Reference Arctic organisms

A deliverable report for EPIC

Project ICA2-CT-2000-10032

Edited by:

N.A.Beresford
S.M.Wright
T.Sazykina

Centre for Ecology & Hydrology
NATURAL ENVIRONMENT RESEARCH COUNCIL

SCIENTIFIC PRODUCTION ASSOCIATION "TYPHOON"
Institute of Experimental Meteorology

Statens strålevern

CENTRE FOR ECOLOGY AND HYDROLOGY
NATURAL ENVIRONMENT RESEARCH COUNCIL

Environmental Protection from Ionising Contaminants (EPIC)

CONTRACT NO: ICA2-CT-2000-10032
CEH PROJECT No: C01608

Reference Arctic Organisms

Edited by N A Beresford[1], S M Wright[1] & T Sazykina[2]

Contributors:
J Brown[3], C L Barnett[1], I Kryshev[2], R Brooker[4], J Bass[5],
B J Howard[1], N Webb[5], D French[4], A Kryshev[2],
P Strand[3] & H Stensrud[3]

November 2001

[1]CEH-Merlewood, Windermere Road, Grange-over-Sands, Cumbria, LA11 6JU, UK.

[2]Scientific & Production Association “TYPHOON”, 82 Lenin Av., Obninsk, Kaluga Region, 249038, Russia.

[3]Stratens Strålevern, Grini Næringspark 13, P.O. Box 55, N1332, Østerås, Norway.

[4]CEH-Banchory, Hill of Brathens, Banchory, Aberdeenshire, AB31 4BY, UK.

[5]CEH-Dorset, Winfrith Technology Centre, Dorchester, Dorset, DT2 8ZD, UK.

Funded under the European Commission Inco-Copernicus programme

<u>E</u>nvironmental <u>P</u>rotection from <u>I</u>onising <u>C</u>ontaminants (EPIC)

To date, the protection of the environment from radiation is based on the premise that if Man is protected from harm, then all other components of the ecosystem will not be at risk. However, this has been increasingly questioned on the basis that it is not always true, it is inconsistent with environmental protection standards for other hazardous materials and conflicts with the recommendations of some international advisory bodies. The aim of the EPIC project is to develop a methodology for the protection of natural populations of organisms in Arctic ecosystems from radiation. This will be achieved by derivation of dose limits for different biota. The project therefore aims to (i) collate information relating to the environmental transfer and fate of selected radionuclides through aquatic and terrestrial ecosystems in the Arctic; (ii) identify reference Arctic biota that can be used to evaluate potential dose rates to biota in different terrestrial, freshwater and marine environments; (iii) model the uptake of a suite of radionuclides to reference Arctic biota; (iv) development of a reference set of dose models for reference Arctic biota; (v) compilation of data on dose-effects relationships and assessments of potential radiological consequences for reference Arctic biota; (vi) and integration of assessments of the environmental impact from radioactive contamination with those for other contaminants.

The EPIC project is funded under the EC Inco-Copernicus research programme and is co-ordinated by the Norwegian Radiation Protection Authority; project partners:

- Centre for Ecology & Hydrology, CEH-Merlewood, Grange-over-Sands, UK.
- Institute of Radiation Hygiene, St Petersburg, Russia.
- Scientific Production Association TYPHOON, Obninsk, Russia.

For further information on the EPIC project contact Dr. Per Strand (per.strand@nrpa.no).

EXECUTIVE SUMMARY

Biota may be exposed to ionising radiation as a consequence of the routine operation of nuclear facilities or in the event of accidents at such facilities. The ethos with regard to protecting the environment has previously been '*if man is adequately protected then other living things are also likely to be sufficiently protected*'. This approach has been increasingly questioned on the basis that it is not always true, it is inconsistent with environmental protection standards for other hazardous materials and conflicts with the recommendations of some international advisory bodies. Whilst some national authorities have established dose assessment methodologies, there is no internationally agreed approach to the protection of the environment to ionising radiations. The overall aim of the EPIC project is to develop a framework for the protection of the Arctic environment (which contains a number of potential sources of radioactive contamination and areas of high natural radiation) from ionising radiation.

One problem in the development of a framework is the diversity and number of flora and fauna species. In response to this the use of *reference organisms* has been suggested (similar to the use of *reference man* in human radiation protection) to represent flora and fauna for which doses and potential effects are to be predicted. In this report, we describe a practical approach for the identification of reference Arctic organisms on the basis of their ecological niche, radiosensitivity, likely internal and/or external exposure to radionuclides and suitability for monitoring and/or future research. As part of this process, ecological characteristics and species present within different Arctic regions have been described Reference organisms have been selected for the marine, terrestrial and freshwater ecosystems in different regions of the Arctic and species representative of these organism groups have been identified where appropriate.

Contents **Page**

1 INTRODUCTION

Biota may be exposed to ionising radiation as a consequence of the routine operation of nuclear facilities or in the event of accidents at such facilities. For instance, following the accidents at both the Mayak production site (1957; southeastern Russian Urals) and the Chernobyl nuclear power plant (1986; Ukraine) biota were exposed to levels of radiation sufficient to result in a range of observable effects (UNSCEAR 1996).

However, radiological protection has traditionally been focused on humans. The ethos with regard to protecting the environment has been '*if man is adequately protected then other living things are also likely to be sufficiently protected*' (ICRP 1977). This approach has been increasingly questioned (e.g. Pentreath 1999) on the basis that it is not always true (i.e. there may be situations where biota can be exposed to harmful doses whilst doses to humans are below recommended limits, e.g. deep sea disposal), it is inconsistent with environmental protection standards for other hazardous materials and conflicts with the recommendations of some international advisory bodies (e.g. IAEA 1995).

Systems for radiological protection of the environment have been proposed (e.g. Pentreath & Woodhead *in-press*) and some national authorities have established dose assessment methodologies (e.g. Bird *et al.* 2000; USDOE 2000; Copplestone *et al.* 2001). However, there is no internationally agreed approach to the protection of the environment from ionising radiation. The EPIC project is one of two funded by the European Commission within the Fifth Framework Programme (the other being the FASSET project (http://www.fasset.org)) the overall aim is the development of a framework for the protection of the environment from ionising radiation (see Strand & Larsson 2001).

1.1 Why the Arctic?

There is increasing concern over potential nuclear contamination of the Arctic due to the wide range of nuclear sources, including nuclear power and reprocessing plants, civil and military nuclear powered vessels, nuclear weapons testing areas, sites of ‘peaceful’ (civil engineering) nuclear explosions, and the current economic situation within the former Soviet Union (fSU) (AMAP 1998; Bøhmer *et al.* 2001). A full discussion of the potential sources of anthropogenic radioactive pollution in the Arctic is given by Strand *et al.* (1997). In summary, within the European Arctic they include:

- the Novaya Zemlya weapons test site;
- seventeen sites of peaceful nuclear explosions within or close to the Arctic Circle;
- the four nuclear reactors at each of the Kola and Bilibino power plants;
- the Russian civilian nuclear fleet which operates from near Murmansk;
- the nuclear powered vessels and resulting spent nuclear fuel of the Russian Northern Fleet;
- riverine transport of discharges from the nuclear fuel reprocessing plants at Chlyabinsk, Krasnoyarsk and Tomsk which may ultimately reach the Kara sea;
- discharges from the reprocessing plants at Cap la Hague and Sellafield which are detected in the Arctic seas.

In addition, within the Komi Autonomous Republic of the Russian Federation, there are a number of small areas with high natural radiation; some of these are within tundra ecosystems.

Low temperatures, extreme seasonal variations in light and lack of nutrients are some of the physical and chemical characteristics which cause environmental stress to organisms in the Arctic, limiting biodiversity and making organisms potentially more vulnerable to contaminants (AMAP 1998). In contrast to the concentration-effects relationships for other contaminants in the Arctic, such as persistent organic pollutants (AMAP 1998), little is known with respect to the potential effects on flora and fauna that would be observed in the Arctic following a significant release of radioactivity; high transfer of radioactivity to many Arctic ecosystems has previously been identified (Strand *et al.* 1997). It is clearly important to be able to model the impact of radionuclides on (sensitive) Arctic ecosystems, not least, so that meaningful comparisons with the impact of other contaminants (real or potential) can be made.

1.2 The Reference Organism Concept

One problem in the development of a framework is the diversity and number of flora and fauna species. To mitigate variation in humans, a *reference Man* have been adopted within radiological protection to provide a standard set of models and datasets to produce information against which other data can be compared (ICRP 1975). A similar use of *reference organisms* to represent flora and fauna has been suggested in a number of articles (e.g. Pentreath & Woodhead 1988; 2000; *in-press*; Pentreath 1999). Strand & Larsson (2001) defined 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.*'

Pentreath & Woodhead (*in-press*) suggested that a pragmatic selection of reference organisms should consider the following criteria:

- the extent to which they are considered to be typical representative fauna or flora of a particular ecosystem;
- the extent to which they are likely to be exposed to radiation from a range of radionuclides in a given situation, both as a result of bioaccumulation and the nature of their surroundings, and because of their overall lifespan, life-cycle and general biology;
- the stage or stages in their life-cycle likely to be of most relevance for evaluating total dose or dose-rate, and of producing different types of dose-effect responses;
- the extent to which their exposure to radiation can be modelled using relatively simple geometries;
- the chances of being able to identify any effects at the level of the individual organism that could be related to radiation exposure;
- the amount of radiobiological information that is already available on them, including data on probable radiation effects;
- their amenability to future research in order to obtain the necessary data on radiation effects;

- the extent to which they have some form of public or political resonance, so that both decision makers and the general public at large are likely to know what these organisms actually are, in common language.

Strand & Larsson (2001) suggested that reference organisms should in addition be ubiquitous and have ecological relevance.

In this report, we select reference organisms for assessments of the impacts of irradiation on flora and fauna within the Arctic. In future reports, subsequently development of internal and external dose models will be described. Our selection of reference organisms will broadly follow the criteria proposed above and the specifics of our methodology are discussed later in Section 3.

1.3 Radionuclides Considered

There are a large range of anthropogenic and natural radionuclides which may need to be considered within environmental impact assessments and in this initial consideration of a framework it is not possible to consider them all. A sub-set of thirteen radionuclides has therefore been selected (Table 1.1). These represent: (i) radionuclides routinely considered in regulatory assessments of waste disposal and releases from different facility types; (ii) a range of environmental mobilities and biological uptake rates (see Table 1.1); and (iii) both anthropogenic and natural radionuclides. Such a range in radionuclides is required to ensure that appropriate reference organisms are selected; those selected on the basis of one radionuclide (or indeed scenario) may not be the same as those selected for others. Subsequently, our framework designed to assess these radionuclides should be readily applicable to the consideration of other radionuclides.

