FASSET

Framework for Assessment of Environmental Impact

Deliverable 1

Identification of candidate reference organisms from a radiation exposure pathways perspective

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Edited by

Per Strand, NRPA; Nick Beresford, CEH; Rodolfo Avila, SSI;
Steve R. Jones, WSC and Carl-Magnus Larsson, SSI

A project within the EC 5th Framework Programme

Contributors

A. Agüero, CIEMAT; C.L. Barnett, CEH; J. Brown, NRPA; M. Gilek, SU; B.J. Howard, CEH; E. Ilus, STUK; U. Kautsky, SKB; L. Kumblad, SU; B. Naeslund, SU; D. Patton, WSC; B. Robles, CIEMAT; A.L. Sanchez, CEH; R. Saxén, STUK; H. Stensrud, NRPA; A. Suañez, CIEMAT; S.M. Wright, CEH

A project within the EC 5th Framework Programme

FASSET will bring to radiation protection a framework for the assessment of environmental impacts of ionising radiation. The framework will link together current knowledge about sources, exposure, dosimetry and environmental effects/consequences for reference organisms and ecosystems. Relevant components of the framework will be identified on an ecosystem basis through systematic consideration of the available data. The application of the framework in assessment situations will be described in an overall report from the project. The project started in November 2000 and is to end by October 2003.

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Norwegian Radiation Protection Authority	NRPA

Assistant Contractors:

Kemakta Konsult AB, Sweden	Kemakta
Stockholm University, Sweden	SU
Centre for Ecology and Hydrology, UK	CEH
Westlakes Scientific Consulting Ltd, UK	WSC
Centre for Environment, Fisheries and Aquaculture Sciences, UK	CEFAS
University of Reading, UK	UR
Institut de Protection et de Sûreté Nucléaire, France	IPSN

Executive summary

Traditionally, radiological protection has focused on the protection of man. The limitation to human health protection is being increasingly questioned and the requirement for an internationally agreed rationale for the protection of the environment to ionizing radiation has been recognized. The overall aim of the FASSET project is to develop a framework within which assessment models can be applied and results analyzed for European ecosystems.

One of the objectives to be met in achieving this aim is: to identify a set of *reference organisms* relevant to different exposure situations. The identification of reference organisms must take into account the environmental fate of radionuclides, exposure pathways, ecological relevance, dosimetry and biological effects.

In this report, resulting from the work within FASSET Work Package 2, environmental compartments where radionuclides can be expected to accumulate and organisms for which enhanced exposure (both external and internal) is likely to occur have been identified. To aid this, a range of different European ecosystems has been considered, namely, forests, semi-natural pastures and heathlands, agricultural ecosystems, wetlands, freshwaters and marine and brackish waters. Compilation of relevant data on the distribution of radionuclides within these ecosystems has been undertaken.

Candidate reference organisms are suggested, based primarily on radioecological criteria (i.e. those organisms which are likely to be the most exposed). To reflect the behaviour of different radionuclides, and conditions of chronic or acute exposure, candidate reference organisms for the soil, canopy and herbaceous layer of the terrestrial ecosystems have been suggested. For aquatic ecosystems candidate reference organisms have been suggested for both benthic (associated with bed sediments) and pelagic foodchains (associated with the water column). In conditions of chronic exposure organisms most likely to be the most exposed are those in closest contact with soil or sediments.

The approach taken towards the selection of these should ensure that suitable reference organisms are available for a range of scenarios (chronic and acute exposure) and different European ecosystems. In total 31 candidate reference organisms have been suggested representing marine, freshwater and a variety of terrestrial ecosystems. These candidate reference organisms will now be used as basis for the development of dosimetric models (FASSET Work Package 1) and will be assessed against radiosensitivity and ecological criteria (FASSET Work Package 3) to select a final set of reference organisms reflecting the different criteria for selection being used within the FASSET project (FASSET Work Package 4).

Background ecosystem information to the selection of reference organisms are provided in two separate appendices to this report, on terrestrial and aquatic ecosystems.

Complete documentation on the FASSET project can be found on the website, www.fasset.org.

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1. Background

The overall aim of the FASSET project (for full documentation, see the project website, www.fasset.org) is to develop a framework for assessment of the impact on non-human biota of a radioactive contamination of the environment with a focus on European ecosystems. The outcome of the assessment should make it possible to address topics such as impacts on sustainability, conservation and biodiversity by taking into account consequences at the individual level.

Development of an environment protection framework within FASSET will require a number of components [Strand & Larsson, 2001], including:

- a set of reference organisms;
- a set of selection criteria for identifying reference organisms, based on:
    - radioecological sensitivity
    - ecological relevance
    - availability of dose-effects relationships;
- a set of quantities and units to express dose to biota. Currently, doses are expressed in units of Grays per unit time excluding a measurement of the different magnitudes of biological effect that can result from exposure to equal absorbed doses arising from different radiation types (i.e. there is not the equivalent of the sievert as used in human dosimetry);
- a defined set of internal and external dose models.

A special feature of the approach taken within FASSET is the focus on reference organisms. The approach is analogous to *reference man* approach and has been adopted within radiological protection to provide a standard set of models and datasets to produce information against which other data can be compared [International Commission on Radiological Protection (ICRP) 1975]. A similar use of *reference organisms* to represent flora and fauna has been suggested in a number of publications [e.g. Pentreath 1999; Pentreath & Woodhead 1988; 2000; *in-press*]. The International Union of Radioecology [International Union of Radioecology (IUR), 2000] and Strand & Larsson [2001] proposed a working definition of reference organisms within the context of the radiological protection of the environment as '*a series of imaginary entities that provide a basis for the estimation of radiation dose rate to a range of organisms which are typical, or representative, of a contaminated environment. These estimates, in turn, would provide a basis for assessing the likelihood and degree of radiation effects. It is important that they are not a direct representation of any identifiable animal or plant species*'.

An initial step in the construction of a framework is thus the selection of appropriate reference organisms; identification of reference organisms being required to enable the subsequent development of dosimetric models. The final choice of reference organisms for consideration within the FASSET framework (which will be discussed in a future report) will be an iterative process taking into account not only radioecological sensitivity but also the other criteria outlined above.

In this report, which is based on work within FASSET Work Package 2 (documented in the Minutes from workshops in Madrid (February 2001) and Helsinki (September 2001), we will select candidate reference organisms primarily on the basis of their radioecological sensitivity, which can be used as a basis for the development of dosimetric models within FASSET Work Package 1. It is, however, important that candidate reference organisms are thought of as a suite which, taken together, are likely to cover the range of both radiation exposures and radiosensitivities which may arise within a contaminated ecosystem. Therefore, to be pragmatic our selection on the basis of radioecological criteria must encompass some aspects of comparative radiosensitivity [see review in UNSCEAR, 1996] and ecological function. For instance, we should not ignore organisms that are especially radiosensitive because they are not radioecologically vulnerable. We must also bear in mind that different stages of the life cycle (e.g. fertilized egg, larva, adult) may have different exposure pathways and radiosensitivities. Our assessment must also adequately cover the trophic levels and functions within ecosystems.

These aspects are further considered within FASSET Work Package 3. A final selection will be made as a part of the development of the assessment framework (FASSET Work Package 4).

The interaction between different Work Packages in the selection of reference organisms is shown schematically in Figure 1-1.

This report summarizes the selection of reference organisms: background ecosystem information is provided in two appendices to this report:

- Ecological characteristics of European terrestrial ecosystems. Overview of radiation exposure pathways relevant for the identification of candidate reference organisms (Deliverable 1, Appendix 1, available on www.fasset.org), and

- Ecological characteristics of European aquatic ecosystems. Overview of radiation exposure pathways relevant for the identification of candidate reference organisms (Deliverable 1, Appendix 2, available on www.fasset.org).

