Radionuclide transfer parameter review

Chief Scientist's Group research report

Environment Agency

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Dr Robert Bradburne
Chief Scientist

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Foreword

This document has been prepared for the Environment Agency by Eden Nuclear and Environment Ltd, working under the Radioactive Substances Regulation (RSR) - Ad-hoc Monitoring and Technical Support Framework Services Contract. The report aims to provide reasonable coverage of the latest environmental transfer parameter values for 10 different radionuclides of interest (as identified in the published scientific literature). It is not an exhaustive account of all transfer parameter values that could potentially be used in the Environment Agency's Initial Radiological Assessment Tool (version 2) (IRAT2) and associated radiological dose assessments. The inclusion of any specific transfer parameter value in this document is not a statement of commitment by the Environment Agency.

This report has made recommendations to resolve identified knowledge and evidence gaps in the literature through practical investigations to generate new parameter datasets. For example, this review identified uncertainties surrounding the behaviour of lutetium-177 (^{177}Lu) in the environment. To address these issues, the Environment Agency has commissioned 2 further research projects to investigate the fate and transport of ^{177}Lu in wastewater systems (Copplestone et al., 2026; Lang et al., 2026). These projects comprise a field monitoring study and a laboratory study which are being published as standalone reports at the same time as this literature review report.

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Executive summary

Environmental transfer parameters are an essential component of models that assess the potential impacts of environmental radioactivity on people and wildlife. These parameters quantitatively describe how radionuclides move through the environment and food chains. The Environment Agency needs its environmental dose assessments and underpinning modelling tools to be based on up-to-date environmental transfer parameters. This is to ensure that the Environment Agency's regulation of radioactive waste discharges and disposals to the environment is informed by scientifically robust data and evidence.

This report presents a detailed literature review of the environmental transfer parameters for ten radionuclides whose importance in environmental dose assessments is novel and/or increasing: tritium (^{3}H), carbon-14 (^{14}C), iodine-129 (^{129}I), phosphorus-32 (^{32}P), yttrium-86 (^{86}Y), lutetium-177 (^{177}Lu), rhenium-186 (^{186}Re), rhenium-188 (^{188}Re), radium-223 (^{223}Ra), and actinium-225 (^{225}Ac). The transfer parameters reviewed for each radionuclide (where relevant to the radionuclide's environmental behaviour) were:

- Distribution coefficients (K_d): The partitioning of radionuclides between contacting solid and liquid phases, such as river sediment and river water, respectively.
- Concentration factors: Used for human exposure pathways to model radionuclide transfer from soil to plants, and plants to animal foodstuffs.
- Concentration ratios: Used for wildlife assessments to model the uptake of radionuclides into an animal's tissue from the surrounding environment.
- Gaseous uptake factors (F): The transfer of airborne radionuclides (gases and volatile substances) to plants.
- Gastrointestinal factors: Gut uptake of radionuclides by an animal and the associated excretion rates.

An examination of specific activity models has also been performed for targeted radionuclides (e.g., ^{3}H and ^{14}C) to identify potential improvements to existing approaches.

The literature review identified opportunities to update parameter values using newly available empirical data and alternative modelling approaches. Key findings include:

- **Tritium:** A revised K_d for the freshwater environment may be useful. Latest International Commission on Radiological Protection (ICRP) recommendations regarding the skin absorption of tritiated water (HTO) may be relevant for some public exposure situations.
- **Carbon-14:** Current modelling approaches often assume that all ^{14}C releases to the environment occur as carbon dioxide ($^{14}CO_2$), which is conservative. It may overestimate short-term soil-plant transfer if other chemical forms are present e.g., methane ($^{14}CH_4$).

- **Iodine-129:** More recent empirical data from the International Atomic Energy Agency (IAEA) 2010 Handbook is available for soil to plant concentration factors. Specific K_d values for organic I in soils could also be considered.

- **Phosphorus-32:** Opportunities exist to harmonise the ^{32}P concentration factors for meat and offal to align with the baseline ratios established in the underpinning FARMLAND model methodology. Transfer factors for cow's milk from the IAEA 2010 Handbook could also be considered. The latest version of ERICA (version 2.0) also has updated parameter values for ^{32}P.

- **Yttrium-86:** A Japanese study has published ^{32}P plant concentration factor data (Uchida et al., 2007). Cerium may be a suitable analogue to establish K_d values.

- **Lutetium-177:** Cerium is currently used as an analogue for ^{177}Lu. However, other lanthanide elements may be better analogues for ^{177}Lu soft tissue distribution in animals. Lutetium-177 concentration factor data for offal could potentially be revised to be consistent with meat values derived from the Food Activity from Radionuclide Movement on Land (FARMLAND) model.

- **Rhenium-186/188:** No recent empirical data was found for the transfer of Re isotopes through food chains. Technetium is currently used as an analogue for Re but its suitability in some environments is limited. For wildlife assessments, modified Re concentration ratios that account for the short half-lives of these radionuclides could be applied.

- **Radium-223:** Transfer factors for beef offal (including liver) may be updated to align with the beef meat values in the IAEA 2010 Handbook. The implementation of ERICA (version 2.0) parameters for wildlife concentration ratios should be carefully checked to prevent 'double discounting' for the short physical life of ^{223}Ra. Current ^{223}Ra K_d values in the Environment Agency's Initial Radiological Assessment Tool version 2 (IRAT2) agree with more recent datasets.

- **Actinium-225:** Radionuclide specific data is limited. In the absence of ^{225}Ac data, americium may be a useful analogue, aligning with ICRP Publication 141 guidance. The Environmental Risk from Ionising Contaminants: Assessment and management (ERICA) Tool (version 2.0) has updated ^{225}Ac parameter data based on analogues.

A notable finding of this review is that ERICA (version 2.0) was updated in 2025. It was found that the underpinning database of ERICA (version 2.0) provides scientifically reliable and modern concentration ratio data that may offer benefits for wildlife dose assessments. However, persistent challenges remain for several medical radionuclides. In some cases, element specific environmental transfer data remains sparse (e.g.,^{186}Re and ^{188}Re). For novel use medical radionuclides (e.g., ^{177}Lu and ^{225}Ac), element specific data was found to be effectively absent from the published scientific literature. As a result, the continued use of analogue elements may be appropriate. Periodic examination of the literature for forthcoming updates (e.g., future ICRP Publications) may be a beneficial course of action.

1 Introduction

1.1 Background

The Environment Agency regulates radioactive waste disposals and discharges in England from nuclear sites, and from non-nuclear sites such as hospitals. A key component of this regulatory work is modelling the behaviour of radionuclides in the environment, providing important insights into the potential radiological impacts of these substances on people and wildlife. One Environment Agency modelling tool provides a system for undertaking a simple and cautious prospective assessment of the dose to people and wildlife arising from discharges of radioactive waste into the environment. This modelling capability is known as the 'Initial Radiological Assessment Tool version 2' (IRAT2).

IRAT2 is an established spreadsheet-based modelling tool that is used for screening (i.e., initial) radiological assessments. It relies heavily on environmental transfer parameters. These parameters quantitatively describe the dispersion and distribution of radionuclides in the environment, including food chains. Within the IRAT2 methodology is a hierarchy of data sources that are used to aid the derivation of transfer parameter values. The hierarchy begins with published data compilations from recognised international bodies such as the International Atomic Energy Agency (IAEA) and includes other grouped data sources. Assessment of published scientific literature and recorded judgement derivations of values is undertaken where grouped data is unavailable. It is essential that IRAT2 uses transfer parameter data that are consistent with this data hierarchy whilst being based on up-to-date scientific information. This requires staying alert to new studies in the published literature that may offer more robust transfer parameter values than current datasets.

There are several radionuclides whose importance in environmental dose assessments is increasing. Similarly, novel use radionuclides are known to be emerging, for example in new medical treatments. It is important that robust and substantiated transfer parameter data are used when assessing the potential impacts associated with these increasing and/or novel radiological risks. This means ensuring that the parameter data used in the IRAT2 tool is clear and based on recent information. However, the Environment Agency last reviewed the published literature for transfer parameter data over a decade ago. Moreover, IRAT2 uses analogue data in cases where element-specific transfer parameter data are unavailable or considered unreliable. This is parameter data for a chemical element with chemical characteristics that are expected to be similar to those of the radionuclide of interest. While the analogue approach can be useful, data derived from the actual radionuclide (e.g., by field monitoring or laboratory experiments) is typically preferred to reduce the number of assumptions (and associated conservatism) during the environmental dose assessment.

The aim of this project is to review the published scientific literature for environmental transfer parameter values for key radionuclides and to assess their suitability compared to existing transfer parameter datasets. The review focuses on ten radionuclides whose importance in environmental dose assessments is novel and/or increasing (see Section 1.2 for further details). The resulting evidence will help support the Environment Agency in its continued use of the IRAT2 model and its associated environmental dose assessments.

1.2 Project scope

This report reviewed the literature to identify up-to-date environmental transfer parameter data for ten radionuclides: tritium (^{3}H), carbon-14 (^{14}C), iodine-129 (^{129}I), phosphorus-32 (^{32}P), yttrium-86 (^{86}Y), lutetium-177 (^{177}Lu), rhenium-186 (^{186}Re), rhenium-188 (^{188}Re), radium-223 (^{223}Ra), and actinium-225 (^{225}Ac). The motivation for selecting these radionuclides for examination in this project is as follows:

- Some radionuclides (i.e., ^{3}H, ^{14}C, ^{129}I) are volatile and can exist in gaseous forms, making them mobile in the environment. These radionuclides are also important in discharges from nuclear power reactors and long-term waste storage facilities.

- Several of the radionuclides (i.e., ^{177}Lu, ^{223}Ra, ^{225}Ac) are finding novel applications in nuclear medicine, such as therapeutic and diagnostic treatments. Consequently, hospitals may increase discharges of these three radionuclides to the environment.

- The remaining radionuclides (^{32}P, ^{86}Y, ^{186}Re and ^{188}Re) are used in nuclear medicine but existing parameter data is lacking. The Environment Agency often relies on data from chemical analogues, such as technetium (Tc) to model Re.

Overall, the importance of these radionuclides in environmental dose assessments, or the paucity of existing transfer parameter data, means it is valuable to investigate if new or updated information is available. The transfer parameters examined in this project are:

- Distribution coefficients (K_d): The ratio of the radionuclide concentration in a solid phase (e.g., sediment) to that in a liquid (e.g., water).
- Concentration factors: The ratio of the radionuclide concentration in a plant to that in soil, or the ratio of the radionuclide concentration in an animal to that in a plant.
- Concentration ratios: The ratio of the radionuclide concentration in an organism to that in the organism’s surrounding environment.
- Gaseous uptake factors (F): The deposition of radionuclide gases into plants.
- Gastrointestinal factors: The uptake of radionuclides into an animal’s gut following ingestion and the associated rate of excretion.

Together, these transfer parameters comprehensively describe the fate and transport of radionuclides in the environment. The IRAT2 capability and related assessments use these transfer parameters to assess the partitioning behaviour of radionuclides between different compartments of the environment, as well as human and non-human biota.

1.3 Report structure

This report is presented with the following sections:

- **Section 2** describes the methodology undertaken, such as the approach used to identify and review relevant literature.
- **Section 3** describes the results of the literature review for ^{3}H.
- **Section 4** describes the results of the literature review for ^{14}C.
- **Section 5** describes the results of the literature review for ^{129}I.
- **Section 6** describes the results of the literature review for ^{32}P.
- **Section 7** describes the results of the literature review for ^{86}Y.
- **Section 8** describes the results of the literature review for ^{177}Lu.
- **Section 9** describes the results of the literature review for ^{186}Re and ^{188}Re. These radionuclides are expected to have identical environmental partitioning behaviours (since radionuclide partitioning is largely determined by the identity of the chemical element, and not by mass). Hence, ^{186}Re and ^{188}Re are covered in one section.
- **Section 10** describes the results of the literature review for ^{223}Ra.
- **Section 11** describes the results of the literature review for ^{225}Ac.
- **Section 12** summarises the main findings of the project, including identified knowledge and evidence gaps, and makes recommendations for future research.

Accordingly, the ten radionuclides of interest are addressed in turn throughout Sections 3-11, with a dedicated section provided for each radionuclide (except for ^{186}Re and ^{188}Re which are discussed together). All sections discuss the parameter values currently used by IRAT2, newly available data found in the literature (where it exists), and recommendations for future parameter data use. In general, the ten radionuclides are discussed in order of increasing atomic mass. An exception to this has been made for ^{129}I. Of note, ^{3}H, ^{14}C, and ^{129}I are highly mobile radionuclides in the environment that can be readily assimilated by plants and animals (and by extension through food chains). These common features are reflected in key similarities in the types of ^{3}H, ^{14}C, and ^{129}I transfer parameter information available in the literature. For clarity, the three radionuclides are discussed in succession.

2 Methodology

This section briefly describes the overarching methodology and important considerations made to deliver this literature review.

The current parameters within IRAT2 are largely based on historical values taken from the model (Computer based) Consequences of Releases to the Environment: Assessment Methodology, 2008 (PC-CREAM 08) and earlier databases from the IAEA. Much of this information pre-dates 2007. Therefore, this project focuses on research published after 2007 to identity potential updates and improvements to the existing parameter values.

For the literature review, information sources were found through a combination of standard search engines, Google Scholar, Web of Science, and Science Direct. The following literature search terms were used (in various combinations) to identify relevant reports: ‘Radionuclide’ (which includes specific radionuclide / chemical element names), ‘nuclear’, ‘transfer parameter’, ‘environment’, ‘fate and transport’, ‘concentration ratio’, ‘concentration factor’, ‘food chain’, ‘foodstuffs’, ‘wildlife’, ‘animals’, ‘plants’, ‘distribution coefficient’, ‘gaseous uptake’.

Numerous articles were found for some radionuclides (i.e., ^{3}H, ^{14}C, ^{129}I), more than could be reasonably examined in this report. In these instances, potentially relevant data were prioritised using the established hierarchy of data sources within the IRAT2 methodology. This hierarchy begins with published data compilations from recognised international bodies (such as the IAEA and the International Commission on Radiological Protection (ICRP)), followed by other grouped data sources (such as modelling databases). It then finally relies on individual scientific studies in the published literature where broader compilations lack specific data.

Specific publications were also targeted for review if they have previously been adopted in international initiatives and analogous modelling capabilities to aid environmental dose assessments. The Environmental Risk from Ionising Contaminants: Assessment and management (ERICA) Tool and its databases are underpinned by international (IAEA) radioecological reviews. In particular, ERICA (version 1.2.1) (Brown et al., 2016) relied on transfer parameter compilations from the IAEA Technical Reports Series 422 (IAEA, 2004) and 472 (IAEA, 2010). In contrast, the latest version of ERICA (version 2.0) (ERICA Consortium, 2021) utilises updated datasets reviewed under the IAEA Modelling and Data for Radiological Impact Assessment (MODARIA) programme (Boyer et al., 2018) and the IAEA wildlife transfer handbook (IAEA, 2014). These documents provide the empirical and review basis for the transfer parameters implemented within the latest ERICA Tool.

3 Tritium

Tritium (^3H) is the radioactive isotope of hydrogen identified by the symbol ^3H (T is often used as an abbreviation to denote ^3H). It has a half-life of ~12 years and undergoes beta decay to form helium-3 (Wilson, 1996). Whether of natural or anthropogenic origin, ^3H is extremely mobile in the environment and in biological systems. Tritium is found in a variety of chemical forms, including hydrogen gas (HT), tritiated water (HTO), tritiated methane (CH_3T), metal tritide, and various organic compounds used in research. Data is usually given for HT, HTO, and organically bound tritium (OBT) (Eyrolle, et al., 2018). Here, OBT refers to C-bound ^3H formed in living systems through biological processes.

Tritium is produced naturally in the environment mainly from reactions induced by cosmic rays in the upper atmosphere. It was also released during nuclear weapon tests in the 1950s and is present in the nuclear industry's routine and accidental discharges. The natural production of ^3H is about three times that released by industry (Boyer et al., 2009).

The high environmental mobility of ^3H, in combination with its presence in nuclear industry waste streams (and possible releases from future nuclear fusion reactors) means that it is important to assess the potential impacts of ^3H on the environment. Of note, a major IAEA report on ^3H in the environment was recently published (Croudace and Ulanowski, 2025).

3.1 Radiological and metabolic data for tritium

Occupational exposures to ^3H are more common for gases or vapours than particulate forms of the radionuclide (ICRP, 2016). Here, ICRP recommended that a gas/vapour form is assumed for dose assessments in the absence of scenario-specific information.

Inhaled HTO is translocated to blood almost completely and instantaneously (100% deposited in the respiratory tract). ICRP Publication 134 noted that HTO absorption through skin can significantly add to ^3H uptake during exposure to airborne HTO (ICRP, 2016). This can be accounted for in workplace control; the intake by inhalation may be 'multiplied by 1.5' to account for skin absorption. A similar approach is also applied in PC-CREAM 08 for public exposures to ^3H; it assesses the dose from skin absorption of ^3H by applying a multiplication factor of 1.5 to the inhalation dose coefficient. Interestingly, this approach is not explicitly mentioned in the underpinning ICRP source of dose coefficient data (Eckerman et al., 2012). It is therefore unclear if ICRP also recommend this approach for assessing public exposures. The dose coefficient for ^3H inhalation in PC-CREAM 08 is that for HTO (1.8×10^{-11} Sv/Bq for an adult) multiplied by 1.5 i.e., PC-CREAM 08 uses 2.7×10^{-11} Sv/Bq for an adult. Here, the scaling factor of 1.5 represents a rounded value for use with all age groups, assuming that the PC-CREAM 08 default inhalation rates are used. Changes to the inhalation rates may require revision to the ^3H absorption factor. Skin absorption is also considered in the global circulation model for ^3H in PC-CREAM 08, where the global circulation model is primarily used to determine collective doses.

ICRP Publication 134 assumed that 0.01% and 0.3% of inhaled HT and CH_3T is deposited in the respiratory tract, respectively, with Type V absorption (instantaneous absorption into body fluids from the respiratory tract) and conversion to HTO (ICRP, 2016). This was for occupational exposure scenarios. In contrast, Type M absorption (moderate/intermediate rate of absorption into blood from the respiratory tract) was assumed for inhaled ^{3}H particulate forms (e.g., glass or luminous paint), which was also the default absorption type. The absorption of ^{3}H from the respiratory tract and the gut uptake factor are both 0.2. Finally, inhalation of solvent vapours was assumed to deposit 100% of the ^{3}H loading in the respiratory tract with Type V absorption. The HTO systemic model may also be applied to unspecified organic vapours and particulates.

The turnover of ^{3}H in the human body is rapid, even in the case of absorption. Tritiated water represents 90% of the total ^{3}H absorbed and is expelled with a biological half-life of ~10 days. Organic forms of ^{3}H (the remaining 10% absorbed) is retained within the body with a biological half-life of ~30 days. Finally, a small fraction of organic ^{3}H remains in the fat tissues or collagen for ~450 days (Okada and Momoshima, 1993). A different biokinetic model has been developed for OBT (ICRP, 2016). Non-biogenic organic compounds (e.g., synthetic ^{3}H labelled organic molecules) are assumed to follow the HTO model.

A respiratory absorption factor of 1 and a gut uptake factor of 1 are assumed for inhalation of biogenic organic compounds (ICRP, 2016). The dose coefficient for humans for OBT is greater than that for HTO and other forms. For ingestion, the gut uptake factor is assumed to be 1 for HTO and organic forms, and 0.1 for metal tritides and luminous paints (ICRP, 2016). The dose coefficient for ingestion of OBT is greater than that for HTO.

The dose per unit intake factors currently used in IRAT2 (Environment Agency, 2022; see Appendix B) are derived from ICRP Publication 119 (Eckerman et al., 2012). Values are given for HTO (1.8×10^{-11} Sv/Bq) and OBT (4.1×10^{-11} Sv/Bq). Of note, these values are for adults, although IRAT2 requires dose per unit release (DPUR) for the most vulnerable groups, which includes young children/offspring. No allowance for skin absorption of HTO is made in these values and exposure through skin absorption is not considered in IRAT2. Tritium ingestion and inhalation dose coefficients may be updated when ICRP publish new dose coefficients for members of the public. Furthermore, ICRP recommendations related to absorption of HTO through the skin may need to be considered. The use of HTO dose coefficients for other ^{3}H forms (i.e., non-biogenic compounds) will overestimate the resulting doses. The appropriate dose coefficient should be used if the ^{3}H form is known.

3.2 Specific activity model for tritium

The transfer of ^{3}H (and ^{14}C) between the atmosphere and the terrestrial environment is more complex than for some other radionuclides. This is because hydrogen (H) and carbon (C) are essential chemical elements in biological systems. A relatively simple ‘specific activity’ approach is implemented in PC-CREAM 08 (and therefore in IRAT2) to calculate the activity concentrations of ^{3}H in foodstuffs. These specific activity models hypothesise that the ^{3}H:^{1}H ratio remains constant from one environmental compartment to another one. An ICRP database of decay data noted that specific activity models are useful for predicting the dose following chronic exposure (ICRP, 2007). Such models are accurate when meteorological data and the population diet during exposure are known.

Radiological assessments typically involve specific activity models in which ^3H is assumed to be transferred through the environment and incorporated into the organisms as HTO. PC-CREAM 08 assumes that all foodstuffs come into instant equilibrium with atmospheric ^3H, and that the specific activity of ^3H in the food is equal to that in the atmospheric water vapour at the point of interest. The IAEA Handbook assumed that HTO released to the atmosphere mixes with air moisture and exchanges with water pools in plants, soil, and animals (IAEA, 2010).

PC-CREAM 08 also refers to the dynamic model for the transfer of tritium through the terrestrial food chain (TRIF) (Higgins et al., 1996). This model included the formation of OBT which is less mobile in the environment than HTO, the form assumed in the specific activity model. A comparison of the specific activity model and the dynamic model outputs (run for a continuous and constant source) showed that the latter are slightly higher, due mainly to the inclusion of OBT. Differences in the modelling predictions were as high as 25% and depended on the foodstuff. Other relevant models such as UFOTRI (Raskob, 1993) and ETMOD (Russell and Ogram, 1992) can describe ^3H fluxes through the major environmental compartments (atmosphere, soil, and plants) for known meteorological conditions. These are complex models that require extensive (prior) information on the environment of interest. In general, it is desirable to find a suitable compromise between a model's complexity, the amount of input data required, and uncertainties in the results.

3.3 Gaseous dispersion of tritium

The IAEA Handbook described ^3H transfer from air to soil through wet and dry deposition from the airborne plume (IAEA, 2010). The recent IAEA 'Tritium in the environment' report gave a deposition velocity of 0.96×10^{-4} – 1.1×10^{-3} m/s (Croudace and Ulanowski, 2025).

In PC-CREAM 08, ^3H is assumed to be returned to the atmosphere (from soil and plants) on a timescale that is short compared to its physical half-life. Therefore, no allowance is made for dry deposition or washout (the corresponding parameter values are set to zero).

Tritium concentrations in soil were derived in IRAT2, although these were not used in the final DPUR calculations. IRAT2 used the following relationship between the ^3H concentration in soil (C_{soil}) and its concentration in air (C_{air}) (Environment Agency, 2022):

$$C_{soil} = 6.3 \text{ Bq/kg per Bq/m}^3 \times C_{air}$$

An assumption of this equation is that the soil is typically 10% organic matter. A similar relationship is found in the IAEA Handbook, for a soil water content of 5% (IAEA, 2010).

3.4 Tritium concentration ratios and factors

3.4.1 Background

IRAT2 uses the ^{3}H specific activity model in PC-CREAM 08. A specific activity model is also used in the IAEA Handbook (TRS472) (IAEA, 2010).

IRAT2 and PC-CREAM 08 use the following formulation:

$$C_{plant} = F \times C_{air}$$

where C_{plant} is the ^{3}H concentration in plant and F is the gaseous uptake factor (dimensionless).

In IRAT2, the parameter values used for organically bound ^{3}H are those for ^{14}C. This is case for all environmental and food activity concentrations with three exceptions:

- Uptake into the terrestrial food chain (for humans) where values for ^{3}H were used.
- Sewage sludge to land for which specific values for OBT were available.
- Irrigated terrestrial foods for which specific values for OBT were available.

The IAEA Handbook applied the specific activity model slightly differently (IAEA, 2010). The specific activity model for ^{3}H is formulated in terms of the ^{3}H concentration in water rather than the ratio of ^{3}H activity to the mass of H in a given compartment. The HTO concentration in fresh plants considered contributions from air moisture and from soil water (plant leaves draw most of their ^{3}H from the air). The equation used is conservative for fruits, tubers, and root crops, which draw a larger fraction of their ^{3}H from the soil (IAEA, 2010). The OBT concentration was expressed as the activity in the water equivalent of the dry matter (the water produced by complete combustion of the dry material (IAEA, 2010). The OBT concentration in the combustion water of the plant dry matter was the same as that in the free water of the leaves, after reduction by a partition factor (default value was 0.54). It is not straightforward to compare the ^{3}H specific activity parameter values in IRAT2 and the IAEA Handbook because the latter depend on other site-specific data (IAEA, 2010).

IRAT2 applies a concentration factor of 100 Bq/kg per Bq/m^{3} for green vegetables, root vegetables, and fruit for both ^{3}H and OBT. The HTO concentrations in green vegetables and root vegetables resulting from the application of sewage sludge are taken to be zero. It is assumed that all the HTO in the soil will have leached away within 10 months.

3.4.2 Animals

Animals can ingest ^{3}H as HTO in feed and drinking water and as OBT in the organic fraction of feed (IAEA, 2010). Inhalation and skin absorption are also possible routes of HTO intake. Exchangeable forms of organic ^{3}H and HTO rapidly equilibrate with body water. Most of the HTO taken in by an animal remains as HTO in its body, with a small fraction converted to OBT. In contrast, about half the OBT ingested is converted to HTO, with the other half remaining in an organic form (IAEA, 2010). A specific activity model is used in IRAT2 which is the same as the specific activity model used in PC-CREAM 08.

The IAEA Handbook used a metabolic model to obtain the ratio of the ^{3}H concentration in the animal product to the ^{3}H concentration in feed, drinking water, and air (IAEA, 2010). The ^{3}H concentration ratios for different animal foodstuffs are given in the table below.

Table 1: Tritium specific activity model parameters for animal foodstuffs (L/kg).

Food	PC-CREAM and IRAT2 (HTO)	PC-CREAM and IRAT2 (OBT)*	IAEA TRS472 (IAEA, 2010) (HTO)		IAEA TRS472 (IAEA, 2010) (OBT)	
	Value	Value	Value	Range	Value	Range
Cow's milk	0.11	0.267	0.87	0.81-0.92	0.24	0.17-0.37
Beef	0.088	0.8	0.66	0.64-0.82	0.4	0.35-0.53
Lamb	0.088	0.8	0.78	0.6-0.81	0.55	0.35-0.67
Egg	0.088	0.8	0.76	0.63-0.81	0.64	0.53-0.69

*IRAT2 and PC-CREAM values for OBT use C as an analogue.

It should be noted that the IRAT2 and PC-CREAM 08 parameter values for HTO are lower than those listed in IAEA Handbook (IAEA, 2010). In IRAT2, ^{3}H concentrations in animal products resulting from the application of sewage sludge were sourced from the National Radiological Protection Board (now part of UKHSA) methodology (Jones et al., 2005).

3.4.3 Freshwater fish

The HTO and OBT concentration ratios for freshwater fish currently used in IRAT2 are 1.0 L/kg and 4×10^{5}, respectively. These values have been taken from PC-CREAM 08.

IAEA TRS472 concluded that the assumption of full specific activity equilibrium is a good approximation to actual HTO concentrations in most aquatic compartments (IAEA, 2010). The water systems to which freshwater fish are exposed, including lake water and water derived from foods at different trophic levels, all have similar HTO concentrations. This implies that the HTO concentration in fresh weight fish (C_{HTO}, Bq/kg, fresh weight) is given by:

$$C_{HTO} = WC_f \times C_W$$

where C_w (Bq L^{-1}) is the HTO concentration in the water column and WC_f is the fractional water content of the fish (L/kg fresh weight). The water content (WC_f) is roughly constant at 0.78 for most fish that form part of the human diet (IAEA, 2010).

The OBT concentration in the fresh weight fish is given by:

$$C_{OBT} = (1\text{-}WC_f) \times WEQ_f \times R_f \times C_W$$

where WEQ_f is the water equivalent factor of the fish and R_f is the partition factor. The IAEA Handbook provided default values of 0.66 and 0.65 for R_f and WEQ_f, respectively (IAEA, 2010).

3.4.4 Marine environment

IRAT2 uses a HTO concentration factor of 1 L/kg for marine fish, crustacea, and molluscs. The same concentration values were recommended in an IAEA compilation (IAEA, 2004). The corresponding OBT concentration factor currently used in IRAT is 2 x 10^4 L/kg. This value is based on ^{14}C as an analogue.

3.4.5 Wildlife

The HTO concentration ratios for wildlife currently used in IRAT2 are taken from ERICA (version 1.2.1) (Brown et al., 2016). The values for marine biota, terrestrial biota, and freshwater biota are summarised in the three tables below.

Table 2: Current HTO concentration ratios for marine biota in IRAT2 (Environment Agency, 2022).

Marine reference organisms	Concentration ratio (L/kg)	Reference source
Benthic fish	1.0	ERICA v.1.2.1
Bird	1.0	ERICA v.1.2.1
Crustacean	1.0	ERICA v.1.2.1
Macro-algae	1.0	ERICA v.1.2.1
Mammal	1.0	ERICA v.1.2.1

Marine reference organisms	Concentration ratio (L/kg)	Reference source
Mollusc – bivalve	1.0	ERICA v.1.2.1
Pelagic fish	1.0	ERICA v.1.2.1
Phytoplankton	1.0	ERICA v.1.2.1
Polychaete worm	1.0	ERICA v.1.2.1
Reptile	1.0	ERICA v.1.2.1
Sea anemones and true coral	1.0	ERICA v.1.2.1
Vascular plant	1.0	ERICA v.1.2.1
Zooplankton	1.0	ERICA v.1.2.1

Table 3: Current HTO concentration ratios for terrestrial biota in IRAT2 (Environment Agency, 2022).

Terrestrial reference organism	Concentration ratio (L/kg)	Reference source
Amphibian	150	ERICA v.1.2.1
Annelid	150	ERICA v.1.2.1
Arthropod – detritivorous	150	ERICA v.1.2.1
Bird	150	ERICA v.1.2.1
Flying insects	150	ERICA v.1.2.1
Grasses and herbs	150	ERICA v.1.2.1
Lichen and bryophytes	150	ERICA v.1.2.1
Mammal – large	150	ERICA v.1.2.1
Mammal – small, burrowing	150	ERICA v.1.2.1

Terrestrial reference organism	Concentration ratio (L/kg)	Reference source
Mollusc – gastropod	150	ERICA v.1.2.1
Reptile	150	ERICA v.1.2.1
Shrub	150	ERICA v.1.2.1
Tree	150	ERICA v.1.2.1

Table 4: Current HTO concentration ratios for freshwater biota in IRAT2 (Environment Agency, 2022).