Table 1.1. Selected radionuclides with generalised adapted from Whicker & Schultz (1982).

Radionuclide (Periodic Group)	Principal Radioisotopes ($T_{½}$)	Sources	Nutrient analogues	Principal biospheric reservoirs	Environmental mobility	Concentration increase with trophic level	Critical organ (vertebrates)	Biological half-life (mammals)
K (Ia)	^{40}K (1.3 x 10^{9} y)	Primordial	K	Lithosphere	High	Approaches 1	Total body	Moderate (weeks)
Cs (Ia)	^{134}Cs (2.06 y), ^{137}Cs (30 y)	Fission	K	Soil, sediments	High	Approaches 3	Total body	Moderate (weeks-months)
Sr (IIa)	^{89}Sr (50.5 d) ^{90}Sr (28.5 y)	Fission	Ca	Soil, biota	High	< 1	Bone	High (years)
Tc (VIIa)	^{99}Tc (2.13 x 10^{5} y)	Fission	None	Biota, soil	High	< 1	Gastrointestinal tract, lung	Low (days)
Po (VIb)	^{210}Po (138 d)	^{238}U decay series	None	Soil, sediment	High	<1-10	Spleen, kidney, lung	Moderate (weeks)
Pu (Actinide series)	^{238}Pu (88 y) ^{239}Pu (2.4 x 10^{5} y) ^{240}Pu (6.5 x 10^{3} y) ^{241}Pu (14.4 y)	Activation, neutron capture	None	Soil, sediment	Very low	< 10^{-2}	Bone, lung	High (years)
Am (Actinide series)	^{241}Am (432 y)	Activation, neutron capture, decay of ^{241}Pu	None	Soil, sediment	Very low	< 10^{-2}		High (years)
I (VIIb)	^{129}I (1.57 x 10^{7} y) ^{131}I (8.04 d)	Fission	I	Biota, soil	High	Up to 10^{3} (thyroid/plants)	Thyroid	Moderate (weeks-months)
Ra (IIa)	^{226}Ra (1600 y)	^{238}U decay series	Ca	Lithosphere	Moderate	< 1	Bone	High (years)
H (Ia)	^{3}H (12 y)	Cosmic, Fission, activation	H	Hydrosphere (tritiated water)	High	Approaches 1	Total body	Low (days)
C (IVb)	^{14}C (5600 y)	Cosmic, activation	C	Atmosphere (CO_2)	High	Approaches 1	Total body	Low (days)
Th (Actinide series)	^{227}Th (18.7 d) ^{228}Th (1.9 y) ^{230}Th (7.7 x 10^{4} y) ^{231}Th (25.5 h) ^{232}Th (1.4 x 10^{10} y) ^{234}Th (24.1 d)	Natural, U & Th series decay chains	None	Lithosphere	Very low	< 10^{-2}	Bone, lung	High (years)
U (Actinide series)	^{234}U (2.45 x 10^{5} y) ^{235}U (7.04 x 10^{8} y) ^{238}U (4.47 x 10^{9} y)	Natural	None	Lithosphere	Low-moderate	< 1	GI, kidney, lung	Moderate (months)

2 ARCTIC ECOSYSTEMS (see AMAP 1998)

The Arctic is a cold region located around the North Pole, consisting of an ocean basin with a number of islands and a surrounding fringe of continental land (Figure 2.1). The extent of the Arctic can be simply delineated using the Arctic Circle (66° 32' N) marking the southern limit of midnight sun. This crude definition ignores the influence of climate and topography.

The area of interest in EPIC is the European Arctic including northern Scandinavia and northwest Russia (west of the Ural Mountains), the islands of Svalbard, Franz Josef Land and Novaya Zemlya and the Barents, Kara, White and Greenland Seas including the northern part of the Norwegian Sea. Within this area, the coast of the mainland European Arctic is generally low-lying and ice free in the summer, whereas ice covers much of the Svalbard archipelago and caps areas of Franz Josef Land and Novaya Zemlya all year round. The Arctic Ocean has a deep (> 4000 m) and complex basin. At its centre a permanent cover of slowly circulating ice, up to 4 m thick and several years old, is surrounded by seasonal pack ice, and ice that extends during winter to reach continental land.

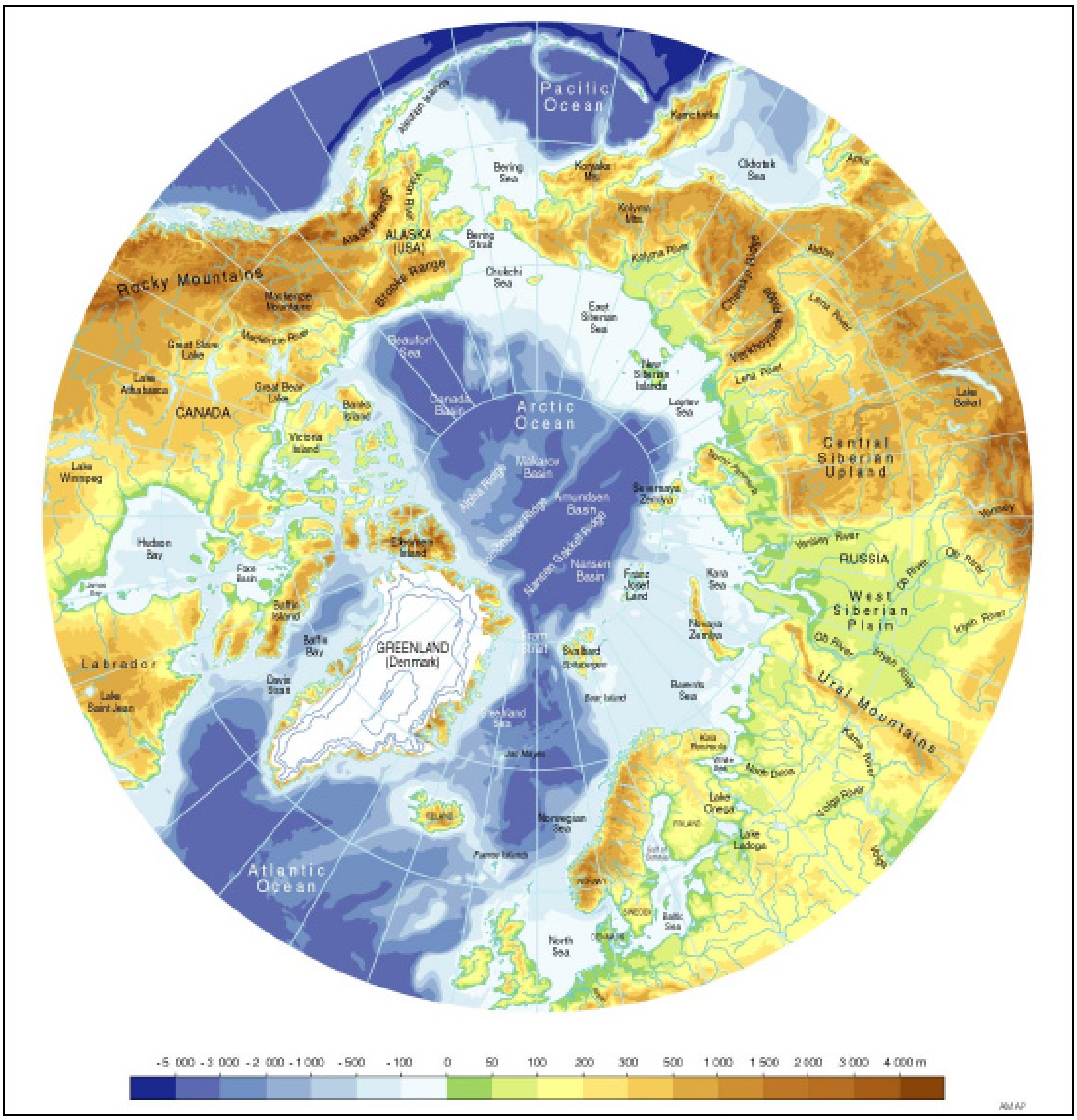

Figure 2.1. Topography and bathymetry of the Arctic (taken from AMAP 1998).

The extreme conditions (seasonal variations in incoming solar radiation, cold temperatures, extensive snow and ice cover and short growing seasons) found in the Arctic ecosystems dramatically influence their productivity, species diversity and organism behaviour. The Arctic receives significantly less incoming solar radiation than temperate regions, which is unevenly distributed throughout the year. Much of the incoming solar radiation is reflected back into space due to the high albedo of snow and ice covering both the land and sea. Incoming solar radiation is received 24 hours per day during the Arctic summer, but annually more than 50 % of the total incoming solar radiation is received before the spring melt.

For this report, the Arctic is divided into three regions, the High, Low and Sub- Arctic, based upon climatic characteristics of terrestrial ecosystems although extended to include marine areas (Figure 2.2):

- **High Arctic** - The most northern region of the Arctic has a growing season of only 1-2.5 months with mean July temperatures of 4-8°C. Much of the High Arctic terrestrial habitat is Polar Desert and is composed primarily of bare ground or rock, lacking the necessary available moisture and warmth to sustain vegetation growth. In Europe, polar deserts are restricted to islands in the Arctic Ocean. Vascular plant cover is typically 0-20% with lichens and mosses increasing this to 50-80% in some areas.
- **Low Arctic** – Has a growing season of between three to four months with mean July temperatures of 4-11°C. Broadly, the Low Arctic occurs where summer temperatures are above freezing with sufficient moisture to support vegetation growth. In Europe, low willow and birch shrub tundra forms a wide transition zone from the forest-tundra areas and often extends to the shore of the Arctic Ocean. Plant cover can typically reach 80-100%.