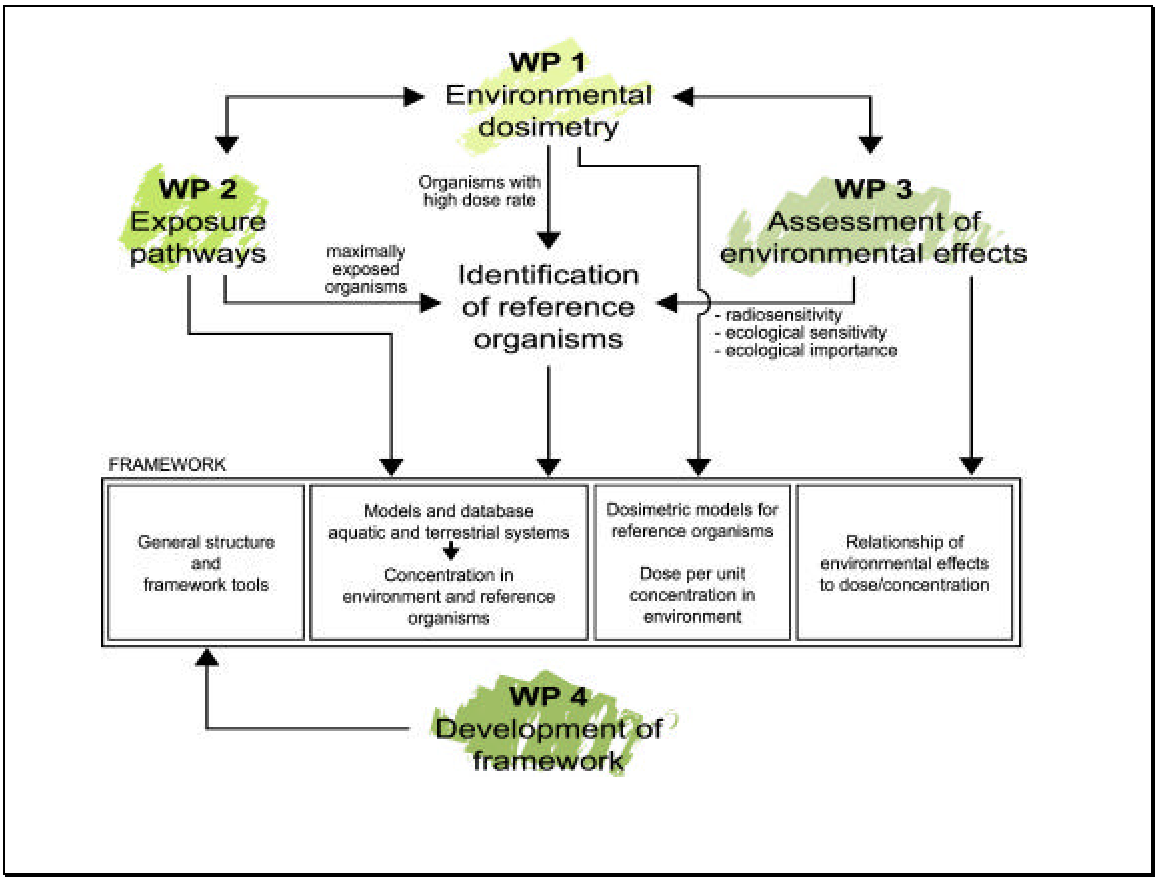

Figure 1-1 The interaction between FASSET Work Packages in the selection of reference organisms.

1.1 Radioecological sensitivity – Identifying candidates from an exposure pathways perspective

We are using the term *radioecological sensitivity* here to identify organisms (or parts of organisms), which will be highly exposed to radioactivity. The factors determining radioecologically sensitivity are:

- whether the habitat or feeding habits of the organism are likely to maximize its potential exposure to radionuclides, based on an understanding of the distribution of the different radionuclides within the ecosystem;
- whether the organism exhibits radionuclide-specific bioconcentration[1] which is likely to maximize internal radionuclide exposures in particular circumstances;
- whether the position of the organism within the foodchain (e.g. top predator) is such that biomagnification[2] of radionuclides up the foodchain may lead to enhanced accumulation.

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[1] Here, *bioconcentration* is used to refer to a situation where an organism accumulates internally (inside the organism body) a radionuclide to concentrations higher than those that exist in the surrounding media, e.g. water column (dissolved phase), sediment or soil.

To identify candidate reference organisms from an exposure pathways perspective we need to make a judgment as to which radionuclides are considered most relevant for the assessment.

There is a large range of anthropogenic and natural radionuclides, which may need to be considered within environmental impact assessments and in this initial consideration of frameworks it is not possible to consider them all. Therefore, a sub-set of radionuclides of twenty elements have been selected (Table 1.1) which includes: (i) radionuclides routinely considered in both regulatory assessments of waste disposal and releases from different facility types, and emergency planning for accidental releases; (ii) a range of environmental mobilities and biological uptake rates; (iii) both anthropogenic and natural radionuclides; (iv) representatives of á-, â- and ã-emitters; radionuclides for which sufficient data is likely to be available. Subsequently, a framework designed to assess these radionuclides should be sufficiently robust to be readily applicable to the consideration of others.

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[2] Similarly, *biomagnification* is used to refer to a situation where concentrations of radionuclides in organisms increase as one moves higher up the foodchain.

Table 1-1 Radionuclides selected for consideration within FASSET.

Radionuclide (Element Group)	Principal Radioisotopes ($T_{½}$)	Radiation type	Sources
H (Ia)	^{3}H (12 y)	â$^{-}$	Cosmic, Fission, activation
C (IVb)	^{14}C (5600 y)	â$^{-}$	Cosmic, activation
K (Ia)	^{40}K (1.3 x 10^{9} y)	â$^{-}$, ã	Primordial
Cl (VIIb, halogen)	^{36}Cl (3.01 x 10^{5} y)	å, e^{-}	Neutron activation
Ni (VIII, heavy metal)	^{63}Ni (96 y)	â$^{-}$	Neutron activation
	^{59}Ni (7.5 x 10^{4})	â$^{+}$, å	
Sr (IIa)	^{89}Sr (50.5 d)	â$^{-}$, ã	Fission
	^{90}Sr (28.5 y)		
Nb (Va)	^{94}Nb (2.03 x 10^{4})	â$^{-}$, ã, e^{-}	
Tc (VIIa,)	^{99}Tc (2.13 x 10^{5} y)	â$^{-}$, ã, e^{-}	Fission
Ru (Group VIII, heavy metal)	^{106}Ru (368 d)	â$^{-}$	Fission
I (VIIb, halogen)	^{129}I (1.57 x 10^{7} y)	â$^{-}$, ã, e^{-}	Fission
	^{131}I (8.04 d)	â$^{-}$, ã	
Cs (Ia)	^{134}Cs (2.06 y)	â$^{-}$, â$^{+}$, ã	Fission
	^{137}Cs (30 y)	â$^{-}$	
	^{135}Cs (2.0 x 10^{5} y)	â$^{-}$	
Po (VIb,)	^{210}Po (138 d)	á, ã	^{238}U decay series
Pb (IVb, heavy metal)	^{210}Pb (22 y)	â$^{-}$, ã	^{238}U decay series
Ra (IIa)	^{226}Ra (1600 y)	á, ã	^{238}U decay series
Th (Actinide series)	^{227}Th (18.7 d)	á, ã, e^{-}	Natural, U & Th series decay chains
	^{228}Th (1.9 y)	á, ã	
	^{230}Th (7.7 x 10^{4} y)	á, ã, e^{-}	
	^{231}Th (25.5 h)	â$^{-}$, ã, e^{-}	
	^{232}Th (1.4 x 10^{10} y)	á, ã	
	^{234}Th (24.1 d)	â$^{-}$, ã, e^{-}	
U(Actinide series)	^{234}U (2.45 x 10^{5} y)	á, ã	Natural
	^{235}U (7.04 x 10^{8} y)	á	
	^{238}U (4.47 x 10^{9} y)	á, e^{-}	
Pu (Actinide series)	^{238}Pu (88 y)	á, â$^{-}$, ã	Activation-Neutron capture
	^{239}Pu (2.4 x 10^{5} y)	á, ã	
	^{240}Pu (6.5 x 10^{3} y)	á, e^{-}	
	^{241}Pu (14.4 y)	á, â$^{-}$, ã	
Am (Actinide series)	^{241}Am (432 y)	á, ã	Activation-Neutron capture decay of ^{241}Pu
Np (Actinide series)	^{237}Np (2.1 x 10^{6})	á, ã, e^{-}	Activation-Neutron capture
Cm (Actinide series)	^{242}Cm (163 d)	á, ã	Activation-Neutron capture
	^{243}Cm (28.5 y)	á, ã, å, e^{-}	
	^{244}Cm (18.1 y)	á, ã	

2. Assessment of radioecological sensitivity in European ecosystems

2.1 European ecosystems

Europe includes a range of ecosystems from Mediterranean systems in the south to Polar deserts in the north. The final framework developed by FASSET will need to be able to assess exposure of biota in any of these ecosystems. In order to evaluate the radioecology of European ecosystems they have been considered in seven broad groups (see Figure 2-1):

Forests Communities dominated by trees. The Food and Agriculture Organization of the United Nations) defines forest as: land with tree crown cover of more than 10 %; an area of more than 0.5 ha; and with trees which are able to reach a minimum *in situ* height of 5 m at maturity.

Semi-natural pastures and heathlands A broad range of ecosystems including mountain (e.g. Alpine pastures) and upland grasslands (e.g. those characteristic of many upland areas of the UK), heath and shrub lands (e.g. Mediterranean garigue), saltmarshes and some Arctic ecosystems. These ecosystems are termed ‘semi-natural’ since, whilst they are comprised of natural species not introduced by man, they have been influenced by human use, for instance by the grazing of livestock.

Agricultural Including arable land, intensively managed pastures and areas used for fruit production. For the purposes of this assessment, wild-life have not been considered as part of the agricultural ecosystem.

Wetlands Areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt.

Freshwaters All freshwater systems including rivers and lakes.

Marine In terms of sea areas, we define the European marine ecosystem as the North-Eastern section of the Atlantic Ocean and its marginal seas including the Mediterranean Sea, Greenland Sea, the Irish Sea, North Sea, Norwegian Sea, Skagerrak, Kattegat and Barents Sea.

Brackish waters In Europe this includes only the non-tidal, shallow Baltic Sea; organisms are mainly immigrants from either marine or freshwater systems, there are only a few endemic brackish water species in the Baltic Sea.

Descriptions of the ecology and typical species of these broad ecosystems can be found in the separate appendices to this report.