Freshwater reference organism	Concentration ratio (L/kg)	Reference source
Amphibian	1.0	ERICA v.1.2.1
Benthic fish	1.0	ERICA v.1.2.1
Bird	1.0	ERICA v.1.2.1
Crustacean	1.0	ERICA v.1.2.1
Insect larvae	1.0	ERICA v.1.2.1
Mammal	1.0	ERICA v.1.2.1
Mollusc – bivalve	1.0	ERICA v.1.2.1
Mollusc – gastropod	1.0	ERICA v.1.2.1
Pelagic fish	1.0	ERICA v.1.2.1
Phytoplankton	1.0	ERICA v.1.2.1
Reptile	1.0	ERICA v.1.2.1
Vascular plant	1.0	ERICA v.1.2.1
Zooplankton	1.0	ERICA v.1.2.1

It should be noted that the OBT concentration ratio values currently used in IRAT2 are taken from C transfer parameter data; OBT was modelled in ERICA (version 1.2.1) using C as an analogue. To avoid unnecessary duplication, these data have not been produced in this section. The OBT/C concentration ratio values for marine, terrestrial, and freshwater biota can be found in tables 14, 15, and 16, respectively (Section 4). A review of concentration ratios in ERICA (version 2.0) found no updated values for ^{3}H (HTO) (ERICA Consortium, 2021). However, ERICA (version 2.0) has updated values for OBT based on C as an analogue. The updated values for marine, terrestrial, and freshwater biota are provided in tables 11, 12, and 13, respectively (see Section 4 for further details).

A review of the literature also identified $^3H_{tot}$ and OBT concentration ratio values and ^3H specific activity in flounder fish (*Platichthys flesus*) and mussels (Croudace and Ulanowski, 2025). These data were obtained between 1999 and 2006. The concentration ratio values for $^3H_{tot}$ and OBT were 3.58 x 10^2-7.667 x 10^3 and 3.30 x 10^2-4 x 10^3, respectively. This report contained noteworthy datasets, and those who have a further interest in ^3H (outside the scope of this project) may find value in consulting the document.

3.5 Tritium distribution coefficients

Distribution coefficient values for ^3H are discussed in the following section. IRAT2 currently includes element specific K_d values for marine and freshwater systems (Environment Agency, 2022).

3.5.1 Tritium chemical speciation

As previously noted, ^3H can exist in several forms, such as (but not limited to) HT, HTO, and inorganic and organic molecules in solution. Tritium exhibits complex behaviour in biological and environmental systems because of its numerous physico-chemical forms. Radiological dose assessments typically involve specific activity models based on HTO.

Water (including HTO) adsorption onto solid surfaces is governed by a balance between water–water hydrogen bonding and water–surface interactions. Together, these processes determine the stability of the water structures formed. Water may also be adsorbed in the hydration sphere of polar sorbents. Isotopic partitioning of ^3H and ^1H may be anticipated based on their mass difference, but such effects are expected to have a minimal effect on adsorption behaviour. This will especially be the case when chemisorption dominates.

Organically bound tritium is a generic term encompassing a wide variety of potential organic species; total OBT, exchangeable OBT, non-exchangeable OBT, soluble OBT, insoluble OBT, tritiated organics etc. Due to the direct association of ^3H with C in organic species, IRAT2 uses C as an analogue element for OBT. Distribution coefficient values for OBT are not considered further here and are discussed in the ^{14}C section (Section 4).

3.5.2 Current tritium K_d values

IRAT2 includes the following element specific parameters as shown in the table below. As previously noted, OBT values are discussed in Section 4.

Table 5: Current tritium K_d values in IRAT2 (Environment Agency, 2022) (see ^{14}C section for IRAT2 OBT values).

Parameter	K_d (L/kg)	Basis
Marine	1	The open ocean and ocean margin value for ^3H was recommended by IAEA (IAEA, 2004). The source report stated that 'A default K_d of 1 was assigned to non-reactive elements such as H, the major elements in sea water (sodium, chlorine, and sulphur) and inert gases (krypton and xenon).'
Freshwater	0.03	This value was taken from the PC-CREAM methodology (Smith and Simmonds, 2009). However, the source reference (therein) was a 1984 (proprietary) report that could not be obtained for review (Kane, 1984).
Organic soil	-	No ^3H specific K_d value was provided for organic soil.

3.5.3 Review of tritium parameter values

The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR, 2016) adopted K_d values of 0 (freshwater; IAEA, 2001) and 1 (marine; IAEA, 2004) in their methodology for estimating public exposures due to radioactive discharges. These K_d data were derived from IAEA sources and argued to provide 'the most recent international compilation of K_d values.' Of note, the freshwater K_d value of 0 (IAEA, 2001) was ultimately derived from a personal communication (Onishi, 1999). The underpinning rationale and basis for this value does not appear to have been outlined in the source report.

The US EPA reviewed K_d values for ^3H in 1999 (US EPA, 1999). They noted that because ^3H readily combines with oxygen to form water, its behaviour in aqueous systems is largely controlled by hydrologic processes. Hence, ^3H migrates at essentially the same velocity as surface and groundwaters. The authors stated that adsorption processes were relatively unimportant in ^3H transport through aqueous environments. In accordance with an IAEA report, a K_d, of 0 L/kg was discussed to model ^3H migration in groundwater environments (IAEA, 2001). An earlier review of published studies provided a K_d range of 0.04-0.1 L/kg for ^3H partitioning to sandy soils (Thibault, et al., 1990).

Adoption of a K_d value of 1 would be consistent with an equal distribution of ^3H (as HTO) within the bulk liquid (water) phase and the adsorbed hydration layer of any wetted (sediment) surface in contact with it. This approach seems to be chemically and physically reasonable. It is unclear how a value of 0 (as used in IAEA, 2001 and UNSCEAR, 2016) could be justified on the same basis, and the disparity between marine and freshwater K_d values is counterintuitive. Such a conclusion is reached despite the findings of the US EPA review (US EPA, 1999). The ^{3}H K_d value of 0.03 L/kg for freshwater systems, as currently used in IRAT2, is consistent with data reported for sandy soils (Thibault, et al., 1990).

3.5.4 Recommendations for tritium K_d values

The disparity between freshwater and marine K_d values could be further investigated and addressed. In the first instance, adopting K_d values of 1 for both freshwater and marine environments would seem defensible for reasons outlined above. Notably, a more recent IAEA compilation for freshwater environments did not offer a K_d value for ^{3}H (IAEA, 2010).

The basis of the current ^{3}H K_d value for freshwater (0.03 L/kg) is a proprietary report. This document should be reviewed if it can be obtained. It is currently not possible to determine the basis of the current parameter value without understanding the supporting rationale. However, the reported value is consistent with data reported elsewhere for sandy soils.

3.6 Summary of tritium review

The main findings for ^{3}H are summarised in the table below.

Table 6: Key literature findings for tritium transfer parameters.

Parameter	Review findings for ^{3}H
Gaseous dispersion	IRAT2 does not explicitly considered deposition due to rapid return to the atmosphere. The HTO inhalation dose coefficient in IRAT2 report does not account for HTO absorption through skin but the default dose coefficient in PC-CREAM 08 does.
K_d	A disparity was identified between the K_d values for freshwater and marine environments. The basis for freshwater K_d value was difficult to find.
Terrestrial food chain	Specific activity model has different values to those presented in the IAEA Handbook (IAEA, 2010).
Marine food chain	IRAT2 and the IAEA Handbook have the same values (IAEA, 2010).
Wildlife	ERICA (version 2.0) has updated wildlife concentration ratios for C which could potentially be used as an analogue for OBT.

4 Carbon-14

Carbon-14 (^{14}C) has a half-life of ~5.7 x 10^3 years and undergoes beta decay to form nitrogen-14 (Wilson, 1996). In the context of nuclear industry waste streams, ^{14}C may be encountered in a variety of chemical forms, including carbon monoxide (^{14}CO), carbon dioxide ($^{14}CO_2$), methane ($^{14}CH_4$), as well as several different organic compounds. Carbon is a non-metallic element that occurs mainly in the +2 and +4 oxidation states.

Nuclear reactors produce ^{14}C through neutron activations reactions in the fuel, the core structural materials, and the moderator (Yim and Caron, 2006). Most of the ^{14}C released in a pressurised water reactor is in the form of alkanes (Davis Jr, 1977). Carbon-14 is also liberated from spent nuclear fuel during fuel dissolution processes in reprocessing plants. Outside the nuclear sector, ^{14}C is widely used for the isotopic labelling of molecules to characterise metabolic processes and aid environmental fate studies (Babin et al., 2022).

ICRP Publication 134 contains biokinetic models for different forms: CO, CO_2, CH_4, and elemental C (ICRP, 2016). ICRP Publication 134 recommended that inhalation of 50% particulate and 50% gas/vapour should be assumed for occupational exposures in the absence of scenario specific information. Gas and vapour ^{14}C forms were assumed to have absorption Type V. All the material in the inhaled air was assumed to be deposited in the body for CO_2, 40% for CO, and a small fraction (0.3%) for CH_4. ICRP Publication 134 also listed absorption data for some organic carbon compounds, and that the fraction absorbed was ≤50%. ICRP Publication 134 also recommended that for occupational exposures, 100% deposition and Type F absorption (fast rate of absorption into blood from the respiratory tract) was assumed for unspecified organic C (gas or vapour).

For particulate ^{14}C forms, the ICRP model for humans (ICRP Publication 134) has a gut uptake factor of 1 for ingestion and for absorption Type F (ICRP, 2016). For Type M (default), the respiratory uptake factor and gut absorption factors provided were 0.2. For ingestion, ^{14}C was assumed to be absorbed completely (i.e., gut uptake factor is 1).

ICRP Publication 134 have adopted new systemic models for CO_2, CH_4 and C (ICRP, 2016). The dose per unit intake by ingestion for workers has reduced by a factor of about 4 compared to the value provided in ICRP Publication 119 (which was based on the previous metabolic model) (Eckerman et al., 2012). The IRAT2 dose per unit intake factors are sourced from ICRP Publication 119. On that basis, the IRAT2 values could potentially be updated to incorporate the latest ^{14}C dose coefficients for members of the public.

4.1 Specific activity model for carbon-14

The main concept underpinning the specific activity model for ^{14}C is that the long-term environmental behaviour of ^{14}C is modulated by environmental cycles of non-radioactive carbon (i.e., ^{12}C). It is assumed that isotopic equilibrium between ^{14}C and ^{12}C is achieved and that a constant isotopic ratio (specific activity) is established. In other words, an identical specific activity will be observed in all system components. The specific activity is defined as the ^{14}C concentration in a medium (expressed in Bq/g or Bq/m^3), divided by the ^{12}C concentration in the same medium (expressed in g C/g or g C/m^3).

The most important volatile C compounds are CH_4 and CO_2. Methane may enter the biosphere and be oxidised to CO_2 via several interim steps (Avila and Pröhl, 2008). The key process that determines the fate of CO_2 in the biosphere is photosynthesis, during which plants convert CO_2 to carbohydrates. For atmospheric releases, it is assumed that the ^{14}C level in the plant canopy atmosphere is the same as that in the discharge plume.

The assumption of full specific activity equilibrium throughout the terrestrial environment is satisfactory for ^{14}C releases to the atmosphere if the radionuclide is discharged as $^{14}CO_2$ (IAEA, 2010). Practical experience has shown this to be the usual case. One safety case for nuclear waste disposal assumed that all terrestrial plant uptake of ^{14}C uptake occurred from the atmosphere (Posiva, 2014). To support this, the BIOPROTA ^{14}C working group assumed that the plant obtained 2% of its C from soil and 98% from the atmosphere, via photosynthesis or foliar uptake (Limer, et al., 2017). Most of the experimental work on root uptake is consistent with a 1-2% contribution to plant C (Smith, 2014).

An assumption that ^{14}C is released to the environment as $^{14}CO_2$ gives more conservative dose assessment results as this C carbon chemical form is most effectively incorporated into organic matter. Consequently, $^{14}CO_2$ can readily be incorporated into plant and animal food products. In contrast, plants cannot assimilate CH_4 (radioactive or non-radioactive).

Environmental field data provide support for the applicability of the ^{14}C specific activity approach. In a recent study conducted in the vicinity of the Kaiga nuclear power plant in India, ^{14}C specific activity was quantified in soils and sediments using batch combustion and liquid scintillation counting (Arya Krishnan et al., 2025). Samples were collected between 1.5 and 12 km from the facility, under tropical monsoonal conditions with high rainfall and a complex terrain. Maximum ^{14}C specific activities of 37 ± 7 Bq kg^{-1} C and 11 ± 7 Bq kg^{-1} C were recorded in soils and sediment, respectively, indicating a small but measurable incorporation of anthropogenic ^{14}C into these environmental media. However, these data were obtained around an Indian nuclear power plant located in a tropical environment with site-specific meteorology, land use, and C cycling characteristics. Caution is therefore required when attempting to extrapolate the findings for UK assessments, which reflect different reactor discharge conditions, climate, soils, agricultural practices etc.

A key concept for airborne releases of ^{14}C is the depth of the "mixed layer" where releases are dispersed in the atmosphere. The concept applies to releases that originate below ground (e.g., from a subsurface disposal facility) as well as to releases that originate above ground. The "mixed layer" is the layer where the ^{14}C released is fully mixed with non-radioactive C. It then enters the food chain through photosynthetic assimilation by plants. The ^{14}C specific activity in the air of the mixing layer is conserved along the components of the food chain. The mixing layer height is the height to supply the canopy with CO_2. 10 m and 20 m have previously been used for agricultural land and forests, respectively (Avila and Pröhl, 2008).

In the case of the irrigation of agricultural lands with water contaminated with ^{14}C, plants may also incorporate ^{14}C from the air via photosynthesis (Avila and Pröhl, 2008). Here, ^{14}C incorporation can be estimated by assuming that all ^{14}C that is input to the system with irrigation water will be immediately released to the atmosphere (as $^{14}CO_2$). It can then be assimilated by the irrigated plants by photosynthesis. IRAT2 uses PC-CREAM 08 datasets and this does not explicitly consider irrigation (Smith and Simmonds, 2009). However, PC-CREAM 08 notes that spray irrigation may be treated as an atmospheric source with deposition onto plants and soil. Default parameter values may be used in the absence of other data. The rate of radionuclide deposition can be obtained by multiplying its concentration in unfiltered water (Bq m^{-3}) by the irrigation rate (m^3 s^{-1} per m^2).

Modelling ^{14}C behaviour in freshwater systems is complicated by the existence of several C pools. The C cycle in lakes starts with consideration of the dissolved inorganic carbon (DIC), derived from atmospheric exchange of CO_2 across the air/water interface or via water exchange (e.g., riverine input). The DIC can be sequestered into organic matter by phytoplankton and aquatic plants, where it is then available for transfer throughout the food web. Once incorporated within the food chain, ^{14}C may be retained within the biomass of organisms or be transferred back to the water column in the form of respired CO_2, which is then available for photosynthetic uptake. Alternatively, ^{14}C may be released from organisms as dissolved organic carbon (DOC) or particulate organic carbon (POC) through processes such as excretion and death. The DOC and POC may return to the biological cycle through incorporation in bacterial biomass or direct consumption by biota, with respiration then returning C for fixation. The POC may settle through sedimentation, providing a C source to benthic organisms. Carbon-14 may also be adsorbed onto sediments and, following sedimentation, be converted by bacteria to $^{14}CH_4$ in anoxic sediments. Methane could potentially be released as marsh gas. An IAEA model assumes that fish are in full specific activity equilibrium with DIC (IAEA, 2010).

The different C pools present in the environment lead to uncertainties in ^{14}C assessments. One report noted that it may be inappropriate to consider C isotopic equilibrium in relation to DIC since this is not the source of C consumed by fish (Smith, 2014). Specific activity models consider inorganic C pools, but organic C may be released and may potentially be more bioavailable than inorganic forms. Dissolved organic matter (DOM) input from non-contaminated sources to water bodies will also affect ^{14}C specific activity and should be considered. An EDF study compared ^{14}C levels in fish sampled from a river with modelling predictions and identified differences between modelled and measured ^{14}C specific activity (Sheppard et al., 2006). This result supports the suggestion that all C sources for fish may not be taken into account. A BIOPROTA publication found that bacteria at oxic-anoxic interfaces within riverbed sediments can convert CH_4 to biomass which can then enter the food chain (Thorne et al., 2018). Another BIOPROTA report concluded that terrestrial sources may contribute ~50% of the C in an aquatic food web for a lake (Limer, 2019).

The ^{14}C specific activity model is also relevant for marine environments. The dissolved C concentration in sea water includes DOC, carbonate, bicarbonate, and CO_2. There are insufficient data to indicate what fraction, if any, would not equilibrate with ^{14}C and to what extent any of the above C forms would become biologically incorporated. An IAEA report adopted an organic C concentration of 7.2 x 10^{-6} kg/kg in seawater (IAEA, 2004). A SKB publication used a nominal value of 11 gC/m^3 DIC in seawater (Avila and Pröhl, 2008). These values are in reasonable agreement, although another investigation used a higher value of 28 ppm (2.8 x 10^{-5} kg/kg) (Karlsson and Bergström, 2002).

The BIOPROTA international forum noted that the form of C in well-water that is used for drinking or irrigation would be inorganic C (Smith, 2014). An appropriate dose coefficient should therefore be used.

Time-dependent modelling analysis found that there was little difference between the model results and a specific activity approach for long timescales, but a time-integrated approach may be more appropriate for a variable source term (Smith, 2014). A dynamic model of a stream found annual variations in stable C stocks in phytoplankton and fish, as expected due to temperature effects on photosynthesis (Limer, 2019).

4.2 Gaseous dispersion of carbon-14

In PC-CREAM 08, ^{14}C is assumed to be returned to the atmosphere (from soil and plants) on a timescale that is short compared to its relatively long half-life (5.7 x 10^3 years) (Smith and Simmonds, 2009) As a result, no allowance is made for dry deposition or washout.

The SKB model for ^{14}C (SKB R-08-16) considered irrigation with water contaminated with ^{14}C (Avila and Pröhl, 2008). It assumed that all ^{14}C that is inputted to the system with irrigation water is released to the atmosphere where it can be assimilated by plants through photosynthesis. The IRSN modelled the irrigation water to plant transfer by assuming that the ^{14}C from irrigation is incorporated via photosynthesis, as a result of emanation of CO_2 from the soil (Alonzo et al., 2001). The IRSN model considered the C flux from the soil (0.5 kg m^{-2} y^{-1}) and the fraction that participates in photosynthesis (0.1).

Soils in aerobic environments are the main biological sink for CH_4. At the soil-atmosphere interface, the CH_4 flux is balanced between the efflux of CH_4 produced by methanogenic bacteria, mainly in deep anaerobic soil layers. Here, methanotrophic bacteria in dry soils consume CH_4 as an energy source. Methane uptake by soils has been studied under different climatic conditions (Rafalska, et al., 2023). This work suggests that grasslands under the influence of warming and drought may absorb more CH_4 due to a reduced soil water content and an increased gas diffusivity.

4.3 Plant uptake of carbon-14

Carbon transfers to plants are governed by photosynthesis. Of note, IRAT2 currently uses the ^{14}C specific activity model in PC-CREAM 08. A specific activity model is also used in the IAEA Handbook (IAEA, 2010). Here, the non-radioactive C concentration in the plant, S_p (g/kg, fresh weight), the non-radioactive C concentration in the air, S_{air} (g/m^3), and the ^{14}C concentration in the air, C_{air} (Bq/m^3) were used to calculate the ^{14}C concentration in the plant, C_{plant} (Bq/g). This was performed using the equation below.

$$C_{plant} = \frac{(C_{air} \times S_p)}{S_{air}}$$

PC-CREAM 08 uses a slightly different formulation:

$$C_{plant} = X \times C_{air}$$

Hence:

$$X = \frac{S_p}{S_{air}}$$

The IAEA Handbook used a value of 0.2 g/m^3 for S_{air} (IAEA, 2010). Similarly, PC-CREAM 08 contains a value of 0.15 g/m^3 for C in the atmosphere (Smith and Simmonds, 2009). The IAEA Safety Reports Series No.19 adopted a value of 0.18 g/m^3 or 330 ppm by volume (IAEA, 2001). Hence, the recommend S_{air} values from different literature sources are comparable. The table below shows the X and S_p values used in PC-CREAM 08 and the IAEA Handbook, respectively (IAEA, 2010).

Table 7: Carbon-14 specific activity model parameters for plants.

Plant	IRAT2 and PC-CREAM 08 X, Bq/kg per Bq/m^3	IRAT 2 and PC-CREAM 08 S_p, g/kg (fresh weight)	IAEA (IAEA, 2010) S_p, g/kg (fresh weight)
Leafy vegetables	533	80	30 (Range: 18-65)
Root vegetables	533	80	46 (Range: 22-95)
Grass	-	-	100 (Range: 40-160)
Silage	-	-	130 (Range: 65-180)
Fruit	533	80	62 (Range: 31-100)

The PC-CREAM 08 (Smith and Simmonds, 2009) values are generally within the range quoted by the IAEA Handbook (IAEA, 2010).

A global analysis of the C content of plants (Ma et al, 2018) reported the plant C content (%) for crops (Alonzo et al., 2001). The C content is based on the dry weight (dw) of the plant. PC-CREAM 08 uses a C content of 40% of dry matter (Smith and Simmonds, 2009). This value is in good agreement with the results of Ma et al. investigation. The C content for root vegetables and green vegetable in PC-CREAM 08 is 8% (80 g/kg, fresh weight (fw)) based on 20% dry matter. This value is in good agreement with Ma et al. (Ma et al., 2018). The key findings of the Ma et al. study are summarised in the table below.

Table 8: Carbon content of plants (Ma et al., 2018).

	Root	Leaf	Stem
Carbon content (%)	38.2 ± 5.23	41.32 ± 3.38	43.26 ± 3.15
Carbon content g/kg fw (10% dry matter)	38.2 ± 5.23	41.32 ± 3.38	43.26 ± 3.15
Carbon content g/kg fw (20% dry matter)	76.4 ± 10.46	82.64 ± 6.76	86.52 ± 6.30

The IAEA Handbook reported a dry matter content of 9-12% for root crops, 8-12% for leafy vegetables, and 7-17% for fruits (IAEA, 2010). PC-CREAM 08 uses higher values of 20% for leafy vegetables and root vegetables. One publication provided water contents of root vegetables, ranging from 75% (horseradish) to 95.3% (radish), with carrot at 88.3% (Knez et al., 2022). This is in agreement with the IAEA Handbook and suggests that the PC-CREAM 08 values are high (IAEA, 2010). If the IAEA handbook values were to be adopted this would affect the ^{3}H and ^{14}C specific activity models.

An alternative specific activity approach is used by SKB (Avila and Pröhl, 2008). Here, it is assumed that the terrestrial environment and man come into rapid equilibrium with the ^{14}C in the atmosphere. In addition, the specific activity of ^{14}C taken in by man by inhalation or ingestion is considered equal to that in the atmosphere at the point of interest. The intake of ^{14}C and ^{3}H in man by inhalation and ingestion can be determined from the respective intakes of C and water by the various routes. PC-CREAM 08 assumes an intake of 0.225 kg/d for an average adult (based on ICRP reference man (ICRP, 1975).

4.4 Animal uptake of carbon-14

Carbon-14 transfers to animals are governed by ingestion. The specific activity model is used in IRAT2 (taken from PC-CREAM 08) (Smith and Simmonds, 2009) and in the IAEA Handbook (IAEA, 2010). The IAEA Handbook used an additional factor representing the fraction of feed that is contaminated. This is set to 1.0 in the absence of a site-specific value. PC-CREAM 08 uses the same formulation as for plants, implicitly using a fraction of feed contaminated of 1.0. For animals, the S_p values used in IRAT2 and PC-CREAM 08 are slightly lower than the values in the IAEA Handbook (TRS472) (IAEA, 2010). The table below summarises the different ^{14}C specific activity model parameter values.

Table 9: Carbon-14 specific activity model parameters for animal foodstuffs.

Food	IRAT2 and PC-CREAM 08 X	IRAT 2 and PC-CREAM 08 S_p	IAEA TRS472 (IAEA, 2010) S_p g/kg C fresh weight
Cow's milk	267	40	65
Beef	800	120	(Range: 62-69)
Lamb	800	120	200
Egg	800	120	(Range: 160-290)

4.5 Carbon-14 concentration ratios and factors

4.5.1 Freshwater and marine fish

The ^{14}C concentration factor for freshwater fish in IRAT2 is currently taken from the IAEA Handbook and corresponds to a geometric mean value for muscle (IAEA, 2010). This is based on the specific activity model and a reference C content of fish of 117 g C kg^{-1} fresh weight. One study cited C as accounting for ~10% of the fish biomass (Saba et al., 2021). In contrast, other researchers quote a C average of 45.1% (Tanner et al., 2000). Another investigation reported the C content of wild fish as 35.6-56.4% (dry weight), and that of aqua-cultured fish as 42.5-62.9% (dry weight) (Czamanski, et al., 2011).

The IAEA Handbook recommended 75% water content in fish (IAEA, 2010), whereas a value of 70% has been suggested for sturgeon (Pourshamsian, et al., 2012). Johnson et al. reported a dry matter content from 15.5% to 44.6% with an average of 27.1% (Johnson et al., 2017). Other researchers characterised the moisture content of marine finish near Bangladesh as 68.3-81.2% (Ullah et al., 2022). Based on these findings, the IAEA Handbook is in agreement with recent data (IAEA, 2010).

4.5.2 Crustacea and molluscs

Carbon-14 transfers to marine animals are mainly governed by ingestion. The current ^{14}C concentration factor in IRAT2 is derived from an IAEA compilation (IAEA, 2004). This gives a single figure, not a range. This is based on the specific activity model and a reference wet weight tissue value for C of 95 g/kg for fish. The table below summarises the ^{14}C concentration factor values given in the IAEA Handbook, which vary by a factor of 10.

Table 10: Carbon-14 concentration factors for fish and seafood, as identified in the literature review (IAEA, 2004).

^{14}C concentration factor				
	Freshwater fish	**Marine fish**	**Marine mollusc**	**Marine crustacea**
IRAT2 concentration factor data (Bq/kg fresh/Bq/L)	4×10^5	2×10^4	2×10^4	2×10^4

Other data include a range of 1.9×10^5-3.2×10^6 (IAEA, 2010) and a range of 5×10^3-5.1×10^4 (Karlsson and Bergström, 2002), both for freshwater fish. The latter value has been superseded but was used in PC-CREAM 08. A ^{14}C concentration factor range of 1.6×10^3-1.9×10^3 was also identified for marine biota (Kumblad, 2008). Of note, the wet weight tissue values for C are 80 g/kg for both crustaceans and molluscs. No new ^{14}C concentration factor data for marine biota was found during this project.

Based on the ^{14}C specific activity model and C data in IAEA compilations, a review of current parametrisations could be performed. Recently published studies on the C content are consistent with IAEA data. Future research could consider establishing ranges for the ^{14}C concentration factors for various marine foodstuffs.

There are updated values for C in ERICA (version 2.0) for some (but not all) reference organisms, mandating the use of appropriate analogues (ERCIA Consortium, 2021). The findings are presented in the following three tables for marine, terrestrial, and freshwater biota. Analogue organisms are listed in the last column, where relevant.

Table 11: Carbon-14 concentration ratios for marine biota, as identified in the literature review.

Marine reference organisms	Concentration ratio (L/kg)	Reference source
Benthic fish	1.20×10^4	ERICA v.2
Bird	1.20×10^4	ERICA v.2, fish

Marine reference organisms	Concentration ratio (L/kg)	Reference source
Crustacean	1.00×10^4	ERICA v.2
Macro-algae	8.07×10^3	ERICA v.2
Mammal	1.20×10^4	ERICA v.2, fish
Mollusc – bivalve	1.20×10^4	ERICA v.2, fish
Pelagic fish	1.20×10^4	ERICA v.2
Phytoplankton	5.60×10^3	ERICA v.2
Polychaete worm	1.00×10^4	ERICA v.2
Reptile	1.20×10^4	ERICA v.2, fish
Sea anemones and true coral	1.20×10^4	ERICA v.2, fish
Vascular plant	8.07×10^3	ERICA v.2, macroalgae
Zooplankton	1.00×10^4	ERICA v.2

Table 12: Carbon-14 concentration ratios for terrestrial biota, as identified in the literature review.

Terrestrial reference organism	Concentration ratio (L/kg)	Reference source
Amphibian	1.34×10^3	ERICA v.2, mammal
Annelid	4.29×10^2	ERICA v.2, based on specific activity model
Arthropod – detritivorous	4.29×10^2	ERICA v.2, annelid
Bird	1.34×10^3	ERICA v.2, mammal

Terrestrial reference organism	Concentration ratio (L/kg)	Reference source
Flying insects	4.29×10^2	ERICA v.2, annelid
Grasses and herbs	8.90×10^2	ERICA v.2, based on specific activity model
Lichen and bryophytes	8.90×10^2	ERICA v.2, Grasses and herbs
Mammal – large	1.34×10^3	ERICA v.2, based on specific activity model
Mammal – small, burrowing	1.34×10^3	ERICA v.2, based on specific activity model
Mollusc – gastropod	4.29×10^2	ERICA v.2, annelid
Reptile	1.34×10^3	ERICA v.2, mammal
Shrub	8.90×10^2	ERICA v.2, Grasses and herbs
Tree	1.30×10^3	ERICA v.2, based on specific activity model

Table 13: Carbon-14 concentration ratios for freshwater biota, as identified in the literature review.

Freshwater reference organism	Concentration ratio (L/kg)	Reference source
Vascular plant	8.62×10^3	ERICA v.2

4.5.3 Wildlife

The ^{14}C concentration ratio values for wildlife in IRAT2 are currently sourced from ERICA (version 1.2.1) (Brown et al., 2016). These data are provided in the following three tables for marine, terrestrial, and freshwater biota.

Table 14: Current ^{14}C concentration ratios for marine biota in IRAT2 (Environment Agency, 2022).

Marine reference organisms	Concentration ratio (L/kg)	Reference source
Benthic fish	1.70×10^3	ERICA v.1.2.1
Bird	1.70×10^3	ERICA v.1.2.1
Crustacean	1.40×10^3	ERICA v.1.2.1
Macro-algae	1.30×10^3	ERICA v.1.2.1
Mammal	1.70×10^3	ERICA v.1.2.1
Mollusc – bivalve	6.50×10^2	ERICA v.1.2.1
Pelagic fish	1.70×10^3	ERICA v.1.2.1
Phytoplankton	2.50×10^2	ERICA v.1.2.1
Polychaete worm	1.00×10^4	ERICA v.1.2.1
Reptile	1.70×10^3	ERICA v.1.2.1
Sea anemones and true coral	1.70×10^3	ERICA v.1.2.1
Vascular plant	1.30×10^3	ERICA v.1.2.1
Zooplankton	1.00×10^4	ERICA v.1.2.1

Table 15: Current ^{14}C concentration ratios for terrestrial biota in IRAT2 (Environment Agency, 2022).

Terrestrial reference organism	Concentration ratio (L/kg)	Reference source
Amphibian	1.30×10^3	ERICA v.1.2.1
Annelid	4.30×10^2	ERICA v.1.2.1
Arthropod – detritivorous	4.30×10^2	ERICA v.1.2.1
Bird	1.30×10^3	ERICA v.1.2.1
Flying insects	4.30×10^2	ERICA v.1.2.1
Grasses and herbs	8.90×10^2	ERICA v.1.2.1
Lichen and bryophytes	8.90×10^2	ERICA v.1.2.1
Mammal – large	1.30×10^3	ERICA v.1.2.1
Mammal – small, burrowing	1.30×10^3	ERICA v.1.2.1
Mollusc – gastropod	4.30×10^2	ERICA v.1.2.1
Reptile	1.30×10^3	ERICA v.1.2.1
Shrub	8.90×10^2	ERICA v.1.2.1
Tree	1.30×10^3	ERICA v.1.2.1

Table 16: Current ^{14}C concentration ratios for freshwater biota in IRAT2 (Environment Agency, 2022).