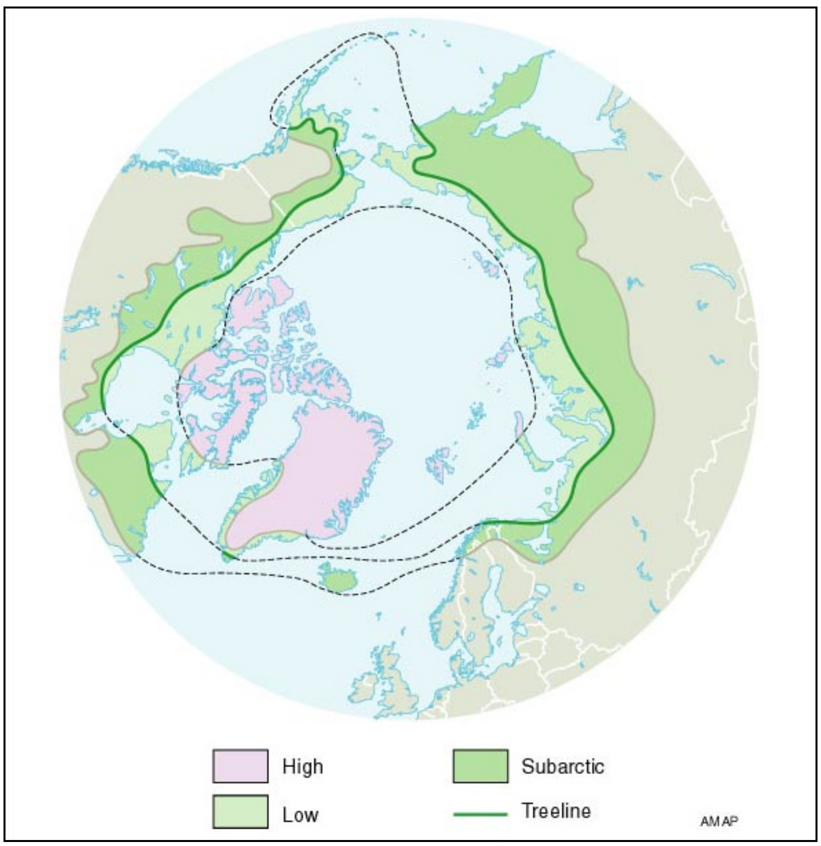

Figure 2.2. Arctic and sub-arctic floristic boundaries (taken from AMAP 1998).

- **Subarctic** –The transition zone between boreal forest and treeless tundra with a growing season of 3.5-12 months and a plant cover of 100%. Sometimes referred to as forest-tundra.

Species lists of European Arctic flora and fauna in terrestrial, freshwater and marine environments are given in Appendix 1, together with details of how these were derived.

2.1 Terrestrial Ecosystems (see AMAP 1998; CAFF 2000; Stonehouse 1989)

The number of species in terrestrial ecosystems is often limited, forming simple foodchains (e.g. lichen ? reindeer ? wolf). The low species diversity has been attributed to slow recovery from past glaciations and low biological productivity. Overall, the number of species declines as latitude increases (see Appendix 1), a general response to the increasing severity of environmental conditions. In terms of flora, the Arctic includes only 1.2, 4.4 and 12.5 % of the worlds vascular plants, mosses and lichens. Genetic and behavioural diversity within species is usually higher in the Arctic than for other regions creating mosaics of different populations and sub-species.

The short length of the growing season is the most significant factor influencing biological productivity. Growing seasons in the Low Arctic can range between three to four months but can be as little as one month in the High Arctic. Climate can vary greatly over relatively short distances due to local topography (e.g. slope influences the amount of incoming solar radiation received and soil temperatures can significantly rise above those of the surrounding air). Arctic ecosystems receive relatively little precipitation, mostly as snow, although areas in proximity to sea or mountains can receive significantly increased levels of precipitation. The availability of moisture and protection from climatic extremes provided by snow cover are key factors in the growth and survival of many plants in the Arctic. The majority of the annual runoff occurs during snowmelt over periods that can be as short as only two to three weeks. In areas of the High Arctic or at high altitudes, biological activity can end abruptly following the cessation of snowmelt. Away from the High Arctic, significant areas of wetlands can develop during the summer due to low rates of evaporation and frozen soil layers.

Arctic soils are poorly developed and can remain frozen for most of the year. The availability of nutrients within Arctic soils tends to be low and decomposition rates can be limited by cold temperatures; cold also reduces the rate of nutrient uptake through plant roots. Carbon accumulates in Arctic soils and nutrients such as N and P remain bound in decaying organic matter and unavailable for plant growth.

As a consequence of these environmental conditions, biological productivity in terrestrial Arctic ecosystems is greatly reduced and organisms tend to be longer-lived with slow growth rates. Many species exhibit physiological and behavioural adaptations to the cold making them sensitive to environmental change. With large variations in environmental conditions during the year, Arctic ecosystems often exhibit seasonal productivity cycles including bursts of primary productivity with increasing solar radiation levels and temperatures in the spring. Survival of many plants and animals in the Arctic, particularly during the winter, is dependent upon their ability to exploit conditions during the summer - organisms store energy and nutrients when food is available. Cold-blooded animals only have a small period during the Arctic summer during which they may develop. With differing environmental conditions both within and between years (e.g. differences in temperature, moisture and food availability), certain Arctic species adjust their feeding habits, growth rates (e.g. Arctic willow (*Salix arctica*)) and reproduction (e.g. the reproduction rates of predators including foxes, weasels and raptors fluctuate with the availability of prey such as lemmings). Indeed, some species will be opportunistic feeders with a number of possible positions within foodchains (e.g. brown bears (*Ursus arctos*) are mainly herbivorous feeding on roots, shoots, berries and wild honey, and occasionally eat fish, small mammals and birds and carrion). Alternatively, some Arctic organisms migrate to overwintering, feeding or spawning areas.

Arctic foodchains are generally short, and changes in environmental conditions can lead to the rapid growth or decline of Arctic organisms (e.g. populations of herbivores and their predators). In a typical terrestrial Arctic foodchain, lichens and plants are the primary producers with relatively few herbivores and one or two main predators (Figure 2.3).

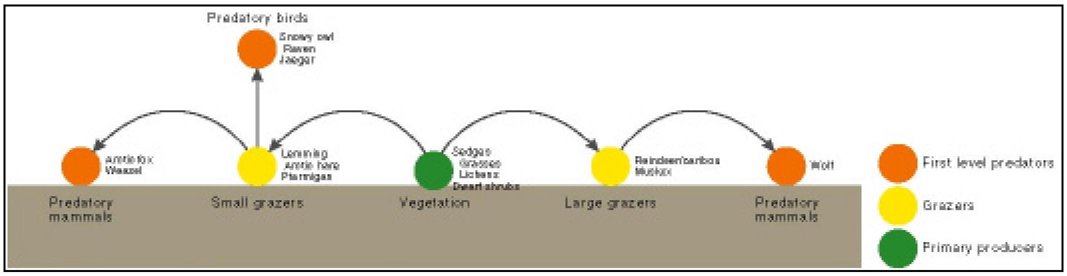

Figure 2.3. A typical terrestrial foodchain (taken from AMAP 1998).

Microbes including bacteria, algae, fungi and protozoans are responsible for a significant part of the primary production and decomposition in Arctic ecosystems. Parasitic (using living plants and animals) and saprophytic (using dead plants and animals) fungi are essential to decay processes in the Arctic.

In the northern Polar Desert there are few, if any, macroscopic plants. Vegetation is present in the form of a thin, single layer with algae, lichens, mosses and liverworts. Patchy ground cover is composed of lichens and mosses; lichens of many forms occur (including *Neuropogon sulpureus*, *Collema*, *Ochrolechia*, *Pertusaria* and *Toninia* species), often as pioneer species colonising bare ground and rock, contributing the most to total biomass. Blue-green algae are present amongst the lichens. Moss species found in Polar Desert include those of the genera *Bryum*, *Pohlia*, *Myurella*, *Rhacomitrium*, *Andreaea* and *Onchophorus*; in wet areas where mires exist, *Orthothecium chryseum*, or species of *Campylium* and *Bryum* occur. Liverworts can be found growing with mosses. Around 60 species of angiosperms are found growing in isolated clusters, including cushion plants (e.g. *Dryas integrifolia*, *Saxifraga oppositifolia*, *Silene acaulis* and *Papaver* spp.), small tufts (e.g. grasses *Phippsia algidae* and *Poa abbreviata*) and prostrate shrubs of *Salix arctica* and rosette species (e.g. *Saxifraga*, *Draba*, and *Minuartia*). In the transition between the High Arctic and tundra some vascular cryptogams (ferns) can also be found. Local 'oases' occur with high species diversity and productivity resulting from favourable environmental conditions (e.g. areas enriched with guano deposits from breeding bird colonies).

Plants typical of the Low Arctic include low shrubs (e.g. *Alnus*, *Salix* and *Betula* spp.), dwarf shrubs of heath species (e.g. *Ledum*, *Vaccinium*, *Cassiope* and *Empetrum* spp.), sedges (e.g. *Carex* and *Eriophorum* spp.), rushes (*Juncus* and *Luzula* spp.), grasses (e.g. *Poa* and *Arctagrostis* spp.), cushion plants (e.g. *Dryas* spp.), chickweeds (*Stellaria* spp.), wintergreen (*Pyrola grandiflora*), willow-herb (*Epilobium latifolium*), mountain vetch (*Astragalus alpinus*), Labrador-tea (*Ledum decumbens*), ferns (e.g. *Woodsia* spp.), lupins (*Lupinus arcticus*), buttercups (*Ranunculus lapponicus*), windflowers (*Anenome parviflora*), louseworts (*Pedicularis* spp.), lichens (e.g. *Cladonia* spp.) and mosses.

The Subarctic contains those plants found in the Low Arctic, some boreal species (e.g. *Deschampsia flexuosa*, *Epilobium angustifolium*, *Empetrum* hermaphroditicum, *Vaccinium myrtillus* and *V. uliginosum*) and stands of trees (e.g. *Pinus sylvestris*, *Pinus pumila*). Birch (*Betula* spp.) forests can be found between the shrub belt and boreal forests.

Arctic soil invertebrates include, nematodes, collembola, enchytraeid worms, copepods, ostracods, cladocerans, platyhelminths, mites, spiders and insect larvae. Even though the diversity of soil organisms in the Arctic is low, there is no apparent reduction in the number of bacterial or fungal processes. Overall, species richness of invertebrates in the Arctic is low compared to temperate ecosystems (e.g. beetles (*Coleoptera* spp.)), with some species, such as earthworms (e.g. *Lumbricus* spp.) absent. In warmer areas of tundra, beetles, moths, butterflies, ichneumon flies, bumblebees, cranefiles, blowflies and other diptera occur. Warble flies parasitise reindeer and biting simuliid flies and mosquitoes are common. Compared to temperate grasslands only larger invertebrate herbivores, such as browsing and grazing insects, are not found in Arctic ecosystems. The majority of Arctic insects are dormant during winter.

Amphibia and viviparous reptiles have been known to reach the northern edge of Boreal Forests, but are rarely found in areas north of the treeline.