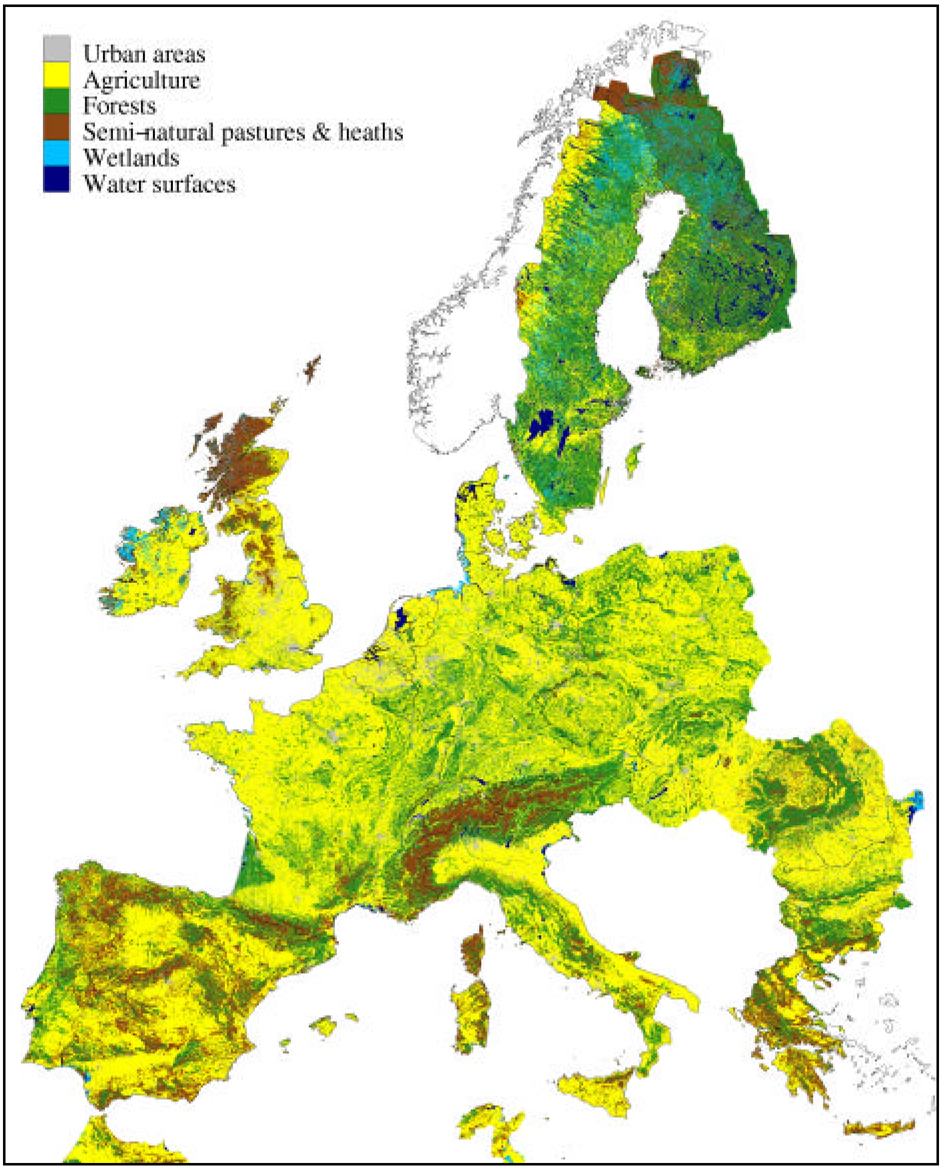

Figure 2-1 Major land cover types of Europe (EEA[3])

2.1.1 Food webs

There are broad similarities in the foodwebs of the terrestrial and aquatic ecosystem types.

Primary producers including trees, shrubs, grasses, herbs, bryophytes and microflora occupy the first trophic level of terrestrial ecosystems (Figure 2-2). The second trophic level comprises herbivores (and omnivores) including vertebrate and invertebrate animals and microorganisms. Predators (vertebrate and invertebrate carnivores) of herbivores occupy the

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[3] European Environment Agency (EEA) *Major Land Cover Types of Europe,* CD-ROM, European Topic Centre on Land Cover, Sweden.

third trophic level and so on through higher levels of predators. Decomposing organisms include invertebrate and vertebrate animals, microorganisms and saprophytic macrofungi.

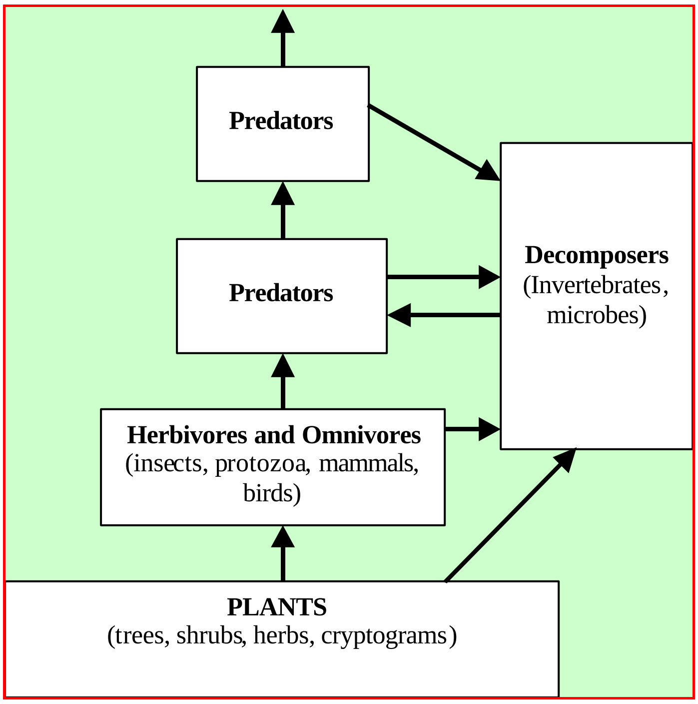

Figure 2-2 Schematic representation of a highly generalised forest food web [adapted from Perry, 1994].

Marine biota are broadly subdivided into pelagic, those inhabiting the water column, and benthic, those inhabiting the bottom sediments (Figure 2-3).

Phytoplankton are the main primary producers within pelagic food webs and act as food for primary consumers, such as protozoa and zooplankton, which are consumed by higher trophic level organisms. In the pelagic components of the ecosystem these higher trophic levels include both vertebrates (fishes, reptiles, mammals, amphibians and birds) and invertebrates (e.g. molluscs and crustaceans). In coastal areas, lakes and estuaries, the main primary producers are often benthic micro- and macroalgae and vascular plants. Benthic food webs are based on detritophagues consuming detritus falling to the bottom of the water column. Benthic organisms, dwelling on or within the upper layers of bottom sediments may be subdivided into two large groups: deposit feeders (including e.g. worms, echinoderms, crustaceans) and filter feeders (e.g. molluscs). In turn, organisms (e.g. mammals and fish) from higher trophic levels prey on benthic organisms.

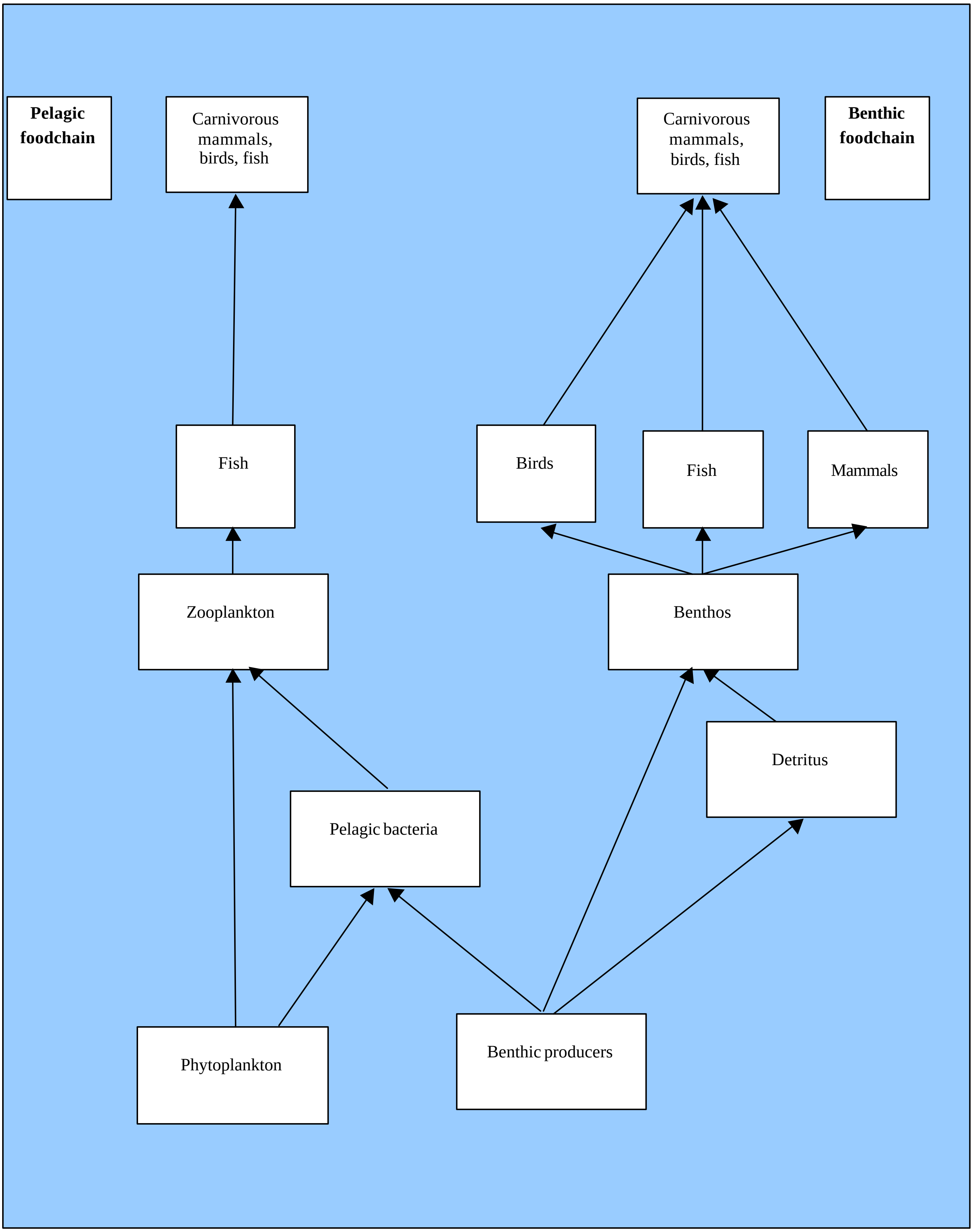

Figure 2-3 Pelagic and benthic aquatic foodchains [adapted from Beresford et al., 2001].

