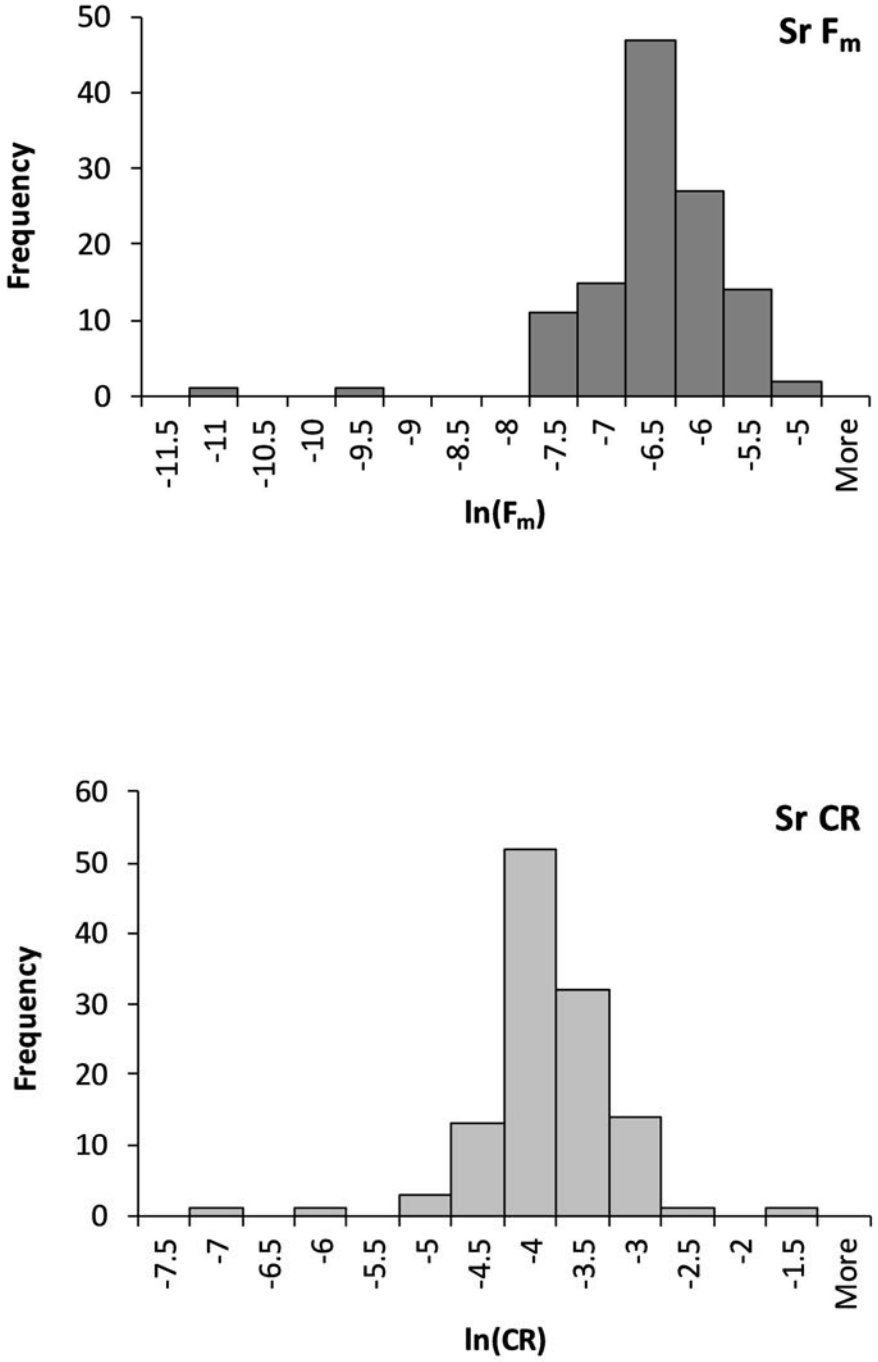

FIG. 12. Histogram for transfer coefficient (F_m, d/kg) and concentration ratio (CR) for Sr data entries in the cow milk dataset.

3.6. RELATIONSHIP BETWEEN GASTROINTESTINAL ABSORPTION AND TRANSFER PARAMETERS FOR RADIONUCLIDES IN MILK

Although many data are available for radioisotopes of three elements (Cs, Sr and I), there are still many data gaps for potentially important radionuclides for radiological impact assessment in the goat and cow milk datasets. Recently, there has been a critical evaluation of the adequacy of the methods used to provide parameter values for missing element or radionuclide/wildlife combinations [4]. Such methods include the use of element analogues, Bayesian statistics, or similar products (e.g. using sheep milk or goat milk as a proxy for cow milk) and modelling. An alternative method is explored here, based on the hypothesis that gut absorption can be used to predict transfer parameters for animal products.