The Arctic has over 150 species of breeding birds, with relatively few resident in tundra areas for the whole year. The majority of permanent resident bird species breed in the far north during the summer, and move to areas with more hospitable winter conditions such as tundra or the coast. Resident bird species in the Arctic include the rock and willow ptarmigan (*Lagopus mutus* and *L. lagopus*), hazel grouse (*Tetrastes bonasia*), capercaillie (*Tetrao urogallus*), raven (*Corvus corax*), snowy owl (*Nyctea scandiaca*), merlin (*Falco columbarius*), gyrfalcon (*Falco rusticolus*), rough legged buzzard (*Buteo lagopus*), white-tailed sea eagle (*Haliaeetus albicilla*) and golden eagle (*Aquila chrysaetos*).

In the summer, over 120 bird species migrate to Arctic areas for breeding, taking advantage of lower population densities and plentiful food. Migratory birds include small, insect eating birds (e.g. white wagtail, *Motacilla alba*; sedge warbler, *Acrocephalus schoenobaenus*; arctic warbler, *Phylloscopus borealis*; reed bunting, *Emberiza schoeniclus*; brambling, *Fringilla montifringilla*; pine grosbeak, *Pinicola enucleator*; Siberian jay, *Perisoreus infaustus*), waders (e.g. *Erolius bairdii*; sandpiper, *Calidris* spp.; ringed plover *Charadrius hiaticula*; the golden plover, *Pluvialis apricaria*), songbirds (e.g. Lapland bunting, *Calcarius lapponicus*; snow bunting, *Plectrophenax nivalis*; common redpoll, *Carduelis flammea*; Arctic redpoll *Carduelis hornemanni*), loons (e.g. red-throated loon, *Gavia stellata*), ducks (e.g. common eider, *Somateria mollissima*; teal, *Anas crecca*; long-tailed duck, *Clangula hyemalis*), geese and swans (e.g. snow goose, *Chen caerulescens*; lesser white-fronted goose, *Anser erythropus*; bean goose, *Anser fabilis*; whooper swan, *Cygnus cygnus*) and birds of prey (e.g. long-tailed skua, *Stercorarius longicaudus*; peregrine falcon, *Falco peregrinus*).

Around 50 species of land mammal live in the Arctic many of which hibernate (e.g. marmots and brown bear). Herbivores include lemmings (e.g. *Lemmus sibiricus*, *Dicrostonyx groenlandicus*, *Myopus schisticolor*), voles (e.g. *Microtus oeconomus*, *M. gregalis*, *Clethrionomys rufocanus*), marmots (e.g. *Marmota camtschatica*), red squirrels (*Sciurus vulgaris*), arctic ground squirrels (*Spremophilus undulates*), northern pika (*Ochotona hyperborean*), mountain hare (*Lepus timidus*), moose (*Alces alces*), reindeer (*Rangifer tarandus*) and muskox (*Ovibos moschatus*). Carniverous animals in the Arctic include shrews (*Sorex* spp.), the stoat (*Mustela erminea*), least weasel (*Mustela* nivalis), European mink (*Mustela* lutreola), pine martin (*Martes martes*), otter (*Lutra canadensis*), Eurasian beaver

(*Castor* fiber), red fox (*Vulpes vulpes*) and the arctic fox (*Alopex lagopus*), lynx (Felis *lynx*), wolverine (*Gulo gulo*), gray wolf (*Canis lupus*) and brown bear (*Ursus arctos*).

2.2 Freshwater Ecosystems (see Stonehouse 1989)

Freshwaters within the Arctic can be classified as still-water or running-water ecosystems.

Still-water environments include wetlands, ponds and lakes. Wetlands are characteristic of the Low Arctic. Many ponds and lakes are also found in the European Arctic having formed in depressions left by retreating glaciers and melting permafrost ice. Large areas of the Kola Peninsula are covered by Arctic wetlands and there are over 100 000 lakes, the largest of which has an area of 812 km^2 and a depth of 67 m.

Within still-water environments, biological activity begins prior to the complete melting of ice. Aquatic algae and bacteria start photosynthesis and form communities on the underside of the ice as early as February when light begins to penetrate the ice. In such environments, the most important factor restricting primary production is the lack of available nutrients. Primary productivity tends to reach a maximum in the early summer corresponding to the peak in release and leaching of nutrients from frost shattered minerals and thawing organic deposits.

Phytoplankton (*Anabaena, Aphanizomenon, Dinobryon, Melosira, Fragillaria, Tabellaria* spp.*)*, zooplankton (Rotatoria, Cladocera, Copepoda spp.) and microflagellates occur in the upper layers of still-water environments. Shallow lakes can have aquatic mosses that oxygenate bottom waters, whilst deeper lakes tend to accumulate sediment and have stagnant bottom waters. Aquatic plants include species of sedge, reed and pondweed. Zoobenthos within still-water environments are dominated by detritus-feeding invertebrates and tend to be restricted to rotifers, tardigrades, a few species of copepods and other crustaceans, enchytraeid worms, chironomid fly larvae and molluscs (*Limnaea*, *Pisidium*, *Planorbis* spp.). Chironomid larvae form the main food for Arctic char (*Salvelinus aplinus*) whilst adults provide a major food source for many insectivorous birds and the young of wildfowl and waders. Plankton-eating fish including the northern whitefish (*Coregonus peled*) are found in High Arctic lakes whilst shallow water cisco (*Coregonus albula*) are found in Low Arctic and Subarctic lakes. Zoobenthos eating fish such as cisco (*Coregonus lavaretus*), bream (*Abramis brama*) and roach (*Rutilus rutilus*) and predatory fish such as pike (*Esox lucius*) and burbot (*Lota lota*) can are common in Low and Sub- Arctic lakes. A typical foodchain of an Arctic lake ecosystem is shown in Figure 2.4.

The flow in Arctic rivers is largely dominated by rain and snow and ice melt due to permafrost limiting the water storage capacity of soils and underlying geology. Most rivers are confined to the Low Arctic region and exhibit regimes where the majority of their discharge occurs during snow melt in the spring; in wetland areas, peak flows occur during the period of snow melt coinciding with the presence of frozen ground in the early spring. Smaller Arctic streams and rivers can be classified into mountain, spring or tundra streams. Mountain streams tend to be the longest, originating in upland areas and collecting tributaries and ground water along their length. Mountain streams flow during the warmer months of the year, with headwaters remaining much cooler than waters flowing across the tundra. Spring-fed streams flow from perennial springs, with many flowing all year round; they form the tributaries of mountain streams and have higher mineral contents. Tundra streams have low flow rates and meander across the tundra. They have a low pH as a result of humic acids from the peaty soils they drain. Of these three types, the least productive, with the smallest standing crop of invertebrates and lowest species diversity are the mountain streams. Tundra and spring-fed streams are richer in invertebrates by factors of 10 and 100 respectively. Arctic char can be found in mountain and spring-fed streams whilst grayling (*Thymalus arcticus*) occur in tundra streams.

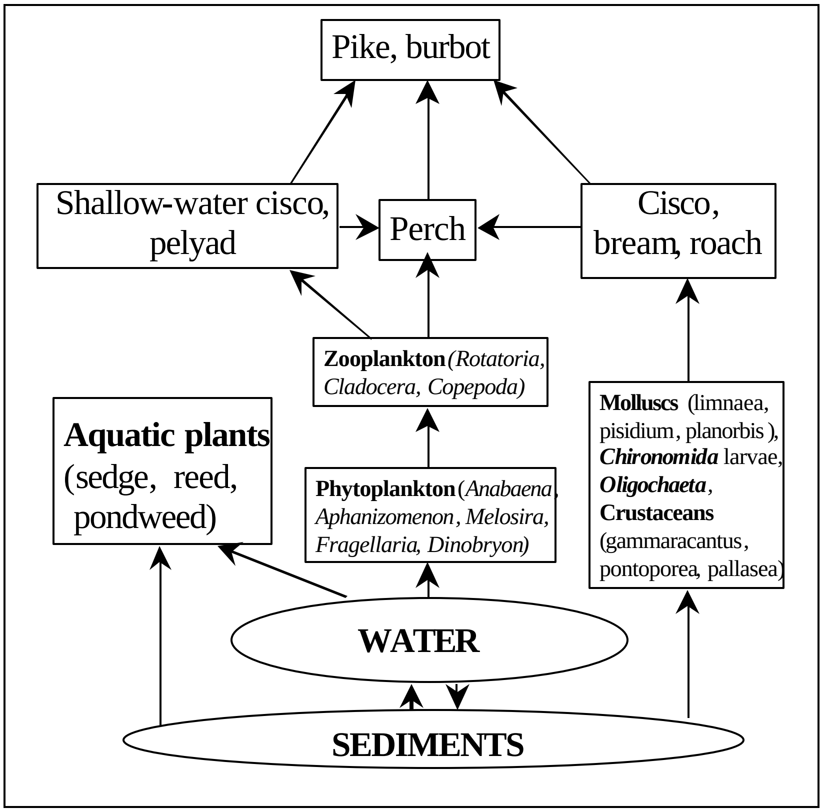

Figure 2.4. Typical foodchain of an Arctic lake ecosystem.

2.3 Marine Ecosystems

The Arctic seas have significant ice cover during periods of the year (especially the Kara, White and Greenland seas), a high proportion of continental shelf areas and shallow waters, and a large influx of freshwater from major river systems and melting ice. Large masses of warmer North-Atlantic waters penetrate into the Norwegian, Barents and White Seas and, in combination with a favourable active light regime during the spring and summer, excellent conditions exist for phytoplankton development making these areas highly productive (Andriyashev 1954; Zenkevich 1963). Due to the influx of warmer waters from the Atlantic, biota within the Norwegian Sea are dominated by more-temperate species whilst in the Barents and White Seas temperate and polar species co-exist; the Kara Sea can be considered as a truly polar sea (Matishov 1989).

The Arctic seas support biological communities comparable to those in northern temperate oceans, although with reduced abundance often leading to simpler foodchains. Marine biota are broadly subdivided into pelagic, those inhabiting the water column, and benthic, those inhabiting the bottom sediments. Pelagic food chains transform solar energy into living matter, whilst benthic food chains accomplish the regeneration of biogenic elements, maintaining the circulation of chemical elements. At the bottom of the water column, the biomass of benthic organisms in Arctic seas is generally low reflecting the reduced quantities of organic matter reaching the seabed. In shallow waters, more organic matter is available to benthos and consequently, marginal seas/shelf areas have higher benthic biomasses, often dominated by large bivalves and other suspension feeders. In coastal waters, a number of different environments can exist providing habitats for different organisms including (i) the intertidal zone with mud flats, estuaries and rocky coastal margins; (ii) coastal cliffs and skerries; and (iii) marginal and shelf seas. Shelf seas are important spawning and feeding areas for numerous fish species.