2.2 Identification of radioecologically sensitive organisms

Amongst the radionuclides of interest in this assessment, aspects of the environmental behaviour of some have been relatively well studied (e.g. Cs, Sr, U, Pu), whilst only sparse data are available for others (e.g. Cl, Cm, Np). The degree of knowledge also varies between ecosystems; a range of radionuclides having been studied within agricultural and marine ecosystems, whilst in other ecosystems of interest data are largely restricted to Cs. Radionuclides that are isotopes of nutrients, as well as those with a nutrient analogue (see Table 2-1), behave in a similar manner to that of the corresponding nutrient. Hence, knowledge about the cycling characteristics of the nutrients in different ecosystems can be used to predict the behaviour of radionuclides. This can be especially valuable when there is a lack of radioecological data (overviews of cycling characteristics of nutrients in different ecosystems can be found in Perry [1994], Mengel and Kirby [1979], Bowen [1979], and Clarkson and Hanson [1980]). An assessment of the behaviour of radionuclides (and available data) in each of the seven ecosystems is given within the Appendices 1 (Terrestrial) and 2 (Aquatic) to this report.

Below we provide a discussion of the radiation exposure pathways of European biota based upon the Appendices. At the level of detail necessary to inform a selection of candidate reference organisms, there is a high degree of similarity in the behaviour of radionuclides in the different terrestrial and aquatic ecosystems. There is also great similarity in the foodchain structures (Figures 2-2 and 2-3) and the types of organisms that inhabit the different terrestrial and aquatic ecosystems, although the actual species involved are quite different. It is therefore helpful to consider the ecosystems in two broad groups for the purpose of selecting candidate reference organisms: terrestrial (i.e. forest, semi-natural pastures and heathlands, agriculture and wetlands) and aquatic (i.e. freshwater, brackish waters and marine).

The total dose received by an organism is the sum of internal and external exposures. Different organisms may be exposed to internal and external doses to differing extents dependent upon contamination scenario. The two pathways will therefore be considered separately.

2.2.1 External exposure

The external exposure received by an organism is dependent on how radionuclides are distributed within the system and the habits of the organism. The distribution of radionuclides among different ecosystem components depends on the time that has passed since the system was contaminated (tending towards approach equilibrium conditions) and the contamination scenario (e.g. aerial discharges versus underground waste repositories).

Under conditions of chronic contamination within terrestrial ecosystems the majority of the radionuclide inventory is found within soil. For example, more than 90 % of the aerially deposited radioactivity can be found in the upper horizons of the soil-litter layer years-decades after the Kysthym and Chernobyl accidents [Tikhomirov & Shcheglov, 1994; Shcheglov, 1999; Fesenko *et al.*, 2001a, 2001b]. The proportion of the inventory found within soils will be greater for less mobile radionuclides; as an example of the comparative mobility of radionuclides within terrestrial ecosystems Table 2-1 compares their transfer to pasture grass.

Consequently, under chronic contamination conditions organisms living within, or partially within the soil will be the most exposed to external irradiation. This will include plant roots, fungal hyphae, soil microbial communities, soil invertebrates and burrowing vertebrates. Because of their small size, soil micro-organisms will be maximally exposed to external radiation by soil radionuclides, including alpha-emitters. Similarly, soil invertebrates may receive significant external irradiation due to beta-emitting radionuclides.

Radionuclide behaviour and distribution within aquatic ecosystems is determined primarily by the partition of radionuclides between the dissolved phase and suspended sediments in the water column; radionuclides, which become sorbed onto suspended sediments, are subsequently incorporated into bed sediments.

When considering aquatic systems radionuclides are often characterised as 'conservative' or 'particle reactive' depending on whether the radionuclide inventory in the water column is dominated by the dissolved phase or radionuclides sorbed onto suspended sediment. On this basis, nuclides such as ^{3}H, ^{90}Sr, ^{99}Tc, ^{129}I, ^{137}Cs, and ^{238}U are regarded as 'conservative' whilst ^{210}Po, ^{232}Th, ^{239}Pu and ^{241}Am are considered 'particle reactive'. Regardless of this classification however, most of these radionuclides accumulate to a higher concentration in terms of activity per unit weight in bed sediment than in water (^{3}H and ^{36}Cl being amongst the few exceptions). Consequently, bed sediment is an important source of potential external radiation exposure for aquatic organisms, especially to benthic organisms.

In the case of aerial contamination of terrestrial ecosystems, the vegetation cover will intercept a large proportion of deposited radionuclides. This is especially the case in forests, 40 to 90 % of deposited radioactivity having been intercepted by the tree canopy following the Kysthym and Chernobyl accidents, depending on radionuclide, forest type and season [Tikhomirov and Shcheglov, 1994; Nimis, 1996]. Consequently, in conditions of acute exposure the above ground plant parts (leaves, branches, etc.) will be amongst the most externally exposed organisms. Animals inhabiting the vegetative layers (e.g. herbivorous insects) may also be highly exposed. Radionuclides intercepted by vegetation are rapidly (over times scales of weeks to months) transferred to the soil by weathering. For instance, *circa* 90 % of the ^{137}Cs activity intercepted by trees was transferred to the forest floor within 6 months of deposition [Tikhomirov and Shcheglov, 1994].

2.2.2 Internal exposure

The internal exposure of biota is proportional to the concentration of the radionuclide inside the organism. This is determined by: the availability of the radionuclides for biological uptake (bioavailability[4]); the capacity of the organisms to concentrate the incorporated radionuclides with respect to the surrounding media (i.e. bioconcentration) or their feed (i.e. biomagnification). Whilst some radionuclides (e.g. Cs, H, C, K) are approximately homogeneously distributed throughout the tissues of organisms others are concentrated in given organs (e.g. in the case of mammals, Ru kidney, Sr and Ra in bone, actinides in liver). Consideration of the distribution of radionuclides within the organism is important for nuclides emitting alpha or soft beta particles (see review by Yankovich & Beaton [2001]).

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[4] Bioavailability is defined here as the potential of the radionuclides in a certain media for biological uptake.

Below we summarise observations of the transfer of radionuclides to biota in terrestrial and aquatic ecosystems. Table 2-1 presents a highly generalised ranking of radionuclides in terms of bioconcentration and biomagnifications, based on Whicker and Schultz [1982].

Terrestrial ecosystems

Plants and fungi

The mobility for transfer through food webs of the radionuclides considered in the project will be determined by their chemical behaviour and various soil properties [e.g. Desmet et al., 1991]. A number of soil properties, which vary spatially, have been identified as influencing the mobility of different radionuclides within the terrestrial environment: Pu mobility is increased by complexing agents such as dissolved organic compounds and extracellular metabolities of microflora [e.g. Negri & Hinchman, 2000]; oxidation state of the actinide elements results in a trend in plant uptake in the order Np(V) > Am(III) ~ Cm(III) > Pu (IV) ~ Np (IV) [Bulman, 1983]; limited data suggest enhanced Ru uptake on sandy soils compared to clay or loam soils; an excess of NO_3^- in soil significantly decreases TcO_4^- transfer to the roots [Echevarria et al., 1998]; Cs activity concentrations in vegetation are determined by soil exchangeable K, pH, clay and organic matter contents [Absalom *et al*., 1999; 2001]; plant uptake of U, Th Pb, Po and Ra will all be influenced by soil pH [Mortvedt, 1994], increasing soil organic matter content and pH both decrease the transfer of Sr [Van Bergeijk *et al*., 1992].

There are limited data on the transfer of many of the radionuclides we are considering to plants growing within natural and semi-natural ecosystems. Plant to soil concentration ratios for grass (in agricultural ecosystems) presented in Table 2-1 demonstrate the low mobility of the majority of radionuclides (i.e. the largest proportion of the radionuclide inventory within terrestrial ecosystems is in the soil). However, there are data to demonstrate that the transfer of some radionuclides will be higher to certain plant types. A number of studies have demonstrated a high transfer of radiocaesium to plants of the Ericaceae family [e.g. Bunzl & Krake 1984; Colgan *et al*. 1990, Horrill *et al*. 1990] compared with other species of higher plants present within upland environments; *Calluna vulgaris* (ling heather) being reported to have the highest radiocaesium uptake of the Ericacae [Bunzl & Krake 1984; Horrill *et al*. 1990]. The fruiting bodies of fungi, especially symbiotic species, accumulate ^{137}Cs to concentrations greatly in excess of those found in higher plants [e.g. Guillitte, 1994; Strandberg 1994; Yoshida & Muramatsu, 1994]. Whilst there are little data for other radionuclides, fungi are know to have high uptakes of many heavy metals [Seeger, 1982] and may therefore be expected to accumulate radionuclides behaving in a similar manner to these elements. The large surface area of lichens and bryophytes means that they intercept atmospheric radionuclides more efficiently than other vegetation, consequently comparatively high concentrations of a number of radionuclides (including ^{137}Cs, ^{210}Pb and ^{210}Po) have been reported [AMAP 1998].