Freshwater reference organism	Concentration ratio (L/kg)	Reference source
Amphibian	1.80×10^5	ERICA v.1.2.1

Freshwater reference organism	Concentration ratio (L/kg)	Reference source
Benthic fish	1.80×10^5	ERICA v.1.2.1
Bird	1.80×10^5	ERICA v.1.2.1
Crustacean	1.80×10^5	ERICA v.1.2.1
Insect larvae	1.80×10^5	ERICA v.1.2.1
Mammal	1.80×10^5	ERICA v.1.2.1
Mollusc – bivalve	1.80×10^5	ERICA v.1.2.1
Mollusc – gastropod	1.80×10^5	ERICA v.1.2.1
Pelagic fish	1.80×10^5	ERICA v.1.2.1
Phytoplankton	4.00×10^3	ERICA v.1.2.1
Reptile	1.80×10^5	ERICA v.1.2.1
Vascular plant	8.80×10^3	ERICA v.1.2.1
Zooplankton	1.80×10^5	ERICA v.1.2.1

4.6 Carbon-14 distribution coefficients

Distribution coefficient values for ^{14}C are discussed in the following sections, noting that IRAT2 currently includes element-specific K_d values for marine and freshwater systems (Environment Agency, 2022).

4.6.1 Carbon speciation

Carbon occurs in a plethora of organic and inorganic forms, many of which can arise as water soluble species. Carbon-14 releases to the environment are predominantly in the form of CO_2, CO, hydrocarbons (principally $^{14}CH_4$ and short chained hydrocarbons), or other organic forms. Carbon dioxide (with/without ^{14}C) dissolves to form bicarbonate and carbonate anions in natural waters. Moreover, ^{14}C can be incorporated into a wide variety of different biomolecules (analogous to OBT). Overall, ^{14}C chemistry in biological and environmental systems is complicated, reflecting these numerous physico-chemical forms.

Chemical speciation will strongly influence ^{14}C adsorption onto environmental media. Highly polar and charged species (e.g., carbonate anions, organic acid anions etc) largely adsorb to solid surfaces through electrostatic interactions. In contrast, non-polar ^{14}C species adsorb predominantly to environmental surfaces by hydrophobic and van der Waals interactions. These ^{14}C compounds typically have low solubility in natural waters.

4.6.2 Current ^{14}C K_d values

IRAT2 currently includes the following C-specific K_d parameter values, as shown in the table below.

Table 17: Current ^{14}C K_d values in IRAT2 (Environment Agency, 2022).

Parameter	K_d (L/kg)	Basis
Marine	1×10^3	Ocean margin value for C was recommended by IAEA (IAEA, 2004). It was based on the ratio of C in carbonaceous sediments to that in dissolved organic and carbonate forms in sea water. It was assumed that all the associated C is available for exchange with C in the dissolved phase. A value of 2×10^3 L/kg was provided for open ocean sediments in the same reference (the difference in value is due to the different nature of the sediments, which were assumed to be fine-grained and clay rich for the open ocean).
Freshwater	2×10^3	Taken from the PC-CREAM methodology (Smith and Simmonds, 2009). However, the source reference (therein) is a US national Laboratory report (stated as 2.2×10^3 L/kg) (Booth, 1976). The original value was based on sediment/water ratios.

4.6.3 Review of ^{14}C K_d parameters

The UNSCEAR has adopted ^{14}C K_d values of 5 L/kg (freshwater, from IAEA, 2001) and 2×10^3 L/kg (open ocean; IAEA, 2004) and 1×10^3 L/kg (ocean margin; IAEA, 2004) in their methodology for estimating public exposures due to radioactive discharges (UNSCEAR, 2016). These K_d values are based on IAEA sources, argued to provide 'the most recent international compilation of K_d values.' The UNSCEAR freshwater K_d values of 5 L/kg (cited to Czamanski et al., 2011) is ultimately derived from an IAEA report and is lower than the current IRAT2 value (2×10^3 L/kg) by ~2 orders of magnitude (IAEA, 1994).

Researchers investigated the influence of the identities of the organic compound and river sediment on the sorption behaviour of organic pharmaceuticals in freshwater systems (Al-Khazrajy and Boxall, 2016). The adsorption of five organic species (with varying chemical properties) to multiple sediments was measured. The results were presented as K_d values and ranged from 7-258 L/kg. These data are lower than the ^{14}C K_d parameter value for freshwater currently used in IRAT2 (2×10^3 L/kg).

4.6.4 Recommendations for K_d values

The current ^{14}C terrestrial freshwater K_d value in IRAT2 is 2×10^3 L/kg. Recent literature and international compilations offer markedly lower values e.g., 5 L/kg, and 7-258 L/kg for organic forms (IAEA, 2001; Al-Khazrajy and Boxall, 2016). The relevance of these studies, especially regarding the specific organic C forms discharged to the environment, warrant further investigation. It is possible that the current IRAT2 value could reasonably be lowered. Of note, UNSCEAR utilised IAEA sources for the freshwater K_d, whilst IRAT2 uses a higher parameter value adopted in PC-CREAM 08 (originally from a US source).

There are no K_d parameter value ranges in the source reports. Chemical speciation effects are likely to strongly affect ^{14}C sorption behaviour, meaning that K_d data ranges would be useful for investigating parameter uncertainty. For this project, no such reliable data range sources have been identified for ^{14}C e.g., the IAEA reports do not include K_d value ranges.

4.7 Summary of carbon-14 review

The review of the ^{14}C parameter values is summarised in the table below.

Table 18: Key literature findings for ^{14}C transfer parameters.

Parameter	Review findings for ^{14}C
Gaseous dispersion	IRAT2 does not consider dry or wet deposition. Assumption that CH_4 behaves as CO_2 will overestimate incorporation into plant and animals, particularly in the short term. Human metabolic model has been updated but is not used for animals.
K_d	There appears to be a major disparity between IRAT2 and more recent values. The latest data provide lower K_d values compared to the current IRAT2 value.
Terrestrial food chain	Current concentration factor values are taken from a specific activity model in PC-CREAM 08. Differences to the values in

Parameter	Review findings for ^{14}C
	IAEA Handbook were found, suggesting that IRAT2 considered higher ^{14}C uptake to plants and lower uptake to animals.
Marine food chain	Concentration factors are taken from an IAEA compilation and are consistent with recent publications.
Wildlife	ERICA (version 2.0) has updated ^{14}C concentration ratios for wildlife. The current IRAT2 parameter values could be updated to align with the new values in the latest version of ERICA.

5 Iodine-129

Iodine-129 (^{129}I) has a half-life of ~1.57 x 10^7 years and undergoes beta decay to form xenon-129 (Wilson, 1996). Iodine is an essential component of the thyroid hormones thyroxine (T4) and triiodothyronine (T3), which regulate metabolic processes and are critical for growth and development. Moreover, I can exist in the environment in numerous physicochemical forms, such as elemental, organic (e.g., molecular), inorganic, particulate, and gaseous forms. Non-radioactive forms of inorganic I are accumulated daily by the adult human thyroid (10s of µg's). Iodine is largely recycled by the body, but the body's supply must be supplemented with dietary I due to obligatory losses in excreta.

Iodine-129 is a fission product of uranium-235 and is produced in nuclear reactors with a cumulative yield ~1% (of all fission products). Most of ^{129}I remains trapped in the spent fuel rod matrix but is regularly present in discharges from nuclear power plants and associated reprocessing facilities. It may also be discharged as a gas from spent fuel in dry storage facilities.

5.1 Gaseous dispersion of iodine-129

5.1.1 Dry and wet I deposition

As described in IRAT2, radionuclides released to the atmosphere enter the terrestrial environment due to dry and wet deposition on soils and vegetation, and then uptake into plants (Environment Agency, 2022). For both dry and wet deposition, the initial deposit is partitioned between deposition on plants (leaves) and deposition directly on soil.

5.1.2 Dry deposition velocity

Default values for the dry deposition velocity (V_g) in IRAT2 have been assumed to be equal to 1 x 10^{-3} m/s for particulate radionuclides and 0.01 m/s for inorganic I. These are the values adopted in PC-CREAM 08 (Smith and Simmonds, 2009). Such data are consistent with experimental studies on grass, as shown in the table below.

Table 19: Dry deposition velocities for I species.

Form	Deposition velocity (m/s)	Reference
Elemental	0.01	IRAT2, PC-CREAM 08 (Smith and Simmonds, 2009), RIMPUFF (Thykier-Nielsen et al., 1999)
	$2x10^{-4}$-4.9 x 10^{-3} (autumn),	(Bah et al., 2020)

Form	Deposition velocity (m/s)	Reference
	4.8×10^{-3} to 1.25×10^{-2} (summer)	
	$1\text{-}5 \times 10^{-3}$	(Parache et al., 2011)
	8×10^{-3}	(Sportisse, 2007)
Particulate	1×10^{-3}	IRAT2, PC-CREAM 08 (Smith and Simmonds, 2009)
	5 times lower than for elemental I	(Bah et al., 2020)
	1×10^{-3}	(Sportisse, 2007)
Organic (methyl iodide)	1×10^{-5}	PC-CREAM 08 (Smith and Simmonds, 2009)
	$1.4\text{-}71 \times 10^{-7}$	(Collins et al., 2004)
	5×10^{-4}	RIMPUFF (Thykier-Nielsen et al., 1999), also cited in (Sportisse, 2007)

PC-CREAM 08 also specifies a low dry deposition velocity of 10^{-5} m/s for organic I. This is similar to the deposition velocity for methyl iodide reported by Collins et al. (Collins et al., 2004). IRAT2 does not explicitly consider organic I. A dry deposition velocity of 10^{-5} m/s could potentially be used for assessments of discharges of organic I. However, this would require rerunning PC-CREAM models. The deposition velocity of only one chemical form of I (inorganic I) is currently included in IRAT2, and data would be constrained by this.

5.1.3 Washout coefficient

There are large uncertainties in the values that have been reported for the washout coefficient of I due to the challenges in undertaking experimental measurements. A value of 1×10^{-4} s^{-1} has been used in IRAT2 for all radionuclides except noble gases (for which washout is assumed to be zero). This is also the default value in PC-CREAM for reactive gases and for particle sizes of 1 µm (Smith and Simmonds, 2009). PC-CREAM 08 gives a range of $3\text{-}30 \times 10^{-5}$ s^{-1} for a rainfall of 1 mm/hr. It is important to consider rainfall patterns as the washout coefficient is proportional to the rainfall rate, specifically to a power of 0.5

to 1.0 (Smith and Simmonds, 2009). A review of the potential for human exposure noted that methyl iodide has a low susceptibility to wet deposition (ATSDR, 2004).

5.1.4 Soil transfer

The transfer coefficients used in the PC-CREAM 08 model to move radionuclides vertically down the soil column are based on the soil migration data for plutonium (Pu) and are assumed to be applicable to all other elements. This approach is conservative for more mobile elements such as I (Smith and Simmonds, 2009). The model used to predict radionuclide concentrations in the terrestrial food chain in PC-CREAM 08 is FARMLAND, which is used to underpin IRAT2 (Brown and Simmonds, 1995).

5.1.5 Interception

Spray irrigation may be treated as an atmospheric source with deposition onto plants and soil and the default parameter values may be used in the absence of other data. However, spray irrigation implemented at a high rate is similar in effect to heavy rain and there will be reduced radionuclide interception by plants.

5.2 Plant uptake of iodine-129

Once deposited on vegetation, radionuclides are lost from plants due to removal by wind and rain, either through leaching or by cuticular abrasion. Alternatively, radionuclides may be taken up into plants by translocation or photosynthesis. Plant growth can also lead to a reduction in radionuclide concentrations, termed 'growth dilution.' Weathering losses and growth dilution effects are often estimated in models using a weathering half-life, typically in the range of 5-30 days. In contrast, translocation from foliage to edible parts of plants is generally represented using an empirical scaling factor. Mobile radionuclides are assumed to behave like caesium.

The IAEA Handbook reports no translocation data for I (IAEA, 2010). One study observed translocation of I, deposited as methyl iodide, from leaves to the crop components that were growing at the time (Collins et al., 2004). The crops studied were bean, carrot, and cabbage. Loss was only observed during leaf fall. A review noted that molecular I is more readily absorbed through the stomata in the leaves than methyl iodide (ATSDR, 2004).

Researchers have performed experiments on the foliar application of potassium iodide solutions on apple trees (the fruits were shielded from the spray) (Budke et al., 2020). The translocation of leaf absorbed I to fruits was negligible. However, fruits directly wetted by the spray solution showed significantly increased levels of I. Another study found that spinach leaves can absorb I via foliar fertilisation, but translocation is severely limited (Humphrey et al., 2019). They concluded that foliar application is unlikely to significantly increase the I content of fruits, grains, or tubers (by translocation). Studies related to the biofortification of plants also concluded that the translocation of I from leaves to fruits or tubers is limited (Caffagni et al., 2012). Investigating I translocation from the plant root to the edible parts, another work established that cabbage plants have a higher I transfer factor (0.09–0.17) than tomato (0.01–0.08) (Dobosy et al., 2020). The partitioning of I in edible parts of cabbage and tomato were in the ranges of 57-83% and 1-4%, respectively.

PC-CREAM 08 indicates that I translocation in root crops is significant and that I levels in root crops are at least as high as other crop types (Smith and Simmonds, 2009). For long-lived radionuclides such as ^{129}I with significant root uptake rates, the assumed rate of migration of activity from surface soil to deeper soil will clearly have an impact on the radioactivity distribution over prolonged timescales (Smith and Simmonds, 2009).

5.3 Animal uptake of iodine-129

Animals can internalise radionuclides through the skin, by inhalation and by ingestion. One of the most critical radionuclide transfer pathways to animals is ingestion of contaminated feed and soil. Radionuclide intake via soil can be significant if the availability for absorption of soil associated radionuclides is high. Arguably the most applied transfer parameter for agricultural animal products is the transfer coefficient, which incorporates all the processes from ingestion of a radionuclide in herbage or soil to its incorporation into a specific tissue. Values for gastrointestinal fractional absorption are also given.

The FARMLAND model in PC-CREAM 08 has two animal models known as ‘simple’ and ‘more complex’; the more complex model form is used for I (Brown and Simmonds, 1995). Iodine concentrates in the thyroid, and this was included as an organ in the metabolic model for I. The model also distinguishes between organic and inorganic I in the body.

Radionuclide transfer from the lung and the gastrointestinal tract of the animal is based, with simplification where appropriate, on the ICRP recommended models for man. The time constants and the fraction of each radionuclide transferred from the animal lung and gastrointestinal tract are based on data given for man, assuming each radionuclide to be in the oxide form and is a 1 µm Activity Median Aerodynamic Diameter (AMAD) aerosol when inhaled. A variety of experimental data were used to derive transfer coefficients for the metabolic models, with the I model fitted to thyroid data (Brown and Simmonds, 1995).

Iodine ingested or inhaled goes to blood or is excreted. From blood it is taken up in the thyroid, converted into organic form which is then distributed among the organs and other tissues of the body. Here, I is eventually converted to inorganic I, represented by a separate compartment. Diffusion from blood to inorganic I is also included. Loss occurs from blood and directly from the organic form. The biological half-life is not required for the animal model for I. The FARMLAND gut uptake factor for cows and sheep are 0.98 (range 0.85-1.0) and 0.87 (range 0.60-1.00), respectively (Brown and Simmonds, 1995).

ICRP have published revised dose coefficients for workers for I, based on an updated metabolic model published in 2010 (ICRP, 2017). The fraction deposited in the lung is 1.00 (0.7 for methyl iodide). The absorbed fraction from the gut is 1.00 for all chemical forms and this is unchanged from the previous value. Key adsorption parameters for inhaled I are summarised in the table below.

Table 20: Absorption parameters for inhaled forms of I (ICRP, 2017).

Form	Fraction deposited in lung	Absorption
Elemental I, I_2	1.0	Type F, gastrointestinal uptake fraction 1.0
Methyl iodide, CH_3I, ethyl iodide, C_2H_5I	0.7	Type V, (instantaneous from respiratory tract)
Unspecified gas or vapour	1.0	Type F, gastrointestinal uptake fraction 1.0
Particulate	1.0	Gastrointestinal uptake factor 1.0

The transfer factor for blood to urine is 11.84 days^{-1}. ICRP note that I occurs in foods mainly as inorganic iodide (ICRP, 2017). Overall, the ICRP dose coefficient for workers has reduced slightly (~10%). Hence, the FARMLAND model for animals is consistent with the updated model for humans. The gastrointestinal fractional absorption for I in ruminants given in the IAEA Handbook is approximately equal to 1.0 (mean 0.98, range 0.7-1.1) (IAEA, 2010). The value used for a monogastric organism (i.e., an animal with a single-compartmented stomach) is that recommended for humans (1.0). Hence, the assumptions in the IAEA Handbook appear to be still valid.

5.3.1 Transfer coefficient for milk

The transfer coefficient is used to quantify radionuclide transfer to milk (F_m, days L^{-1} or days kg^{-1}) and meat (F_f, days kg^{-1}). It is defined as the equilibrium ratio of the radionuclide concentration in milk/meat to the daily dietary radionuclide intake. The transfer coefficient is expressed in terms of the fresh weight of the milk/meat. An alternative method for quantifying transfer from herbage to animal products is the concentration ratio which is the equilibrium ratio of the radionuclide concentrations in the food product (in fw) and the feed (dry matter). Both F_m and F_f values can be derived by dividing a concentration ratio value by the daily dietary intake (in kg days^{-1}), and concentration ratio values can be derived by multiplying the transfer coefficient value by the daily dietary intake (in kg days^{-1}).

Most forms of I are rapidly reduced to iodide within the digestive tract (IAEA, 2009). It is therefore unlikely that the source of radioiodine ingested by lactating ruminants will be a major factor in determining its activity concentration in milk.

There are several studies on I transfer to milk as a result of feeding I supplements to cows. However, it is difficult to obtain uptake data from these works as there may be other I sources or external factors (farm management, I antagonists) that affect the total I in milk (Flachowsky et al., 2014). One publication reported µg/L concentrations of I in milk for different dietary amounts of I ranging from 16.64 mg/days to 146.7 mg/days (Antaya et al., 2015). The measured I fractions transferred to milk (F) varied from 9.3 x 10^{-3} to 1.1 x 10^{-2}, with the lower fraction corresponding to the higher dietary amounts. The results from other studies can be used to generate F values of 6.4 x 10^{-3} (van der Reijden, et al., 2019), 5.8 x 10^{-3} (Moschini, et al., 2010), and 5 x 10^{-3} (Flachowsky et al., 2014). Experiments with seaweed in feed imply F values of 0.01-1.8 x 10^{-3} (Rey-Crespo, et al., 2014). FARMLAND has 5 x 10^{-3} of daily intake transferred to one litre of milk i.e., at the low end of the range reported.

The IRAT2 transfer factor for milk is taken from the IAEA Handbook (IAEA, 2010). The IAEA Handbook provides a comprehensive review of current parameter data available at the time. Iodine transfer coefficients for milk obtained from the IAEA Handbook and more recent studies are listed in the following table.

Table 21: Iodine transfer factors for cow's milk and goat's milk, as identified in the literature review (Bq/L/Bq/days or Bq/kg/Bq/days).

Cow's milk	Goat's milk	Reference
5.4 x 10^{-3} (Range: 4 x 10^{-4}-2.5 x 10^{-2})	0.22 (Range: 2.7 x 10^{-2}-0.77)	(IAEA, 2010); cow's milk value currently used in IRAT2.
4.3 x 10^{-2}	-	(Sheppard et al., 2009)
3.6 x 10^{-3}	2.8 x 10^{-2}	(Parache et al., 2011)
6.4 x 10^{-3}	-	(van der Reijden, et al., 2019),
1.0 x 10^{-2} (Range: 9.3x10^{-3}-1.1x10^{-2})	-	(Antaya et al., 2015).
5.8 x 10^{-3}	-	(Moschini et al., 2010)
5 x 10^{-3}	-	(Flachowsky et al., 2014)
1.08 x 10^{-2}-1.76 x 10^{-2}	-	(Rey-Crespo, et al., 2014)

Many of these later studies focus on I deficiency and the biofortification of milk. The values reported are consistent with the IAEA Handbook data (used in IRAT2) and therefore suggest that the IRAT2 values for cow's milk are satisfactory. The IAEA values for goat's milk could be considered if goat's milk was relevant to a specific assessment (IAEA, 2010).

5.3.2 Transfer coefficient for meat and eggs

IRAT2 considers I transfer to beef and mutton, and the values are taken from the IAEA Handbook (IAEA, 2010). IRAT2 also considers cow liver and sheep liver. These I transfer coefficients in IRAT2 are the same as those reported in FARMLAND model (Brown and Simmonds, 1995). In FARMLAND, the I transfer coefficients for beef and cow liver are the same (2.0×10^{-3} days kg^{-1}). Similarly, the transfer coefficients for mutton and sheep's liver are also the same (5×10^{-2} days kg^{-1}). Therefore, FARMLAND does not distinguish between the different foodstuffs from the same animal. The IAEA Handbook only presents values for beef and sheep meat, and these are different to the FARMLAND values for beef and mutton (IAEA, 2010). Iodine is stored in the thyroid and actively taken up by the mammary gland (IAEA, 2009). Flachowsky (Flachowsky, 2007) and EFSA (EFSA, 2013) report higher I concentrations in beef liver than in beef muscle by a factor of at least two, in conjunction with other datasets (Meyer et al., 2008). The table below show these results.

Table 22: Iodine data for beef and liver samples (Meyer et al., 2008).

Parameter	Measurement 1	Measurement 2	Measurement 3
Dry mass intake (DMI) (mg/kg)	7.79	7.66	7.70
Feed rate (days/kg)	7.79	7.66	7.7
Beef (long. dorsi) (µg/kg)	16	45	80
Beef (lutaeus medius) (µg/kg)	32	83	147
Liver (µg/kg)	73	138	245
Ratio liver/beef	2.9	2.1	2.1
F, beef* (days/kg)	3.9×10^{-3}	2.4×10^{-3}	1.8×10^{-3}
F, liver (days/kg)	1.2×10^{-2}	5.1×10^{-3}	3.8×10^{-3}

*Average of the two types of beef.

The transfer factor (F) for beef/liver is calculated by taking the feed rate and multiplying this value by the dry mass intake of I. The measured I in the tissue compartments (beef or liver) is then divided by this number to give final F value.

The collective data indicate that the I transfer coefficient for liver should be the same or greater than the transfer coefficient for beef. The range of transfer coefficients for beef and liver shown in Table 22 (1.8×10^{-3}-3.9×10^{-3} and 2×10^{-3}-3.8×10^{-2}, respectively) is consistent with the range in the IAEA Handbook (2×10^{-3}-3.8×10^{-2}). Interestingly, the current IRAT2 value for liver is lower than the value for beef. The transfer coefficient for beef liver could be increased to 6.7×10^{-3} days kg^{-1} to be the same as the value for beef.

No recent information has been found on I transfer to sheep's liver. It is not clear if the value of 5×10^{-2} provided in FARMLAND model is simply the same as the one used for mutton (Brown and Simmonds, 1995). Alternatively, the value might be based on data for sheep's liver. Assuming that it is based on the value for mutton, the slightly lower value of 3×10^{-2} for mutton given in the IAEA Handbook implies that the transfer coefficient for sheep's liver could also be slightly reduced to be the same value (IAEA, 2010). That is, the IRAT2 transfer coefficient for sheep's liver could potentially be reduced to 3.0×10^{-2} days kg^{-1} to align with the value for mutton, or specifically for more detailed assessments.

The IAEA Handbook also includes pork, chicken, and eggs and the values (IAEA, 2010). These foodstuffs could be relevant for site-specific studies. Flachowsky et al. found that I supplementation significantly increased the I concentration in all analysed body samples and in eggs (Flachowsky et al., 2017). Their results for the transfer of I from feed to eggs yielded average carry over values of 15.3%-18.6%. Using a dry matter feed rate of 0.07 kg/days (IAEA, 2009), this gives transfer coefficients of 2.2-2.7 days/kg. These values are consistent with the IAEA Handbook value of 2.4 d/kg (IAEA, 2010). The IAEA Handbook values are used in the Posiva biosphere model and the SKB biosphere model (IAEA, 2010). Identified I transfer factors to meat and eggs are summarised in the table below.

Table 23: Iodine transfer factors for animal's meat, as identified in the literature review.

Current parameters							
	Cow meat	Cow liver	Pork	Sheep meat	Sheep liver	Chicken	Eggs
(Bq/L)/(Bq/d) or Bq/kg/(Bq/d) fresh	6.7×10^{-3}	2.0×10^{-3}	-	3.0×10^{-2}	5.0×10^{-2}	-	-
Reference source	(IAEA, 2010)	(Brown and	-	(IAEA, 2010)	(Brown and	-	-

Current parameters							
		Simmonds 1995)			Simmonds 1995)		
Other values							
(Sheppard et al., 2009) **fresh d/kg or d/litre**	1.8 x 10^{-3}	-	4 x 10^{-3}	4.1 x 10^{-3}	-	0.18	2.7
(IAEA, 2010) **d/kg or d/litre fresh**	6.7 x 10^{-3} Range: 2 x 10^{-3}- 3.8 x 10^{-2}	-	4.1 x 10^{-2} Range: 1.5x10^{-2}- 6.6 x 10^{-2}	3.0 x 10^{-2}	-	8.7x10^{-3} Range: 4x10^{-3}- 1.5x10^{-2}	2.4 Range: 1.9-3.2
(EFSA, 2013)	1.5 x 10^{-3} – 6.4 x 10^{-3}	3.2 x 10^{-3} – 1.9 x 10^{-2}	-	-	-	-	-
(Posiva, 2014)	6.7 x 10^{-3}, (IAEA, 2010)	-	4.1x10^{-2}, (IAEA, 2010)	As beef	-	8.7x10^{-3} (IAEA, 2010)	2.4 (IAEA, 2010)
(Staven et al., 2003)	4 x 10^{-2}	-	-	-	-	5 x 10^{-2}	4.4
(Flachowsky et al., 2017)	-	-	-	-	-	-	2.2-2.7

The review of the current I parameterisation data shows that existing transfer factor values are largely derived from international compilations. While these sources provide a consistent basis for assessment, they may not fully reflect more recent scientific findings.

Recently published studies offered additional evidence to help inform I parameter value selection. The IAEA Handbook was published more recently than several of the references currently used in the FARMLAND model. However, the IAEA Handbook does not explicitly address I concentrations in liver. Other data indicate that I concentration in cows' liver may be approximately twice that in beef, although the reported (large) ranges do overlap. No new data have been identified on I transfer to sheep's liver. Moreover, seaweed containing I from coastal releases may be used as fertiliser, which could enhance the transfer of I to soil and subsequently into the food chain.

Based on these considerations, the I transfer factor values for beef liver and sheep's liver could reasonably be revised to match the IAEA Handbook values for beef and sheep meat, respectively. For more detailed assessments, IAEA Handbook values could also be considered for pork, chicken, and eggs, where relevant.

5.4 Iodine-129 concentration ratios and factors

5.4.1 Plants

Iodine in soil can be present in several chemical forms; inorganic iodide (I^-) and iodate (IO_3^-) ions, and organic forms (Gonzali et al., 2017). The bioavailability of ^{129}I is expected to be strongly dependent on its chemical speciation, where iodide and iodate uptake by plants and animals should be higher than the I fraction associated with organic matter (Hou et al., 2009). It is expected that the water-soluble and exchangeable forms of ^{129}I can easily be taken up by plants through the roots, while the bound I fractions (such as organic I, oxides, and minerals) may be more difficult to assimilate. Iodide ions are most likely to be taken up because plants have substantial capacity for the chemically similar chloride ions (Siasou and Willey, 2015). Nevertheless, leaf uptake of gaseous I from atmosphere is also a major I accumulation pathway for plants.

Iodine concentration ratios values for plants are typically low, indicating that this element is not readily transferred from the soil to plants. One possible reason for this is the strong soil adsorption of I in the oxic region of soils where plant roots predominate (Ashworth, 2009). However, plants with roots that can survive in anoxic soils. Under these conditions, I tends to partition to the liquid phase and would therefore be expected to exhibit greater transfer to plants. Volatilisation of I (e.g., methyl iodide) occurs from both soil and plants.

A study of I in pasture on limestone and millstone grit areas demonstrated that organic matter could restrict I mobility (Mehra et al., 2014). Iodine transfer factors as a ratio of I in the aerial plant parts to the roots and soil were considerably lower in the limestone area than in the millstone grit area. In addition, I volatilisation from organic-rich soils may be limited, thus depriving plants growing on such soils of an atmospherically derived source of I (Bostock et al., 2003). Fuge and Johnson noted that I in the soils over limestones is biologically unavailable (Fuge and Johnson, 2015). This may be because iodate is more prevalent than iodide in the alkaline-neutral pH soils in the limestone areas. Limited I volatilisation in soils occurs where iodate is the dominant form, thus depriving plants of a major I transfer pathway. The lack of iodide and iodate mobility in soils means that iodide in fresh deposits is primarily the driver of I transfer into vegetation (McKernan et al., 2020).

Iodine is not currently considered a micronutrient for higher plants, although it is essential for animals and strongly accumulated in marine algae e.g., seaweed, kelp. However, a growing body of evidence suggests that I is involved in plant physiological and biochemical processes (Gonzali et al., 2017).

Pasture I concentrations were negatively correlated with the distance from the sea (Jensen et al., 2019). This is because the main source of I in the terrestrial environment is seawater, where it is accumulated by seaweed and then volatilised (Uchida and Tagami, 2010). Hence, I is strongly enriched in near-coastal soils; the major zone of marine influence generally stretches to 50-80 km inland (Fuge and Johnson, 2015). Sea spray will likely be a major contributor of I to the terrestrial environment in coastal areas. In addition, elemental I is could be transferred to the atmosphere from extensive beds of brown algae. Of note, I-rich plants can be cultivated if I-rich algae fertilisers are added to soils.

The soil-plant transfer factor concept implies equilibrium or quasi-equilibrium conditions in the soil-plant system (IAEA, 2009). The concentration in soil should represent the average concentration in the rooting zone. An IAEA review (IAEA, 2009) is the source data for the IAEA Handbook (IAEA, 2010). The data in these reports were based on standardised soil depths. For grass, this soil depth value was 10 cm; for all other crops (including fruit trees) it was 20 cm. Most I data were based on short experiments using short lived ioine-125 (half-life of ~60 days) and these were given lower weight in the IAEA review due to possible decay effects and non-equilibrium. Inductively coupled plasma mass spectrometry may help improve these analytical methods (Sheppard et al., 2009).

Current IRAT2 concentration factor values are based on a fresh weight (CF_{fw}) of the foodstuff, whereas most published data is based on a dry weight (CF_{dw}), apart from fruit. The moisture factor (MF) can be used to convert from dry weight to fresh weight:

$$CF_{fw} = CF_{dw} \times MF$$

Where MF = 1 - MC

And MC = moisture content = fresh mass / dry mass

The table below summarises the moisture content and moisture factor values currently used in IRAT2 for different foodstuffs.

Table 24: Dry weight to fresh weight conversion factors used in IRAT2.

Dry weight	Moisture content (MC)	Moisture factor (MF)	IRAT2 foodstuff
10%	0.9	0.1	Green vegetables
20%	0.8	0.2	Root vegetables, fruit
30%	0.7	0.3	Pasture

IRAT2 concentration factors values for pasture, green vegetables, and root vegetables are based on an International Union of Radioecology (IUR) compilation from 1994, a robust data source, cited in PC-CREAM 08 (Smith and Simmonds, 2009). Of note, more recent compilations are available. The I value for fruit in IRAT2 (1.1×10^{-3}) is based on the IAEA

Handbook but does not correspond to the value in that compilation (1.2 x 10^{-3}) (IAEA, 2010). This small inconsistency may be attributed to an erroneous input of the value into IRAT2. Relevant plant biofortification studies may aid the selection of I concentration factor values, although these were not specifically designed for this purpose. As such, these types of studies are not considered in this project. A Finnish safety case for the disposal of spent nuclear fuel reviewed concentration factors and selected values relevant to the local environment (Posiva, 2014). The local data is unrepresentative of the UK environment. This is important as transfer parameter values ideally need to account for local conditions. Consequently, adopting international parameter datasets that were generated under markedly different climatic conditions to those of the UK should be done cautiously.