The majority of primary production in marine waters is accomplished by single-celled 0.5-10 µm phototrophs (bacteria and protists, including diatoms, flagellates, dinoflagellates and coccolithophores), which act as food for primary consumers, such as protozoa and zooplankton; these in turn are consumed by higher trophic level organisms. Zooplankton can be divided into holoplankton, which exist as plankton for all their lives, and meroplankton that only spend part of their life cycle, usually the larval or juvenile stage, as plankton. Meroplankton tend to form a significant component of zooplankton communities.

In the pelagic component of the ecosystem, freely swimming organisms (termed nekton) occupy successively higher predatory trophic levels (Figure 2.5). The vast majority of nekton are vertebrates (including fishes, reptiles, and mammals), molluscs, and crustaceans. However, the distinction between nekton and plankton is not always clear as many large marine animals, such as cod, spend the larval stage of their lives as plankton and their adult stage as large and active members of the nekton. Over 150 species of fish inhabit Arctic and subarctic marine waters, however, most are present in low numbers. Smaller fish, such as capelin (*Mallotus villosus*), Arctic cod (*Boreogadus saida*) and herring (*Clupea harengus*), and baleen (e.g. bowhead (*Balaena mysticetus*), blue (*Balaenoptera musculus*), minke (*Balaenoptera acutorostrata*), humpback (*Megaptera novaeangliae*) and fin (*Balaenoptera physalus*)) whales are examples of first-level predators that consume zooplankton. Second- and third-level predators include a variety of fish and mammals that prey upon some of these organisms (with the exception of large baleen whales). In Arctic seas, Atlantic cod (*Gadus morhua*), Greenland halibut (*Reinhardtius hippoglossoides*), redfish (*Sebastes* spp.) and pollock (*Pollachius virens*) feed on populations of capelin and Arctic cod. Many predators have varied diets consuming organisms from several different trophic levels; for example, the grey seal (*Halichoerus grypus*) feeds on a variety of fish along with cephalopods and crustaceans. Further species of seal found in the Arctic include bearded seal (*Erignathus barbatus*), harp seal (*Phoca groenlandica*), hooded seal (*Cystophora cristata*) and walrus (*Odobaenus rosmarus*). Top-level predators include toothed whales (e.g., the killer whale (*Orcinus orca*)), sharks and the polar bear (*Ursus maritimus*). Polar bear feed mainly on ringed seal but also prey on bearded seal, beluga whales and walrus.

In coastal areas, seabirds are also part of the marine food chain as first- and second-level predators feeding on plankton and fish (e.g. Atlantic puffin (*Fratercula arctica*) and Atlantic guillemot (*Uria aalge*)) and top predators feeding on fish and other seabirds (e.g. parasitic skua (*Stercorarius parasiticus*) and White-tailed sea-eagle, *Haliaeetus albicilla*).

Benthic food chains (Figure 2.5) 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 worms, echinoderms, crustaceans) and filter feeders (e.g. molluscs). In turn, organisms from higher trophic levels, including plaice (*Pleuronectes platessa*), haddock (*Melanogrammus aeglefinus*), bearded seal, ringed seal, walrus, prey on benthic organisms.

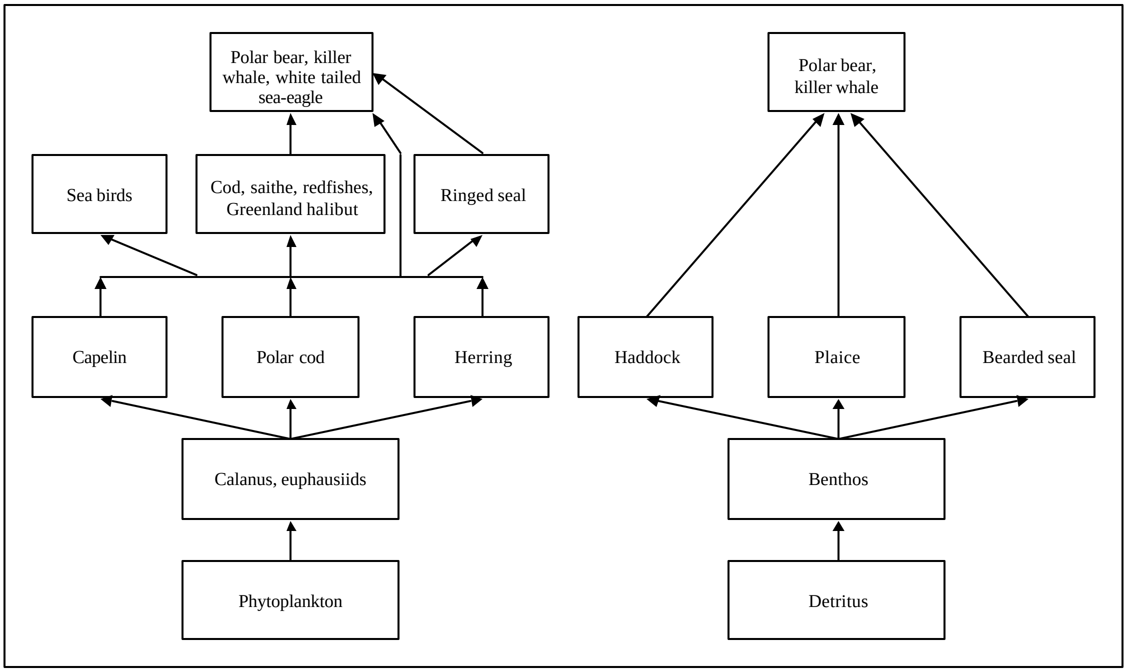

Figure 2.5. Basic foodchains of Arctic seas.

3 CRITERIA FOR THE SELECTION OF REFERENCE ORGANISMS

The criteria described within this section and used to select reference organisms for the Arctic broadly follows that suggested by Pentreath & Woodhead (*in-press*) (see Section 1.2). In the following sections, we evaluate the criteria of ecological niche, radiosensitivity, radioecological sensitivity and data availability/amenability to data collection to aid our selection of Arctic reference organisms. Because, as will become evident, many of the ecological niches, radiosensitivities and radioecological sensitivities of marine and freshwater systems are similar they are considered together in much of the following discussion. The conclusions of each stage of the selection are tabulated (Table 3.1 for terrestrial and Table 3.2 for aquatic) to demonstrate and aid the iterative process of reference organism selection.

3.1 Ecological Niche

Strand & Larsson (2001) suggested that selected reference organisms should have 'ecological relevance'. The concept of ecological relevance, in terms of 'importance' of an organism to the ecosystem, is however difficult to address objectively. For instance, seed eating birds, whilst contributing little to the biomass and energy flows of Arctic terrestrial ecosystems, play a vital, if short-term, role in ecosystem function and survival through the dispersal of seeds. Perhaps one approach to the issue of ecological relevance is to assess the requirements for representation of each trophic level. Dominant organisms in each trophic level are responsible for the major energy and nutrient flows in the ecosystems; therefore, it could be argued that protection of these organisms (by selection as reference organisms) will ensure the protection of the ecosystem as a whole.

On the basis of the food webs discussed within Section 2 (see Figures 2.3-2.5) trophic levels have been identified in Tables 3.1 and 3.2. For aquatic systems, both pelagic and benthic foodchains are shown. Where a given trophic level may be occupied by different taxonomic groups (e.g. terrestrial herbivores may include insects, birds or mammals) we have included all groups in recognition that this may be required for subsequent criteria. Similarly, to be pragmatic and aid later discussion, other groupings have been applied (e.g. macrofungi, soil micro-organisms, lichens and bryophytes etc.) and certain organisms have been allocated to one ecosystem type only (e.g. amphibia to aquatic) when they may occur in both (and, in the interests of simplicity, interactions between ecosystems have not been considered).

3.2 Classification of Radiosensitivities (see UNSCEAR 1996)

The theme of effects of ionising radiation on living organisms has been reviewed extensively elsewhere (Rose 1992; UNSCEAR 1996). UNSCEAR (1996) presents a comparative sensitivity of different organisms to radiation in terms of acute lethal dose (Figure 3.1). We recognised that other radiation-induced effects (e.g. morbidity, fertility and fecundity) may be of importance when assessing the impacts of ionising radiation on individuals, populations and the environment. However, given the current lack of a thorough review of these factors for different biota we will use comparative lethal dose (mortality) to aid in the selection of reference organisms. A comprehensive assessment of dose-effect relationships against different end-points will be an output of the FASSET project (http://www.fasset.org).

3.2.1 Micro-organisms

Micro-organisms (including bacteria, unicellular algae, protozoa and microscopic fungi), are the least radiosensitive of organisms. Whilst reductions in *Pseudomonas* numbers have been observed at acute doses of 20 Gy (H. Jones *pers comm.*[1]) some species of bacteria survive doses in excess of 50 kGy (Yardin *et al.* 2000).

3.2.2 Plants and fungi

Plants and fungi can be placed in the following order of decreasing radiosensitivity (Woodwell & Rebuck 1967; Woodwell & Whittaker 1968):

coniferous trees > deciduous trees > shrubs > herbaceous plants

> lichen, mosses, algae and fungi

Lichen, can survive at dose rates in excess of 1 Gy hr^{-1}, over long exposure periods, and are clearly radioresistant. Macrofungi have also been shown to be resistant to the effects of ionising radiation and produce fruiting bodies at dose rates in excess of 100 mGy hr^{-1} (UNSCEAR 1996). Although data for other lower plants, including mosses and macroalgae, are limited, the available information on classification of organisms according to molecular and cellular characteristics, suggests that these biota types are also relatively radioresistant (UNSCEAR 1996). At the other end of the scale, coniferous trees are relatively radiosensitive exhibiting LD_{50}[2] values that are not greatly above those observed for birds and mammals. LD_{50} values as a consequence of acute exposure have been measured in the range 30-50 Gy (Karaban *et al.* 1980) dependent, to some extent, on the season of exposure.

3.2.3 Invertebrates

The generic group "invertebrates" includes biota expressing great diversity in form and physiology. For example, the category includes anything from highly complex cephalopods (e.g. octopus, cuttle fish) to physiologically primitive animals such as flat worms (*Platyhelminthes*) and annelid worms. The number of radiation studies conducted for the group as a whole is fairly limited although a large database exists on radiation effects for some invertebrate groups. Only tentative conclusions can therefore be drawn on the available data and by considering common types of invertebrate.

O'Brien & Wolfe (1964) concluded that insects are, in general terms, far less sensitive to radiation than vertebrates. No significant mortality effects were observed at 10 mGy h^{-1} over the 24 week lifespan of the freshwater snail *Physa heterostropha* (Cooley 1973). For food-limited populations of daphnia (a freshwater crustacean) mortality was increased at 35-40 mGy hr^{-1} (Marshall 1966).