Most reported radionuclides transfer values are for above ground plant parts and fungal fruit bodies. However, the majority of the radionuclides incorporated in plants and fungi remain in the roots/mycelia (i.e. there is low translocation to above ground tissues) [Yankovich & Beaton, 2000]. This is true even for elements with a comparatively high environmental mobility (see Table 2-1) (e.g. estimations made by Olsen *et al*. [1990] indicate that soil mycelia could retain, on average, 32 % of the radiocaesium in the soil-litter layer). Consequently, taking into account the small size of roots and the high radionuclide inventory within soil, it may be suggested that the bioconcentration of radionuclides, and thus internal exposure, is of lesser importance than external exposure in conditions of chronic contamination. Similarly, even though soil microflora can accumulate considerable levels of radiocaesium [Brückmann & Wolters, 1994] their small size perhaps negates any requirement to consider bioaccumulation from a dosimetric viewpoint.

Animals

There is a limited amount of data available to demonstrate animal species, which may accumulate high levels of radionuclides. A number of animals inhabiting semi-natural and forest ecosystems have been shown to have especially high radionuclide (largely radiocaesium) levels as a consequence of their dietary habits (e.g. radiocaesium concentrations in reindeer, roe deer, moose, red grouse, mountain hare in the range 10^3-10^4 Bq kg^{-1} have been relatively commonly recorded). However, many of these species are not ubiquitous, being restricted to rather specific habitats.

High activity concentrations of ^{226}Ra have been determined in burrowing animals [Maslov *et al.*, 1967].

There is clear evidence of a concentration of radiocaesium from the flesh of prey to carnivorous species (biomagnification). Lowe & Horrill [1991] report an increase in radiocaesium concentrations of approximately one order of magnitude from rabbits (*Oryctolagus cuniculus*) to red foxes (*Vulpes vulpes*). Maximum radiocaesium activity concentrations (87 000 Bq kg^{-1}) observed in Norwegian Lynx were considerably higher than in their prey species [Gaare & Staaland, 1994]. Radiocaesium activity concentrations in the flesh of cougars *circa* 3 fold higher than those in the flesh of mule deer have been observed [Pendleton *et al*., 1964]. A similar approximately three-fold increase in radiocaesium activity concentrations was also observed in small mammal – snake foodchains [Brisbin *et al*., 1974]. However, there is (perhaps) less evidence of a concentration of radiocaesium from invertebrate prey species to the mammals and birds consuming them; only the data of Rudge et al. [1993a] indicating a concentration process of five studies considering this pathway [NERC, 1993; Rudge et al., 1993b; Kålås *et al*., 1994; Copplestone 1996]. This may, in some instances, be the result of the ingestion of soil together with prey species. However, it is probable that vertebrate species feeding on soil dwelling invertebrates will have comparatively high rates of intake of the less mobile radionuclides such as the actinides.

There are less data on the transfer of other radionuclides through terrestrial *prey-carnivore* foodchains. Limited data for wolves suggest that radionuclides, which accumulate in organs such as bone or liver, will not show elevated concentrations from the muscle of prey to that of carnivores (as the muscle of the prey species, which contributes most to the dietary intake of the carnivore, has comparatively low levels of such radionuclides) [Hanson 1967; Hanson *et al*., 1967]. In an extensive survey of biota across eight ‘background’ sites in the former Soviet Union Pokarzhevskii & Krivolutzkii [1997] reported that concentration ratio (CR) values for ^{226}Ra for soil-plant, plant–animal and prey–carnivore were usually close to or less than unity.

Table 2-1 General ecological properties of radionuclides selected for ecological sensitivity analysis, adapted from Whicker & Schultz [1982].

Element	Nutrient analogues	Principal reservoirs	Environ-mental mobility	Concentration ratios for pasture	Biomagnifi-cation	Target organ (for vertebrates)	Biological half-life (for mammals)
H	H	Hydrosphere (HTO)	High		Approaches 1	Total body	Low (days)
C	C	Atmosphere (CO_2)	High		Approaches 1	Total body	Low (days)
K	K	Lithosphere	High		Approaches 1	Total body	Moderate (weeks)
Cl	Cl	Hydrosphere, Atmosphere	Moderate		< 1		
Ni	Ni	Soil, sediment	Low	(1-18)x10^{-2}	< 1		
Sr	Ca	Soil, biota	High	(2-26)x10^{-2}	< 1	Bone	High (years)
Nb	None	Soil, sediment	Low	(4-10)x10^{-3}	< 1		
Tc	N (NO_3^-)	Biota, soil	High	(0.5-7)x10^{1}	< 1	GI, lung	Low (days)
Ru	None	Soil, sediment	High	(0.3-20)x10^{-3}	< 1	GI, lung	Low (days)
I	I	Biota, soil	High	1x10^{-1}	Up to 10^{3} (thyroid/plants)	Thyroid	Moderate (weeks-months)
Cs	K	Soil, sediments	High	(5-40)x10^{-3}	Approaches 3	Total body	Moderate (weeks-months)
Po	None	Soil, sediment	High	(0.2-90)x10^{-3}	<1-10	Spleen, kidney, lung	Moderate (weeks)
Pb	None	Soil, sediment	High		<1-10	Kidney, lung	High (years)
Ra	Ca	Lithosphere	Moderate	7 10^{-6}	< 1	Bone	High (years)
Th	None	Lithosphere	Very low	1.10^{-4}	< 10^{-2}	Bone, lung	High (years)
U	None	Lithosphere	Low-moderate		< 1	GI, kidney, lung	Moderate (months)
Pu	None	Soil, sediment	Very low	(0.5-3.4)x10^{-4}	< 10^{-2}	Bone, lung, liver	High (years)
Am	None	Soil, sediment	Very low	3.9x10^{-4}	< 10^{-2}	Bone, liver	High (years)
Np	None	Soil, sediment	Very low	(1-6.9)x10^{-2}	< 1		High (years)
Cm	None	Soil, sediment	Very low	1x10^{-3}	< 10^{-2}		High (years)

[*] Taken from the description of agricultural ecosystems in Appendix I to this report. The concentration ratio (CR) is defined as the ratio between the dry matter activity concentration in pasture and that in soil.

A number of studies of the movement of radionuclides through invertebrate foodchains have demonstrated that detritivorous species have higher concentrations of radionuclides (Cs, Pu, Am) than herbivore and predatory species [Crossley, 1993; Rudge *et al*., 1993b; Copplestone, 1996; Copplestone *et al*., 1999].

Whilst there are little data on radionuclide transfer to reptiles within European ecosystems, observations from North America suggest that they may have comparatively long biological half-lives (*circa* 6 months) of radiocaesium compared to animals of a similar size [Bagshaw & Brisbin, 1984].

Aquatic ecosystems

There is comparatively less data for freshwater than marine species, however general aspects of radioecological behaviour can be considered to be similar for the two ecosystem types. Table 2-2 presents recommended concentration factor (CF)[5] values for generic marine organisms for the radionuclides under consideration [International Atomic Energy Agency (IAEA), 1985]. These, together with other data, can be used to identify those organisms, which are likely to concentrate the highest levels of radionuclides. The following discussion identifies organisms which may be prone to comparatively high exposure for each of the radionuclides considered.

Table 2-2 International Atomic Energy Agency (IAEA) [1985] recommended CF values to various generic marine organisms.

Element	Phytoplankton	Macroalgae	Zooplankton	Mollusca*	Crustaceans	Fish
Cs	2×10^{1}	5×10^{1}	3×10^{1}	3×10^{1}	3×10^{1}	1×10^{2}
Tc	5×10^{0}	1×10^{3}	1×10^{2}	1×10^{3}	1×10^{3}	3×10^{1}
Sr	3×10^{0}	5×10^{0}	1×10^{0}	1×10^{0}	2×10^{0}	2×10^{0}
U	2×10^{1}	1×10^{2}	5×10^{0}	3×10^{1}	1×10^{1}	1×10^{0}
Th	2×10^{4}	2×10^{2}	1×10^{4}	1×10^{3}	1×10^{3}	6×10^{2}
Pu	1×10^{5}	1×10^{3}	1×10^{3}	3×10^{3}	3×10^{2}	4×10^{1}
Am	2×10^{5}	2×10^{3}	2×10^{3}	2×10^{4}	5×10^{2}	5×10^{1}
Cm	3×10^{5}	8×10^{3}	2×10^{3}	3×10^{4}	5×10^{2}	5×10^{1}
Np	1×10^{2}	5×10^{1}	1×10^{2}	4×10^{2}	1×10^{2}	1×10^{1}
Ra	2×10^{3}	1×10^{2}	1×10^{2}	1×10^{3}	1×10^{2}	5×10^{2}
Pb	7×10^{3}	1×10^{3}	1×10^{3}	1×10^{3}	1×10^{3}	2×10^{2}
Po	3×10^{4}	1×10^{3}	3×10^{4}	1×10^{4}	5×10^{4}	2×10^{3}
C	9×10^{3}	1×10^{4}	2×10^{4}	2×10^{4}	2×10^{4}	2×10^{4}
H	1×10^{0}	1×10^{0}	1×10^{0}	1×10^{0}	1×10^{0}	1×10^{0}
Nb	1×10^{3}	3×10^{3}	2×10^{4}	1×10^{3}	2×10^{2}	3×10^{1}
Ni	3×10^{3}	2×10^{3}	1×10^{3}	2×10^{3}	1×10^{3}	1×10^{3}
Ru	2×10^{5}	2×10^{3}	3×10^{4}	2×10^{3}	1×10^{2}	2×10^{0}
I	1×10^{3}	1×10^{3}	3×10^{3}	1×10^{1}	1×10^{1}	1×10^{1}
Cl	1×10^{0}	5×10^{-2}	1×10^{0}	5×10^{-2}	5×10^{-2}	5×10^{-2}

*excluding cephalopods

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[5] Concentration factor is defined as the activity concentration in biota (Bq kg^{-1}) relative to that of the ambient seawater (Bq kg^{-1})

^{40}K

There is little difference in the internal ^{40}K body burden of different aquatic animals and plants; activity concentrations in phytoplankton, zooplankton, molluscs, crustaceans and the muscle of teleost fish are consistently in the range 90-110 Bq kg^{-1} [International Atomic Energy Agency (IAEA), 1988; Woodhead 1973].