An I concentration factor value for pasture in a temperate climate was provided in an IAEA review (3.7 x 10^{-3}), derived from a 1992 report (IAEA, 2009). However, this value is not clearly referred to in the IAEA Handbook (IAEA, 2010). One safety case report used the significantly higher value of 0.03, but no clear derivation was given (Posiva, 2014). An I concentration factor value used for the whole organism (as part of wildlife assessments) was 0.24. In addition, a value of 0.05 for monocots is available (Siasou and Wiley, 2015).

The IAEA gave an I concentration factor of 6.5 x 10^{-3} for green vegetables in a temperate climate (IAEA, 2009). A higher value of 2 x 10^{-2} was adopted elsewhere but the basis for this value was not clear (Posiva, 2014). Sheppard et al. reported 3.3 x 10^{-2} (and values of 1.7 x 10^{-2} and 5.1 x 10^{-2} in other locations for inner leaves) (Sheppard et al., 2009). In a later study, values of 9 x 10^{-3}-3.2 x 10^{-2} (geometric mean = 2.4 x 10^{-2}) and 2.0-8.2 x 10^{-2} (geometric mean = 3.6 x 10^{-2}) were obtained for interior and exposed leaves, respectively (Sheppard et al., 2010a). Japanese studies obtain similar I concentration factor values (Uchida and Tagami, 2010). However, a follow-up investigation reported a notably higher value of 0.142 (Uchida and Tagami, 2011). The reason for this large increase is unclear.

The IAEA provided an I concentration factor value of 7.7 x 10^{-3} for root vegetables (IAEA, 2009) and this was later used in the Finnish safety case (Posiva, 2014). Similar values of 9 x 10^{-3} (Sheppard et al., 2009) and 0.01 (Sheppard et al., 2010a) can be found in the wider published literature. The ranges reported in other studies (Sheppard et al., 2010a; Uchida and Tagami, 2010) are consistent with the IAEA data (IAEA, 2009).

The IAEA Handbook published an I concentration factor value of 6.3 x 10^{-3} for fruit (IAEA, 2010). This was the geometric mean of the values from an earlier IAEA document (IAEA, 2009). For completeness, the arithmetic mean of the values was 1.2 x 10^{-2}. One safety case used 1 x 10^{-2} and 2.7 x 10^{-2}, which are similar to the arithmetic mean of the IAEA values (Posiva, 2014). Another study reported a value of 6 x 10^{-3} (Sheppard et al., 2010a), which is consistent with Japanese study findings (Uchida and Tagami, 2010). Finally, the current IRAT2 value of 1.1 x 10^{-3} is referenced to the IAEA Handbook but does not seem to actually correspond to it (IAEA, 2010). It is useful to note that PC-CREAM 08 contains I concentration factor values of 2 x 10^{-2} for fruit and all other foodstuffs mentioned above in this section. The main I concentration factor values for foodstuffs are outlined in the table below. The current IRAT2 parameter values are included to aid comparisons.

Table 25: Current ^{129}I concentration factors for foodstuffs in IRAT2 (Environment Agency, 2022).

Current parameters in IRAT2				
	Pasture	**Green vegetables**	**Root vegetables**	**Fruit**
Concentration factor data (Bq/kg fresh/Bq/kg dry soil)	1.1×10^{-3}	2×10^{-2}	2.0×10^{-2}	1.1×10^{-3}
Basis	FARMLAND from IUR database 1989 mobile translocation	FARMLAND from IUR database 1989	FARMLAND from IUR database 1989	IAEA compilation
Reference source	(Smith and Simmonds, 2009)	(Smith and Simmonds, 2009)	(Smith and Simmonds, 2009)	(IAEA, 2010)
Other values				
(Sheppard et al., 2009) dry wt.	-	3.3×10^{-2}	9×10^{-3}	6×10^{-3}
(IAEA, 2010) dry wt.	-	3.0×10^{-2} (sub-tropical)	5.6×10^{-2} (sub-tropical)	6.3×10^{-3} (woody; fresh weight) 1.5×10^{-2} (herbaceous; fresh weight)
(IAEA, 2009) dry wt.	-	3.0×10^{-2} (GM)* 3.9×10^{-2} (AM)	5.6×10^{-2} (AM)**	-

Current parameters in IRAT2				
(IAEA, 2009) dry wt.	3.7×10^{-3} (GM) 4.5×10^{-2} (AM) Range: 9×10^{-4} – 0.50	6.5×10^{-3} (GM) 1.6×10^{-2} (AM) Range: 1.1×10^{-3} – 0.10 quoting reference 12 (2004)	7.7×10^{-3} (GM) 1.3×10^{-2} (AM) Range: 1.4×10^{-3} – 4.7×10^{-2} (also 0.1 for potato)	Woody 6.3×10^{-3} (GM) 1.2×10^{-2} (AM) Range: 4.1×10^{-4} - 3.1×10^{-2} (herbaceous; fresh weight) 1.5×10^{-2} fresh weight (AM)
(DEFRA, 2011)	-	4×10^{-3}	-	-
(Posiva, 2014) wildlife	0.24	2.6×10^{-2}	0.47 0.1 (potato)	2.7×10^{-2}
(Posiva, 2014) humans	3×10^{-2}	2×10^{-2}	7.7×10^{-3} (root) 2×10^{-2} (potato)	1×10^{-2}
(Helin et al., 2011) local experiments	-	2.6×10^{-2}	0.47 root (sugar beet) 0.1 (potato)	2.7×10^{-2}
(Sheppard et al., 2010a) dry wt.	-	Range: 2.4×10^{-2} – 8.2×10^{-2}	Range: 5×10^{-3}- 1.2×10^{-2}	6×10^{-3} (apple)
(Smith and Simmonds, 2009)	2×10^{-2}	2×10^{-2}	2×10^{-2}	2×10^{-2}

Current parameters in IRAT2				
(Uchida and Tagami, 2010) dry wt.	-	Range: 3.6×10^{-3} – 9.4×10^{-2}	Range: 3.4×10^{-3} – 0.13 Range: 9.3×10^{-4} – 1.8×10^{-2} (potato/tuber)	Range: 9.5×10^{-4} – 5.9×10^{-2}
(Uchida and Tagami, 2011) (dry wt.)	-	1.4×10^{-2} (Range: 9.8×10^{-4} – 0.49)	6.1×10^{-3} (Range: 8.7×10^{-4} – 6.7×10^{-2}) 6.9×10^{-3} (Range: 9.4×10^{-4} – 9.4×10^{-2}) (potato/tuber	1.4×10^{-2} (Range: 1.6×10^{-3} – 0.14)
(Hou et al., 2009)	Range: 7×10^{-2} – 2.9 dry wt. (citing 156)	-	-	-
(Siasou and Willey, 2015)	5×10^{-2} (monocots/grass)	-	-	-
(US NRC, 2012) dry wt.	-	-	0.94 (potato); 3.3 (on different soils)	-

*Geometric mean; **Arithmetic mean

More recent studies provide useful information on I concentration factor values. In particular, IAEA Technical Document 1616, which underpins the IAEA Handbook, presented a comprehensive review of the available data (IAEA, 2010). The experimental data reported in this report are generally consistent with those currently used in IRAT2. However, a review of the current IRAT2 parameter values indicates that the I data for pasture, green vegetables, and root vegetables are derived from an older data source. This is despite the availability of more recent international compilations. In contrast, the I value used for fruit is based on the IAEA Handbook and may therefore be more up to date (IAEA, 2010).

Iodine concentration factor values for pasture and root vegetables could potentially be updated in IRAT2 to align with temperate climate data in IAEA Technical Document 1616 (IAEA, 2009). Values for green vegetables could also be updated to match those in Sheppard et al. (Sheppard et al., 2009). Although, this would require conversion of dry weight to fresh weight values needed for use in IRAT2. Here, IRAT2 assumes 10% dry matter content, resulting in a concentration factor value of 3.3×10^{-3}. The value based on the dry weight value given is 6.5×10^{-4} i.e., a notable decrease (IAEA, 2009). The I concentration factor value for root vegetables could also be updated to align with IAEA data (IAEA, 2009). Similar to green vegetables, this would require a conversion of the data to fresh weight for use in IRAT2. Of note, IRAT2 assumes 20% dry matter content for root vegetables. Making such a revision creates a new I concentration factor value of 1.54×10^{-3}, which corresponds to a reduction.

For assessments requiring a generic and conservative estimate of soil-to-fruit transfer, the equilibrium I soil-to-plant concentration ratio for fruit given in PC-CREAM is 2×10^{-2} (Smith and Simmonds, 2009). This may be appropriate, as it exceeds the mean transfer factor (6.3×10^{-3}) reported for woody fruit crops and herbaceous plants in the IAEA Handbook (IAEA, 2010). The PC-CREAM value also accounts for UK temperate conditions and are generally applicable to northwest and central European temperate environments.

5.4.2 Freshwater fish

Dietary and gill uptake are both considered the main sources of I for freshwater fish (Higgs et al., 1982; Geven et al., 2007). The current I concentration ratio for freshwater fish in IRAT2 is derived from the IAEA Handbook and corresponds to the geometric mean value for muscle (IAEA, 2010). This value was also adopted in assessments to support a safety case for the disposal of nuclear waste, in conjunction with similar values for specific types of freshwater fish (Posiva. 2014). No new sources of information were found in this project. The I concentration ratio values given in the IAEA Handbook vary by up to a factor of ~40 (IAEA, 2010). These data values are summarised in the table below.

Table 26: Iodine-129 concentration ratios for fish and seafood, as identified in the literature review.

	Freshwater fish	Marine fish	Marine mollusc	Marine crustacea
Concentration ratio data (Bq/kg fresh/Bq/L)	30 (Range: 10-400)	9	10	3
Reference source	(IAEA, 2010)	(IAEA, 2004)	(IAEA, 2004)	(IAEA, 2004)
Other values				

	Freshwater fish	Marine fish	Marine mollusc	Marine crustacea
(Posiva, 2014) **(µg/kg)/(µg/m³) fresh wt.**	0.29 (forage fish), 5.5×10^{-2} (benthic), 2.4×10^{-2} (piscivorous), 3.0×10^{-2} ("other")	3×10^{-2} (brackish) 0.14 (seawater)	-	-
(Sheppard et al., 2009) (L/kg)	34	-	-	-
(Staven et al., 2003)	40	10	50	50
(Sprague et al., 2021) (L/kg)	-	4 (Range: 1-11)	10 (Range: 1-50)	12 (Range: 0.8-88)

5.4.3 Marine fish

Marine fish drink seawater, ensuring an adequate intestinal I absorption, which is then supplemented by I in food and uptake through body surfaces (Moren et al., 2008). Overall, wild fish tended to exhibit higher I concentrations than farmed fish (Sprague et al., 2021). However, no significant differences were observed between wild and farmed Atlantic salmon (*Salmo salar*), rainbow trout (*Oncorhynchus mykiss*), and turbot (*Psetta maxima*).

The current I concentration factor in IRAT2 can be traced to an IAEA compilation (IAEA, 2004). This gives a single figure, not a range. The range between fish species is large: Nerhus et al. found that I concentrations in wild fish species varied between 18 µg/100 g (Atlantic halibut) and 1.2×10^3 µg/100 g (pollack) i.e., a factor of over 50 (Nerhus et al., 2018). Similarly, a study reported I concentrations in fish ranging from 5.28-54.69 µg/100 g, i.e., a factor of 10 (Sprague et al., 2021). Here, the geometric mean I content was found to be 19.97 µg/100 g (IAEA, 2004). Of note, total inorganic I concentration in seawater is ~50-60 µg/L (Ito, 1997). Taking a value of 50 µg/L (a commonly quoted value) yields a mean I concentration ratio of 4 L/kg from the Sprague et al. data (Sprague et al., 2021). This is lower than the IAEA value of 9 L/kg (IAEA, 2004). However, the IAEA concentration factor value is consistent with the range of I data values from the Sprague et al. research (1-11 L/kg) (Sprague et al., 2021). Such a range could be useful for sensitivity analysis.

5.4.4 Crustacea and molluscs

The current IRAT2 concentration ratio values for I are taken from the IAEA compilation (IAEA, 2004). No new concentration ratio data was found. However, measurements of I concentrations in crustacea and molluscs have been reported. One project calculated I concentrations of 60.26 µg/100 g (geometric mean) for crustacea, with a range of 3.81-440.18 µg/100 g i.e., a factor of 100 (Sprague et al., 2021). The I concentration in crustacea is three times that in marine fish whereas the IAEA concentration ratio for crustacea is a third of that in marine fish (IAEA, 2004). Using an I concentration of 50 µg/L in seawater leads to a concentration ratio of 12 L/kg. This is significantly higher than the IAEA value concentration ratio of 3 L/kg, which is based on 1979 data on I concentrations in the environment (IAEA, 2004). The IAEA concentration ratio is consistent with the range of 0.8-88 L/kg obtained from the Sprague et al. investigation (Sprague et al., 2021). The I concentration ratio for crustacea could potentially be increased to 10 L/kg and a range of concentration ratios might be considered in sensitivity analyses.

Sprague et al. measured I concentrations of 48.29 µg/100g (geometric mean) for molluscs (bivalves), with a range of 5.59-241.45 µg/100g i.e., a factor of 40 (Sprague et al., 2021). The I concentration in molluscs was 0.8 and 2.5 times of that measured in crustacea and fish, respectively. Using an I concentration of 50 µg/l in seawater affords a concentration ratio of 10 L/kg, in good agreement with the IAEA value of 10 L/kg (IAEA, 2004). The IAEA concentration ratio is based on 1979 data on I concentrations in the environment. A range of concentration factor from 1-50 L/kg is obtained from the Sprague et al. (Sprague et al., 2021) data. A range of concentration factors could be considered in sensitivity analyses.

Overall, a review of the current I parameterisation revealed that the IAEA data for the marine environment are largely derived from a single publication (IAEA, 2004). This document was based on measurements of I environmental levels in 1979. As a result, these values may not fully reflect more recent understanding of I behaviour in marine systems. More recent studies are available to inform the selection of I transfer parameter values, particularly for marine foodstuffs. These publications provide updated data that could be useful to help assess, validate, and/or refine I concentration factors for seafood. Potential areas for further work might include a more detailed examination of the ranges associated with I concentration factors for seafood. This would help explore the impact of uncertainty in I transfer parameters on the environmental dose assessment outcomes.

5.4.5 Wildlife

The I concentration ratios for wildlife currently used in IRAT2 are derived from ERICA (version 1.2.1) (Brown et al., 2016). These data are provided in the following three tables.

Table 27: Current ^{129}I concentration ratios for marine biota in IRAT2 (Environment Agency, 2022).

Marine reference organisms	Concentration ratio (L/kg)	Reference source
Benthic fish	9.00	ERICA v.1.2.1

Marine reference organisms	Concentration ratio (L/kg)	Reference source
Bird	0.68	ERICA v.1.2.1
Crustacean	39.0	ERICA v.1.2.1
Macro-algae	4.20×10^3	ERICA v.1.2.1
Mammal	0.68	ERICA v.1.2.1
Mollusc – bivalve	8.80×10^3	ERICA v.1.2.1
Pelagic fish	9.00	ERICA v.1.2.1
Phytoplankton	9.50×10^2	ERICA v.1.2.1
Polychaete worm	8.80×10^3	ERICA v.1.2.1
Reptile	0.68	ERICA v.1.2.1
Sea anemones and true coral	8.80×10^3	ERICA v.1.2.1
Vascular plant	24.0	ERICA v.1.2.1
Zooplankton	3.10×10^3	ERICA v.1.2.1

Table 28: Current ^{129}I concentration ratios for terrestrial biota for in IRAT2 (Environment Agency, 2022).

Terrestrial reference organism	Concentration ratio (L/kg)	Reference source
Amphibian	0.40	ERICA v.1.2.1
Annelid	0.16	ERICA v.1.2.1
Arthropod – detritivorous	0.30	ERICA v.1.2.1
Bird	0.40	ERICA v.1.2.1

Terrestrial reference organism	Concentration ratio (L/kg)	Reference source
Flying insects	0.30	ERICA v.1.2.1
Grasses and herbs	0.14	ERICA v.1.2.1
Lichen and bryophytes	0.14	ERICA v.1.2.1
Mammal – large	0.40	ERICA v.1.2.1
Mammal – small, burrowing	0.40	ERICA v.1.2.1
Mollusc – gastropod	0.18	ERICA v.1.2.1
Reptile	0.40	ERICA v.1.2.1
Shrub	7.0×10^{-4}	ERICA v.1.2.1
Tree	0.14	ERICA v.1.2.1

Table 29: Current ^{129}I concentration ratios for freshwater biota in IRAT2 (Environment Agency, 2022).

Freshwater reference organism	Concentration ratio (L/kg)	Reference source
Amphibian	3.20×10^{2}	ERICA v.1.2.1
Benthic fish	3.20×10^{2}	ERICA v.1.2.1
Bird	39.0	ERICA v.1.2.1
Crustacean	83.0	ERICA v.1.2.1
Insect larvae	83.0	ERICA v.1.2.1
Mammal	3.20×10^{2}	ERICA v.1.2.1
Mollusc – bivalve	83.0	ERICA v.1.2.1

Freshwater reference organism	Concentration ratio (L/kg)	Reference source
Mollusc – gastropod	83.0	ERICA v.1.2.1
Pelagic fish	3.20 x 10^2	ERICA v.1.2.1
Phytoplankton	54.0	ERICA v.1.2.1
Reptile	3.20 x 10^2	ERICA v.1.2.1
Vascular plant	54.0	ERICA v.1.2.1
Zooplankton	83.0	ERICA v.1.2.1

Updated I concentrations ratio values for marine, terrestrial, and freshwater biota are available in ERICA (version 2.0) (ERICA Consortium, 2021). These data are shown in the three tables below, together with the source reference.

Table: 30 Iodine-129 concentration ratios for marine biota, as identified in the literature review.

Marine reference organisms	Concentration ratio (L/kg)	Reference source
Benthic fish	8.08	ERICA v.2, estuarine
Bird	0.68	ERICA v.2 mammal
Crustacean	39.2	ERICA v.2, estuarine
Macro-algae	5.56 x 10^3	ERICA v.2
	4.2 x 10^3	(IAEA, 2014)
	5 x 10^2-5 x 10^3	(Holm et al., 1994), ^{131}I
	8.6 x 10^2	(Kumblad, 2008)

Marine reference organisms	Concentration ratio (L/kg)	Reference source
Mammal	0.68	ERICA v.2, (IAEA, 2014), carnivorous
Mollusc – bivalve	53.7	ERICA v.2
	8.8×10^3	(IAEA, 2014)
	22	(Kumblad, 2008)
Mollusc – snail	1.1×10^2	(Kumblad, 2008)
Pelagic fish	8.08	ERICA v.2, estuarine
	1.7×10^2	(Kumblad, 2008)
Phytoplankton	9.50×10^2	ERICA v.2
	9.5×10^2	(IAEA, 2014)
	13	(Kumblad, 2008)
	2×10^3	(Hou and Yan, 1998), algae (approximated value from graph)
Polychaete worm	53.7	ERICA v.2, mollusc – bivalve
Reptile	0.68	ERICA v.2, mammal
Sea anemones and true coral	4.69×10^3	ERICA v.2, zooplankton
Vascular plant	24.0	ERICA v.2, (IAEA, 2014)
Zooplankton	4.69×10^3	ERICA v.2

Marine reference organisms	Concentration ratio (L/kg)	Reference source
	3.1×10^{3}	(IAEA, 2014)
	25	(Kumblad, 2008)

Table 31: Iodine-129 concentration ratios for terrestrial biota, as identified in the literature review.

Terrestrial reference organism	Concentration ratio (L/kg)	Reference source
Amphibian	4.97×10^{-3}	ERICA v.2
Annelid	0.192	ERICA v.2
	0.16	(IAEA, 2014)
	0.299	(Barnett et al., 2020) average
Arthropod – detritivorous	0.295	ERICA v.2
	0.32	(IAEA, 2014)
	0.156	(Pokarzhevskii and Zhulidov, 1995), soil invertebrate
	0.301	(Pokarzhevskii and Zhulidov, 1995)
Bird	5.65×10^{-3}	ERICA v.2, mammal
Flying insects	0.145	ERICA v.2
	1.75×10^{-2}	(Barnett, et al., 2020), average
Grasses and herbs	6.59×10^{-2}	ERICA v.2

Terrestrial reference organism	Concentration ratio (L/kg)	Reference source
	0.14	(IAEA, 2014)
	0.101	(Deitermann et al., 1989), average
	20.4×10^{-3}	(Barnett et al., 2020), average
Lichen and bryophytes	7.37×10^{-3}	ERICA v.2
	7.4×10^{-3}	(Barnett et al., 2020), average
Mammal – large	5.65×10^{-3}	ERICA v.2
	0.117×10^{-2}	(Barnett et al., 2020)
Mammal – small, burrowing	5.65×10^{-3}	ERICA v.2
	7.10×10^{-3}	(Barnett et al., 2020), wood mouse, average
	0.729×10^{-4}	(Barnett et al., 2020), vole, av.
Mollusc – gastropod	0.175	ERICA v.2
	0.18	(IAEA, 2014)
	0.18	(Pokarzhevskii and Zhulidov, 1995)
Reptile	5.65×10^{-3}	ERICA v.2 (Barnett et al., 2020)

Terrestrial reference organism	Concentration ratio (L/kg)	Reference source
Shrub	8.22×10^{-3}	ERICA v.2
	3.9×10^{-3}	(Sheppard, et al., 2010), berry dw, (GM)
	9.5×10^{-3}	(Barnett et al., 2020), average
Tree	2.71×10^{-2}	ERICA v.2
	1.53×10^{-2}	(Barnett et al., 2020)

Table 32: Iodine-129 concentration ratios for freshwater biota, as identified in the literature review.

Freshwater reference organism	Concentration ratio (L/kg)	Reference source
Algae	1.2×10^{2}	(IAEA, 2014)
Amphibian	3.10×10^{2}	ERICA v.2, fish
Benthic fish	3.10×10^{2}	ERICA v.2
	2.8×10^{2}	(Sheppard, et al., 2010), fillets
Bird	39.1	ERICA v.2
	0.54	(Sheppard, et al., 2010), geese, GM
Crustacean	80.0	ERICA v.2, mollusc-bivalve

Freshwater reference organism	Concentration ratio (L/kg)	Reference source
Insect larvae	80.0	ERICA v.2, mollusc-bivalve
Mammal	3.10×10^2	ERICA v.2, fish
Mollusc – bivalve	80.0	ERICA v.2
	83	(IAEA, 2014)
Mollusc – gastropod	1.02×10^2	ERICA v.2
	83	(IAEA, 2014)
Pelagic fish	3.10×10^2	ERICA v.2
	3.7×10^2	(IAEA, 2014)
	2.8×10^2	(Sheppard, et al., 2010), fillets
	1.1×10^2	(Kumblad, 2008), ruffe
	78	(Kumblad, 2008), roach
	3.7×10^2	(IAEA, 2014)
Phytoplankton	52.9	ERICA v.2, vascular plant
Reptile	3.10×10^2	ERICA v.2, fish
Vascular plant	52.9	ERICA v.2
	50	(IAEA, 2014)

Freshwater reference organism	Concentration ratio (L/kg)	Reference source
Zooplankton	80.0	ERICA v.2, mollusc-bivalve

These ERICA (version 2.0) parameter values are supported by recently obtained empirical field data. A 2023 study of freshwater fish in both the Fukushima and Chernobyl exclusion zones determined I concentration ratio values ranging from 85-544 (dry weight) in isolated ecosystems (Teien et al., 2023). The monitoring field datasets are broadly consistent with the ERICA (version 2.0) value of 310 for benthic and pelagic fish. Accordingly, the I wildlife concentration ratio values currently used in IRAT2 could possibly be updated to match those contained within the latest version of ERICA (version 2.0).

5.5 Iodine-129 distribution coefficients

Distribution coefficient values for I are discussed in the following sections, noting that IRAT2 currently includes element specific K_d values for marine and freshwater systems (Environment Agency, 2022).

5.5.1 Iodine speciation

Iodine is a redox sensitive, electronegative element with oxidation states of -1, 0, +1, +3, +5, and +7. A wide variety of organic and inorganic I species are known and the different chemical forms are expected to exhibit different I adsorption properties in the environment.

The dominant dissolved I species in natural waters are (inorganic) iodide and iodate ions, and organoiodine species. Iodate is thermodynamically favoured under oxygenated (oxic) conditions, whereas iodide is the dominant inorganic species in oxygen depleted (anoxic) waters. Iodine can also exist as dissolved organic species, for example by complexation with organic matter. Such chemical species are typically present in low levels in seawater but can often be found in appreciable quantities in freshwater and estuarine systems.

5.5.2 Current I K_d values

IRAT2 includes the I-specific K_d parameters given in the following table.

Table 33: Current ^{129}I K_d values in IRAT2 (Environment Agency, 2022).

Parameter	K_d (L/kg)	Basis
Marine	70	Ocean margin value for I obtained by dividing the mean exchangeable coastal sedimentary abundance by the coastal water concentration (IAEA, 2004).
Freshwater	4.4×10^3	Iodine partitioning to sediment; the Kd value was a geometric mean of a large data set (n = 124) (IAEA, 2010). The data ranged from 59 to 3.4×10^5 L/kg (i.e., spanning 4 orders of magnitude). Reported data were for 'oxic conditions.'
Organic soil	11	See IAEA handbook for organic soil (IAEA, 2010).

5.5.3 Review of I K_d parameters

The adsorption of I species (non-radioactive and radioactive) in the environment has been the topic of multiple research investigations. This includes studies of I association with marine sediments (Hansen et al., 2011), river sediments and suspended sediments (Juranová, et al., 2020), porewaters (Li et al., 2022), and soils (Shaw et al., 2018).

The freshwater K_d databases and K_d distributions given in TRS 472 (IAEA, 2010) have since been updated (Boyer et al., 2018; IAEA, 2021). These latest data includes I, with K_d values defined based on experimental and field data. The "enhanced" K_d dataset suggests that the I K_d values for suspended sediments are significantly higher than for those for deposited sediments. Moreover, the variation in the I K_d value was higher for deposited sediments than for than suspended sediments. It was shown that the deposited sediment and suspended sediment K_d values had a geometric mean of 19.3 L/kg (range 0.07-4 x 10^3 L/kg, n = 89) and 3.6×10^3 L/kg (range 170-1.05 x 10^5 L/kg, n = 71), respectively. These values were obtained from laboratory adsorption experiments. A similar geometric mean I K_d value of 3.32×10^3 L/kg (range 788-4.6 x 10^3 L/kg, n = 20) L/kg was obtained by analysing field samples of suspended sediment. Overall, the suspended sediment values are in good agreement with the current IRAT2 parameter value of 4.4×10^3 L/kg.

One study of the behaviour of anthropogenic radionuclides in a river system calculated apparent K_d values for iodine-131 (^{131}I) (Juranová, et al., 2020). The measured K_d values ranged from 14 L/kg (river bottom sediment, n = 15) to 1.4×10^4 L/kg (suspended solids, n = 15), which is consistent with other works which reported a high I adsorption affinity for suspended solids in freshwater systems (Boyer et al., 2018). A strong, positive correlation between ^{131}I uptake and the feldspar, organic matter, and mica contents of the sediment was identified (Juranová, et al., 2020). The reported K_d value for bottom sediment is lower than the current IRAT2 parameter value of 4.4×10^3 L/kg by a factor of 310 (two orders of magnitude), whilst that measured for suspended sediment is higher by a factor of 3.

The I K_d values used in biosphere studies to support a recently published safety case for nuclear waste disposal are noteworthy (Hjerpe, 2021). This project adopted values of 280 L/kg (river and lake) and 17 L/kg (sea; suspended solids), which are slightly different from the analogous IRAT2 K_d values of 4.4 x 10^3 L/kg and 70 L/kg, as currently provided.

Another study investigated the adsorption of different chemical forms of I to sandy and clay-based sediments (Lin et al., 2025). Of note, the adsorption experiments were performed using subsurface sediments from the Savannah River Site (SRS) in South Carolina, USA. This is a U.S. Department of Energy facility, and the land was contaminated in the 1950s during the production of nuclear weapon materials. Iodide uptake to the solids from the solutions was minimal, except for groundwater. Here, the measured K_d values were 0.9–5.6 L/kg. In contrast, the iodate K_d values ranged from 2.1-14 L/kg and from 3.9-54 L/kg for sandy sediment and clay-based sediments, respectively. An organoiodine compound exhibited the greatest adsorption to both sediments, and the K_d values were 20-149 L/kg and 17-117 L/kg for sandy sediment and clay-based sediments, respectively.

Another study investigated the influence of pH on iodide adsorption onto different clay minerals present in the SRS aquifer sediments (Cooke, 2025). The study focused on iodide because it was the dominant chemical form of ^{129}I in the aquifer. Batch adsorption experiments were conducted using several mineral adsorbents; kaolinite, illite, Na bentonite MX-80, goethite, quartz, and sand. The experiments evaluated iodide adsorption behaviour across a pH range of 3-9 and the results are presented in the following table.

Table 34: Iodide and iodate K_d values for mineral phases (Cooke, 2025).

Type	Iodide K_d, mL/kg	pH	Iodate K_d, mL/kg	pH
Quartz	0.04 ± 0.02	5.8-6.2	15.7 ± 4.0	7.7
Kaolinite	0	-	19.0 ± 3.6	7.7
Goethite	0.10 ± 0.03	5.8-6.2	5.0 ± 2.2	7.7
Illite	15.14 ± 2.84	5.8-6.2	-	-
Montmorillonite	-0.42 ± 0.08*	5.8-6.2	-	-
Na-Bentonite	184	0.55	-	-
MX-80 Bentonite	297	0.55	-	-

*Effectively zero adsorption.

The minerals were equilibrated in a 0.01 M $NaNO_3$ solution with an initial iodide concentration of 100 parts per billion. Overall, the adsorption capacity of the tested minerals for I was generally low, with most samples removing less than 20% of the dissolved I. However, specific minerals behaved differently across the pH gradient.

The current I K_d values in IRAT2 are based on IAEA recommendations and are broadly consistent with the recent literature. Accordingly, I parameter value updates may not be required. However, if revisions are to be pursued, then the values presented in the Boyer et al. systematic study appear to be well founded (Boyer et al., 2018).

It should also be noted that studies at the SRS demonstrate that I adsorption to colloidal organic matter could be significant. These works show that these organic substances may provide chemical control of ^{129}I the transfer and retention in certain clay/sediment media. Distinct K_d parameter values could therefore be considered for organic soils/sediments to better account for I speciation and adsorption phenomena in these specific environments.

5.6 Summary of iodine-129 review

The review of parameter values for ^{129}I is summarised in the following table.

Table 35: Key literature findings for ^{129}I transfer parameters.

Parameter	Review findings for ^{129}I
Gaseous dispersion	A low dry deposition velocity of 10^{-5} m/s could be considered for organic I. The metabolic model for humans gives a slightly reduced dose coefficient.
K_d	Current K_d values are based on the IAEA Handbook. Recent data compares well. Values for aquatic soils and sediments could potentially be updated with recent data publications.
Terrestrial food chain	Current plant uptake values in IRAT2 are based on a 1994 compilation. Since then, updates have been made to values in the source document, the IAEA Handbook (IAEA, 2010). The IRAT2 values could therefore be revised to match this update. Recent data is available for green vegetables. Current animal uptake values are based on the IAEA Handbook, except for offal (IAEA, 2010). The offal value could potentially be updated to be the same as the analogous meat value. More recent data is consistent with the IAEA Handbook.

Parameter	Review findings for ^{129}I
Marine food chain	Current IRAT2 values are based on IAEA complied data (IAEA, 2004). This document in turn is based on I measurements conducted in 1979. New data suggests that an increase in the I concentration factor value for crustacea may be needed.
Wildlife	Current IRAT2 concentration ratio values could be updated to align with ERICA (version 2.0) values.