The mortality of the blue crab (*Callinectes sapidus*) was increased at dose rates of 290 mGy h^{-1} over a 50-day period (Engel 1967).

---

[1] H. Jones, School of Life and Environmental Sciences, The University of Nottingham, UK.

[2] LD_{50} – the dose which cause the death of 50 % of the irradiated organisms; the dose required to achieve LD_{50} 30 days after acute irradiation is notated as $LD_{50/30}$ etc.

Table 3.1 Selection of terrestrial reference organisms.

Organism group	Trophic Level	Radiosensitivity	Radionuclides these organisms are likely to have relatively high activity concentrations of?	Is external exposure an important pathway?	Number of species present in Arctic regions (Summer migrants)			Suitability for monitoring (M) and/or research (R)?	Select as reference organism?
					High	Low	Sub		
Lichens & bryophytes	Primary producer	Low	Cs, Sr, Pu, Po, Am	Yes	178	188	188	M, R	Yes
Gymnosperms	Primary producer	Medium	-	Yes (roots)	1	3	3	M	Yes
Monocotyledons	Primary producer	Medium	Cs, C, H	Yes (roots)	57	134	134	M, R	Yes
Dicotyledons	Primary producer	Medium	Cs, C, H	Yes (roots)	128	341	342	M, R	Yes
Pteridophytes	Primary producer	Medium	Cs, C, H	Yes (roots)	10	28	28	M, R	No
Soil micro-organisms	Various	Low	-	Yes	-	-	-	M, R	Yes
Macrofungi	Various	Low	Cs	Yes (hyphae)	-	-	-	M, R	No
Soil invertebrates	Various	Low	-	Yes	-	-	-	M, R	Yes
Above ground invertebrates	Various	Low	Cs, Am, Pu, C, H	Dependant upon species	-	-	-	M, R	No
Herbivorous mammals	Herbivore	High	Cs, Sr, I, C, H, (Ra)	Dependant upon species	2	14	27	M, R	Yes
Herbivorous birds	Herbivore	High	Cs, Sr, I, C, H	Dependant upon species	5 (4)	13 (9)	31 (15)	M, R	No
Insectivorous mammals	Insectivore	High	Cs, Sr, I, C, H, (Ra)	Dependant upon species	0	4	11	M, R	No
Insectivorous birds	Insectivore	High	Cs, Sr, C, H	Dependant upon species	1 (1)	15 (13)	44 (37)	M, R	No
Carnivorous mammals	Carnivore	High	Cs, Sr, I, C, H, (Ra)	Dependant upon species	3	6	11	M, R	Yes
Carnivorous birds	Carnivore	High	Cs, C, H	No	1	4 (3)	17 (9)	-	No
Reptiles	Carnivore	Medium	Cs, Sr, C, H	Yes	0	0	1	-	No
Bird eggs	n/a	High	Sr, I, Tc	Dependant upon species	-	-	-	M, R	Yes

Table 3.2 Selection of aquatic reference organisms.

Organism group	Trophic Level	Radiosensitivity	Radionuclides these organisms are likely to have relatively high activity concentrations of?	Is external exposure an important pathway?	Number of species present in Arctic regions (Summer migrants) F – freshwater, M - marine: High F	High M	Low F	Low M	Sub F	Sub M	Suitable for monitoring (M) and/or research (R)?	Select as reference organism ?
Benthic bacteria	Primary producer	Low	-	Yes	-	-	-	-	-	-	M, R	Yes
Macroalgae (marine)	Primary producer	Low	Tc, Sr, U, C, H, I	No	-	-	-	-	-	-	M, R	Yes
Aquatic plants (freshwater)	Primary producer	Medium	Ra, U	Yes (roots)	3	-	16	-	16	-	M, R	Yes
Phytoplankton	Primary producer	Low	Sr, Pu, Am, Ra, Po, C, H, I	No	-	-	-	-	-	-	-	Yes
Zooplankton	Planktotrophic	Low	Th, Po, C, H, I	No	-	-	-	-	-	-	M, R	Yes
Crustaceans	Largely detritivorous	Medium	Tc, Po, C, H	Yes	-	-	-	-	-	-	M, R	No
Molluscs	Largely detritivorous	Low	Tc, U, Pu, Ra, C, H	Yes	-	-	-	-	-	-	M, R	Yes
Polychaetes (marine)	Largely detritivorous	Low	-	Yes	-	-	-	-	-	-	R	Yes
Insect larvae (freshwater - benthos)	Various	Medium	-	Yes	-	-	-	-	-	-	R	Yes
Pelagic fish	Planktotrophic	Medium	Cs, Sr, C, H	No	0	3	2	8	2	4	M, R	Yes
Benthic fish	Carnivorous	Medium	Cs, Sr, C, H	Yes	2	8	5	27	7	10	M, R	Yes
Pelagic fish	Carnivorous	Medium	Cs, Sr, C, H	No	2	0	17	6	27	3	M, R	Yes
Amphibians	Insectivorous	Medium	-	Yes	0	-	0	-	3	-	R	No
Mammals	Planktotrophic	High	Cs, Sr, C, H, I	No	0	-	0	-	0	-	-	No
Mammals	Carnivorous	High	Cs, Sr, C, H, I	Dependant upon species	0	6	1	7	2	4	M	Yes
Benthos eating birds	Carnivorous	High	Cs, Sr, C, H, I	Yes	4 (3)	9 (7)	9 (8)	11 (7)	12 (10)	16 (11)	M, R	Yes
Fish eating birds	Carnivorous	High	Cs, Sr, C, H, I	Dependant upon species	3	7 (2)	8 (1)	13 (6)	8 (1)	13 (6)	M, R	No
Fish/amphibian eggs	n/a	High	-	Dependant upon species	-	-	-	-	-	-	R	Yes

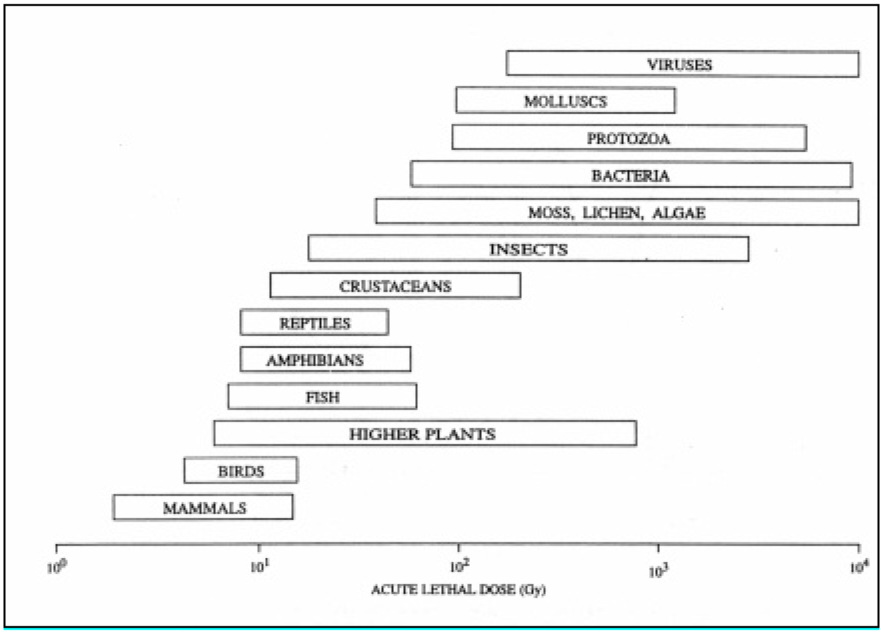

Figure 3.1 Comparative radiosensitivity of different organisms demonstrated as the acute lethal dose ranges (reproduced from UNSCEAR 1996).

3.2.4 Vertebrates

Fish are more radiosensitive than most other aquatic organism although it would seem that freshwater and marine mammals are more radiosensitive. The LD_{50} for acute irradiation of marine fish is in the range 10-25 Gy for assessment periods of up to 60 days following exposure.

Data on radiation sensitivity of terrestrial animals is dominated by that on mammals, the most sensitive class of organism. Acute lethal doses ($LD_{50/30}$) are of the order of 6-10 Gy for small mammals and 1.5-2.5 Gy for larger mammals. There is substantial inter-species variability but, in general, there is little indication that dose rates below 10 mGy d^{-1} to the most exposed individual would seriously affect mortality in the population (UNSCEAR 1996). In terms of mortality, wild birds appear to exhibit LD_{50} values that are in the same general range as those expressed for small mammals, i.e. in the range 5-12 Gy (UNSCEAR 1996).

Studies on reptiles and amphibians suggest that these classes of animal have similar radiosensitivities to birds and mammals with LD_{50} values in the approximate range 2-22 Gy (UNSCEAR 1996).

3.2.5 Life-stages

The habits and habitat of different life-stages of some organisms may vary considerably (e.g. bird and egg, larvae and adult forms of insects) and this may lead to different exposure pathways. Effects on embryonic development in birds have been observed at doses of 8-10 mG h^{-1}; LD_{50} values at hatching in the range 9-13 Gy having been determined (UNSCEAR 1996). $LD_{50/90}$ levels of 0.16 Gy have been observed for salmon embryos (Bonham & Welander 1961); considerably lower than those determined for adults. From the radiosensitivity view point there is an argument for including fish (and amphibian in freshwaters) and bird eggs as reference organisms in their own right (Tables 3.1-3.2). Whilst juvenile invertebrates are also more radiosensitive than adults, they do not warrant consideration as an additional reference organism within aquatic systems as they are included within zooplankton and benthic organisms. However, in freshwater systems it may be more appropriate to consider insect larvae as the reference benthic organism rather than polychaetes. Seeds are the least radiosensitive component of plants and we have therefore not included them in Table 3.1.

3.2.6 Radiosensitivity Categorisation

On the basis of the available data on acute lethal doses (see Figure 3.1), we have classified the radiosensitivity of organisms as *high* (10^0-10^1 Gy; mammals, birds and fish eggs), *medium* (10^1-10^2 Gy; higher plants, fish, amphibians, reptiles, crustaceans and insect larvae) and *low* (>10^2 Gy; insects, molluscs, bryophytes, algae and micro-organisms) when considering them as candidate reference organisms (see Tables 3.1-3.2). We accept that this approach is crude, and that mortality is perhaps the least likely effect of radiation within the environment. However, it is sufficient to rank radiosensitivities for the purpose of reference organism selection within this assessment.