Cs

The ambient activity concentrations of Cs in sediments are likely to become higher than those observed in water following a release of caesium to aquatic systems, although a major fraction of the Cs inventory may remain in the aqueous phase. Uptake and transfer of radiocaesium through foodchains occurs to a limited extent. Once radiocaesium becomes associated with bottom sediments, the bioavailable fraction tends to be reduced. Those benthic organisms residing near the top of the foodchain (e.g. plaice (*Pleuronectes platessa*), carrion-feeding crustaceans, some species of seal) may receive an extra internal exposure from elevated Cs body burdens, compared to organisms residing at lower levels in the food-chain, and can be identified as organisms that are most vulnerable to inputs of radiocaesium to aquatic system. Seabirds, especially those that are categorised as top predators, e.g. great black-backed gulls (*Larus marinus*), great skuas (*Catharacta skua*), may also be prone to elevated Cs exposure via ingestion [Rissanen *et al*. 1997; Fisher *et al*. 1999]. There is little evidence of concentrations being higher in top level marine (fish and mammal) predators (Brown 2000). However, for deep oceanic systems, the intermediate half life of ^{137}Cs (30 yrs) may prevent substantial amounts of the radionuclide from ever reaching the seabed and therefore a high trophic level pelagic organism may be more vulnerable to inputs of this radionuclide than benthic species. For freshwater fish there is clear evidence of concentration of radiocaesium up trophic levels. Rowan & Rasmussen [1994] found an approximately two-fold increase in radiocaesium concentrations in predatory over non-predatory fish. A five to ten fold increase was reported for predatory perch (*Perca fluviatilis*) compared to their prey species roach (*Rutilus rutilus*) and tench (*Tinca tinca*) [Smith *et al*., 2000].

Sr

Strontium concentrations decline with successive trophic levels in (marine) aquatic ecosystems.

Tc

On the basis of the concentration factor data reported in the open literature three aquatic organism types can be identified as potentially vulnerable to exposure from coastal input of ^{99}Tc: brown seaweeds; benthic molluscs, in particular from the class *Gastropoda*; crustaceans, in particular from the order *Decapoda*.

U

Radioisotopes of uranium are not highly concentrated by the soft tissues of aquatic organisms [International Atomic Energy Agency (IAEA), 1988]. However, uranium is incorporated into the skeleton and marked differences occur between different phyla [International Atomic Energy Agency (IAEA), 1988]. For fish, apart from accumulation by the bones and scales, highest concentrations are found in the liver at levels of the same magnitude as those observed in seawater [International Atomic Energy Agency (IAEA), 1988]. Molluscs concentrate U to the highest degree of all marine organism types and express concentration factors in the range 30-100 [International Atomic Energy Agency (IAEA), 1985, Hodge et al., 1979].

Th

Concentration factor data for Th are fairly limited and are often restricted to “not greater than” values. Highest CFs appear to be associated with phytoplankton probably reflecting their large surface area from which adsorption can take place.

^{210}Pb, ^{210}Po and ^{226}Ra

Phytoplankton are significant accumulators of ^{210}Pb, ^{210}Po and ^{226}Ra. Other organisms vulnerable to high internal/surficial concentrations of radioisotopes of Ra, Pb and Po include benthic species in particular crustaceans, which tend to accumulate ^{210}Po to a higher degree than other aquatic organisms.

Actinides

Phytoplankton have comparatively high CF values for the actinide elements [Fisher *et al.*, 1983]. Neither Pu nor Am derived from Windscale/Sellafield, are highly accumulated by benthic or pelagic fish [Pentreath *et al.*, 1979]. Rissanen *et al.* [1997] calculated a CF of 1 x 10^3 for ^{239,240}Pu for a ray sampled from the Barents Sea although values of <0.3 x 10^3 were derived for bony fish. In contrast, transfer to invertebrates and algae can be significant and the consumption of these marine-derived organisms is considered to be an important dose-forming pathway for man for Sellafield-derived radioactivity [Kershaw et al., 1992]. Limited data on the activity concentration of Pu in marine mammals from northern European seas suggest that transfer to these organism types is very low [Brown, 2000]. The limited data on the uptake of radioisotopes of Np by marine organisms suggest that molluscs accumulate Np to the greatest extent under equilibrium conditions. It is likely that animals (including fish, mammals and birds) feeding on benthic invertebrate organisms will have comparatively high dietary intake rates of actinide elements as a consequence of the inadvertent ingestion of contaminated sediment.

^{3}H and ^{14}C

Hydrogen is one of the few elements for which the sediment-water concentration factor is < 1. All types of pelagic organism would be exposed to similar levels of radiation following an input of ^{3}H to oceanic surface waters. The sediment-water concentration factor data suggest that sediment may act as a sink for ^{14}C over long time periods and that benthic organism might be vulnerable to the highest exposures from this radionuclide. Benthic fish, molluscs and crustaceans have similar tissue concentrations of C and therefore might be expected to experience similar levels of internal exposure following the equilibration of ^{14}C in the system.

^{36}Cl and I

The highest concentrations of iodine occur at lower marine trophic levels (e.g. brown seaweeds). Chlorine generally forms highly soluble salts in solution and is present as chloride (Cl^-) ions in seawater; interaction with the sedimentary material is negligible. The pelagic foodchain is therefore more likely to be exposed to ^{36}Cl than the benthic. However, recommended CFs are low < 1 for the organisms.

^{106}Ru

Some species of benthic macroalgae are known to concentrate ^{106}Ru to a high degree notably *Porphyra umbilicalis* [Kershaw et al., 1992].

Ni

Concentration factors for nickel in marine ecosystems tend to be similar for all organisms.

^{94}Nb

Recommended biota CF values for Nb illustrate that transfer to high trophic levels is limited and that zooplankton appear to accumulate radioisotopes of this element to the greatest degree.

3. Selection of reference organisms

From the discussion above on the environmental behaviour of radionuclides it can be seen that different organisms will be exposed under different scenarios dependent upon their habitat. Based upon our knowledge of the distribution of radionuclides within the environment a simplified compartmentalisation of the ecosystems has been used: bed sediment and water column for aquatic ecosystems; soil, herbaceous layer and canopy for terrestrial ecosystems. Some organisms may be represented in different compartments, most notably the roots and above ground parts of plants. In an effort to determine that our candidate reference organisms will be sufficient to ensure that the environment as a whole is protected within any assessments, we have considered simplified ecological niches/organism groupings within the selection process. In this selection, the availability of data for an organism, or the ability in the future to obtain the required data are also considered.

3.1 Terrestrial ecosystems

3.1.1 Soil (see Table 3-1)

Soil micro-organisms

Because of their small size this group of organisms will be maximally exposed to external radiation by soil radionuclides, including alpha-emitters. Soil micro-organisms are therefore suggested as candidate reference organism for semi-natural, forest and wetland ecosystems.

Soil invertebrates

Highly exposed to external radiation, including by beta-emitters. Whilst a wide range of organisms is incorporated within this grouping it is suggested that ‘worms’ represent the candidate reference organism. Worms may receive enhanced exposure because of the passage of soil through their alimentary tract and unlike many smaller soil invertebrates (e.g. collembola, mites) they are large enough to potentially bioconcentrate radionuclides. They also lack the chitinous exoskeleton of some soil invertebrate species which may reduce exposure to external radiation.

Plants and fungi

The roots of plants and hyphae of fungi will be exposed to higher rates of external radiation in conditions of chronic exposure than other plant parts. Both plants and fungi are therefore suggested as reference organisms.

Burrowing mammals

Represent the group of terrestrial mammals which are likely to be subject to the highest external exposure rates (especially for hibernating species). Ingestion of soil whilst grooming and consumption of soil invertebrates (by some species) may lead to enhanced internal exposure. Small burrowing mammals (e.g. voles or mice) are ubiquitous and are suggested as a candidate reference organism for semi-natural and forest ecosystems.

Burrowing birds

Some species of burrowing bird (e.g. *Riparia riparia*) occur in some terrestrial ecosystems. However, given we have no evidence to suggest that they would be more exposed to external or internal exposure than (more radiosensitive) small mammals we do not suggest that they are selected as candidate reference organisms.

3.1.2 Herbaceous layer (see Table 3-2)

The term 'herbaceous layer' is used here to represent the understorey layer of forests, crop or pasture layer of agricultural systems, and the above ground components of semi-natural heathlands and pastures, and wetlands.

Bryophytes

In many circumstances these may represent the most contaminated primary producer. They are suggested as candidate reference organism for all terrestrial ecosystems except agricultural.

Grasses, herbs and crops

The foliage of plants may represent a more exposed part of an organism with respect to acute exposure. In conditions of chronic exposure, mobile radionuclides may bioconcentrate in the foliage of some plants. This group of plants is therefore suggested as a candidate reference organism for all terrestrial ecosystems except forests.