6 Phosphorus-32

Phosphorus-32 (^{32}P) has a half-life of ~14 days and is a pure beta emitter (Creager, 2009; Cheng et al., 2015). It is a non-metal that can exist in numerous oxidation states, with +5 being the most common. Phosphorous can react chemically with many other elements to form organic and inorganic compounds. One of the most common P compounds in natural waters are phosphates. Phosphorus-32 can be used to produce radiolabelled compounds and has found many applications in nuclear medicine, biochemistry, and molecular biology (Benjamin et al., 1950; Creager, 2009; Cheng et al., 2015).

The ICRP biokinetic model for P for humans has a removal half-time from blood plasma of 25 minutes, with 51.15% transferred to soft tissue and 20% transferred to bone surfaces (ICRP, 2016). The behaviour of P in bone resembles that of calcium (Ca). Within a period of hours or days, P or Ca can diffuse throughout the bone volume. Type M is the default absorption type for inhaled P and the gut uptake factor for ingested P is 0.8.

6.1 Phosphorus-32 concentration ratios and factors

6.1.1 Foodstuffs

The current ^{32}P concentration ratios and concentration factor values for foodstuffs are heavily reliant on IAEA data compilations. The two tables below show the parameter values for terrestrial, freshwater, and marine foodstuffs.

Table 36: Current ^{32}P concentration ratios and transfer factors for terrestrial foodstuffs in IRAT2 (Environment Agency, 2022).

Terrestrial food stuff	Current plant: soil concentration ratio (Bq/kg plant wet weight per Bq/kg soil dry weight)	Current transfer factor (TF) pasture to animal product (Bq/kg wet muscle or liver or Bq/L per Bq/days intake)	Reference source
Pasture	0.6	-	(IAEA, 2010)
Green vegetable	0.1	-	(IAEA, 2010)
Root vegetable	0.2	-	(IAEA, 2010)

Terrestrial food stuff	Current plant: soil concentration ratio (Bq/kg plant wet weight per Bq/kg soil dry weight)	Current transfer factor (TF) pasture to animal product (Bq/kg wet muscle or liver or Bq/L per Bq/days intake)	Reference source
Fruit	1	-	FARMLAND (Brown and Simmonds, 1995)
Sheep meat	-	5.0×10^{-2}	FARMLAND (Brown and Simmonds, 1995)
Sheep offal	-	2.0×10^{-2}	FARMLAND (Brown and Simmonds, 1995)
Beef meat	-	5.5×10^{-2}	IAEA Handbook (IAEA, 2010)
Beef liver	-	3.0×10^{-3}	FARMLAND (Brown and Simmonds, 1995)
Cow's milk	-	-	FARMLAND (Brown and Simmonds, 1995)

Table 37: Current ^{32}P concentration factors for freshwater fish and marine foodstuffs in IRAT2 (Environment Agency, 2022).

Food stuff	Current concentration factor (L/kg)	Reference source
Freshwater fish	1.4×10^{5}	(IAEA, 2010)
Marine fish	3.0×10^{4}	(IAEA, 2001)
Marine crustacea	2.0×10^{4}	(IAEA, 2001)
Marine molluscs	2.0×10^{4}	(IAEA, 2001)

Gastrointestinal uptake factor for P in the IAEA Handbook is 0.67 (IAEA, 2010).

The meat and liver biological half-life in the FARMLAND report for P is 0.03 years for both meat and liver (Brown and Simmonds, 1995). A value of 0.003 years is used in IRAT2. It is unclear which value was used in the derivation of IRAT2 DPUR values.

The current transfer factors for cow meat and cow liver in IRAT2 are taken from different literature sources. Here, the transfer factors for cow meat and cow liver are derived from the IAEA Handbook and the FARMLAND module of PC-CREAM 08, respectively (IAEA, 2010; Brown and Simmonds, 1995). However, the value listed in IRAT2 is 0.003 Bq/kg per Bq/day whereas the value listed in FARMLAND is 0.03 Bq/kg per Bq/day. It is unclear which value was used in the derivation of IRAT2 DPUR values. The FARMLAND module assumes that the transfer factor to liver is the same as to meat unless human data suggest otherwise (Brown and Simmonds, 1995).

The current IRAT2 transfer factors for sheep meat and sheep liver reference FARMLAND (Brown and Simmonds, 1995). Once again, the values are a factor of 10 smaller than the values given in the FARMLAND report. It is unclear which value was used in the derivation of IRAT2 DPUR values.

The IAEA Handbook contains a ^{32}P transfer factor of 0.02 days/L for cow's milk (IAEA, 2010). No transfer factor is used in IRAT2. Instead, a ratio between activity concentrations of P isotopes in cow liver/cow milk was taken from data in the original version of IRAT. This ratio was then applied to cow liver in IRAT2 to generate activity concentrations of P isotopes in cow milk. This is understood to be due to erroneous values arising from the use of PC-CREAM 08 for these isotopes/foodstuffs during the development of IRAT2.

One study of fish in the River Cam predicted a concentration factor of 2 x 10^3 L/kg (muscle tissue) and assumes that the edible portion is primarily muscle tissue (Smith et al., 2011).

The table below shows the ^{32}P concentration factors values for marine foodstuffs identified during the literature review.

Table 38: Phosphorus-32 concentration factors for marine foodstuffs, as identified in the literature review.

Marine foodstuff	Concentration factor (L/kg)	Reference source
Fish	2.0 x 10^3	(Smith et al., 2011), for edible portion of freshwater fish.
Molluscs	11.7	(Vernon, 2018), value averaged from 11.2, 11.7, 11.9.

No new ^{32}P transfer factors for terrestrial foodstuffs were identified. The IAEA Handbook value for the transfer factor to cow's milk could be used in assessments (IAEA, 2010).

Discrepancies were identified between the parameter values listed in the IRAT2 and the source reference (i.e., FARMLAND) for meat and liver transfer factors and biological half-lives (Brown and Simmonds, 1995). It is recommended that the original FARMLAND values are rechecked as there is no clear evidence base for the values used in IRAT2.

The current ^{32}P concentration factor in IRAT2 is 3.0 x 10^4 L/kg for marine fish; marine molluscs have a current value of 2.0 x 10^4 L/kg. The new values found in the literature are smaller by at least one order of magnitude (Table 38). One study noted that the current IAEA values are excessively high (Smith et al., 2011). The values found in the review could be adopted by any model which seeks to use empirically derived data for foodstuffs, instead of that derived previously for the purposes of building a highly conservative assessment.

6.1.2 Wildlife

The current ^{32}P concentration ratios for biota in IRAT2 are taken from ERICA (version 1.2.1) (Brown et al., 2016). This information is summarised in the following three tables.

Table 39: Current ^{32}P concentration ratios for marine biota in IRAT2 (Brown et al., 2016; Environment Agency, 2022).

Marine reference organisms	Concentration ratio (L/kg)	Reference source
Benthic fish	9.90 x 10^4	ERICA v.1.2.1
Bird	3.80 x 10^4	ERICA v.1.2.1
Crustacean	9.90 x 10^4	ERICA v.1.2.1
Macro-algae	9.80 x 10^3	ERICA v.1.2.1
Mammal	3.80 x 10^4	ERICA v.1.2.1
Mollusc – bivalve	2.00 x 10^4	ERICA v.1.2.1
Pelagic fish	9.90 x 10^4	ERICA v.1.2.1
Phytoplankton	3.30 x 10^4	ERICA v.1.2.1
Polychaete worm	2.60 x 10^4	ERICA v.1.2.1
Reptile	3.80 x 10^4	ERICA v.1.2.1

Marine reference organisms	Concentration ratio (L/kg)	Reference source
Sea anemones and true coral	9.90×10^4	ERICA v.1.2.1
Vascular plant	9.80×10^3	ERICA v.1.2.1
Zooplankton	2.30×10^4	ERICA v.1.2.1

Table 40: Current ^{32}P concentration ratios for terrestrial biota in IRAT2 (Brown et al., 2016; Environment Agency, 2022).

Terrestrial reference organism	Concentration ratio (L/kg)	Reference source
Amphibian	1.30×10^3	ERICA v.1.2.1
Annelid	4.30×10^2	ERICA v.1.2.1
Arthropod – detritivorous	4.30×10^2	ERICA v.1.2.1
Bird	1.30×10^3	ERICA v.1.2.1
Flying insects	4.30×10^2	ERICA v.1.2.1
Grasses and herbs	8.90×10^2	ERICA v.1.2.1
Lichen and bryophytes	8.90×10^2	ERICA v.1.2.1
Mammal – large	1.30×10^3	ERICA v.1.2.1
Mammal – small, burrowing	1.30×10^3	ERICA v.1.2.1
Mollusc – gastropod	4.30×10^2	ERICA v.1.2.1
Reptile	1.30×10^3	ERICA v.1.2.1
Shrub	8.90×10^2	ERICA v.1.2.1
Tree	1.30×10^3	ERICA v.1.2.1

Table 41: Current ^{32}P concentration ratios for freshwater biota in IRAT2 (Brown et al., 2016; Environment Agency, 2022).

Freshwater reference organism	Concentration ratio (L/kg)	Reference source
Amphibian	6.80×10^5	ERICA v.1.2.1
Benthic fish	6.80×10^5	ERICA v.1.2.1
Bird	6.80×10^5	ERICA v.1.2.1
Crustacean	6.00×10^4	ERICA v.1.2.1
Insect larvae	6.00×10^4	ERICA v.1.2.1
Mammal	6.80×10^5	ERICA v.1.2.1
Mollusc – bivalve	6.00×10^4	ERICA v.1.2.1
Mollusc – gastropod	6.00×10^4	ERICA v.1.2.1
Pelagic fish	6.80×10^5	ERICA v.1.2.1
Phytoplankton	1.30×10^3	ERICA v.1.2.1
Reptile	6.80×10^5	ERICA v.1.2.1
Vascular plant	1.30×10^3	ERICA v.1.2.1
Zooplankton	6.00×10^4	ERICA v.1.2.1

A PhD project at the University of Portsmouth studied the effects of ^{32}P on crustaceans (Fuller, 2018). The research examined both marine and freshwater crustacean species, with ^{32}P exposure from water rather than contaminated feed. Concentration ratio values of 33.18 ± 6.21 L/kg and 174.76 ± 49.89 L/kg were determined for marine and freshwater, environments, respectively.

A study of ^{32}P bioaccumulation in freshwater and marine bivalve molluscs was undertaken at the University of Plymouth (Vernon, 2018). This work calculated average concentration ratios for the tissues of the mollusc (i.e., everything but the shell); 11.6 ± 0.4 L/kg and 3.73 ± 1.86 L/kg for marine and freshwater species, respectively.

Interestingly, one study into fish in the River Cam predicts a lower ^{32}P concentration ratio value than the current IAEA recommendations (Smith et al., 2011). This study predicts a concentration ratio of 5 x 10^3 L/kg (whole fish).

There are additional studies of the concentration ratios of a variety of radionuclides in specific environments/locations. These have been included in the summary values for the updated biota concentration ratios in ERICA (version 2.0) (ERICA Consortium, 2021) and the wildlife transfer database (WTD) (Copplestone, et al., 2013). Further assessment for the data which have been used to produce concentration ratios to biota in ERICA (version 2.0) could be carried out to assess which values best reflect UK climate and conditions.

The updated values for ^{32}P concentration ratios to biota listed in ERICA (version 2.0) are likely to be sufficiently robust for use in IRAT2 assessments. Identified parameter values for marine, terrestrial, and freshwater biota are summarised in the following three tables.

Table 42: Phosphorus-32 concentration ratios for marine biota, as identified in the literature review.

Marine reference organisms	Concentration ratio (L/kg)	Reference source
Annelids	2.6 x 10^4	(IAEA, 2014)
Benthic fish	1.73 x 10^5	ERICA v.2
	3.4 x 10^5	(Thørring et al., 2016)
Bird	2.89 x 10^4	ERICA v.2, mammal
Crustacean	4.80 x 10^5	ERICA v.2
	4.8 x 10^5	(Thørring et al., 2016), crab
	33.1	(Fuller, 2018)
Macro-algae	4.15 x 10^3	ERICA v.2
	9.8 x 10^3	(IAEA, 2014)
	2.2 x 10^3	(Thørring et al., 2016)
Mammal	2.89 x 10^4	ERICA v.2

Marine reference organisms	Concentration ratio (L/kg)	Reference source
	3.8×10^4	(IAEA, 2014)
Mollusc – bivalve	4.80×10^5	ERICA v.2, crustacean
	2.0×10^4	(IAEA, 2014)
	1.16×10^2	(Vernon, 2018)
Pelagic fish	1.73×10^5	ERICA v.2
	9.9×10^4	(IAEA, 2014)
Phytoplankton	2.2×10^4	ERICA v.2
	3.3×10^4	(IAEA, 2014)
Polychaete worm	2.6×10^4	ERICA v.2
Reptile	2.89×10^4	ERICA v.2, mammal
Sea anemones and true coral	4.80×10^5	ERICA v.2, crustacean
Vascular plant	4.15×10^3	ERICA v.2, macro-algae
Zooplankton	2.3×10^4	ERICA v.2, (IAEA, 2014)

Table 43: Phosphorus-32 concentration ratios for terrestrial biota, as identified in the literature review.

Terrestrial reference organism	Concentration ratio (L/kg)	Reference source
Amphibian	14.7	ERICA v.2
	5.2	(Thørring et al., 2016), frog

Terrestrial reference organism	Concentration ratio (L/kg)	Reference source
	21	(Guillén et al., 2018), frog
	12.6	(Beresford et al., 2018), frog (average)
Annelid	3.36	ERICA v.2 (Barnett et al., 2020)
	1.9	(Thørring et al., 2016)
	5.1	(Guillén et al., 2018), earthworm
	4.55	(Beresford et al., 2018), earthworm (average)
Arthropod – detritivorous	3.36	ERICA v.2, annelid
Bird	20.7	ERICA v.2
	17	(Thørring et al., 2016), duck
	15	(Guillén et al., 2018), duck
Flying insects	10.9	ERICA v.2
	4.61	(Barnett et al., 2018) (average)
	10	(Thørring et al., 2016)
	32.7	(Guillén et al., 2018), bee

Terrestrial reference organism	Concentration ratio (L/kg)	Reference source
	9.73	(Beresford et al., 2018), bee (average)
Grasses and herbs	1.54	ERICA v.2
	0.909	(Barnett et al., 2018)
	0.32	(Thørring et al., 2016), wild grass
	7	(Guillén et al., 2018), wild grass
	2.45	(Beresford et al., 2018), wild grass (average)
Lichen and bryophytes	0.804	ERICA v.2 (Barnett, et al., 2020)
Mammal – large	28.5	ERICA v.2
	51	(Thørring et al., 2016), moose
	46.5	(Barnett et al., 2018), deer (average)
	47	(Guillén et al., 2018), deer
Mammal – small, burrowing	28.5	ERICA v.2
	41	(Barnett et al., 2018), wood mouse (average)
	15.7	(Barnett et al., 2018), vole (average)

Terrestrial reference organism	Concentration ratio (L/kg)	Reference source
	7.8	(Thørring et al., 2016), mouse
	21	(Guillén et al., 2018), rat
	6.85	(Beresford et al., 2018)
Mollusc – gastropod	3.36	ERICA v.2, annelid
Reptile	26.7	ERICA v.2
Shrub	0.637	ERICA v.2
	0.889	(Barnett et al., 2018)
Tree	0.699	ERICA v.2
	0.697	(Barnett et al., 2020), various trees (average)
	0.7	(Thørring et al., 2016)
	0.26	(Guillén et al., 2018), trunk only
	1.69	(Beresford et al., 2018), pine tree (average)

Table 44: Phosphorus-32 concentration ratios for freshwater biota, as identified in the literature review.

Freshwater reference organism	Concentration ratio (L/kg)	Reference source
Amphibian	5.80×10^5	ERICA v.2, (Thørring et al., 2016)

Freshwater reference organism	Concentration ratio (L/kg)	Reference source
Benthic fish	6.77×10^5	ERICA v.2
	7.1×10^5	(IAEA, 2014)
	2.8×10^5	(Doering et al., 2019) (AM)
Bird	1.80×10^6	ERICA v.2
	1.8×10^6	(Thørring et al., 2016), duck
Crustacean	2.27×10^5	ERICA v.2. mollusc-bivalve
	1.74×10^3	(Fuller, 2018)
Insect larvae	2.27×10^5	ERICA v.2, mollusc-bivalve
Mammal	5.80×10^5	ERICA v.2, amphibian
Mollusc – bivalve	2.27×10^5	ERICA v.2
	2.3×10^5	(Doering et al., 2019; Doering, 2019) (AM)
	9.87	(Vernon, 2018)
Mollusc – gastropod	2.27×10^5	ERICA v.2, mollusc-bivalve
Pelagic fish	6.77×10^5	ERICA v.2
	6.8×10^5	(IAEA, 2014)
	2.8×10^5	(Doering et al., 2019) (AM)

Freshwater reference organism	Concentration ratio (L/kg)	Reference source
	9.1×10^5	(Thørring et al., 2016)
	5.00×10^3	(Smith et al., 2011)
Phytoplankton	1.37×10^3	ERICA v.2
	1.3×10^3	(IAEA, 2014)
Reptile	5.80×10^5	ERICA v.2, amphibian
Vascular plant	1.37×10^3	ERICA v.2, phytoplankton
Zooplankton	2.27×10^5	ERICA v.2, mollusc-bivalve

6.2 Phosphorus-32 distribution coefficients

Distribution coefficient values for ^{32}P are discussed in the following section, noting that IRAT2 currently includes element-specific K_d values for marine and freshwater systems (Environment Agency, 2022).

6.2.1 Phosphorus speciation

The most frequent soluble forms of P encountered in natural waters are orthophosphate anions (i.e., $H_2PO_4^-$ and HPO_4^{2-}). Condensed phosphates such as pyro-, meta-, and other polyphosphates and organic phosphorus species are also known.

Orthophosphates are readily available for assimilation by organisms, and P constitutes a limiting nutrient determining biological productivity. Phosphorous is a constituent of many biological molecules. Notable examples of dissolved organic P compounds include adenosine triphosphate, deoxyribonucleic acid (DNA), and phospholipids.

Orthophosphates and organic P compounds are commonly associated with iron (Fe), manganese (Mn), and aluminium rich surfaces in the environment. Surface adsorption on freshly precipitated metal oxyhydrate gels may be an important uptake mechanism.

6.2.2 Current ^{32}P K_d values

IRAT2 includes some P-specific K_d values, and these are given in the following table.

Table 45: Current ^{32}P K_d values in IRAT2 (Environment Agency, 2022).

Parameter	K_d (L/kg)	Basis
Marine	100	Distribution coefficient values for elements in natural freshwater and marine environments, with emphasis on oxidising conditions (Smith and Simmonds, 2009). The source document is an IAEA report (IAEA, 2001) and the source reference therein is a personal communication (Onishi, 1999).
Freshwater	50	Distribution coefficient values for elements in natural freshwater and marine environments, with emphasis on oxidising conditions (Smith and Simmonds, 2009). The source document is an IAEA report (IAEA, 2001) and the source reference therein is a personal communication (Onishi, 1999).
Organic soil	-	No K_d for P partitioning on organic soil is provided in IRAT2 (Environment Agency, 2022). The same IAEA source used in IRAT2 to provide organic soil K_d parameters for several other elements only provides an 'all soils' K_d value for P.

The adsorption of P species in environmental systems has been subject to extensive research, with publications available on P adsorption/desorption rates and mineralisation (in soils). Some recently reported K_d values can be compared with current IRAT2 values.

An investigation into the effects of temperature and salinity on phosphate adsorption on marine (Florida Bay, USA) sediments reported K_d values ranging from 0-320 L/kg (Zhang and Huang, 2011). This wide value range is in reasonable agreement with the current marine K_d value in IRAT2 (100 L/kg). This study found that phosphate adsorption increased with increasing temperature or decreasing salinity.

A study of the factors influencing P adsorption onto river sediments reported K_d values ranging from ~20-140 L/kg (Li et al., 2016). The current ^{32}P terrestrial K_d value in IRAT2 (50 L/kg) is within the range reported in the Li et al. study.

Overall, the current IRAT2 parameters for P appear to be well founded and are broadly consistent with IAEA recommendations a sample of recent published literature.

6.3 Summary of phosphorus-32 review

The review of parameter values for ^{32}P is summarised in the following table.

Table 46: Key literature findings for ^{32}P transfer parameters.

Parameter	Review findings for ^{32}P
K_d	Current IRAT2 K_d values appear to be well founded.
Terrestrial food chain	Concentration factor values for meat and liver appear to be inconsistent. IRAT2 approach for the transfer factor to cow's milk seems to be different to that described in IAEA Handbook.
Marine food chain	Updated concentration factor values could be considered for molluscs, based on a single UK study.
Wildlife	ERICA (version 2.0) has updated concentration ratios.

7 Yttrium-86

Yttrium-86 (^{86}Y) has a half-life of ~15 hours and undergoes decay by electron capture and positron (β^+) to form strontium-86 (Zhu and El Fakhri., 2009). Yttrium-86 is used in nuclear medicine as a tracer for positron emission tomography (PET) imaging (Coenen and Ermert, 2021). However, ^{86}Y is a non-ideal radionuclide for PET imaging because ~67% of its β^+ decay processes are accompanied by the emission of gamma rays, resulting in background signals. Yttrium-86 tracers are therefore often used in combination with other radionuclides e.g., with yttrium-90 to predict the distribution and dosimetry of subsequently injected radiotherapeutics. Additionally, ^{86}Y analogues have been utilised to predict the biodistribution and clearance pathways of gadolinium-based MRI contrast agents (Tickner and Duckett, 2020).

Yttrium-86 tends to form colloids in liver, spleen, or bone marrow, and is retained by bone. The ICRP metabolic model for humans has gut uptake factors from inhalation of 1×10^{-4} for absorption Type F, 2×10^{-5} for Type M and 1×10^{-6} for Type S absorption (slow rate of absorption) (ICRP, 2016). The gut uptake factor for ingestion is 1×10^{-4} for all chemical forms.

The transfer factor for blood to urine is 2.49 days^{-1}; the biological half-life of 1 hour. Approximately 20% of injected ^{86}Y is excreted from the body within a few days (ICRP, 2016).

7.1 Yttrium-86 concentration ratios and factors

7.1.1 Current ^{86}Y concentration factors

The current ^{86}Y concentration ratio values for foodstuffs in IRAT2 are largely based on multiple IAEA data compilations. The data for terrestrial, freshwater, and marine foodstuffs are summarised in the following two tables.

Table 47: Current ^{86}Y concentration ratios and transfer factors for terrestrial foodstuffs in IRAT2 (Environment Agency, 2022).

Terrestrial food stuff	Current plant: soil concentration ratio (Bq/kg plant wet weight per Bq/kg soil dry weight)	Current transfer factor (TF) pasture to animal product (Bq/kg wet muscle or liver or Bq/L per Bq/days intake)	Reference source
Pasture	1.5×10^{-3}	-	(IAEA, 2010)
Green vegetable	2.0×10^{-4}	-	(IAEA, 2010)

Terrestrial food stuff	Current plant: soil concentration ratio (Bq/kg plant wet weight per Bq/kg soil dry weight)	Current transfer factor (TF) pasture to animal product (Bq/kg wet muscle or liver or Bq/L per Bq/days intake)	Reference source
Root vegetable	4.0×10^{-4}	-	(IAEA, 2010)
Fruit	1.0×10^{-2}	-	(Brown and Simmonds, 1995)
Sheep meat	-	1.0×10^{-2}	(Brown and Simmonds, 1995)
Sheep offal	-	0.10	(Brown and Simmonds, 1995)
Beef meat	-	1.0×10^{-3}	(Brown and Simmonds, 1995)
Beef offal	-	1.0×10^{-2}	(Brown and Simmonds, 1995)
Cow's milk	-	2.0×10^{-5}	(Brown and Simmonds, 1995)

Table 48: Current ^{86}Y concentration factors for freshwater fish and marine foodstuffs in IRAT2 (Environment Agency, 2022).

Foodstuff	Current concentration factor (L/kg)	Reference source
Freshwater fish	40	(IAEA, 2010), zirconium (Zr) analogue
Marine fish	20	(IAEA, 2004)
Marine crustacea	1×10^{3}	(IAEA, 2004)
Marine molluscs	1×10^{3}	(IAEA, 2004)

One Japanese study was identified during the literature review that includes experimental data for a number green and root vegetables (Uchida et al., 2007). The values presented in the study were for dry plant weight but have been converted using the equation in Section 5.4.1 to fresh weight. The fresh weight values are given in the following table.

Table 49: Yttrium-86 concentration ratios for terrestrial foodstuffs, as identified in the literature review.

Terrestrial food stuff	Current plant: soil concentration ratio (Bq/kg plant wet weight per Bq/kg soil dry weight)	Reference source
Green vegetable	1.65×10^{-4}	(Uchida et al., 2007), converted from dry weight (GM)
Root vegetable	2.46×10^{-4}	(Uchida et al., 2007), converted from dry weight (GM)
	1.72×10^{-4} (potato)	

New concentration factor values for marine and terrestrial foodstuffs, except for vegetables, were not identified. The applicability of Japanese data could be considered for use in future assessments (e.g., Uchida et al., 2007). While these works represent more recent empirical data than current IRAT2 values, their applicability to UK soils and temperate climates must be carefully evaluated before adoption in UK assessments.

7.1.2 Wildlife

The current concentration ratios for biota in IRAT2 are taken from ERICA version 1.2.1 (Brown et al., 2016). These values are shown in the following three tables.

Table 50: Current ^{86}Y concentration ratios for marine biota in IRAT2 (Environment Agency, 2022).

Marine reference organisms	Concentration ratio (L/kg)	Reference source
Benthic fish	85.0	ERICA v.1.2.1
Bird	85.0	ERICA v.1.2.1
Crustacean	49.0	ERICA v.1.2.1

Marine reference organisms	Concentration ratio (L/kg)	Reference source
Macro-algae	1.70×10^3	ERICA v.1.2.1
Mammal	85.0	ERICA v.1.2.1
Mollusc – bivalve	3.30×10^3	ERICA v.1.2.1
Pelagic fish	85.0	ERICA v.1.2.1
Phytoplankton	3.30×10^4	ERICA v.1.2.1
Polychaete worm	3.30×10^3	ERICA v.1.2.1
Reptile	85.0	ERICA v.1.2.1
Sea anemones and true coral	1.30×10^2	ERICA v.1.2.1
Vascular plant	1.10×10^3	ERICA v.1.2.1
Zooplankton	2.20×10^4	ERICA v.1.2.1

Table 51: Current ^{86}Y concentration ratios for terrestrial biota in IRAT2 (Environment Agency, 2022).

Terrestrial reference organism	Concentration ratio (L/kg)	Reference source
Amphibian	0.13	ERICA v.1.2.1
Annelid	9.60×10^{-3}	ERICA v.1.2.1
Arthropod – detritivorous	7.70×10^{-3}	ERICA v.1.2.1
Bird	0.13	ERICA v.1.2.1
Flying insects	7.70×10^{-3}	ERICA v.1.2.1
Grasses and herbs	3.90×10^{-2}	ERICA v.1.2.1

Terrestrial reference organism	Concentration ratio (L/kg)	Reference source
Lichen and bryophytes	0.18	ERICA v.1.2.1
Mammal – large	2.50×10^{-4}	ERICA v.1.2.1
Mammal – small, burrowing	2.50×10^{-4}	ERICA v.1.2.1
Mollusc – gastropod	9.60×10^{-3}	ERICA v.1.2.1
Reptile	0.13	ERICA v.1.2.1
Shrub	5.30×10^{-3}	ERICA v.1.2.1
Tree	1.10×10^{-2}	ERICA v.1.2.1

Table 52: Current ^{86}Y concentration ratios for freshwater biota in IRAT2 (Environment Agency, 2022).

Freshwater reference organism	Concentration ratio (L/kg)	Reference source
Amphibian	1.20×10^{3}	ERICA v.1.2.1
Benthic fish	9.30×10^{2}	ERICA v.1.2.1
Bird	30.0	ERICA v.1.2.1
Crustacean	9.60×10^{2}	ERICA v.1.2.1
Insect larvae	9.60×10^{2}	ERICA v.1.2.1
Mammal	1.20×10^{3}	ERICA v.1.2.1
Mollusc – bivalve	9.60×10^{2}	ERICA v.1.2.1
Mollusc – gastropod	9.60×10^{2}	ERICA v.1.2.1
Pelagic fish	9.30×10^{2}	ERICA v.1.2.1

Freshwater reference organism	Concentration ratio (L/kg)	Reference source
Phytoplankton	1.70 x 10^3	ERICA v.1.2.1
Reptile	1.20 x 10^3	ERICA v.1.2.1
Vascular plant	99.0	ERICA v.1.2.1
Zooplankton	9.60 x 10^2	ERICA v.1.2.1

There appears to be no recent studies specific to ^{86}Y. However, there are a small number of new studies that have been incorporated in the latest version of ERICA, based on other isotopes of Y (ERCIA Consortium, 2021). Additionally, some of the marine data are based upon studies in an estuarine environment. The updated ERICA (version 2.0) values are summarised in the following three tables for marine, terrestrial, and freshwater biota.

Table 53: Yttrium-86 concentration ratios for marine biota, as identified in the literature review.

Marine reference organisms	Concentration ratio (L/kg)	Reference source
Benthic fish	16.0	ERICA v.2, (Thørring et al., 2016)
Bird	16.0	ERICA v.2, fish
Crustacean	8.20 x 10^2	ERICA v.2
Macro-algae	1.70 x 10^2	ERICA v.2, (Thørring et al., 2016)
Mammal	16.0	ERICA v.2, fish
Mollusc – bivalve	2.66 x 10^3	ERICA v.2, estuarine
	3.7 x 10^2	(Takata et al., 2010)
Pelagic fish	16.0	ERICA v.2
Phytoplankton	2.85 x 10^3	ERICA v.2, vascular plant

Marine reference organisms	Concentration ratio (L/kg)	Reference source
Polychaete worm	2.66×10^3	ERICA v.2, estuarine, mollusc-bivalve
Reptile	16.0	ERICA v.2, fish
Sea anemones and true coral	2.66×10^3	ERICA v.2, estuarine, mollusc-bivalve
Vascular plant	2.85×10^3	ERICA v.2, estuarine
Zooplankton	2.66×10^3	ERICA v.2, estuarine, mollusc-bivalve

Table 54: Yttrium-86 concentration ratios for terrestrial biota, as identified in the literature review.

Terrestrial reference organism	Concentration ratio (L/kg)	Reference source
Amphibian	0.55	ERICA v.2, (Thørring et al., 2016)
Annelid	1.85×10^{-2}	ERICA v.2
	1.7×10^{-2}	(Thørring et al., 2016)
	8.13×10^{-3}	(Barnett et al., 2013), stable Y (average)
Arthropod – detritivorous	1.85×10^{-2}	ERICA v.2, annelid
Bird	2.80×10^{-4}	ERICA v.2, (Thørring et al., 2016)
Flying insects	7.60×10^{-4}	ERICA v.2
	1.38×10^{-4}	(Barnett et al., 2013), bee, stable Y (average)
	4.5×10^{-3}	(Thørring et al., 2016)

Terrestrial reference organism	Concentration ratio (L/kg)	Reference source
Grasses and herbs	1.96×10^{-3}	ERICA v.2
	1.7×10^{-4}	(Thørring et al., 2016)
	3.7×10^{-3}	(Sheppard et al., 2008)
	4.08×10^{-4}	(Barnett et al., 2013), wild grass (average)
Lichen and bryophytes	5.05×10^{-2}	ERICA v.2 (Sheppard et al., 2004)
Mammal – large	2.30×10^{-4}	ERICA v.2
	2.9×10^{-4}	(Thørring et al., 2016)
	6.98×10^{-5}	(Barnett et al., 2013), roe deer (average)
Mammal – small, burrowing	2.30×10^{-4}	ERICA v.2
	3.6×10^{-4}	(Thørring et al., 2016)
	7.22×10^{-5}	(Barnett et al., 2013), wood mouse (average)
Mollusc – gastropod	1.85×10^{-2}	ERICA v.2, annelid
Reptile	2.80×10^{-4}	ERICA v.2, bird
Shrub	1.87×10^{-3}	ERICA v.2
Tree	2.81×10^{-3}	ERICA v.2
	6.27×10^{-5}	(Barnett et al., 2013), trunk only (average)

Table 55: Yttrium-86 concentration ratios for freshwater biota, as identified in the literature review.