3.2.7 Radiosensitivity in the Arctic

Whilst there is insufficient data to include within our categorisation above, Arctic biota may be more or less radiosensitive than similar species in other environments as suggested by the following two references:

i) Low temperatures reduce metabolic rate; Blaylock & Trabalka (1978) report that the effects of irradiation developed over longer periods for fish at low compared to high temperatures;

ii) Irradiation can cause the peroxidation of lipids producing toxic compounds (Kuzin 1986); can we therefore hypothesise that the high lipid content of many Arctic biota will result in a higher radiosensitivity?

3.3 Radioecological Sensitivity

We are using the term *radioecological sensitivity* here to identify organisms (or parts of organisms) which will be highly exposed to radioactivity either as a result of external exposure or as a consequence of biological uptake. Under this criteria, it may be necessary to identify different candidate reference organisms depending upon contamination scenario and radionuclides present. An analysis of candidate reference organisms for European ecosystems on radioecological criteria can be found in Strand *et al.* (2001). Here, we structure our discussion to an analysis of the organism groups within Table 3.1-3.2; there are no additional candidate reference organism required from a radioecological viewpoint.

3.3.1 Terrestrial Ecosystems

3.3.1.1 Observations within the Arctic

The Arctic foodchain *lichen-reindeer* has received considerable attention following deposition from both weapons fallout and the Chernobyl accident (see AMAP 1998). The large surface area of lichens means that they intercept atmospheric radionuclides more efficiently than other vegetation. Thus airborne radionuclides, particularly ^{137}Cs, ^{210}Pb and ^{210}Po are efficiently trapped and retained on slow-growing lichens, which form the main food source for reindeer in winter. Radiocaesium activity concentrations in the range of 10^4 Bq kg^{-1} have been commonly recorded for both lichen species (AMAP database) and reindeer (Gaare & Staaland 1994). Transfer coefficients have been derived for reindeer feeding on lichen of

0.65 d kg^{-1} (Jones 1989); the comparative value for summer feeding on pasture was 0.3 d kg^{-1}. Aggregated transfer coefficients (T_{ag}; the ratio of the activity concentration in reindeer meat to ground deposition) for radiocaesium and ^{90}Sr have recently been reviewed by Howard & Wright (in preparation). For radiocaesium, a T_{ag} value of 1.4 m^2 kg^{-1} was derived from >900 measurements of reindeer in Finnmark. A T_{ag} value for ^{90}Sr of 0.0014 m^2 kg^{-1} based upon available data for the transfer of ^{90}Sr to lichen and from lichen to reindeer. Hanson (1967) reports ^{90}Sr activity concentrations in the bone of reindeer to be 6-15 times higher than those in lichen.

In addition to the well known accumulation of ^{137}Cs, high levels of ^{210}Po and ^{210}Pb have been reported in reindeer. Both ^{210}Pb and ^{210}Po, levels were highest in bone; in soft tissues concentrations were highest in liver and kidney. Concentration ratios have been reported for reindeer muscle compared to lichen of 0.01-0.16 for U, 0.06-0.25 for ^{226}Ra, 0.01-0.02 for ^{210}Pb, 0.06-0.26 for ^{210}Po; these values can be compared with that of 2.60-3.70 for ^{137}Cs (Thomas & Gates 1999). Concentration ratios greater than unity were also determined for ^{226}Ra in bone, in part due to its long biological half-life in this tissue.

The transfer of radiocaesium to Eurasian woodcock (*Scolopax rusticola*) from their main food source earthworms was determined in a Norwegian sub-alpine ecosystem (1986-90) (Kålås *et al.* 1994). The ratio of radiocaesium concentrations in Woodcock to those in earthworms decreased from 6.1 in 1986 to <1 in 1988-90. Radiocaesium activity concentrations in Woodcock were 5-10 times higher than in Willow Grouse and Rock Ptarmigan (*Lagopus mutus*) collected from the same area.

Radiocaesium activity concentrations in the flesh of wolves was observed to be *circa* 2 fold higher than that in reindeer flesh during studies of weapons fallout radionuclides in Alaskan Arctic ecosytems (Hanson 1967). In contrast, ^{90}Sr concentrations in wolf flesh were approximately 0.3 times those in reindeer meat (Hanson 1967) although ^{90}Sr activity concentration in wolf bone were 260 times higher than those in reindeer meat (^{90}Sr activity concentration in wolf bone were *circa* 60 % of those in reindeer bone) (Hanson *et al.* 1967). As for ^{90}Sr, the (limited) data presented by Hanson *et al.* (1967) for ^{110m}Ag (which like actinides accumulates in the liver) and ^{228}Th (which accumulates in bone) suggests that radionuclides which are localised in a given tissue will not be accumulated within the muscle of carnivores (as these tissues generally form only a small component of the diet).

3.3.1.2 Useful Generic observations

In addition to the above there is clear evidence of a concentration of radiocaesium from the flesh of prey to carnivorous species. Lowe & Horrill (1991) report a concentration of radiocaesium from the muscle of rabbits (*Oryctolagus cuniculus*) to that of foxes (*Vulpes vulpes*) approaching one order of magnitude. Maximum radiocaesium activity concentrations of 87 000 Bq kg^{-1} were observed in Norwegian Lynx in 1989; this was 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 also been observed (Pendleton *et al.* 1964). 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 the four studies discussed above (i.e. 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.

In an extensive survey of biota across eight “background” sites in the former Soviet Union, Pokarzhevskii & Krivolutzkii (1997) reported that CR values for ^{226}Ra for soil-plant, plant–animal and prey–carnivore were usually close to or less than unity. High activity concentrations of ^{226}Ra have been determined in burrowing animals (Maslov *et al.* 1967).

Data supplied for the EPIC project for areas of high natural radiation in the Komi Autonomous Republic (V. Goligov *pers comm.*[3]) suggest that concentrations of Ra, U and Th will be highest in burrowing animals (namely moles, otters and vole) than above ground mammals (e.g. squirrels) and birds (*Lagopus* spp.).

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 1963; Rudge *et al.* 1993b; Copplestone 1996; Copplestone *et al.* 1999).

A number of studies have demonstrated a high transfer of radiocaesium to plants of the *Ericaceae* family (e.g. Bunzl & Krake 1984; Horrill *et al.* 1990) compared with other species of higher plants. The fruit bodies of mychorrizal fungal species have especially high concentrations of radiocaesium (Barnett *et al.* 1999; Gillett & Crout 2000); whilst there is little data for other radionuclides fungi are know to have high uptakes of many heavy metals (Seeger 1982) and hence could be expected to concentrate any radionuclides with behaviours similar to heavy metals.

3.3.1.3 Radioecologically sensitive terrestrial biota

When considering chronic exposure the organisms most exposed to external irradiation will be those living totally or partially within the soil. These will include: micro-organisms which on account of their small size may receive some dose from external alpha-emitters; soil invertebrates; burrowing mammals. Roots of plants and hyphae of fungi will be more exposed than above ground tissues. Birds and mammals consuming soil dwelling invertebrates may be prone to ingestion of comparatively high rates of radionuclides and the eggs of birds nesting on the ground may receive high external exposures.

Lichens will accumulate many aerially deposited radionuclides, whereas Ericaceous shrub species common in Arctic ecosystems are likely to be amongst the plants with highest internal contamination (with radiocaesium). Of the above ground invertebrates, detritivorous species should be considered as a candidate reference organism. For larger animals, in the case of radiocaesium there is clear evidence of a concentration through foodchains. Therefore predatory species should be candidate reference organisms. For organ seeking radionuclides (e.g. Pu, Am, Ru and Sr) higher concentrations may be found in herbivores compared with carnivores.

3.3.2 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 ecosystems.

Benthic organisms, especially those living over/within sediments rich in potassium are likely to be exposed to the highest levels of radiation arising from ^{40}K. Organisms of small size will be prone to a significant external exposure by β radiation. The concomitant emission of a medium energy γ photon at 1460 keV, albeit at low yield, leads to irradiation of all sizes of organism.

The ambient activity concentrations of ^{137}Cs in sediments are likely to become higher than those observed in seawater following a release of this radionuclide to coastal waters although a major fraction of the ^{137}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. A major

[3] V. Goligov, Institute of Radiation Hygiene, St. Petersburg, Russia.

exposure pathway is therefore likely to be the irradiation of benthic organisms from contaminated sediments. Those benthic organisms residing near the top of the foodchain (e.g. plaice (*Pleuronectes platessa*), carrion-feeding crustaceans) may receive an extra internal exposure from elevated ^{137}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 ^{137}Cs exposure via an ingestion pathway (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 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 (see Table 3.3).

Strontium concentrations decline with successive trophic levels of marine ecosystems. Table 3.3 compares ^{90}Sr transfer to predatory and non-predatory fish in Arctic lakes; unlike for ^{137}Cs there is no increase with trophic level. Although Sr behaves conservatively in marine environments, under equilibrium conditions activity concentrations per unit mass of sediment will be higher than those per unit mass of water. The most radioecologically sensitive organisms with respect to Sr are the benthos. Of these, macroalgae and possibly molluscs appear to accumulate the highest body burdens of radiostrontium and might therefore form suitable reference flora and fauna. However, there is some evidence to suggest that small fish may be more radiosensitive to internally accumulated ^{90}Sr than larger fish. Shekhanova (1983) observed that ^{90}Sr accumulated in bones resulted in damage to the eyes of small fish and high rates of exposure to their gonads.

Table 3.3. Concentration factors* for ^{137}Cs and ^{90}Sr freshwater fish from lakes in Arctic Russia (data collated by SPA Typhoon).

Fish species	Trophic level	^{137}Cs mean±SD	^{90}Sr mean±SD
Shallow-water cisco	Planktophage	1349±286	1026±822
Cisco	Benthophage	1509±630	1730±1540
Perch	Predatory	7313±4687	1244±1202
Pike	Predatory	3860±2405	1029±728

*Concentration factor (CF) is defined as the ratio of the activity concentration in fish to that in water.

Although Tc has a low affinity for sediment, data suggest that where equilibrium conditions exist (e.g. coastal sediments in prolonged contact with contaminated water masses) activity concentrations per unit mass in the sediment will be higher than those observed in the aqueous phase. Slightly higher external exposures may therefore be observed for benthic fauna, compared to pelagic organisms, although the fact that ^{99}Tc is a soft β-emitter ($E_{\beta max}$=293 keV) suggests that exposures from the surrounding habitat will only be significant for small organisms with correspondingly thin cuticle/shell surfaces. From a basic consideration of the concentration factor data reported in the open literature, three organism types can be identified as potentially vulnerable to exposure from coastal input of ^{99}Tc. These are brown seaweeds, benthic molluscs, in particular from the class *Gastropoda*, and crustaceans, in particular from the order *Decapoda*.