As part of the work of MODARIA WG4, an approach was developed that used a relationship between gastrointestinal absorption in ruminants and the transfer to milk to predict radionuclide transfer to animal products. Detailed information on the procedures used for further revision of the datasets is given in Ref. [58], so only a summary is provided here.

For a radioisotope to be present in milk or meat, it must pass through the wall of the ruminant's gastrointestinal tract. Therefore, it can be expected that fractional absorption (F_a), which varies considerably between different elements, may be correlated with transfer parameter values for milk and meat. The correlation would be expected to vary by animal product and by element, as some elements are homeostatically controlled and others accumulate in certain tissues. Therefore, a hypothesis that there is a relationship between fractional absorption in ruminants and the transfer of elements or radioisotopes to milk was tested. Such a relationship would allow the prediction of missing data if data on fractional absorption were available.

3.6.1. The use of absorption to predict transfer coefficient and concentation ratio for milk

The source of ruminant F_a values used for this study [48] were the values reported in TRS 472 [1] and also in Ref. [36]. The latter paper incorporated a review of Russian language information on ruminant absorption which was written after the data for TRS 472 were compiled. The values of F_m used were those given in Tables 24 and 26 for the goat and cow milk datasets. The study [48] focused on goat and cow milk, as it was anticipated that these products are likely to be directly influenced by absorption in the gut and subsequent presence of elements in the plasma, whereas for meat, the influence of longer and differing biological half-lives for different elements may reduce the correlation.

A strong relationship was derived between the GM of F_a and those of either F_m or CR [59]. The correlation between ruminant absorption and CR can be seen in Figs 13 and 14 for goat milk and cow milk, respectively.

The correlations shown in Figs 13 and 14, and in the associated publication [58], for goat and cow milk, respectively, are adequately robust to assume that a published value of F_a can be used to derive a value of F_m or CR. When published fractional absorption values for specific elements in ruminants are not available, the F_a values reported by the ICRP [59] can be used as a surrogate to estimate F_m or CR values.

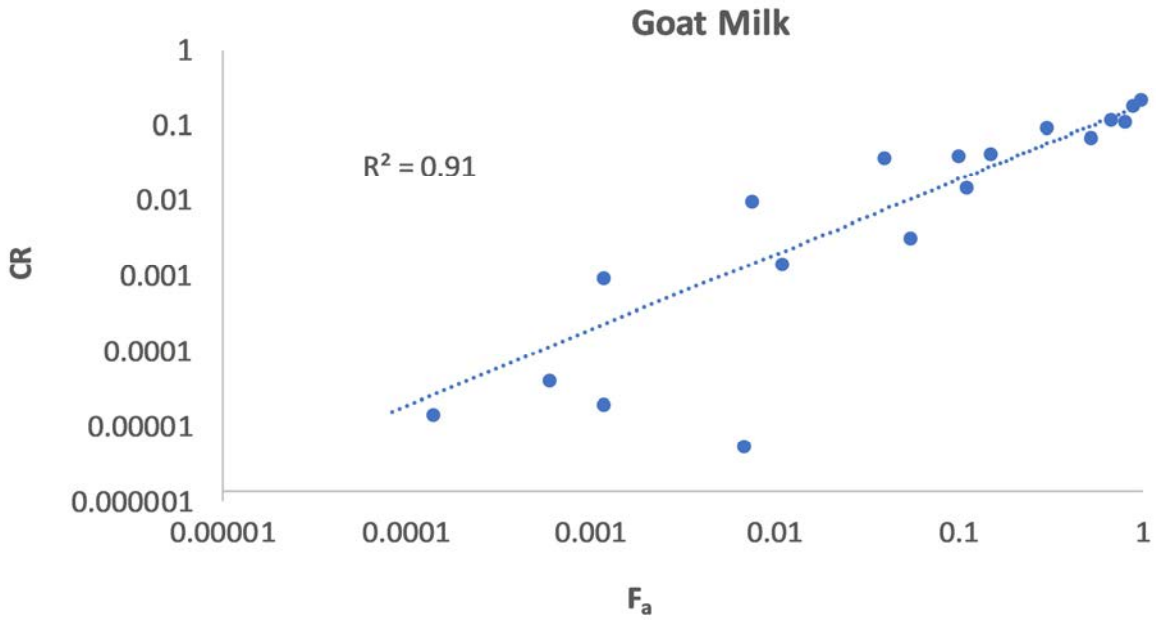

FIG. 13. Comparison of MODARIA goat milk concentration ratio (CR) versus ruminant fractional absorption (F_a) (adapted from Ref. [58]).