Freshwater reference organism	Concentration ratio (L/kg)	Reference source
Amphibian	51.0	ERICA v.2
	5.1	(Thørring et al., 2016)
Benthic fish	79.0	ERICA v.2
Bird	30.0	ERICA v.2, (Thørring et al., 2016)
Crustacean	2.28×10^3	ERICA v.2, mollusc (bivalve)
Insect larvae	2.28×10^3	ERICA v.2, mollusc (bivalve)
Mammal	30.0	ERICA v.2, bird
Mollusc – bivalve	2.28×10^3	ERICA v.2
Mollusc – gastropod	2.28×10^3	ERICA v.2, mollusc (bivalve)
Pelagic fish	79.0	ERICA v.2 (Thørring et al., 2016)
	11	(Thørring et al., 2016)
Phytoplankton	6.94×10^3	ERICA v.2
Reptile	4.98×10^2	ERICA v.2, (Wood et al., 2010), turtle
Vascular plant	3.80×10^2	ERICA v.2
Zooplankton	2.28×10^3	ERICA v.2, mollusc (bivalve)

Wildlife concentration ratios could be updated to align with the updated values in ERICA (version 2).

7.2 Yttrium-86 distribution coefficients

Distribution coefficient (K_d) values for ^{86}Y are discussed in the following sections, noting that IRAT2 currently includes element-specific K_d values for marine and freshwater systems (Environment Agency, 2022).

7.2.1 Yttrium speciation

Yttrium is a transition metal that exists almost exclusively in the +3 oxidation state. Yttrium is chemically similar to the lanthanide elements, and they are often found together in nature. In some ways, Y behaves as a heavy lanthanide, given its similar oxidation state and ionic radius to those lanthanide elements with the highest atomic numbers.

The use of Zr as an analogue for the current terrestrial K_d value may be considered slightly unusual, given that the typical oxidation state of Zr is +4 (not +3). Moreover, the trivalent nature of the lanthanide ions suggests that these species may be more suitable as analogues for Y. Lanthanide adsorption data is relatively extensive in the published literature.

7.2.2 Current ^{86}Y K_d values

IRAT2 includes the following parameter values for ^{86}Y (marine) and based on Zr (freshwater) as an analogue. This information is summarised in the table below.

Table 56: Current ^{86}Y K_d values in IRAT2 (Environment Agency, 2022).

Parameter	K_d (L/kg)	Basis
Marine	9×10^5	Ocean margin value for Y. The value was calculated by dividing the mean exchangeable coastal sedimentary abundance by the coastal water concentration (IAEA, 2004).
Freshwater	1×10^3	'Expected value' gross average K_d value for Zr in aqueous systems. The minimum and maximum values were 1×10^3 and 1×10^4 L/kg, respectively (Environment Agency, 2022).

No ^{86}Y K_d value for soil is provided in IRAT2.

7.2.3 Review of ^{86}Y K_d parameters

No specific K_d data for ^{86}Y has been identified in recent, systematic K_d compilations.

7.2.4 Recommendations for ^{86}Y K_d values

Given similarity with the lanthanides, it is recommended that where Y-specific values are not available, a lanthanide analogue should be used (with cerium (Ce) being useful in terms of data availability, as discussed in relation to lutetium in Section 8.2.3). On that basis, a freshwater K_d parameter value of 2.2 x 10^5 L/kg could be adopted (Environment Agency, 2022), replacing the current value of 1 x10^3 L/kg value based on Zr, which seems low in comparison to lanthanide (and trivalent actinide) analogues.

7.3 Summary of yttrium-86 review

The review of parameter values for ^{86}Y is summarised in the following table.

Table 57: Key literature findings for ^{86}Y transfer parameters.

Parameter	Review findings for ^{86}Y
K_d	Cerium freshwater K_d value of 2.2 x 10^5 may represent a suitable analogue.
Terrestrial food chain	New data has been identified for green and root vegetables using Japanese data (Uchida et al., 2007).
Marine food chain	No updated concentration factors have been identified.
Wildlife	ERICA (version 2.0) has updated concentration ratios.

8 Lutetium-177

Lutetium-177 (^{177}Lu) has a half-life of ~7 days and undergoes beta decay to form hafnium-177 (Schötzig et al., 2001). Lutetium-177 is being used in relatively novel targeted radionuclide therapies (Niu et al., 2024). The ^{177}Lu-DOTATATE complex for example has been used to treat stomach, pancreatic, and intestinal cancer (Strosberg et al., 2017). A ^{177}Lu vipivotide tetraxetan injection is used to treat a certain type of prostate cancer (Sartor et al., 2021).

The gut absorption parameter values for ^{177}Lu in ICRP Publication 141 are based on Ce, as is the case for many of the lanthanide elements (ICRP, 2019). The gut uptake factor, f_1, for Lu is 5×10^{-4} in ICRP Publication 141, the same as the previous (ICRP Publication 68) value for trivalent actinides and is slightly increased from the value of 3×10^{-4} recommended in ICRP Publication 30 (ICRP, 1979; 2019). Values are given for water soluble forms, the metal dioxide, and absorption classes F, M and S (ICRP, 2019). ICRP Publication 141 also notes that lung class F should not be used without evidence, and it was not included in the previous ICRP compilation (Eckerman et al., 2012). Type M is the default, and Type S applies to irradiated fuel fragments.

ICRP Publication 141 has a generic biokinetic model for the lanthanides, developed in 2003, and is a generic structure for elements that accumulate largely in the liver and on bone surfaces (ICRP, 2019). This includes most actinides. Moreover, there are some element-specific parameter values included. The Lu removal half time for kidney to urinary bladder content is 7 days (transfer coefficient is 9.9×10^{-2} days^{-1}). Removal half time for liver 1 (relatively fast removal) is 30 days and is 1 year for liver 2 (relatively slow removal) to blood. ICRP has different transfer coefficients for Lu and Ce for liver 2 to blood and for blood to soft tissue 1 in the generic biokinetic model (ICRP, 2019). The deposition fraction in liver is 10 times higher for Ce than for Lu, and the deposition fraction in soft tissue for Ce is roughly 50% that of Lu.

IAEA note that the target organs for Ce are bone and liver (IAEA, 2010). The IAEA and ICRP have both reported a gut uptake factor of 5×10^{-4} for Ce (IAEA, 2010; ICRP, 2019).

8.1 Lutetium-177 concentration ratios and factors

8.1.1 Foodstuffs

For IRAT2, almost all of the Lu transfer parameters for foodstuffs are currently based on a Ce analogue. The IRAT2 values for terrestrial foodstuffs and for freshwater and marine foodstuffs are summarised in the following two tables.

Table 58. Current ^{177}Lu concentration factors and transfer factors for terrestrial foodstuffs in IRAT2 (Environment Agency, 2022).

Foodstuff	Current plant: soil concentration factor (Bq/kg plant wet weight per Bq/kg soil dry weight)	Current transfer factor (TF) pasture to animal product (Bq/kg wet muscle or liver or Bq/L per Bq/days intake)	Reference source
Pasture	0.11	-	(IAEA, 2010), Ce analogue
Green vegetable	1.30×10^{-3}	-	(IAEA, 2010), Ce analogue
Root vegetable	1.20×10^{-3}	-	(IAEA, 2010), Ce analogue
Fruit	4.20×10^{-5}	-	(IAEA, 2010), Ce analogue
Sheep meat	-	2.50×10^{-4}	(IAEA, 2010), Ce analogue
Sheep offal	-	2.00	(Brown and Simmonds, 1995), Ce analogue
Beef meat	-	1.03×10^{-3}	(Brown and Simmonds, 1995), Ce analogue
Beef offal	-	0.10	(Brown and Simmonds, 1995), Ce analogue
Cow's milk	-	2.00×10^{-5}	(IAEA, 2010), Ce analogue

Table 59: Current ^{177}Lu concentration factors for freshwater fish and marine foodstuffs in IRAT2 (Environment Agency, 2022).

Foodstuff	Current concentration factor (L/kg)	Reference source
Freshwater fish	30	(IAEA, 2010), promethium (Pr) analogue
Marine fish	50	(IAEA, 2004), Ce analogue
Marine crustacea	1×10^3	(IAEA, 2004), Ce analogue
Marine molluscs	2×10^3	(IAEA, 2010), Ce analogue

A European study, which used some British soil as part of its experimental methodology, examined the concentration factors of the lanthanide elements (including Lu) in vegetables (Qvarforth et al., 2022). Lettuce, chard, and carrots were grown as part of this study and are directly relevant to the categories of green vegetables and root vegetables in the UK environment. The authors presented two concentration factors for each of the vegetables, determined via two different soil extraction media (*Aqua Regia* and 0.1 M HNO_3). Lutetium values were identified for terrestrial foodstuffs and are described in the table below.

Table 60: Lutetium-177 concentration factors for terrestrial foodstuffs, as identified in the literature review.

Foodstuff	Plant: soil concentration factor (Bq/kg plant wet weight per Bq/kg soil dry weight)	Reference source
Green vegetable	2.8×10^{-3} lettuce (*Aqua Regia* soil digestion)	(Qvarforth et al., 2022)
	5.9×10^{-2} lettuce (0.1 HNO_3 soil digestion)	
	5.5×10^{-3} chard (*Aqua Regia* soil digestion)	
	8.8×10^{-2} chard (0.1 HNO_3 soil digestion)	
Root vegetable	2.9×10^{-3} carrot (*Aqua Regia* soil digestion)	

Foodstuff	Plant: soil concentration factor (Bq/kg plant wet weight per Bq/kg soil dry weight)	Reference source
	5.5×10^{-2} carrot (0.1 HNO_3 soil digestion)	(Qvarforth et al., 2022)

The transfer factor for beef liver for Ce in a PC-CREAM 08 report is 0.2 days/kg, although IRAT2 quotes a value of 0.1 days/kg from PC-CREAM 08 (Smith and Simmonds, 2009; Environment Agency, 2022). The reason for this apparent discrepancy is unclear, although it may relate to an incorrect reference. The transfer factor for cow meat in IRAT2 is correctly cited as 1×10^{-3} days/kg (Smith and Simmonds, 2009; Environment Agency, 2022). The IRAT2 transfer factors for europium (Eu), another lanthanide element, are 4×10^{-2} and 5×10^{-3} days/kg for liver and meat, respectively (Environment Agency, 2022), The transfer factors for sheep meat and liver are from different references. Hence, the ratio between the transfer to sheep meat and sheep liver may appear inconsistent. Using the IAEA Handbook transfer factor to sheep meat of 2.5×10^{-4} days/kg, the transfer factor to liver would be 5×10^{-2} days/kg (IAEA, 2010). This calculation is based on the Ce ratio contained within PC-CREAM 08 data (Smith and Simmonds, 2009). This is significantly lower than the value of 2 days/kg used in IRAT2. Similarly, the transfer factor for Eu for sheep meat is 5×10^{-2} days/kg and for sheep liver is 0.3 days/kg.

The PC-CREAM 08 parameters show greater transfer of Ce to liver than to meat; the ratio of transfer factors for Ce are 1×10^{-2} (meat) and 2 (liver). The ICRP Publication 141 metabolic model for humans assumes greater Lu activity deposited in tissue than in liver; the deposition fraction is 0.15 for tissue and 0.05 for liver (ICRP, 2019). In contrast, higher levels of Ce are expected in liver than tissue. The deposition fraction for Ce is 8×10^{-2} in tissue and 0.5 in liver. ICRP Publication 141 quotes data for rats where the percentage of injected activity in liver and other tissues is similar for Lu (3% and 4%, respectively) whereas the percentages for Ce are 51% and 6%, respectively (ICRP, 2019). On that basis, Ce may not be an appropriate analogue for Lu in animals. Despite this, ICRP Publication 141 assumes that Lu behaves similarly to other lanthanide elements (e.g., terbium, dysprosium, holmium, erbium, thulium, and ytterbium) and that ~10% of the activity entering the blood is deposited in the liver.

Additional work may be required to establish which concentration factor values should be used in vegetables based on the experimental methods. The transfer factor for beef liver is inconsistent with the value given in the FARMLAND report (Brown and Simmonds, 1995). The ratio between the transfer factor for sheep meat and sheep liver could be maintained, and the value for sheep liver could be based on the IAEA Handbook value for sheep meat.

Cerium could be further investigated as a biological analogue for Lu in animal food chain modelling. ICRP metabolic data indicates that Ce deposits heavily in the liver, whereas, by contrast, Lu distributes more evenly into soft tissue. This caveat should be borne in mind when using Ce as analogue for Lu, and alternative data sources may be required. This could be either from a better analogue that reflects the properties of Lu, or using more specific Lu data, should it become available.

8.1.2 Wildlife

The ^{177}Lu concentration ratio values for marine, terrestrial, and freshwater biota in IRAT2 are taken from ERICA (version 1.2.1) (Brown et al., 2016). Analogues for Lu are used, and the reported values are summarised in the following three tables.

Table 61: Current ^{177}Lu concentration ratios for marine biota in IRAT2 (Environment Agency, 2022).

Marine reference organisms	Concentration ratio (L/kg)	Reference source
Benthic fish	3.90×10^{2}	ERICA v1.2.1, Ce analogue
Bird	2.20×10^{3}	ERICA v1.2.1, Ce analogue
Crustacean	1.00×10^{2}	ERICA v1.2.1, Ce analogue
Macro-algae	2.10×10^{3}	ERICA v1.2.1, Ce analogue
Mammal	2.20×10^{3}	ERICA v1.2.1, Ce analogue
Mollusc – bivalve	2.20×10^{3}	ERICA v1.2.1, Ce analogue
Pelagic fish	3.90×10^{2}	ERICA v1.2.1, Ce analogue
Phytoplankton	1.10×10^{4}	ERICA v1.2.1, Ce analogue
Polychaete worm	2.20×10^{3}	ERICA v1.2.1, Ce analogue

Marine reference organisms	Concentration ratio (L/kg)	Reference source
Reptile	2.20×10^{3}	ERICA v1.2.1, Ce analogue
Sea anemones and true coral	1.30×10^{2}	ERICA v1.2.1, Ce analogue
Vascular plant	1.60×10^{2}	ERICA v1.2.1, Ce analogue
Zooplankton	6.00×10^{3}	ERICA v1.2.1, Ce analogue

Table 62: Current ^{177}Lu concentration ratios for terrestrial biota in IRAT2 (Environment Agency, 2022).

Terrestrial reference organism	Concentration ratio (L/kg)	Reference source
Amphibian	4.90×10^{-3}	ERICA v1.2.1, Ce analogue
Annelid	4.80×10^{-3}	ERICA v1.2.1, Ce analogue
Arthropod - detritivores	2.20×10^{-3}	ERICA v1.2.1, Ce analogue
Bird	6.90×10^{-2}	ERICA v1.2.1, Ce analogue
Flying insects	2.20×10^{-3}	ERICA v1.2.1, Ce analogue
Grasses and herbs	1.40×10^{-2}	ERICA v1.2.1, Ce analogue
Lichen and bryophytes	1.60×10^{-2}	ERICA v1.2.1, Ce analogue

Terrestrial reference organism	Concentration ratio (L/kg)	Reference source
Mammal – large	4.90×10^{-3}	ERICA v1.2.1, Ce analogue
Mammal – small, burrowing	4.90×10^{-3}	ERICA v1.2.1, Ce analogue
Mollusc – gastropod	6.90×10^{-2}	ERICA v1.2.1, Ce analogue
Reptile	4.90×10^{-3}	ERICA v1.2.1, Ce analogue
Shrub	9.10×10^{-3}	ERICA v1.2.1, Ce analogue
Tree	1.70×10^{-3}	ERICA v1.2.1, Ce analogue

Table 63: Current ^{177}Lu concentration ratios for freshwater biota in IRAT2 (Environment Agency, 2022).

Freshwater reference organism	Concentration ratio (L/kg)	Reference source
Amphibian	1.70×10^{2}	ERICA v1.2.1, Ce analogue
Benthic fish	1.70×10^{2}	ERICA v1.2.1, Ce analogue
Bird	4.40×10^{3}	ERICA v1.2.1, Ce analogue
Crustacean	1.00×10^{3}	ERICA v1.2.1, Ce analogue
Insect larvae	1.00×10^{3}	ERICA v1.2.1, Ce analogue

Freshwater reference organism	Concentration ratio (L/kg)	Reference source
Mammal	1.70×10^2	ERICA v1.2.1, Ce analogue
Mollusc – bivalve	1.00×10^3	ERICA v1.2.1, Ce analogue
Mollusc – gastropod	1.00×10^3	ERICA v1.2.1, Ce analogue
Pelagic fish	1.70×10^2	ERICA v1.2.1, Ce analogue
Phytoplankton	8.80×10^3	ERICA v1.2.1, Ce analogue
Reptile	6.30×10^2	ERICA v1.2.1, Ce analogue
Vascular plant	8.80×10^2	ERICA v1.2.1, Ce analogue
Zooplankton	1.00×10^3	ERICA v1.2.1, Ce analogue

8.1.3 Review of ^{177}Lu concentration ratios

All ^{177}Lu concentration ratio parameter values in IRAT2 are currently based on Ce as an analogue and there is no additional data for Lu in biota in the latest version of ERICA (version 2.0) (ERICA Consortium, 2021). A PhD student at Oregon State University, USA, experimentally determined the concentration ratio of Lu in several different biotas in three specific sites in Washington State, USA (Napier, 2012). Further work would likely be needed to identify the plants which could be considered most similar to the ecology of the UK. Of note, the doctoral thesis has not been peer reviewed, although the values for some reference organisms have been incorporated into the WTD (Copplestone et al., 2013).

There is an additional study of the bioaccumulation of elements in anti-diabetic medicinal plants in Nigeria (Magili and Bwatanglang, 2018). This research yielded a concentration ratio for a specific herb (*Ageratum conyzoides*) but does not quote values for the entire analysis. Overall, the investigation is likely too narrow and in a markedly different climate, suggesting that the proposed concentration ratio is insufficiently robust for use in the UK.

The updated Ce concentration ratios (which has frequently been used as an analogue for Lu) for biota from ERICA (version 2.0) and the additional references identified are provided in the following three tables.

Table 64: Lutetium-177 concentration ratios for marine biota, as identified in the literature review.

Marine reference organisms	Concentration ratio (L/kg)	Reference source
Benthic fish	1.15×10^2	ERICA v.2, Ce analogue
Bird	1.15×10^2	ERICA v. 2, Ce analogue, fish
Crustacean	1.87×10^3	ERICA v.2, Ce analogue
	3.3×10^4	(IAEA, 2014) brackish
Macro-algae	1.71×10^3	ERICA v.2, Ce analogue
	9.1×10^3	(IAEA, 2014), brackish
Mammal	1.15×10^2	ERICA v.2, Ce analogue, fish
Mollusc – bivalve	1.19×10^3	ERICA v.2, Ce analogue
	2.1×10^4	(IAEA, 2014), brackish
Pelagic fish	1.15×10^2	ERICA v.2, Ce analogue
Phytoplankton	1.07×10^4	ERICA v.2, Ce analogue
Polychaete worm	1.87×10^3	ERICA v.2, Ce analogue, crustacean
Reptile	1.15×10^2	ERICA v.2, Ce analogue, fish
Sea anemones and true coral	1.27×10^2	ERICA v.2, Ce analogue
Vascular plant	1.55×10^2	ERICA v.2, Ce analogue

Marine reference organisms	Concentration ratio (L/kg)	Reference source
Zooplankton	1.87×10^{3}	ERICA v.2, Ce analogue, crustacean

Table 65: Lutetium-177 concentration ratios for terrestrial biota, as identified in the literature review.

Terrestrial reference organism	Concentration ratio (L/kg)	Reference source
Amphibian	1.80×10^{-4}	ERICA v.2, Ce analogue
Annelid	7.6×10^{-3}	WTD, (Barnett et al., 2013)
	1.91×10^{-2}	ERICA v.2, Ce analogue
Arthropod – detritivorous	8.8×10^{-3}	WTD, (Napier, 2012)
	1.91×10^{-2}	ERICA v.2, Ce analogue
Bird	3.82×10^{-2}	ERICA v.2, Ce analogue
Flying insects	3.5×10^{-2}	(Napier, 2012), cricket/grasshopper (three separate locations)
	1.2×10^{-2}	
	7.1×10^{-3}	
	2.48×10^{-3}	ERICA v.2, Ce analogue
Grasses and herbs	6.1×10^{-3}	(Higley, 2010)
	6.1×10^{-3}	(IAEA, 2014)
	0.14	(Napier, 2012), grass
	0.13	(Napier, 2012), rush

Terrestrial reference organism	Concentration ratio (L/kg)	Reference source
	0.31	(Magili and Bwatanglang, 2018), herb tropical
	2.00×10^{-2}	ERICA v.2, Ce analogue
Lichen and bryophytes	1.51×10^{-2}	ERICA v.2, Ce analogue
	1.4×10^{-2}	(IAEA, 2014)
	1.4×10^{-2}	(Higley, 2010)
Mammal – large	1.71×10^{-3}	ERICA v.2, Ce analogue
Mammal – small, burrowing	1.71×10^{-3}	ERICA v.2, Ce analogue
Mollusc – gastropod	1.91×10^{-2}	ERICA v.2, Ce analogue
Reptile	3.82×10^{-2}	ERICA v.2, Ce analogue
Shrub	1.8×10^{-3}	(Sheppard et al., 2008), plant collated value
	1.1×10^{-2}	(IAEA, 2014)
	1.1×10^{-2}	(Higley, 2010)
	8.69×10^{-3}	ERICA v.2, Ce analogue
Tree	4.0×10^{-3}	(Higley, 2010), (IAEA, 2014), coniferous
	5.90×10^{-3}	(Napier, 2012), Siberian elm (two locations)
	1.1×10^{-2}	
	1.36×10^{-3}	ERICA v.2, Ce analogue

Table 66: Lutetium-177 concentration ratios for freshwater biota, as identified in the literature review.

Freshwater reference organism	Concentration ratio (L/kg)	Reference source
Amphibian	9.3	ERICA v.2, Ce analogue
Benthic fish	4.72×10^{2}	(Sheppard et al., 2010b)
	1.58×10^{2}	ERICA v.2, Ce analogue
Crustacean	2.1×10^{3}	(Napier, 2012), crayfish
	4.39×10^{3}	ERICA v.2, Ce analogue, mollusc-bivalve
Insect larvae	4.39×10^{3}	ERICA v.2, Ce analogue mollusc-bivalve
Mammal	8.35×10^{2}	ERICA v.2, Ce analogue, bird
	2.5×10^{2}	(IAEA, 2014)
	4.39×10^{3}	ERICA v.2, Ce analogue
Mollusc – gastropod	4.39×10^{3}	ERICA v.2, Ce analogue
	4.72×10^{-2}	WTD (Sheppard et al., 2010b)
Mollusc – bivalve	2.5×10^{2}	(IAEA, 2014)

Freshwater reference organism	Concentration ratio (L/kg)	Reference source
Pelagic fish	4.72×10^2	WTD (Sheppard et al., 2010b)
	1.58×10^2	ERICA v.2, Ce analogue
Phytoplankton	8.32×10^3	ERICA v.2, Ce analogue
Reptile	6.26×10^3	ERICA v.2, Ce analogue
Vascular plant	2.5×10^2	(Napier, 2012)
	31	(IAEA, 2014)
	1.33×10^3	ERICA v.2, Ce analogue
Zooplankton	4.39×10^3	ERICA v.2, Ce analogue

The values identified outside the WTD are unlikely to be sufficiently relevant or robust to warrant inclusion in IRAT2 (or similar UK) assessments. Instead, the continued use of an analogue may be appropriate.

8.2 Lutetium-177 distribution coefficients

Distribution coefficient values for ^{177}Lu are discussed in the following section, noting that IRAT2 currently includes analogue element K_d values for marine and freshwater systems (Environment Agency, 2022).

8.2.1 Lutetium speciation

Lutetium is the heaviest of the 14 lanthanide elements, which are noted for their similar chemical properties. For this reason, the lanthanides are typically found together in nature and can be difficult to separate. The lanthanides are known to form fairly strong carbonate complexes, and can strongly associate with dissolved organic ligands, and sometimes with Fe colloids (Rönnback, et al., 2008).

Lutetium and the other lanthanide elements are predominantly found in the trivalent (+3) oxidation state (Kaltsoyannis and Scott, 1999). Differences in chemical behaviour among the lanthanides are primarily due to variations in ionic radius, often with a slight variation between light and heavy lanthanides (with the "light" elements comprising lanthanum to samarium (Sm) and "heavy" elements comprising Eu to Lu). Cerium and Eu sometimes occur in other oxidation states in the natural environment; Ce in the tetravalent oxidation state (i.e., Ce^{4+} ion) and Eu in the divalent oxidation state (i.e., Eu^{2+} ion). The broad similarities in reported K_d values across the lanthanides suggests that these differences are not significant in relation to partitioning phenomena in aquatic environments of interest.

8.2.2 Current ^{177}Lu K_d values

IRAT2 includes several parameter values for ^{177}Lu based on a Ce analogue. This information is provided in the table below.

Table 67: Current ^{177}Lu K_d values in IRAT2 (Environment Agency, 2022).

Parameter	K_d (L/kg)	Basis
Marine	3×10^6	Ocean margin value for Ce. The value was calculated by dividing the mean exchangeable coastal sedimentary abundance by the coastal water concentration (IAEA, 2004).
Freshwater	2.2×10^5	Partitioning of Ce to sediment, geometric mean of a large data set (n = 124), with the data ranging from 4.2×10^4 to 1.2×10^6 L/kg (i.e., spanning 4 orders of magnitude) (IAEA, 2010).
Organic Soil	3×10^3	A Ce specific K_d value of 3×10^3 L/kg is provided by IAEA for organic soil (IAEA, 2010).

8.2.3 Review of ^{177}Lu K_d parameters

No data on ^{177}Lu adsorption in environmental systems has been found in this project, where large systematic studies typically report data for the other lanthanide elements. No substantive new literature sources providing Lu specific K_d values were identified. Recent compilations of freshwater K_d data for the lanthanides include the following.

Boyer et al. published data that includes Ce (and other lanthanides) (Boyer et al., 2018). The "enhanced" K_d dataset show that K_d values for suspended sediments are significantly higher than for deposited sediments. The variability of K_d distributions are higher for deposited than for suspended sediments. For Ce adsorbed on suspended sediment, the experimentally determined K_d values had a geometric mean of 1.81×10^5 L/kg (range: 5.3×10^4-9.21×10^6 L/kg, n = 6). Similarly, a geometric mean of 1.66×10^5 L/kg (range: 7.25 x

10^4 –1.5 x 10^6 L/kg n = 23) was calculated from field data. These suspended sediment values compare well with the current IRAT2 parameter value of 2.2 x 10^5 L/kg.

A study of the behaviour of radionuclides in a river system identified apparent K_d values for Ce (based on cerium-139; ^{139}Ce) (Juranová, et al., 2020). The values ranged from 3.2 x 10^3 L/kg (river bottom sediment, n = 9) to 1.2 x 10^6 L/kg (suspended solids, n = 15). This work also identified a significant positive correlation between ^{139}Ce adsorption to sediment and the silt, feldspar, and organic matter contents of the sediment. The reported value for bottom sediment is lower than the current IRAT2 parameter value of 2.2 x 10^5 L/kg (by a factor of 68), whilst that measured for suspended sediment is higher by a factor of 5.

Biosphere studies undertaken to support a recently published safety case for geological disposal offer potentially useful Sm data (Hjerpe, 2021). 1.17 x 10^4 L/kg (river and lake) and 5.22 x 10^5 L/kg (sea) suspended solids. These values are an order of magnitude lower than the current IRAT2 K_d parameter values of 2.2 x 10^5 L/kg and 3 x 10^6 L/kg for Ce partitioning to suspended solids in freshwater and marine environments, respectively.

8.2.4 Recommendations for ^{177}Lu K_d values

The current IRAT2 parameters for Lu are based on Ce analogue element data. These parameter values are typically in good agreement with recently published compilations and data analyses (albeit within the large data ranges quoted). In the absence of element specific data for Lu, Ce based K_d analogue values could reasonably be adopted.

Reflecting the broad similarities in the environmental behaviour of the lanthanides, direct Lu data may not add much value (besides confidence building and validation purposes). However, the influence of radiopharmaceutical ligands on the partitioning behaviour of ^{177}Lu in the environment is not well understood. It is not clear if the medical (complexed) form of ^{177}Lu would persist following patient excretion, during sewage treatment, and after discharge to river. Field monitoring studies to empirically determine K_d values for ^{177}Lu in river systems downstream of UK sewage treatment facilities may be beneficial. Such data could be useful for ^{177}Lu K_d parameter refinements and to better understand the role of the ^{177}Lu chemical form on the radionuclide’s partitioning behaviour in wastewater systems.

8.3 Summary of lutetium-177 review

The review of parameter values for ^{177}Lu is summarised in the following table.

Table 68: Key literature findings for ^{177}Lu transfer parameters.

Parameter	Review findings for ^{177}Lu
K_d	Currently based on Ce analogue values.
Terrestrial food chain	The transfer factor for beef liver is not consistent with the value given in the FARMLAND report. The ratio between the transfer factor for sheep meat and sheep liver could be maintained and based on the IAEA Handbook value for sheep meat. Other lanthanides may be better analogues for transfer to animals, and this possibility could be further explored. There are updated values available for green and root vegetables, which require further assessment.
Marine food chain	No new data found.
Wildlife	There are a small number of experimental parameter values available in the WTD. ERICA (version 2.0) has updated parameter values for the Ce analogue.

9 Rhenium-186 and rhenium-188

Rhenium-186 (^{186}Re) and rhenium-188 (^{188}Re) are both used in nuclear medicine. Rhenium-186 is routinely produced in nuclear reactors through the neutron activation of rhenium-185. In contrast, ^{188}Re is the daughter of tungsten-188 (^{188}W), which is generated in a nuclear reactor by irradiation of tungsten oxide (Argyrou et al., 2013). Separation of ^{186}Re is typically performed using a chromatographic ^{188}W /^{188}Re generator in which ^{188}W is adsorbed on the alumina column, and the radionuclide is eluted in saline solution.

Rhenium-186 (half-life of ~4 days) decays to ^{186}W by electron capture (7.47%) and to osmium-186 by β^- particle emission (92.53%), respectively (Uccelli, et al., 2022). The low energy beta emission and its maximum tissue penetration of 4.5 mm means that ^{186}Re is a promising candidate for the radiotherapy treatment of tumours (Uccelli, et al., 2022). This radionuclide also emits a low-abundance (9.47%) 137 keV γ-ray, making it suitable for in-vivo imaging of radiolabelled biomolecules via single photon emission tomography. Rhenium-188 (half-life of ~17 hours) is a candidate radiopharmaceutical since it decays by emitting β^- particles (100%) with a maximum tissue penetration of 11 mm, suitable for treating large size tumour (Schötzig et al., 2001). In addition, ^{188}Re emits γ photons (E_γ = 155 keV) that could potentially be exploited in scintigraphy procedures.