Shrubs

Similar arguments apply for the foliage of shrubs as for that of grasses etc. above. Some shrub species (ericaeceous) can accumulate comparatively high activity concentrations of radiocaesium. Suggested as a candidate reference organism for semi-natural heathlands and agricultural systems (to represent fruit bushes and vines).

Fungi

The often short-lived fungal fruit bodies of some (especially mycorrhizal) species accumulate high concentrations of radiocaesium. However, there is no evidence to suggest that they have a high interception of aerially deposited radionuclides. It is therefore unlikely that there will be a requirement to consider exposure of fungi beyond the consideration of the soil dwelling mycelia.

Above ground invertebrates

Detritivores have been shown to have highest activity concentrations of many radionuclides (e.g. actinides, Cs). Living in the litter layer, they will also be more exposed to external radiation than species living on plants. Therefore, detritivorous invertebrates are recommended as a candidate reference organism for semi-natural, forest and wetland ecosystems.

Insectivorous mammals

Not suggested as a candidate reference organism in its own right; the inclusion of burrowing mammal as a reference organism will adequately consider the most exposed insectivorous mammals.

Herbivorous mammals

Can have comparatively high transfer of mobile radionuclides (Cs, I, Sr) to tissues and are likely to have higher activity concentrations of 'organ seeking' radionuclides (Pu, Sr, Am, Ru) than carnivores inhabiting the same ecosystem. In acute phase herbivores ingest herbage with surface contamination of freshly deposited material. Suggested as a candidate reference organism for all four terrestrial ecosystems.

Herbivorous birds

There is no evidence that herbivorous birds will be more exposed than herbivorous mammals in most circumstances. Exceptions may include the high transfer of radiocaesium to red grouse and exposure of geese grazing on saltmarshes. However, red grouse are comparatively localised, whilst consideration of wading birds on saltmarshes should adequately represent exposure of grazing species. Consequently, herbivorous birds are not suggested as candidate reference organisms.

Carnivorous mammals

Known biomagnification of radiocaesium through the foodchain to top predators, potential for other radionuclides to behave similarly. Suggested as candidate reference organism for all terrestrial ecosystems except agricultural.

Carnivorous birds

Whilst above applies there is no evidence to suggest that carnivorous birds will be exposed to a greater degree than (more radiosensitive) carnivorous mammals. Because many raptors are protected species it would be difficult to obtain data to estimate radionuclide exposure. Consequently, they are not recommended as a candidate reference organism.

Reptiles

Whilst there are little radioecological data for reptiles within Europe, reptiles may be exposed to external radiation because of contact with the ground and they have especially long biological half-lives for some radionuclides. Reptiles cannot be currently suggested as potential candidate reference organism because of the probable lack of data but this should be reconsidered pending a further review of the available data.

Vertebrate eggs

Eggs of ground nesting birds will be prone to external exposure from the soil surface. Radiostrontium will accumulate in the egg shell and a number of radionuclides have a higher rate of transfer to the contents of (hen) eggs than to meat; most notable of the radionuclides being considered the transfer of both I and Tc to egg contents is two orders of magnitude higher than that to poultry meat (International Atomic Energy Agency (IAEA) 1994). Consequently, bird eggs are suggested as a reference organism in forest and semi-natural pastures and heathlands.

Reptile eggs may also be exposed to external radiation as they often are buried. However, there is a lack of knowledge on exposure of and transfer to reptile eggs and they are consequently not suggested as candidate reference organisms.

3.1.3 Canopy (see Table 3-3)

Trees

As discussed above the canopy layer of forests can retain significant proportions of aerially deposited radionuclides (in the range 40–90 %). Trees should therefore be considered as a candidate reference organism, especially with respect to assessment of acute exposure. In agricultural ecosystems this reference organism would represent the fruit trees, although interception or aerially deposited radionuclides may be less than in forest ecosystems.

Invertebrates

If acute exposure is being considered it may be necessary to include invertebrates living in the tree canopy as a candidate reference organism.

3.2 Aquatic ecosystems

3.2.1 Bed sediment (see Table 3-4)

Benthic microorganisms

Because of their small size benthic bacteria and protozoans are exposed to the total dose delivered to the sediment itself, including that from alpha radiation; and many important alpha emitters are highly particle reactive so they accumulate readily in sediments. Such microorganisms are present in all three aquatic environments and are suggested as candidate reference organisms.

Benthic invertebrates

Benthic invertebrates will receive elevated external radiation doses from radionuclides in sediment; in this case, from beta and gamma emitting radionuclides only. Deposit feeding invertebrates such as worms feed by passing sediment through their gut in order to extract nutrients; therefore there is potential for internal incorporation of radionuclides. A benthic worm is proposed as one of the reference organisms for marine and brackish environments; an insect larvae is proposed because of the abundance and overall ecological importance of insect larvae in these environments, and the greater radiosensitivity of this life-stage.

Molluscs

In addition to receiving external beta and gamma radiation from sediments, molluscs have a well demonstrated capacity to bioconcentrate a range of particle reactive radionuclides. Many bivalve molluscs feed by filtering particles out of the water, whereas most gastropod molluscs feed by ‘grazing’ algae from the surface of sediments and rocks. Despite these very different feeding habits, accumulation factors relative to water for most radionuclides for the two types of mollusc are similar, suggesting that a single ‘generic mollusc’ may be suitable as a reference organism. Possible differences in accumulation do however, need to be explored.

Crustaceans

Crustaceans demonstrate the potential to selectively bioconcentrate certain radionuclides. In some cases (e.g. ^{99}Tc) the accumulation factors can be higher than case for molluscs; in other cases (e.g. ^{239}Pu) the accumulation factors can be lower. Therefore benthic crustaceans would be complementary to molluscs as a reference organism.

Vascular plants

In the freshwater and brackish environments, vascular plants have roots in the sediment layer and these root systems will be exposed to external beta and gamma radiation from the sediments. In addition, plants have the ability to bioconcentrate some specific radionuclides (e.g. ^{226}Ra, ^{238}U) and so merit consideration as reference organisms.

Amphibians

Amphibians have a close association with sediments, which will lead to external beta and gamma radiation exposure (especially during hibernation). Data on the bioconcentration of radionuclides by amphibians are very limited, although there are indications that the clearance rates of radionuclides from these organisms are slow. As for reptiles, amphibians cannot be currently suggested as potential candidate reference organism because of the lack of data but this should be reconsidered pending a further review of the available data.

Fish and fish eggs

Benthic fish, such as the marine flatfishes and the freshwater catfishes spend a large proportion of their time on or near the bed sediment, so being exposed to external beta and gamma radiation. In addition, their feeding habits lead to significant inadvertent ingestion of sediment, so increasing the likelihood of internal accumulation of radionuclides. Fish of this type are proposed as a reference organism for all three aquatic ecosystems.

Some fish lay eggs on bed sediments and these eggs will be exposed to external beta and gamma radiation from the sediments. Depending on the size of the eggs, alpha radiation from the sediments may also penetrate far enough into the egg to deliver a significant dose. Such eggs merit consideration as a reference organism; however, unless radionuclides are concentrated within the eggs to a greater extent than they are in the sediment itself, the doses calculated for bacteria will represent a limiting case for such fish eggs. The necessity to include these ‘benthic’ fish eggs as a separate reference organism needs to be reviewed during the next stage of investigation, as well as the general inclusion of ‘egg’ for organisms with external fertilisation (e.g. amphibians).

Wading birds

Wading birds are not normally considered as ‘benthic organisms’ but, in the context of potential radiation exposure, they are closely associated with sediment and with any nuclides, which the sediment may contain. In the intertidal areas of the marine environment they will spend considerable portions of their time over exposed sediments and so be exposed to external beta and gamma radiation. In the brackish environments tidal ranges are likely to be much smaller, and in freshwater environments absent altogether, so greatly reducing this source of exposure. However, in some circumstances contamination of floodplains may be important in this context. Most wading birds obtain their food from within the sediment, either in the form of benthic invertebrates or plant material. There is therefore a potential for internal accumulation of radionuclides associated with the sediment. Wading birds are therefore proposed as a candidate reference organism for all three aquatic ecosystems

Sea mammals

Some seals, like the ringed seal are benthic eaters and therefore will be exposed to sediments containing radionuclides. Owing to their sensitivity and position on top of the food chain, sea mammals should at least be considered as reference organisms. However, it is likely that little data exist regarding exposure of sea mammals to radioactivity.

3.2.2 Water column (see Table 3-5)

Organisms which spend all or most of their time in the water column will generally receive much lower external radiation doses than do the benthic organisms, because the water provides effective shielding from radiation emitted by radionuclides which have accumulated in sediment. However if these organisms exhibit bioconcentration of radionuclides to a high degree they merit consideration as candidate reference organisms.

Phytoplankton

Perhaps because of their high surface area to volume ratio, phytoplankton exhibit high bioconcentration of some radionuclides, including alpha emitters such as ^{210}Po, ^{226}Ra and ^{239}Pu which, despite the small size of the organisms, can deliver substantial internal doses. Phytoplankton are therefore recommended as candidate reference organisms for all three aquatic ecosystems.

Zooplankton

Data on bioconcentration of radionuclides by zooplankton are much more sparse than that for phytoplankton; and in any case zooplankton represent a particularly diverse group of organisms. However zooplankton do appear to bioconcentrate many alpha emitting radionuclides and also beta emitting Ru and Cl nuclides. Generally accumulation or concentration factors are a little lower than for phytoplankton, but in the particular case of ^{210}Po some particularly high concentration factors have been reported. Given the possible radiosensitivity of larval and juvenile forms of many organisms which occur in this group, zooplankton are recommended as candidate reference organisms for all three aquatic ecosystems.