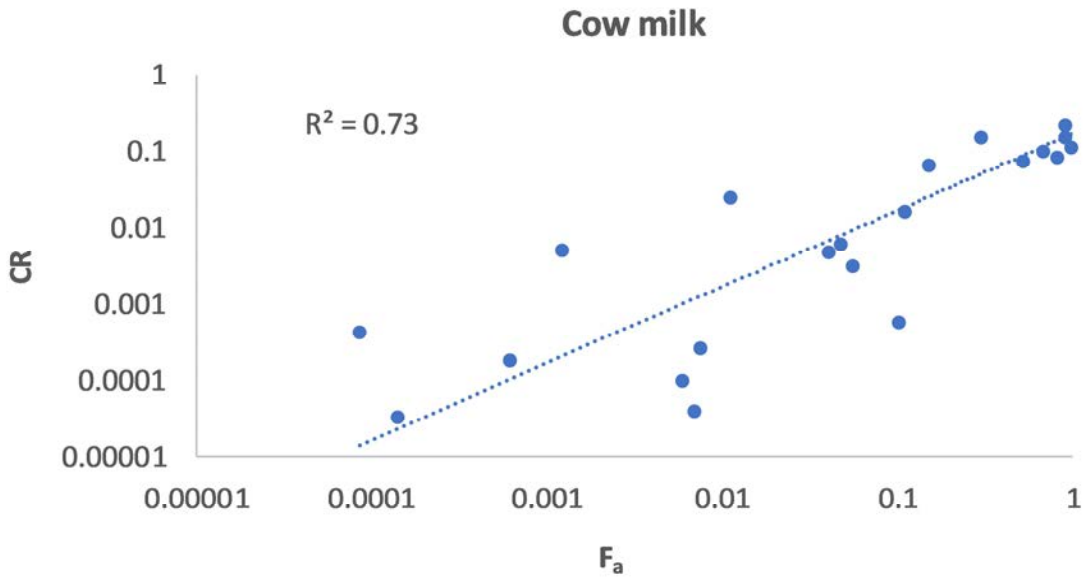

FIG. 14. Comparison of MODARIA cow milk concentration ratio (CR) versus ruminant fractional absorption (F_a) (adapted from Ref. [58]).

3.7. SUMMARY

A substantial revision of the dataset of goat and cow milk transfer parameters has improved information on both the provenance and transparency of the data used in previous international data reviews; these values replace those given in TRS 472 [1]. In the revised cow milk dataset produced under MODARIA WG4, F_m and *CR* values are now reported for 43 elements, based upon 825 data entries for F_m and 824 data entries for *CR*. The improved data are intended to support national authorities in meeting the requirements of IAEA Safety Standards Series No. GSR Part 3, Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards [59], with respect to REIA for facilities and activities.

The F_m values in the cow milk dataset are within an order of magnitude of those reported in TRS 472. Slightly larger changes are seen in the *CR* values, but the increase in size of the dataset creates greater confidence in the updated values compared with those given in TRS 472. *CR* values for a further 14 elements are now included in the dataset for goat milk. Overall, there are only minor differences in values for *CR* and F_m reported in the goat milk dataset compared with TRS 472. Data gaps remain for elements with isotopes that are potentially relevant to radiological impact assessment, such as many naturally occurring radionuclides, plutonium and americium.

Correlations were found between fractional gastrointestinal absorption and transfer to goat and cow milk. In the absence of available data, gut absorption values for ruminants in TRS 472 [1] or for humans in ICRP publications [60, 61] can be used to estimate order of magnitude values of transfer parameters to milk for different radionuclides.

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LIST OF ABBREVIATIONS

AM	Arithmetic mean
ASD	Arithmetic standard deviation
CEA	Commissariat à l'énergie atomique et aux énergies alternatives
CR	Concentration ratio
CV	Coefficient of variation
DMI	Dry matter intake
EDF	Électricité de France
EMRAS	Environmental Modelling for Radiation Safety
ERICA	Environmental Risk from Ionising Contaminants: Assessment and Management
GM	Geometric mean
GSD	Geometric standard deviation
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
IRSN	Institut de radioprotection et de sûreté nucléaire, France
MODARIA	Modelling and Data for Radiological Impact Assessments
NORM	Naturally occuring radioactive material
PDF	Probabilistic density function
REIA	Radiological environmental impact assessment
RAPs	Reference animals and plants
TECDOC	Technical document
TRS	Technical Reports Series
WG4	Working Group 4

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