One characteristic feature of Re is its chemical similarity with Tc. This means that diagnostic Tc analogues labelled with radiorhenium can be developed for therapeutic applications. Rhenium also exhibits similar biokinetic properties to Tc. The ICRP metabolic models for Re and Tc are therefore comparable (ICRP, 2022). The default Re parameter values for absorption to blood following inhalation (default absorption Type M) are used, and a gut absorption factor of 0.9 is used based on the chemical analogy with Tc.

9.1 Rhenium concentration ratios and factors

9.1.1 Foodstuffs

The Re transfer parameters in IRAT2 are currently based on Tc as an analogue, using IAEA compilation data (IAEA, 2004; 2010) and information from the FARMLAND model in PC-CREAM 08 (Smith and Simmonds, 2009). These data are summarised in the two tables below.

Table 69: Current Re concentration factors and transfer factors for terrestrial foodstuffs in IRAT2 (Environment Agency, 2022).

Terrestrial food stuff	Current plant: soil concentration ratio (Bq/kg plant wet weight per Bq/kg soil dry weight)	Current transfer factor (TF) pasture to animal product (Bq/kg wet muscle or liver or Bq/L per Bq/days intake)	Reference source
Pasture	23	-	(Brown and Simmonds, 1995), Tc analogue
Green vegetable	18	-	(IAEA, 2010), Tc analogue
Root vegetable	9.2	-	(IAEA, 2010), Tc analogue
Fruit	5.0	-	(Brown and Simmonds, 1995), Tc analogue
Sheep meat	-	0.10	(Brown and Simmonds, 1995), Tc analogue
Sheep offal	-	1.00×10^{-3}	(Brown and Simmonds, 1995), Tc analogue
Beef meat	-	1.00×10^{-2}	(Brown and Simmonds, 1995), Tc analogue
Beef offal	-	4.00×10^{-2}	(Brown and Simmonds,

Terrestrial food stuff	Current plant: soil concentration ratio (Bq/kg plant wet weight per Bq/kg soil dry weight)	Current transfer factor (TF) pasture to animal product (Bq/kg wet muscle or liver or Bq/L per Bq/days intake)	Reference source
			1995), Tc analogue
Cow's milk	-	1.00×10^{-2}	(Brown and Simmonds, 1995), Tc analogue

Table 70: Current Re concentration factors for freshwater fish and marine foodstuffs in IRAT2 (Environment Agency, 2022).

Food stuff	Current concentration factor (L/kg)	Reference source
Freshwater fish	20	(IAEA, 2010), Tc analogue
Marine fish	80	(IAEA, 2004), Tc analogue
Marine crustacea	1×10^{3}	(IAEA, 2004), Tc analogue
Marine molluscs	5×10^{2}	(IAEA, 2004), Tc analogue

Overall, no new data for Re was found. The continued use of Tc concentration factors as an analogue for Re may therefore be required.

9.1.2 Wildlife

The Re concentration ratio values for marine, terrestrial, and freshwater biota are taken from ERICA (version 1.2.1), using Tc as an analogue (Brown et al., 2016). The parameter values are provided in the three tables below.

Table 71: Current Re concentration ratios for marine biota in IRAT2 (Environment Agency, 2022).

Marine reference organisms	Concentration ratio (L/kg)	Reference source
Benthic fish	80.0	ERICA v.1.2.1, Tc analogue
Bird	1.70×10^4	ERICA v.1.2.1, Tc analogue
Crustacean	1.70×10^4	ERICA v.1.2.1, Tc analogue
Macro-algae	5.30×10^4	ERICA v.1.2.1, Tc analogue
Mammal	1.70×10^4	ERICA v.1.2.1, Tc analogue
Mollusc – bivalve	8.20×10^3	ERICA v.1.2.1, Tc analogue
Pelagic fish	80	ERICA v.1.2.1, Tc analogue
Phytoplankton	4.9	ERICA v.1.2.1, Tc analogue
Polychaete worm	1.70×10^4	ERICA v.1.2.1, Tc analogue
Reptile	1.70×10^4	ERICA v.1.2.1, Tc analogue
Sea anemones and true coral	1.70×10^4	ERICA v.1.2.1, Tc analogue
Vascular plant	5.30×10^4	ERICA v.1.2.1, Tc analogue
Zooplankton	1.00×10^2	ERICA v.1.2.1, Tc analogue

Table 72: Current Re concentration ratios for terrestrial biota in IRAT2 (Environment Agency, 2022).

Terrestrial reference organism	Concentration ratio (L/kg)	Reference source
Amphibian	0.39	ERICA v.1.2.1, Tc analogue

Terrestrial reference organism	Concentration ratio (L/kg)	Reference source
Annelid	0.39	ERICA v.1.2.1, Tc analogue
Arthropod – detritivorous	0.39	ERICA v.1.2.1, Tc analogue
Bird	0.17	ERICA v.1.2.1, Tc analogue
Flying insects	0.39	ERICA v.1.2.1, Tc analogue
Grasses and herbs	14.0	ERICA v.1.2.1, Tc analogue
Lichen and bryophytes	14.0	ERICA v.1.2.1, Tc analogue
Mammal – large	0.39	ERICA v.1.2.1, Tc analogue
Mammal – small, burrowing	0.39	ERICA v.1.2.1, Tc analogue
Mollusc – gastropod	0.39	ERICA v.1.2.1, Tc analogue
Reptile	0.39	ERICA v.1.2.1, Tc analogue
Shrub	1.20×10^{-2}	ERICA v.1.2.1, Tc analogue
Tree	1.20×10^{-2}	ERICA v.1.2.1, Tc analogue

Table 73: Current Re concentration ratios for freshwater biota in IRAT2 (Environment Agency, 2022).

Freshwater reference organism	Concentration ratio (L/kg)	Reference source
Amphibian	99	ERICA v.1.2.1, Tc analogue
Benthic fish	99	ERICA v.1.2.1, Tc analogue
Bird	99	ERICA v.1.2.1, Tc analogue
Crustacean	99	ERICA v.1.2.1, Tc analogue

Freshwater reference organism	Concentration ratio (L/kg)	Reference source
Insect larvae	99	ERICA v.1.2.1, Tc analogue
Mammal	99	ERICA v.1.2.1, Tc analogue
Mollusc – bivalve	99	ERICA v.1.2.1, Tc analogue
Mollusc – gastropod	99	ERICA v.1.2.1, Tc analogue
Pelagic fish	99	ERICA v.1.2.1, Tc analogue
Phytoplankton	40	ERICA v.1.2.1, Tc analogue
Reptile	99	ERICA v.1.2.1, Tc analogue
Vascular plant	40	ERICA v.1.2.1, Tc analogue
Zooplankton	99	ERICA v.1.2.1, Tc analogue

There appears to be ongoing research into Re phytomining, given the metal's high commercial value, which may yield concentration ratio values for plants in the future. The references below discuss the results from some research into the topic but do not provide concentration ratios (Bozhkov et al., 2012; Novo et al., 2015; Tzvetkova et al., 2021).

A small number of Canadian studies have produced environmental transfer factor values for terrestrial and freshwater organisms. These values are present in the WTD but have not been adopted in ERICA (version 2.0) (Copplestone et al., 2013). There are no other recently published studies with Re specific parameters. However, the values for Tc in ERICA (version 2.0) have been updated, albeit for a small number of reference organisms. Uccelli et al. note that one of the advantages of Re is its chemical similarity with Tc (Uccelli et al., 2022). However, further work may be beneficial to ascertain whether Tc remains the most suitable analogue and if the new ERICA concentration ratios should be used.

It has been noted elsewhere that new parameters for terrestrial and freshwater organisms are present in the WTD but have not been adopted in the new version of ERICA (ERICA Consortium, 2021). The values for the Tc analogue in the ERICA tool have been updated. The updated concentration ratios for biota and data are given in the following three tables.

Table 74: Rhenium concentration ratios for marine biota, as identified in the literature review.

Marine reference organisms	Concentration ratio (L/kg)	Reference source
Benthic fish	1.69×10^4	ERICA v.2, Tc analogue crustacean
Bird	1.69×10^4	ERICA v.2, Tc analogue, crustacean
Crustacean	1.69×10^4	ERICA v.2, Tc analogue
Macro-algae	5.42×10^4	ERICA v.2, Tc analogue
Mammal	1.69×10^4	ERICA v.2, Tc analogue crustacean
Mollusc – bivalve	1.05×10^4	ERICA v.2, Tc analogue
Pelagic fish	1.69×10^4	ERICA v.2, Tc analogue, crustacean
Phytoplankton	4.90	ERICA v.2, Tc analogue
Polychaete worm	1.69×10^4	ERICA v.2, Tc analogue, crustacean
Reptile	1.69×10^4	ERICA v.2, Tc analogue, crustacean
Sea anemones and true coral	1.69×10^4	ERICA v.2, Tc analogue, crustacean
Vascular plant	5.42×10^4	ERICA v.2, Tc analogue, macroalgae
Zooplankton	1.69×10^4	ERICA v.2, Tc analogue, crustacean

Table 75: Rhenium concentration ratios for terrestrial biota, as identified in the literature review.

Terrestrial reference organism	Concentration ratio (L/kg)	Reference source
Amphibian	0.358	ERICA v.2, Tc analogue
Annelid	4.43	ERICA v.2, Tc analogue Annelid Cd
Arthropod – detritivorous	4.43	ERICA v.2, Tc analogue, Annelid Cd
Bird	0.167	ERICA v.2, Tc analogue
Flying insects	4.43	ERICA v.2, Tc analogue, Annelid Cd
Grasses and herbs	37	(Sheppard et al., 2008), all plants in study
	16.6	ERICA v.2, Tc analogue
Lichen and bryophytes	16.6	ERICA v.2, Tc analogue, Grasses and herbs
Mammal – large	0.358	ERICA v.2, Tc analogue, amphibian
Mammal – small, burrowing	0.358	ERICA v.2, Tc analogue, amphibian
Mollusc – gastropod	4.43	ERICA v.2, Tc analogue, Annelid Cd
Reptile	0.358	ERICA v.2, Tc analogue amphibian
Shrub	1.16×10^{-2}	ERICA v.2, Tc analogue

Terrestrial reference organism	Concentration ratio (L/kg)	Reference source
Tree	1.16×10^{-2}	ERICA v.2, Tc analogue shrub

Table 76: Rhenium concentration ratios for freshwater biota, as identified in the literature review.

Freshwater reference organism	Concentration ratio (L/kg)	Reference source
Phytoplankton	99.0	ERICA v.2, Tc analogue, fish
Vascular plant	99.0	ERICA v.2, Tc analogue, fish

Rhenium-188 has a notably short half-life (~4 days) and is not included in the IRAT2 wildlife dose per unit release tables (Environment Agency, 2022). Derivation of a modified concentration ratio for ^{188}Re may be appropriate, using the approach taken for ^{223}Ra and lead-211 (^{211}Pb) in IRAT2 (Environment Agency, 2022).

9.2 Rhenium distribution coefficients

Distribution coefficient values for Re are discussed in the following sections, noting that IRAT2 currently includes element-specific K_d values for marine and freshwater systems (Environment Agency, 2022).

9.2.1 Rhenium speciation

Rhenium compounds are known in all the oxidation states between −3 and +7, except for −2. The +7 and +4 oxidation states are probably the most common in the natural environment. Rhenium can exist in the +7 oxidation state as the perrhenate ion (ReO_4^-) in oxygen-rich (oxic) natural waters (including seawater). The chemical speciation of Re in oxygen-fee (anoxic) environments is not well established. The distribution of Re in environmental samples is influenced by its relatively high solubility in oxic water and its lower solubility in anoxic waters. Rhenium will precipitate primarily as Re(IV) oxides under reducing conditions (when sulphur is absent). In the presence of sulphur, Re^{4+} ions will often incorporate into sulphide minerals.

While Re and Tc possess similar chemical properties, differences also exist. For example, there is a greater stability of the higher oxidation states of Re than those of Tc. For example, the Tc^{7+} ion (as TcO_4^-) is easier to reduce than the Re^{7+} ion (as ReO_4^-), with the mobile TcO_4^- ion being more stable over a wider range of conditions than the ReO_4^- ion. Accordingly, Tc may not always be an ideal analogue for Re, particularly for reducing environments. Such differences should be considered when using Tc analogue data.

9.2.2 Current Re K_d values

IRAT2 includes Re specific K_d parameters, and these are shown in the following table.

Table 77: Current Re K_d values in IRAT2 (Environment Agency, 2022).

Parameter	K_d (L/kg)	Basis
Marine	110	K_d for sea particulate matter (Kemnitz et al., 2023), range 18-680 L/kg.
Freshwater	430	K_d for lake particulate matter (Kemnitz et al., 2023), range 70-670 L/kg.

9.2.3 Review of Re K_d parameters

Rhenium adsorption data in environmental systems is sparse. No substantive new literature sources have been identified in this project. Much of the recent literature on Re adsorption behaviour is specific to hydrometallurgical systems and to aid understanding of Re behaviour in anoxic sediments (with no direct relevance to K_d).

One study includes a freshwater K_d for sediments collected from 20 lakes in several locations and depths (Sheppard et al., 2009). A K_d value of 270 L/kg (n = 14) was determined, which is in reasonable agreement with the current freshwater K_d value in IRAT2.

9.2.4 Recommendations for Re K_d values

The current IRAT2 parameters for Re seem to be based on limited, element-specific data. Notably, no substantive compilation of Re K_d data exists. For these reasons, consideration could be given to use of Tc as an analogue. Of note, new Tc data appears to be limited.

No recent evidence was found in the literature to warrant revising the current element-specific K_d values for Re. The freshwater value is reasonably well supported by empirical data (270 L/kg) (Sheppard et al., 2009). Technetium should be treated with a little caution as an analogue in the context of Re K_d values, as their chemical behaviours diverge significantly in reducing environments, where Re is more stable in higher oxidation states.

9.3 Summary of rhenium review

The review of Re parameter values is summarised in the following table.

Table 78: Key literature findings for Re transfer parameters.

Parameter	Review findings for Re-186 and Re-188
K_d	Current values are based on limited data. Technetium may be a suitable analogue, but should be used cautiously, particularly in reducing environments.
Terrestrial food chain	No new data has been found. The continued use of Tc analogue data may be appropriate.
Marine food chain	No new data has been found. The continued use of Tc analogue data may be appropriate.
Wildlife	Some Re concentration ratios have been found. Updating some Re concentration ratios may be appropriate. ERICA (version 2.0) has updated parameter values for the Tc analogue.

10 Radium-223

Radium-223 (^{223}Ra) has a half-life of ~11 days and undergoes alpha decay to form radon-219 (^{219}Rn) (Wilson, 1996). Radon is a chemically inert (noble) element that is typically encountered as a gas (in its elemental form). Radon can also be found in the environment in a dissolved form in water (although its water solubility is relatively low). Radon-219 has a half-life of ~4 seconds and undergoes alpha decay; its daughter is polonium-215 (^{215}Po, $t_{1/2}$ ~1.78 ms). Although Rn is chemically unreactive, a proportion of any inhaled Rn gas is absorbed into the blood stream from the lungs, where it moves rapidly within the body. Barium (Ba) and Ca are commonly used chemical analogues of Ra in assessments.

The ICRP recommend a default lung absorption of Type M and a gut uptake factor of 0.2 for ingested Ra in adults (ICRP, 2017). The gut uptake factors for children and 3-month-old infants are 0.3 and 0.6, respectively (ICRP, 2024).

Hospitals use ^{223}Ra to treat prostate cancer that has metastasised to bones (NHS, 2026). As such, ^{223}Ra is routinely discharged in medical waste to wastewater environments.

10.1 Radium-223 concentration ratios and factors

10.1.1 Foodstuffs

A study from 1992 performed a detailed review and synthesis of Ra bioaccumulation data in marine organisms (Meinhold and Hamilton, 1992). Literature values were combined with site-specific field measurements from coastal Louisiana, USA. Concentration factors were reported and analysed for several organism groups relevant to human exposure. Using probabilistic analysis, the authors derived expected (mean) concentration factor values of ~30 for whole fish, ~40 for the edible, soft parts of molluscs, and ~86 for whole crustaceans. The upper confidence values provided in the report indicate substantial biological and environmental variability in the data.

The IRAT2 transfer factors for ^{223}Ra for pasture, green vegetables, and root vegetables are taken from the IAEA Handbook (IAEA, 2010). The concentration factor for fruit is the value from the FARMLAND module in PC-CREAM 08 (Ba analogue) (Brown and Simmonds, 1995).

The transfer factors to cow meat and milk in IRAT2 are taken from the IAEA Handbook (IAEA, 2010). The values for the transfer factors for cow offal (including liver), sheep meat, and sheep offal (including liver) are taken from PC-CREAM 08 (Ba analogue) FARMLAND module (Brown and Simmonds, 1995).

The IRAT2 concentration factors for ^{223}Ra for freshwater fish are taken from the IAEA Handbook (IAEA, 2010) and for marine foodstuffs are taken from the 2004 IAEA compilation (IAEA, 2004).

The current concentration factor values for terrestrial, freshwater fish, and marine foodstuffs in IRAT2 are given in the following two tables.

Table 79: Current ^{223}Ra concentration factors for terrestrial foods in IRAT2 (Environment Agency, 2022).

Terrestrial food stuff	Current plant: soil concentration ratio (Bq/kg plant wet weight per Bq/kg soil dry weight)	Current transfer factor (TF) pasture to animal product (Bq/kg wet muscle or liver or Bq/L per Bq/days intake)	Reference source
Pasture	3.90×10^{-2}	-	(IAEA, 2010)
Green vegetable	9.10×10^{-3}	-	(IAEA, 2010)
Root vegetable	1.40×10^{-2}	-	(IAEA, 2010)
Fruit	1.02×10^{-2}	-	(Brown and Simmonds, 1995), barium analogue
Sheep meat	-	5.00×10^{-3}	(Brown and Simmonds, 1995), barium analogue
Sheep offal (including liver)	-	5.00×10^{-3}	(Brown and Simmonds, 1995), barium analogue
Beef meat	-	1.70×10^{-3}	(IAEA, 2010)
Beef offal (including liver)	-	5.00×10^{-4}	(Brown and Simmonds, 1995), barium analogue
Cow's milk	-	3.80×10^{-4}	(IAEA, 2010)

Table 80: Current ^{223}Ra concentration factors for marine foods in IRAT2 (Environment Agency, 2022).

Foodstuff	Current concentration factor (L/kg)	Reference source
Freshwater fish	4	(IAEA, 2010)
Marine fish	100	(IAEA, 2004)
Marine crustacea	100	(IAEA, 2004)
Marine molluscs	100	(IAEA, 2004)

Of note, Ra translocation in plants is considered 'slow' (Smith and Simmonds, 2009).

No new data was found on Ra concentration factors in plants. A concentration factor for Ba in grass of 0.06 (dry weight) was reported in one study (Kowalska et al. 2012). Although this is slightly higher than the current value in IRAT2, the IRAT2 data is based on a comprehensive review. Hence, a revision to the IRAT2 value for Ra may not be justified on the basis of a single, new concentration factor value for a chemical analogue.

The use of different references for the transfer factor to beef meat and to liver in IRAT2 has resulted in different values, whereas the values are the same are in the FARMLAND module (Brown and Simmonds, 1995). Here, FARMLAND assumes that the transfer factor to liver is the same as to meat unless human data suggest otherwise. A beef liver concentration factor equal to that for beef meat may be considered in detailed assessments.

A study on bioaccumulation in minnows fed environmentally relevant levels of radium-226 (^{226}Ra) reported a maximum concentration factor of 2.489 from feed at 10 mBq/g (Shi et al., 2017). This is slightly different to the value of 4 in the IAEA Handbook that is used in IRAT2 (IAEA, 2010). The current IRAT2 values appear to be well founded. A beef liver concentration factor equal to that for beef meat could be considered in detailed assessments.

The transfer factor for beef offal in detailed assessments could potentially be updated so that it is, at a minimum, equal to the IAEA Handbook value for beef meat. This would address the current anomaly in the database where the transfer factor for offal is lower than that for meat, thus deviating from the baseline ratios established in the FARMLAND methodology.

10.1.2 Wildlife

For IRAT2, amended concentration ratios were calculated for ^{223}Ra and its progeny, ^{211}Pb, (half-life of ~36 mins), and used to calculate dose per unit concentration (DPUC) values for freshwater and marine reference organisms. This approach was taken due to the physical half-life of ^{223}Ra being relatively short compared to the biological half-life. Concentration ratios for stable elements are often conservative when used to represent radionuclides with relatively short half-lives and relatively long biological half-lives, as radioactive decay of these radionuclides can reduce their concentration in biota. To account for the relatively short physical half-life of ^{223}Ra, the concentration ratios for this radionuclide are typically multiplied by a scaling factor (K), which is defined as:

$$K = \frac{\lambda_b}{(\lambda_b + \lambda_r)}$$

where:
t_b = Biological half-life (days) (assumed to be 30 days for ^{223}Ra)

t_r = Radiological half-life (days)

λ_b = Biological decay constant (~0.693 t_b^{-1}; days^{-1})

λ_r = Radiological decay constant (~0.693 t_r^{-1}; days^{-1})

For ^{223}Ra, K is calculated as ~0.276.

The default concentration ratios from the ERICA tool (v.1.2.1) (Brown et al., 2016) were therefore multiplied by K to give amended concentration ratios for ^{223}Ra for freshwater and marine reference organisms. These amended concentration ratios were used in the ERICA tool (v.1.2.1) to derive DPUCs for wildlife in IRAT2. The concentration ratios for terrestrial reference organisms in the ERICA tool (v.1.2.1) were not amended.

A similar approach was taken for ^{211}Pb, progeny of ^{223}Ra (K = 8.35 x 10^{-4} for ^{211}Pb).

The ^{223}Ra concentration ratios for marine biota in IRAT2 (used to generate the DPUR values for reference organisms in IRAT2) are given in the table below.

Table 81: Current ^{223}Ra concentration ratios for marine biota in IRAT2 (amended values) (Environment Agency, 2022).

Marine reference organisms	Concentration ratio (L/kg)	Reference source*
Benthic fish	39.0	ERICA v.1.2.1
Bird	45.0	ERICA v.1.2.1
Crustacean	24.0	ERICA v.1.2.1

Marine reference organisms	Concentration ratio (L/kg)	Reference source*
Macro-algae	25.0	ERICA v.1.2.1
Mammal	45.0	ERICA v.1.2.1
Mollusc – bivalve	18.0	ERICA v.1.2.1
Pelagic fish	39.0	ERICA v.1.2.1
Phytoplankton	3.20×10^{2}	ERICA v.1.2.1
Polychaete worm	39.0	ERICA v.1.2.1
Reptile	45.0	ERICA v.1.2.1
Sea anemones and true coral	39.0	ERICA v.1.2.1
Vascular plant	25.0	ERICA v.1.2.1
Zooplankton	22.0	ERICA v.1.2.1

*There is a conversion factor for marine and freshwater concentrations for ^{223}Ra from the general Ra figure used in ERICA (version 1.2.1).

The ^{223}Ra concentration ratios for terrestrial and freshwater biota (described above) are summarised in the tables below.

Table 82: Current ^{223}Ra concentration ratios for terrestrial biota in IRAT2 (amended values) (Environment Agency, 2022).

Terrestrial reference organism	Concentration ratio (L/kg)	Reference source
Amphibian	4.40×10^{-2}	ERICA v.1.2.1
Annelid	4.30×10^{-2}	ERICA v.1.2.1
Arthropod – detritivorous	4.30×10^{-2}	ERICA v.1.2.1
Bird	3.60×10^{-2}	ERICA v.1.2.1

Terrestrial reference organism	Concentration ratio (L/kg)	Reference source
Flying insects	4.30×10^{-2}	ERICA v.1.2.1
Grasses and herbs	0.18	ERICA v.1.2.1
Lichen and bryophytes	0.71	ERICA v.1.2.1
Mammal – large	4.40×10^{-2}	ERICA v.1.2.1
Mammal – small, burrowing	4.40×10^{-2}	ERICA v.1.2.1
Mollusc – gastropod	4.80×10^{-2}	ERICA v.1.2.1
Reptile	4.40×10^{-2}	ERICA v.1.2.1
Shrub	0.33	ERICA v.1.2.1
Tree	1.20×10^{-2}	ERICA v.1.2.1

Table 83: Current ^{223}Ra concentration ratios for freshwater biota in IRAT2 (amended values) (Environment Agency, 2022).

Freshwater reference organism	Concentration ratio (L/kg)	Reference source
Amphibian	1.70×10^{3}	ERICA v.1.2.1
Benthic fish	50.0	ERICA v.1.2.1
Bird	1.70×10^{3}	ERICA v.1.2.1
Crustacean	74.0	ERICA v.1.2.1
Insect larvae	6.60×10^{3}	ERICA v.1.2.1
Mammal	5.80×10^{-2}	ERICA v.1.2.1
Mollusc – bivalve	6.60×10^{3}	ERICA v.1.2.1

Freshwater reference organism	Concentration ratio (L/kg)	Reference source
Mollusc – gastropod	6.60×10^3	ERICA v.1.2.1
Pelagic fish	50.0	ERICA v.1.2.1
Phytoplankton	1.50×10^2	ERICA v.1.2.1
Reptile	2.10×10^2	ERICA v.1.2.1
Vascular plant	3.00×10^2	ERICA v.1.2.1
Zooplankton	6.60×10^3	ERICA v.1.2.1

10.1.3 Review of Ra concentration ratios

There are no recent studies specific to ^{223}Ra available. However, there are several new studies that have been incorporated in the new version of ERICA (version 2.0), based on other isotopes of Ra (ERICA Consortium, 2021).

One study from 1992 presents extensive data on natural radionuclide concentrations in river water, sediments, aquatic vegetation, and fish across multiple French river systems (Lambrechts et al., 1992). The study reports a wide range of values for ^{226}Ra, reflecting substantial spatial, biological, and geochemical variability rather than a single representative concentration. Because these values span orders of magnitude and are context-dependent, reproducing/summarising them in a single table or average values, risks obscuring variability. It is therefore recommended that readers directly examine the Lambrechts et al., paper for their original environmental and methodological context.

ERICA (version 2.0) includes updated concentration ratios for Ra, reflecting revised treatment of short-lived radionuclides. Prior to the availability of these data, IRAT2 applied a scaling approach to ERICA (version 1.2.1) concentration ratios to account for the short physical half-life of ^{223}Ra (relative to its biological half-life). This resulted in the application of a reduction factor of ~0.3 to the ERICA (version 1.2.1) concentration ratios to represent non-equilibrium conditions. The same scaling approach has been applied in this project to the ERICA (version 2.0) concentration ratios to derive ^{223}Ra concentration ratios. The three tables below summarise these concentration ratio values.

Table 84: Radium-223 concentration ratios for marine biota, as identified in the literature review (amended values).

Marine reference organisms	Concentration ratio* (L/kg)	Reference source
Crustaceans	86	(IAEA, 2014)
Benthic fish	38.1	ERICA v.2
	94	(IAEA, 2014)
	8.6	(Antovic and Antovic, 2011), ^{226}Ra
	8-184	(Porntepkasemsan and Nevissi, 1990)
Bird	44.2	ERICA v.2, mammal, Sr
Crustacean	23.7	ERICA v.2
Macro-algae	46	ERICA v.2
	90	(IAEA, 2014)
	82	(Bonotto et al., 1981), brown algae (average)
	2×10^3	(Cherry and Shannon, 1974)
Mammal	44.2	ERICA v.2, mammal, Sr
Mollusc – bivalve	15.8	ERICA v.2
	67	(IAEA, 2014)
Pelagic fish	38.1	ERICA v.2
	8.6	(Antovic and Antovic, 2011), ^{226}Ra

Marine reference organisms	Concentration ratio* (L/kg)	Reference source
Phytoplankton	1.87×10^2	ERICA v.2
	1.1×10^3	(IAEA, 2014)
	2×10^3	(Cherry and Shannon, 1974)
Polychaete worm	1.30×10^2	ERICA v.2, crustacean, Ba
Reptile	44.2	ERICA v.2, mammal, Sr
Sea anemones and true coral	23.7	ERICA v.2, crustacean
Vascular plant	46.0	ERICA v.2, macroalgae
Zooplankton	8.31	ERICA v.2
	81	(IAEA, 2014)
	8.1	(Gomez et al., 1991)
	1×10^2	(Cherry and Shannon, 1974)

*Amended value to account for short half-life of ^{223}Ra.

Table 85: Radium-223 concentration ratios for terrestrial biota, as identified in the literature review (amended values).

Terrestrial reference organism	Concentration ratio (L/kg)	Reference source
Amphibian	0.20	ERICA v.2, reptile
Annelid	0.205	ERICA v.2, arthropod
Arthropod	3.2	(IAEA, 2014)

Terrestrial reference organism	Concentration ratio (L/kg)	Reference source
Arthropod – detritivorous	0.205	ERICA v.2
Bird	3.47×10^{-2}	ERICA v.2
	3.6×10^{-2}	(IAEA, 2014)
	3.6×10^{-2}	(Verkhovskaya, 1972)
Flying insects	5.31×10^{-2}	ERICA v.2
	<0.13	(Thørring et al., 2016), Apidae, ^{226}Ra
Grasses and herbs	0.166	ERICA v.2
	0.19	(IAEA, 2014)
	0.6	(Dowdall et al., 2005), Ra-226, calculated av.
	0.06	(Sheppard et al., 2008)
	0.23	(Sussa et al., 2013), aerial
	0.627	(Sussa et al., 2013), root
	3.0×10^{-2}	(Thørring et al., 2016)
Lichen and bryophytes	0.71	ERICA v.2
	1.7	(IAEA, 2014)
Mammal	8.93×10^{-2}	ERICA v.2
	4.7×10^{-2}	(IAEA, 2014)

Terrestrial reference organism	Concentration ratio (L/kg)	Reference source
Mollusc – gastropod	2.74×10^{-2}	ERICA v.2
	4.8×10^{-2}	(IAEA, 2014)
Reptile	0.20	ERICA v.2
Shrub	0.334	ERICA v.2
	1.0	(IAEA, 2014)
	5.3×10^{-2}	(Sheppard et al., 2008)
Tree	1.65×10^{-2}	ERICA v.2
	6.8×10^{-4}	(IAEA, 2014)
	0.04	(Sheppard et al., 2008), coniferous
	0.075	(Sheppard et al., 2008), deciduous
	6.3×10^{-2}	(Thørring et al., 2016) (AM)

Table 86: Radium-223 concentration ratios for freshwater biota, as identified in the literature review (amended values).

Freshwater reference organism	Concentration ratio* (L/kg)	Reference source
Amphibian	7.28×10^{2}	ERICA v.2, reptile
Benthic fish	2.87×10^{2}	ERICA v.2
	3.1×10^{2}	(IAEA, 2014)
	3.0×10^{3}	(Doering et al., 2019) (AM)

Freshwater reference organism	Concentration ratio* (L/kg)	Reference source
Bird	1.73×10^3	ERICA v.2
Crustacean	76.1	ERICA v.2
	2.7×10^2	(IAEA, 2014)
	180	(Martin et al., 1995), shrimp, (^{226}Ra)
Insect larvae	1.44×10^4	ERICA v.2, mollusc-bivalve
Mammal	5.86×10^{-2}	ERICA v.2
	0.21	(IAEA, 2014), herbivorous
Mollusc – bivalve	1.44×10^4	ERICA v.2
	2.4×10^4	(IAEA, 2014)
	5.6×10^4	(Doering et al., 2019) (AM)
Mollusc – gastropod	1.44×10^4	ERICA v.2, mollusc-bivalve
Pelagic fish	287	ERICA v.2
	3.0×10^3	(Doering et al., 2019) (AM)
Phytoplankton	1.43×10^2	ERICA v.2
	5.5×10^2	(IAEA, 2014)
Reptile	7.28×10^2	ERICA v.2
	8.0×10^2	(IAEA, 2014)
	5.3×10^3	(Doering et al., 2019) (AM)

Freshwater reference organism	Concentration ratio* (L/kg)	Reference source
Vascular plant	2.41×10^2	ERICA v.2
	2.2×10^3	(IAEA, 2014)
	5×10^2	(Doering et al., 2019) (AM)
Zooplankton	1.44×10^4	ERICA v.2, mollusc-bivalve

*Amended value to account for short half-life of ^{223}Ra.