Macroalgae

Macroalgae (seaweeds) are, along with phytoplankton, the important primary producers in marine aquatic ecosystems. They exhibit high degrees of bioconcentration for some specific nuclides (e.g. ^{99}Tc, ^{90}Sr, ^{129}I and ^{106}Ru) and so merit consideration as candidate reference organisms in marine and brackish water ecosystems.

Fish

For most radionuclides there is little or no evidence of biomagnification in aquatic foodchains, but for ^{137}Cs, for which fish exhibit significant bioconcentration, there is some evidence that this may occur (especially in freshwater ecosystems). Therefore it would be sensible to consider predatory pelagic fish as candidate reference organisms for all three aquatic ecosystems.

Sea mammals

For similar reasons, mammals such as seals, whales or otters, which are the ‘top predators’ in the aquatic foodchain, may accumulate particularly high levels of ^{137}Cs. Mammals are likely to be more radiosensitive than fish, and moreover appear to have a high perceived conservation value, so it would be sensible to consider aquatic mammals as candidate reference organisms for all three aquatic ecosystems. However, it is likely that there are only limited data for these species.

Fish eating birds

Fish eating birds (e.g. cormorant, heron) are also ‘top predators’. However explicit consideration of fish eating birds would only be necessary if they showed significantly higher bioconcentration than do aquatic mammals; currently we have no evidence of this.

3.3 Concluding remarks

In this first deliverable we have suggested candidate reference organisms based primarily on radioecological criteria (i.e. potentially those who will be most exposed). The approach taken towards the selection of these organisms should ensure that suitable reference organisms are available for a range of scenarios (chronic and acute exposure) and European ecosystems. In total 31 candidate reference organisms have been suggested. From within these, appropriate organisms would be used within different assessments (i.e. shrubs may be selected instead of grasses in some semi-natural ecosystems). They should also be appropriate reference organisms for radionuclides not included within the initial FASSET assessment. These candidate reference organisms now need to be assessed against radiosensitivity and ecological criteria.

The identification that different parts of an organism may be exposed under various circumstances will require that a range of dosimetric models are developed. For instance, under conditions of acute exposure above ground plant parts should be modelled whilst roots and hyphae should be considered for chronic exposure. Similarly, models will need to be generated for the different live-cycles of some organisms (e.g. adult birds and fertilised eggs). This report provides the necessary input to the dosimetric work, which will be reported in the FASSET Deliverable 3. The final selection of reference organisms will be shown in the framework report, FASSET Deliverable 6.

Table 3-1 Candidate soil-associated reference organisms for terrestrial ecosystems.

Organism type	Forest	Semi-natural	Agricultural	Wetlands	Rationale for inclusion
Micro-organisms	✓	✓	✖	✓	Maximum external exposure to radionuclides in soil including alpha emitters.
Worm	✓	✓	✖	✓	High external exposure to beta and gamma emitting nuclides in soil plus potential to bioconcentrate.
Plants	✓	✓	✓	✓	High external exposure to beta and gamma emitting nuclides.
Fungi	✓	✓	✖	✖	Fungal hyphae receive a high external exposure to beta and gamma emitting nuclides in soil
Burrowing mammal	✓	✓	✖	✖	High external exposure to beta and gamma emitting nuclides in soil plus potential to ingest soil associated with invertebrate prey or whilst grooming etc; may be more exposed to ^{226}Ra than other mammals.

✓ Suggested as candidate reference organism in specified ecosystem
✖ Not suggested as candidate reference organism in specified ecosystem

Table 3-2 Candidate reference organisms for herbaceous layer of terrestrial ecosystems.

Organism type	Forest	Semi-natural	Agricultural	Wetlands	Rationale for inclusion
Lichen and bryophytes	✓	✓	✖	✓	Well documented as bioconcentrator of many aerially deposited radionuclides.
Grass, herbs and crop plants	✓	✓	✓	✓	The foliage can intercept aerially deposited radionuclides, which may lead to high acute exposure. Mobile radionuclides may bioconcentrate in some plant species.
Shrubs	✖	✓	✓	✖	As above, some species have considerably higher uptake of Cs than others.
Detritivorous invertebrates	✓	✓	✖	✖	High concentrations of a number of radionuclides (Am, Pu, Cs). Comparatively highly exposed to external radiation as live in litter layer.
Herbivorous mammals	✓	✓	✓	✓	Comparatively high transfer of mobile radionuclides (Cs, I, Sr) and accumulate less mobile radionuclides (Pu, Am, Ru,) in tissues such as liver. Radiosensitive.
Carnivorous mammals	✓	✓	✖	✓	Top predator may biomagnify some radionuclides (observed for Cs). Radiosensitive.
Bird eggs	✓	✓	✖	✖	The bird egg can potentially be highly exposed to external radiation; accumulation of Sr in shell and comparatively high transfer of some radionuclides to egg contents. Likely to be more radiosensitive life-stage.

✓ Suggested as candidate reference organism in specified ecosystem
✖ Not suggested as candidate reference organism in specified ecosystem

Table 3-3 Candidate reference organisms for canopy layer of terrestrial ecosystems.

Organism type	Forest	Semi-natural	Agricultural	Wetlands	Rationale for inclusion
Trees	✓	✖	✓	✖	The tree foliage has the ability to intercept large proportion (up to 90 %) of aerially deposited radionuclides.
Invertebrates	✓	✖	✖	✖	Residing in the canopy of trees will lead to exposure as a consequence of the ability of the canopy to intercept aerially deposited radionuclides.

✓ Suggested as candidate reference organism in specified ecosystem
✖ Not suggested as candidate reference organism in specified ecosystem

Table 3-4 Candidate sediment-associated reference organisms for aquatic ecosystems.

Organism type	Marine	Brackish	Freshwater	Rationale for inclusion
Bacteria	✓	✓	✓	Maximum external exposure to particle reactive nuclides in sediment including alpha emitters
Worm	✓	✓	✖	High external exposure to beta gamma emitting nuclides in sediment plus potential to bioconcentrate internal emitters. Consideration of insect larvae for brackish and freshwater would better fill this niche for those systems.
Insect larvae	✖	✓	✓	High external exposure to beta gamma emitting nuclides in sediment plus potential to bioconcentrate. Important component of freshwater benthic biomass.
Bivalve molluscs Gastropod molluscs	✓	✓	✓	High external exposure to beta gamma emitting nuclides in sediment plus proven high accumulation of particle reactive radionuclides e.g. ^{106}Ru, ^{210}Po, ^{239}Pu, ^{241}Am.
Crustaceans (lobster, crayfish)	✓	✓	✓	High external exposure to beta gamma emitting nuclides in sediment; potential for bioconcentration of particle reactive radionuclides; evidence of high nuclide specitic bioconcentration (e.g. ^{99}Tc, ^{210}Po)
Amphibians	✖	✖	✓	High exposure to external radiation from beta gamma emitters in sediments – there is little or no data on bioaccumulation.
Fish (e.g. plaice, sole, catfish)	✓	✓	✓	High external exposure to beta gamma emitting nuclides in sediment coupled with bioaccumulation of conservative radionuclides (e.g ^{137}Cs). Fish eggs might be considered, but unless there are data showing high bioconcentration, doses for bacteria will be a 'worst case'.
Vascular plants	✓	✓	✓	High exposure of roots to external radiation from beta gamma emitters in sediments. Proven ability to selectively bioaccumulate (e.g. ^{226}Ra, ^{238}U)
Mammals (e.g. seals)	✓	✓	✓	Feeding on sediment invertebrates maximises possible internal exposure to particle reactive radionuclides, including alpha emitters. Perceived high conservation value; likely to be radiosensitive
Wading birds (e.g. tern, mallard)	✓	✓	✓	Maximises external exposure to beta gamma emitters in sediments; feeding on sediment invertebrates maximises possible internal exposure to particle reactive radionuclides, including alpha

Organism type	Marine	Brackish	Freshwater	Rationale for inclusion
				emitters. Perceived high conservation value.

✓ Recommended as candidate reference organism
✖ Not required as candidate reference organism

Table 3-5 Recommended water column-associated reference organisms.

Organism type	Marine	Brackish	Freshwater	Rationale for inclusion
Phytoplankton (microalgae)	✓	✓	✓	Proven high bioconcentration of certain radionuclides (especially particle reactive) e.g. ^{210}Po, ^{226}Ra, ^{239}Pu
Zooplankton	✓	✓	✓	Bioconcentration data limited but shown to be high in some cases (e.g. ^{210}Po). Represents juvenile form of many species, may be specially radiosensitive including fish eggs
Macroalgae (seaweed)	✓	✓	✖	Proven ability to selectively bioaccumulate (e.g. ^{99}Tc, ^{106}Ru)
Fish (e.g. cod, salmonids)	✓	✓	✓	Proven ability to bioaccumulate (e.g. ^{137}Cs); predatory feeding habits may lead to biomagnification
Mammals (e.g. seals, whales, otters)	✓	✓	✓	As above; position at top of aquatic foodchain may predispose to bioaccumualtion and/or biomagnification. Perceived high conservation value; likely to be radiosensitive
Wading birds (e.g. tern, mallard)	✓	✓	✓	Wading habit maximises external exposure to beta gamma emitters in sediments; feeding on sediment invertebrates maximises possible internal exposure to particle reactive radionuclides, including alpha emitters. Perceived high conservation value (e.g. RAMSAR sites)

✓ Recommended as candidate reference organism
✖ Not required as candidate reference organism

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