Although IRAT2 does not use ERICA (version 2.0) concentration ratios directly, the Ra concentration ratios in ERICA (version 2.0) appear to have been updated using essentially the same conceptual basis. Consequently, the IRAT2 scaled version 1.2 values and ERICA (version 2.0) values are broadly consistent. Scaling could be factored into future updates to the software to ensure consistency, after confirming whether ERICA itself uses this scaling approach. If it does, then the scaling does not need to be applied.

10.2 Radium-223 distribution coefficients

10.2.1 Radium speciation

Radium is an alkaline earth metal and exists as Ra^{2+} in natural environments. The Ra^{2+} cation is highly basic and, like other Group 2 chemical elements, does not form strong complexes with inorganic, natural ligands (compared to many transition metal ions). The behaviour of Ra^2 is less sensitive to co-precipitation with calcite ($CaCO_3$) than the smaller alkaline earth metal cations, such as strontium (Sr^{2+}). This is due to the large ionic radius of Ra^{2+} that makes incorporation into the calcite crystal structure unfavourable. Barium is a useful analogue for Ra due to their similarities in both chemical properties and ionic radii.

10.2.2 Current Ra K_d values

IRAT2 includes element specific parameter K_d values for Ra. This is shown in the following table.

Table 87: Current ^{223}Ra K_d values in IRAT2 (Environment Agency, 2022).

Parameter	K_d (L/kg)	Basis
Marine	2×10^3	Recommended value for radium (Recommended value for Ra (Tröjbom, et al., 2013).
Freshwater	7.4×10^3	Partitioning of Ra to sediment, geometric mean of a large data set (n = 75) (IAEA, 2010), with the data ranging from 1.1×10^3 -5.2×10^4 L/kg (i.e., spanning two orders of magnitude).
Organic soil (basis for sewage sludge/effluent partitioning)	1.3×10^3	Radium specific K_d value of 1.3×10^3 L/kg is provided by IAEA for organic soil (IAEA, 2010). This is the average of the 2 values (200 and 2.4×10^3 L/kg).

10.2.3 Review of Ra K_d parameters

Some K_d values for Ra have been identified in recent work, including systematic K_d compilations. Kemnitz et al. reported experimentally determined distribution coefficients for Ra (based on Ra-228) associated with five sediment cores from the Northeast Pacific (Kemnitz et al., 2023). Radium K_d values ranged from 1×10^3-3×10^3 L/kg, in excellent agreement with the current marine K_d value for Ra used in IRAT2 (2×10^3 L/kg).

Beck and Cochran investigated controls on the partitioning of Ra in saturated marine sands (Beck and Cochran, 2013). A strong correlation was found between the Ra distribution coefficient with surface area for size-fractionated sediments and Ra adsorption showed no direct relationship to the solid-phase Fe or Mn content of the sands. Removal of surficial oxide coatings with dilute acid reduced the K_d by a factor of 2-3. Synthetic Fe-oxides (representing Fe mineral phases) showed ~2 orders of magnitude difference in Ra adsorption, ranging from 1535 ± 410 L/kg (for ferrihydrite) to 20 ± 8 L/kg (for goethite).

Boyer et al. published a review of terrestrial data that included Ra (Boyer et al., 2018). The 'enhanced' K_d dataset showed that K_d values for suspended sediments are significantly higher than for deposited sediments. Moreover, the variability of K_d distributions was higher for deposited sediments than suspended sediments. In the case of Ra associated with suspended sediment, K_d values had a geometric mean of 1.18×10^4 (range 6.3×10^3-2.42×10^4, n = 9) L/kg and deposited sediments had a geometric mean of 1.2×10^3 (range 82-1.67×10^5, n = 5) L/kg (measured in field studies) and a geometric mean of 8.18×10^3 (range 5.63×10^3-2.42×10^4, n = 10) (measured experimentally). These suspended sediment values are higher than the current IRAT2 parameter value of 7.4×10^3 L/kg (by more than an order of magnitude). In contrast, the deposited sediment K_d values are in good agreement (i.e., the same order of magnitude).

A study of the behaviour of anthropogenic radionuclides in a river system identified apparent K_d values for Ba (anthropogenic barium-133 was used as an analogue for Ra) (Juranová, et al., 2020). The values ranged from 570 (160-1.3 x 10^3) L/kg (river bottom sediment, n = 15) to 1.4 x 10^4 (3.7 x 10^3-7.5 x 10^4) L/kg (suspended solids, n = 15). The reported value for bottom sediment is lower than the current IRAT2 parameter value of 7.5 x 10^3 L/kg for Ra (by more than an order of magnitude), whilst that measured for suspended sediment is almost double.

Biosphere studies commissioned to support a recently published safety case for geological disposal provide useful comparative values for Ra (Tröjbom, et al., 2013). The authors proposed K_d values of 2.01 x 10^3 L/kg (river and lake) and 1.02 x 10^4 L/kg (sea) for suspended solids. Of note, the river/lake and sea values are the same order of magnitude as the analogous 7.4 x 10^3 L/kg and 2 x10^3 L/kg parameter values provided in IRAT2.

Overall, the current IRAT2 parameters for Ra are element specific and appear to be in reasonable agreement with recent published data.

10.3 Summary of radium-223 review

The review of parameter values for ^{223}Ra is summarised in the following table.

Table 88: Key literature findings for ^{223}Ra transfer parameters.

Parameter	Review findings for ^{223}Ra
K_d	Current values are in reasonable agreement with recent data.
Terrestrial food chain	Beef liver could potentially be updated to be the same as the IAEA Handbook value for beef meat.
Marine food chain	No new data found.
Wildlife	Concentration ratios have been amended to account for the short physical half-life of ^{223}Ra. ERICA (version 2.0) has updated concentration ratio values.

11 Actinium-225

Actinium-225 (^{225}Ac) has a half-life of ~10 days and undergoes alpha decay to form francium-221 (Wilson, 1996). Actinium-225 has medical applications in cancer therapy, where ^{225}Ac-PSMA-617 has recently been developed as a radiopharmaceutical. Actinium-225 could potentially be used in the therapy of various illnesses, including brain tumours, bladder cancer, neuroendocrine tumours, and leukaemia (Rahman et al., 2024).

ICRP Publication 141 applies a generic actinide biokinetic model, with some element-specific parameter values (ICRP, 2019). Little Ac data was found, so americium (Am) absorption data was used. ICRP Publication 141 recommends the use of specific analogues such as Am when data is not available for ^{225}Ac. The main sites of deposition of absorbed or injected Ac activity in humans are bone surfaces and liver (ICRP, 2019). Default Type M absorption is used for inhaled Ac and the gut uptake factor for ingested material is 5×10^{-4}.

11.1 Actinium-225 concentration ratios and factors

11.1.1 Foodstuffs

The current concentration ratios for soil, vegetables, and fruit and the transfer factors for animal products in IRAT2 are based on data from the FARMLAND module of PC-CREAM 08 (Smith and Simmonds, 2009). The concentration factors for freshwater and marine fish are based on IAEA Safety Report 19 (IAEA, 2001), and IAEA Technical Report 422 respectively (IAEA, 2004). The Ac concentration ratios and transfer factor values for terrestrial and marine foodstuffs are summarised in the two tables below.

Table 89: Current ^{225}Ac concentration ratios and transfer factors for terrestrial foodstuffs in IRAT2 (Environment Agency, 2022).

Terrestrial food stuff	Current plant: soil concentration ratio (Bq/kg plant wet weight per Bq/kg soil dry weight)	Current transfer factor (TF) pasture to animal product) Bq/kg wet muscle or liver or Bq/L per Bq/d intake)	Reference source
Pasture	1.00×10^{-3}	-	(Brown and Simmonds, 1995)

Terrestrial food stuff	Current plant: soil concentration ratio (Bq/kg plant wet weight per Bq/kg soil dry weight)	Current transfer factor (TF) pasture to animal product) Bq/kg wet muscle or liver or Bq/L per Bq/d intake)	Reference source
Green vegetable	1.00×10^{-3}	-	(Brown and Simmonds, 1995)
Root vegetable	1.00×10^{-3}	-	(Brown and Simmonds, 1995)
Fruit	1.00×10^{-3}	-	(Brown and Simmonds, 1995)
Sheep meat	-	1.00×10^{-3}	(Brown and Simmonds, 1995)
Sheep offal	-	10.0	(Brown and Simmonds, 1995)
Beef meat	-	1.00×10^{-4}	(Brown and Simmonds, 1995)
Beef offal	-	2.00×10^{-2}	(Brown and Simmonds, 1995)
Cow's milk	-	3.00×10^{-6}	(Brown and Simmonds, 1995)

Table 90: Current ^{225}Ac concentration factors for aquatic foodstuffs in IRAT2 (Environment Agency, 2022).

Foodstuff	Current concentration factor (L/kg)	Reference source
Freshwater fish	15	(IAEA, 2001), Sm analogue
Marine fish	50	(IAEA, 2004)

Foodstuff	Current concentration factor (L/kg)	Reference source
Marine crustacea	1×10^3	(IAEA, 2004)
Marine molluscs	1×10^3	(IAEA, 2004)

No recently published studies were identified with specific reference to ^{225}Ac.

There are no recent studies on Ac available, however analogue data was obtained. ERICA (version 2.0) uses a mix of Am, thorium (Th), and Pu. ICRP guidance recommends using Am as the primary biological and environmental analogue for Ac when radionuclide specific data is unavailable (ICRP, 2019).

11.1.2 Wildlife

The current parameter values in IRAT2 for reference organisms are based on data which is in ERICA (version 1.2.1) (Brown et al., 2016). This information is summarised in the three tables below.

Table 91: Current ^{225}Ac concentration ratios for fish and marine biota in IRAT2 (Environment Agency, 2022).

Marine reference organisms	Concentration ratio (L/kg)	Reference source
Benthic fish	1.30×10^3	ERICA v.1.2.1, Th analogue
Bird	1.70×10^3	ERICA v.1.2.1, Th analogue
Crustacean	3.80×10^4	ERICA v.1.2.1, Th analogue
Macro-algae	4.60×10^3	ERICA v.1.2.1, Th analogue
Mammal	1.70×10^3	ERICA v.1.2.1, Th analogue
Mollusc – bivalve	1.70×10^3	ERICA v.1.2.1, Th analogue
Pelagic fish	1.30×10^3	ERICA v.1.2.1, Th analogue
Phytoplankton	7.30×10^5	ERICA v.1.2.1, Th analogue

Marine reference organisms	Concentration ratio (L/kg)	Reference source
Polychaete worm	1.70×10^{3}	ERICA v.1.2.1, Th analogue
Reptile	1.70×10^{3}	ERICA v.1.2.1, Th analogue
Sea anemones and true coral	1.70×10^{3}	ERICA v.1.2.1, Th analogue
Vascular plant	4.60×10^{3}	ERICA v.1.2.1, Th analogue
Zooplankton	7.20×10^{3}	ERICA v.1.2.1, Th analogue

Table 92: Current ^{225}Ac concentration ratios for terrestrial biota in IRAT2 (Environment Agency, 2022).

Terrestrial reference organism	Concentration ratio (L/kg)	Reference source
Amphibian	3.90×10^{-4}	ERICA v.1.2.1
Annelid	9.20×10^{-3}	ERICA v.1.2.1
Arthropod - detritivores	5.10×10^{-3}	ERICA v.1.2.1
Bird	3.90×10^{-4}	ERICA v.1.2.1
Flying insects	5.10×10^{-3}	ERICA v.1.2.1
Grasses and herbs	0.16	ERICA v.1.2.1
Lichen and bryophytes	0.38	ERICA v.1.2.1
Mammal – large	1.40×10^{-4}	ERICA v.1.2.1
Mammal – small, burrowing	1.40×10^{-4}	ERICA v.1.2.1
Mollusc – gastropod	9.20×10^{-3}	ERICA v.1.2.1
Reptile	2.20×10^{-3}	ERICA v.1.2.1

Terrestrial reference organism	Concentration ratio (L/kg)	Reference source
Shrub	6.10×10^{-2}	ERICA v.1.2.1
Tree	1.30×10^{-3}	ERICA v.1.2.1

Table 93: Current ^{225}Ac concentration ratios for freshwater biota in IRAT2 (Environment Agency, 2022).

Freshwater reference organism	Concentration ratio (L/kg)	Reference source
Amphibian	3.20×10^{3}	ERICA v.1.2.1
Benthic fish	7.10×10^{2}	ERICA v.1.2.1
Bird	3.20×10^{3}	ERICA v.1.2.1
Crustacean	6.00×10^{2}	ERICA v.1.2.1
Insect larvae	2.50×10^{3}	ERICA v.1.2.1
Mammal	3.20×10^{3}	ERICA v.1.2.1
Mollusc – bivalve	1.00×10^{4}	ERICA v.1.2.1
Mollusc – gastropod	1.00×10^{4}	ERICA v.1.2.1
Pelagic fish	7.10×10^{2}	ERICA v.1.2.1
Phytoplankton	1.20×10^{4}	ERICA v.1.2.1
Reptile	1.00×10^{3}	ERICA v.1.2.1
Vascular plant	9.80×10^{4}	ERICA v.1.2.1
Zooplankton	5.40×10^{2}	ERICA v.1.2.1

No recently published studies were identified with specific reference to ^{225}Ac. However, new values have been adopted in ERICA (version 2.0) based on different analogue radionuclides (ERICA Consortium); Th for concentration factors and Sm for the distribution coefficient in freshwater environments.

Several analogues have been used in ERICA (version 2.0), depending on the available data and reference organism. It should be established whether any of these analogues would be suitable for deriving Ac concentration factors or transfer factors for foodstuffs.

There are no recent studies relevant to ^{225}Ac available. However, the concentration ratios for biota have been updated in the new version of ERICA, using various analogues. It may be useful to further examine these data and to evaluate their usefulness. Updated values for marine, terrestrial, and freshwater biota are summarised in the three tables below.

Table 94: Actinium-225 concentration ratios for marine biota, as identified in the literature review.

Marine reference organisms	Concentration ratio (L/kg)	Reference source
Benthic fish	1.37×10^{3}	ERICA v.2, Pu analogue
Bird	1.24×10^{3}	ERICA v.2, Pu analogue, mammal
Crustacean	7.40×10^{2}	ERICA v.2, Th analogue, crustacean
Macro-algae	1.22×10^{4}	ERICA v.2, curium (Cm) analogue
Mammal	1.24×10^{3}	ERICA v.2, Pu analogue
Mollusc (bivalve)	7.33×10^{2}	ERICA v.2, Th analogue, derived
Pelagic fish	1.37×10^{3}	ERICA v.2, Pu analogue
Phytoplankton	7.24×10^{5}	ERICA v.2, Th analogue
Polychaete worm	9.91×10^{2}	ERICA v.2, Th analogue, derived
Reptile	1.24×10^{3}	ERICA v.2, Pu analogue, mammal

Marine reference organisms	Concentration ratio (L/kg)	Reference source
Sea anemones and true coral	9.84×10^{2}	ERICA v.2, U analogue
Vascular plant	1.22×10^{4}	ERICA v.2, Cm analogue, macroalgae
Zooplankton	7.04×10^{3}	ERICA v.2, Th analogue

Table 95: Actinium-225 concentration ratios for terrestrial biota, as identified in the literature review.

Terrestrial reference organism	Concentration ratio (L/kg)	Reference source
Amphibian	9.82×10^{-2}	ERICA v.2, Am analogue
Annelid	0.123	ERICA v.2, Am analogue
Arthropod – detritivorous	0.137	ERICA v.2, Cm analogue, derived
Bird	2.83×10^{-2}	ERICA v.2 Am analogue, derived
Flying insects	0.114	ERICA v.2, Am analogue
Grasses and herbs	0.150	ERICA v.2, uranium analogue
Lichen and bryophytes	1.20	ERICA v.2, Am analogue
Mammal	0.274	ERICA v.2, Am analogue
Mollusc – gastropod	0.158	ERICA v.2, Am analogue

Terrestrial reference organism	Concentration ratio (L/kg)	Reference source
Reptile	6.60×10^{-2}	ERICA v.2, Am analogue
Shrub	5.99×10^{-2}	ERICA v.2, U analogue
Tree	9.35×10^{-3}	ERICA v.2, Cm analogue

Table 96: Actinium-225 concentration ratios for freshwater biota, as identified in the literature review.

Freshwater reference organism	Concentration ratio (L/kg)	Reference source
Amphibian	4.79×10^{3}	ERICA v.2, Pu analogue, derived
Benthic fish	1.13×10^{3}	ERICA v.2, Pu analogue
Bird	2.91×10^{3}	ERICA v.2, Pu analogue
Crustacean	3.35×10^{4}	ERICA v.2, mollusc-bivalve, Am analogue
Insect larvae	3.35×10^{4}	ERICA v.2, mollusc-bivalve, Am analogue
Mammal	4.79×10^{3}	ERICA v.2, reptile, derived, Pu analogue
Mollusc – bivalve	3.35×10^{4}	ERICA v.2, Am analogue

Freshwater reference organism	Concentration ratio (L/kg)	Reference source
Mollusc – gastropod	1.67×10^4	ERICA v.2, Pu analogue
Pelagic fish	1.13×10^3	ERICA v.2, Pu analogue
Phytoplankton	1.19×10^4	ERICA v.2, Th analogue
Reptile	4.79×10^3	ERICA v.2, derived, Pu analogue
Vascular plant	4.44×10^4	ERICA v.2, Th analogue
Zooplankton	3.35×10^4	ERICA v.2, mollusc-bivalve, Am analogue

11.2 Actinium-225 distribution coefficients

Distribution coefficient values for ^{225}Ac are discussed in the following sections, noting that IRAT2 currently includes element-specific K_d values for marine and analogue data (based on Sm) for freshwater systems (Environment Agency, 2022).

11.2.1 Actinium speciation

Actinium is an actinide element and predominantly exists in the trivalent (+3) oxidation state in environmental systems. Actinium and the lanthanide elements have similar chemical properties, and the latter are often used as ^{225}Ac analogues when Ac specific data is absent. Other predominantly trivalent actinides (i.e., Am and Cm) can also be considered as potential analogues for Ac. It is also worth consulting IRAT2 for the specific contexts in which a certain analogue is most suitable (Environment Agency, 2022).

11.2.2 Current ^{225}Ac K_d values

IRAT2 includes the following parameter values for Ac (marine) and Sm (as an analogue; freshwater). An organic soil K_d value is also provided. These data are summarised in the table below.

Table 97: Current ^{225}Ac K_d values in IRAT2 (Environment Agency, 2022).

Parameter	K_d (L/kg)	Basis
Marine	2×10^6	Ac specific value (Tröjbom et al., 2013).
Freshwater	9×10^4	Sm K_d values for lake particulate matter, with a reported range of 1.5×10^4-5.6×10^5 L/kg (Kemnitz et al., 2023).
Organic soil (basis for sewage sludge/effluent partitioning)	5.4×10^3	Actinium specific K_d value of 5.4×10^3 L/kg for organic soil was provided by the IAEA (Table 14 in IAEA, 2010). This was a single point datum value.

11.2.3 Review of ^{225}Ac K_d parameters

Some recent data for Ac (and/or useful analogue elements) have been identified in recent work, including systematic K_d compilations. Kemnitz et al. determined multiple K_d values for actinium-227 associated with five sediment cores from the Northeast Pacific (Kemnitz, et al., 2023). These data may be the first reported marine K_d measurements for Ac. Measured K_d values for Ac ranged from $3.5 \times 10^3 – 2.2 \times 10^4$ L/kg. This range is two magnitudes lower than the current marine K_d value used for Ac in IRAT2 (2×10^6 L/kg).

Boyer et al. reviewed terrestrial data that includes Am (a possible analogue for Ac) (Boyer et al., 2018). As noted in Section 10, the metal ion K_d values for suspended sediments were significantly higher than for deposited sediments. In addition, the variability of K_d distributions was higher for deposited than for suspended sediments. In the case of Am, suspended sediment K_d values had a geometric mean of 2.2×10^5 (range 2.7×10^4-2.25×10^6; n = 88) L/kg, as measured experimentally in desorption experiments. A geometric mean of 7.9×10^4 L/kg (range 1.1×10^3-1.31×10^6; n = 44), was derived from field study data. These suspended sediment values are lower than the current IRAT2 parameter value for Ac of 2×10^6 L/kg (by one to four orders of magnitude). As an alternative analogue to Am, one of the lanthanide elements reported by Boyer et al. could be considered (Boyer et al., 2018). This publication was discussed in Section 8.1.7.

A study of the behaviour of anthropogenic radionuclides in a river system identified apparent K_d values for Am (Juranová, et al., 2020). These ranged from 2.7×10^3 (210-1.9×10^4) L/kg (river bottom sediment, n = 10) to 1.1×10^6 ($1 \times 10^5 – 7.9 \times 10^6$) L/kg (suspended solids, n = 15). The reported value for bottom sediment is lower than the current IRAT2 parameter value of 9.1×10^4 L/kg (by a factor of 33). In contrast, the measured value for suspended sediment is higher than the IRAT2 value by a factor of 12.

Biosphere studies undertaken to support a recently published safety case for geological disposal provide valuable comparative values for Ac (Hjerpe, 2021). The authors offered values of 1.56 x 10^4 L/kg (river and lake) and 1.383 x 10^6 L/kg (sea) for suspended solids. Of note, the river/lake and sea values are the same order of magnitude as the analogous 9.1 x 10^4 L/kg and 2 x 10^6 L/kg parameter values provided in IRAT2.

11.2.4 Recommendations for ^{225}Ac K_d values

The current IRAT2 parameter values for ^{225}Ac are element-specific or based on analogue element data (e.g., Sm in the case of the freshwater K_d). Recent data for other analogue elements including Am and other lanthanides are useful for comparison (e.g., for terrestrial K_d values). Given a lack of inclusion of Sm freshwater K_d values in the analysis reported in Boyer et al. (due to limitations in data quality for Sm), alternative lanthanide elements, or Am, could be considered as potential analogues (Boyer et al., 2018).

Recently published marine K_d values for ^{225}Ac are significantly lower than the currently adopted value in IRAT2 (Kemnitz et al., 2023). One option is to reduce the IRAT2 value by at least a factor of 10 (if conservatism needs to be reserved). Alternatively, the value could be reduced further to be more consistent with the latest experimental data. Consideration of the environmental conditions is likely required when making such a decision.

11.3 Summary of actinium-225 review

The review of parameter values for ^{225}Ac is summarised in the following table.

Table 98: key literature findings for ^{225}Ac transfer parameters.

Parameter	Review findings for Ac-225
K_d	Other elements could be considered for use as analogues to derive a new freshwater K_d. A reduction of the marine K_d value may be considered to align with more recent experimental data.
Terrestrial food chain	Other elements could be considered for use as analogues.
Marine food chain	Other elements could be considered for use as analogues.
Wildlife	Updated values have been identified in ERICA (version 2.0).

12 Conclusions and recommendations

A comprehensive review of the recent scientific literature and international databases has been conducted to examine environmental transfer parameter information for ten radionuclides (^{3}H, ^{14}C, ^{129}I, ^{32}P, ^{86}Y, ^{177}Lu, ^{186}Re, ^{188}Re, ^{223}Ra, and ^{225}Ac). For several of these radionuclides (but not all), the review identified scientifically robust and modern datasets that could potentially be used in IRAT2 and related radiological assessments:

- A consistent finding across most of the reviewed radionuclides is that the recently released ERICA (version 2.0) database provides updated and reliable concentration ratio parameter values for wildlife assessments.

- The IAEA has collated extensive and modern ^{129}I data, supporting possible updates for the soil-to-plant concentration factors for pasture, green vegetables, and root vegetables. These values may more accurately reflect the temperate UK climate than some of the currently used IRAT2 concentration factor values.

- This project identified several instances where current IRAT2 values for animal foodstuffs diverge from the FARMLAND model's methodology. Opportunities have been highlighted where transfer factors might be altered for meat, liver, and offal for ^{32}P, ^{129}I, ^{177}Lu, and ^{223}Ra to ensure physiological baselines are consistent and up to date. Such changes could potentially be treated as structural database corrections.

Despite an extensive literature search, element-specific transfer parameter data remains sparse or entirely absent for several radionuclides. This is particularly the case for novel medical use radionuclides. Notable examples from this literature review project include:

- No new ^{32}P concentration factors for transfer to terrestrial foodstuffs were identified in the recent literature. Assessments may need to rely on historical data.

- No new data could be found for Re in either the terrestrial or marine food chains. Current K_d values are based on extremely limited empirical data. While Tc is often used as an analogue for Re, its suitability is highly limited in reducing environments. This is because Tc frequently reduces to the immobile Tc(IV) form under reducing conditions, whereas Re can exist in higher (and more mobile) oxidation states.

- No updated ^{86}Y or ^{177}Lu concentration factors were identified for transfer to the marine food chain. Both radionuclides lack element-specific K_d data in the published literature. Hence, the continued use of analogues (such as Ce) may be required.

- Element-specific environmental data for ^{225}Ac is limited. Radiological assessments may need to rely heavily on analogues (such as Am or lanthanide elements) for K_d values and food chain transfer parameters.

Overall, the literature review has identified many instances where new or updated transfer parameter data may become valuable additions to the IRAT2 model. Some of these data were derived from locations and climates that are diverge from typical UK conditions. Care is therefore needed when utilising such data for IRAT2 and similar UK assessments. In addition, there are several instances where data on unfamiliar radionuclides is limited or effectively absent from the published literature. These identified knowledge and evidence gaps have implications for the continued use and development of environmental dose assessment tools. The following recommendations for further research are proposed here that are intended to aid and potentially enhance those radiological assessments:

- Further investigate the disparities identified between freshwater, terrestrial, and marine K_d values for ^{3}H and ^{14}C. For ^{3}H, the terrestrial value relies on an unverified 1984 proprietary report and therefore warrants clarification. For ^{14}C, current IRAT2 values appear to be orders of magnitude higher than recent IAEA recommendations and this disparity may justify further examination.

- Some of the radionuclides examined in this project have short physical half-lives relative to their biological half-lives (e.g., ^{186}Re, ^{188}Re, and ^{223}Ra). Modified radionuclide concentration ratios that account for radioactive decay within the organism could be systematically applied to prevent overestimating wildlife doses.

- The Environment Agency could consider commissioning field monitoring and/or laboratory studies to generate new datasets for those radionuclides for which there is currently a lack of element-specific transfer parameter data. A specific example of further research are 2 experimental studies for ^{177}Lu that are being published concurrently with this review. These studies focussed on ^{177}Lu in wastewater environments and were designed to address key uncertainties identified here.

Finally, this project has demonstrated that the published scientific literature can offer meaningful updates to existing radionuclide transfer parameter data. It may therefore be pragmatic to re-examine the literature at appropriate intervals to check for further updates. This may be especially beneficial for those novel use medical radionuclides for which little information was found in this research project. It is reasonable to assume that new studies and data will emerge in the literature as these radionuclides become more established. Such an approach may help reduce the current reliance of analogues for environmental dose assessments involving novel or less commonly encountered radionuclides.

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List of abbreviations and acronyms

Term	Definition
AM	Arithmetic mean
BAT	Best available technique(s)
DIC	Dissolved inorganic carbon
DOC	Dissolved organic carbon
DOTATATE	Dodecanetetraacetic acid-tyrosine-3-octreotate
DPUC	Dose per unit concentration
DPUR	Dose per unit release
dw	Dry weight
ERICA	Environmental Risk from Ionising Contaminants: Assessment and Management
ERICA v.1.2.1	ERICA version 1.2.1
ERICA v.2	ERICA version 2.0
F	Gaseous uptake factor
FARMLAND	Food activity from radionuclide movement on land
fw	fresh weight
GM	Geometric mean
HTO	Tritiated water
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection

Term	Definition
IRAT2	Initial radiological assessment tool, version 2
IRSN	Institut de Radioprotection et de Sûréte Nucléaire i.e., (French) Institute for Radiation Protection and Nuclear Safety
K_d	Distribution coefficient
OBT	Organically bound tritium
PC-CREAM 08	(Computer based) Consequences of Releases to the Environment: Assessment Methodology. 08 Denotes the year of the last update, 2008.
POC	Particulate organic carbon
SKB	Svensk Kärnbränslehantering AB (Swedish Nuclear Fuel and Waste Management Company)
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
WTD	Wildlife transfer database

Glossary

Term	Definition
Absorption	The uptake of one substance (e.g., a radionuclide) into the interior of another substance (e.g., skin).
Adsorption	The adhesion of a substance (e.g., a radionuclide) onto the surface of another material, the adsorbent (e.g., a mineral surface).
Aerobic	A biological process that occurs in the presence of oxygen.
Anaerobic	A biological process that occurs in the absence of oxygen.
Anoxic	An environment where dissolved oxygen is absent e.g., in soil.
Biological half-life	The time required for the body to reduce the concentration of a radioactive substance by 50% through natural processes (e.g., by excretion).
BIOPROTA	An international and collaborative forum that seeks to address uncertainties surrounding the long-term impacts of radioactive waste disposal on people and wildlife.
Concentration factor	The ratio of the activity concentration of a radionuclide in an organism to that activity concentration in water or soil, often used in the context of human consumption.
Concentration ratio	The ratio of the concentration of a radionuclide within the whole body of an organism to the concentration of the same radionuclide in an environmental media (e.g., soil, water or air).
Distribution coefficient, K_d	The ratio of the radionuclide concentration in a solid phase (e.g., sediment) to that in a liquid (e.g., water).
Dose per unit concentration	The radiation dose rate received by a reference organism or person resulting from a unit concentration of a radionuclide in an environmental medium (such as air, water, soil).

Term	Definition
Dose per unit release	The calculated dose received by a representative person or reference organism per unit discharge of a radionuclide.
DOTATATE	A chelating agent with the chemical formula $C_{65}H_{90}N_{14}O_{19}S_2$ that is commonly used in nuclear medicine. DOTATATE binds to medical radionuclides such as ^{177}Lu, forming a chemical complex.
ERICA	A software system for assessing the radiological risk to non-human (terrestrial, freshwater and marine) biota from ionising radiation in the environment.
FARMLAND	A model for simulating radionuclide transfer through different parts of the food chain.
Gaseous uptake factor	A transfer parameter that describes the deposition of radionuclide gases into plants.
IAEA Handbook	A log of parameter values for the prediction of radionuclide transfer in terrestrial and freshwater environments. The most recent publication is TRS 472.
IRAT2	An Environment Agency screening tool. Used to initially assess the radiological doses to people and wildlife from proposed radioactive waste discharges to the environment.
Oxic	An environment where dissolved oxygen is present e.g., in soil.
PC-CREAM 08	Software tool used to assess the radiological impact of routine discharges of radioactive material into the environment.
Radioactive decay	The process where radionuclides emit ionising radiation to reach a more stable state. Ionising radiation can take the form of alpha (α), beta (β), neutron (n), gamma (γ) radiation.
Radiological half-life	The time required for half of the radionuclides in a sample to undergo radioactive decay.

Term	Definition
Radionuclide	An unstable atom that spontaneously undergoes radioactive decay and emits ionising radiation.
Specific activity	The radioactivity of a radionuclide per unit mass of that radionuclide.
Type F materials:	Deposited materials that are readily absorbed into blood from the respiratory tract (fast rate of absorption).
Type M materials	Deposited materials that have intermediate rates of absorption into blood from the respiratory tract (moderate rate of absorption).
Type S materials	Deposited materials that are relatively insoluble in the respiratory tract (slow rate of absorption).
Type V materials	Type V materials: Deposited materials that, for dosimetry purposes, are assumed to be instantaneously absorbed into body fluids from the respiratory tract; this only applies to certain gases and vapours (extremely fast absorption).

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