On the basis of the biogeochemical behaviour of Pu and Am in marine systems, it is apparent that for coastal areas, sediments will be a primary reservoir for these radionuclides. For this reason, benthic organisms, especially those with concomitantly high concentration factors, examples include brown seaweeds and molluscs, might be considered vulnerable to (external and internal) exposure. Phytoplankton appears to accumulate high Pu and Am levels.

Phytoplankton is a significant accumulator of Ra and ^{210}Po. Po-210 concentrations in different tissues of marine organisms vary enormously, but on a whole body basis concentration factor values in both pelagic and benthic food chains are thought to be similar at about 10^4. Variations in ^{210}Po concentrations do not appear to be generally related to the trophic level in fishes, although large pelagic carnivores are often the highest concentrators (Pentreath 1977). Species vulnerable to high habitat and internal/surficial concentrations of radioisotopes of Ra, and Po include phytoplankton and benthic organisms, in particular crustaceans, because of their tendency to accumulate ^{210}Po.

Hydrogen is one of the few elements for which the sediment water concentration factor is < 1. All types of pelagic marine organism would be exposed to similar levels of radiation following an input of ^{3}H to oceanic surface waters. The basic sediment-water concentration factor data suggest that sediment may act as a sink for ^{14}C over long time periods and that benthic organisms 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.

The highest accumulation of iodine occurs at lower marine trophic levels. Brown seaweeds accumulate iodine and may be considered as a suitable reference organism.

Table 3.4 compares concentration factors for the radionuclides of interest to different groups of marine organisms (IAEA 1985).

Table 3.4. Recommended concentration factor values for generic marine organisms (adapted from IAEA (1985).

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
Ra	2×10^3	1×10^2	1×10^2	1×10^3	1×10^2	5×10^2
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
I	1×10^3	1×10^3	3×10^3	1×10^1	1×10^1	1×10^1

*excluding cephalopods

3.3.3 Application of Radioecological Criteria

To assess radioecological sensitivity of the various organisms in Tables 3.1 and 3.2, we have identified those organisms likely to have the highest activity concentrations of the different radionuclides. For aquatic ecosystems this has largely been achieved by referring to the concentration factors presented in Table 3.4. A similar summary is not available for natural biota in terrestrial ecosystems; therefore, it is based upon available knowledge as summarised above.

In marine ecosystems, the importance of external exposure has been assessed on the basis of whether the animal is benthic (most likely to be exposed by close contact with contaminated sediments) or pelagic (for which external irradiation is unlikely to be important). In the case of terrestrial ecosystems, we have identified organisms for which external exposure will be especially important as those residing in or partially within the soil (e.g. roots of plants, burrowing animals). For some organism groups this will be dependent upon species, for instance most groups of mammals have some burrowing species (some of which are likely to hibernate underground).

3.4 Distribution and Amenability for Research and Monitoring

There is little point in selecting reference organisms which are not common and widely distributed at least through one of the three Arctic regions. Within Tables 3.1 and 3.2 we have summarised the number of species known to be present in each of the High, Low and Sub-Arctic regions for those organism groups for which we have sufficient information (see Appendix 1). For species of birds, we have identified the numbers present throughout the year and also summer residents. This was not possible for invertebrates and micro-organisms (limited information on invertebrate distribution can be found in Appendix 1). There are fewer organisms which are represented within the High Arctic and consequently those which are absent could not be suggested as reference organisms for all Arctic systems (e.g. reptiles and amphibians only occur in the Subarctic were few species are present).

A further consideration is the ability to collect reference organisms for monitoring purposes (either to determine radionuclide content or to assess any effects due to exposure) or to enable further radiosensitivity and radioecological studies. For some organism groups, this would be difficult either due to protected status (e.g. raptors, sea mammals) or public acceptability (sea mammals, large terrestrial carnivores). However, a number of potential Arctic marine reference organisms are of a commercial importance including: macroalgae in the Norwegian, Barents and White Seas; northern pink shrimp (*Pandalus borealis*, classified here as zooplankton); planktophagic fish – Arctic cod, capelin, herring; benthophagic fish – haddock, Greenland halibut, European plaice, red fish, saithe; pelagic carnivorous fish - Atlantic cod. This would provide a ready supply of organisms for monitoring should this be required. Indeed, perhaps there is merit in suggesting that commercial importance is a criteria which should be considered within reference organism selection. There is also some commercial exploitation of sea mammals (e.g. Greenland seal, bearded seal, ringed seal, beluga and minke whale). Within terrestrial and freshwater systems, reindeer are mostly semi-domesticated and a number of game species are commonly collected (e.g. moose, salmon, trout, willow grouse, etc.). Tables 3.1 and 3.2 contain a categorisation as to whether candidate reference organisms would be suitable for monitoring or further research based upon their ease of collection and endangered status. This process is subjective and amenability to research or monitoring may be applicable to only radiosensitivity or radioecological parameters in some instances (e.g. whilst the effect on bacteria could be assessed determining the transfer of radioisotopes to them would be more difficult). Public acceptability towards the choice of species for monitoring and research may vary between countries and be less of an issue within the European Arctic nations than some other countries (e.g. Norway is the only European whaling nation and currently has a policy of culling wolves which are protected in some other European countries).

4 DISCUSSION

In the previous section we have categorised candidate reference organisms against a number of criteria (Tables 3.1 and 3.2). On the basis of this, we can assess if each candidate reference organism requires consideration within a framework to ensure environmental protection within the Arctic (Tables 3.1 and 3.2).

4.1 Terrestrial Ecosystems

Lichens and *bryophytes* – selected as a reference organism, important primary producers especially in High and Low Arctic known to intercept and retain most aerially deposited radionuclides. Lichens (e.g. *Cladonia* spp.) would be typical of this group and are found throughout all three Arctic regions.

Gymnosperms - selected as a reference organism, the most radiosensitive of the higher plants, roots highly exposed to external radiation in conditions of chronic exposure whilst above ground foliage will be exposed in conditions of acute exposure. *Juniperus communis* is found throughout all three Arctic Regions, whilst *Larix dahurica* and *Picea obovata* are common in the Low and Sub- Arctic.

Monocotyledons – selected as a reference organism, roots highly exposed to external radiation in conditions of chronic exposure whilst above ground foliage will be exposed in conditions of acute exposure, and some species can accumulate more mobile radionuclides. *Carex* spp., *Luzula* spp. and *Festuca* spp. are commonly found in all three Arctic regions and are typical of this group.

Dicotyledons – selected as a reference organism, as for monocotyledons. *Vaccinium* spp., *Salix* spp. and *Betula nana* are typical of this group and found in all three Arctic regions.

Pteridophytes – not selected as a reference organism, should be adequately protected by considering other plant group as reference organism. There is no evidence to suggest a higher rate of radionuclide uptake.

The selection of three higher plant groups as reference organisms may seem excessive, however, this is required to ensure adequate representation of all possible environments (e.g. little point considering gymnosperms as reference organisms for an area in which they do not occur).

Soil micro-organisms (bacteria, algae, fungi and protozoa) – selected as a reference organism, responsible for a significant part of the primary production and decomposition in Arctic ecosystems, because of their small size this group of organisms will be maximally exposed to external radiation by soil radionuclides, including alpha-emitters.

Macrofungi – not selected as reference organisms, less radiosensitive than higher plants, little information on distribution and taxonomic classification within the Arctic. Although known to accumulate high concentrations of radiocaesium, internal dose is likely to be negligible compared to dose received by hyphae which is likely to be similar to that received by plant roots.

Soil invertebrates – selected as a reference organism, highly exposed to external radiation, including by beta-emitters. Species of collembola and mite occur throughout all three Arctic regions.

Above ground invertebrates – not selected as reference organism, although detritivores can accumulate a number of radionuclides little information on distribution within the Arctic is available. Should be adequately protected by considering soil dwelling species which will be more exposed to high external irradiation.

Herbivorous mammals – selected as reference organisms, highly radiosensitive and can accumulate comparatively high concentrations of mobile radionuclides, organ seeking radionuclides (e.g. Pu, Am, Po) are likely to be higher in this group than carnivorous species. Burrowing species are likely to be maximally exposed to external irradiation and may also accumulate high internal concentrations of Ra. A number of species of lemmings (*Dicrostonyx* spp., *Myopus* spp., *Lemmus* spp.) and voles (*Microtus* spp., *Clethrionomys* spp., *Eothenomys* spp.) are common in the Low and Sub- Artic. However, no burrowing small mammals occur in the High Arctic; both reindeer and musk ox occur in all three Arctic regions.

Herbivorous birds – not selected as reference organism, no evidence to suggest they are more exposed than more radiosensitive mammals.

Insectivorous mammals – not selected as reference organism, no evidence of concentration of radionuclides through insect foodchains, consideration of burrowing herbivorous mammals should provide protection to most exposed members of this group.

Insectivorous birds - not selected as reference organism, see insectivorous mammals and herbivorous birds.

Carnivorous mammals – selected as reference organism, radiosensitive, accumulation of mobile radionuclides through foodchain. Species living in burrows may be exposed to Ra. Red fox (*Vulpes vulpes*) and Arctic fox (*Alopex lagopus*) are representative of this group and occur in all three Arctic regions.

Carnivorous birds – not selected as reference organism, no evidence to suggest they are more exposed than more radiosensitive mammals and many species are protected making monitoring/research difficult.

Reptiles – not selected as reference organism, only one species present within the Subarctic, few data.

Bird eggs – selected as a reference organism, more radiosensitive life-stage, eggs of ground nesting birds (e.g. *Lagopus mutus*) will be prone to external exposure from the soil surface, Sr accumulates in shell and some radionuclides have a comparatively higher rate of transfer to the eggs contents.

Selected terrestrial reference organisms are summarised in Table 4.1.

Table 4.1 Summary of terrestrial reference organisms.

Lichens & bryophytes	Dicotyledons	Herbivorous mammals
Gymnosperms	Soil micro-organisms	Carnivorous mammals
Monocotyledons	Soil invertebrates	Bird eggs

4.2 Aquatic Ecosystems

Benthic bacteria - selected as a reference organism, because of their small size this group of organisms will be maximally exposed to external radiation by bed sediment radionuclides, including alpha-emitters.

Macroalgae – selected as a reference organism for marine ecosystems, high rate of accumulation of a number of radionuclides (Tc, I, U, Sr). *Fucus* spp. and *Laminaria* spp. are representative of this group and occur within the Low and Sub- Arctic (there are no species within the High Arctic).

Aquatic plants – selected as a reference organism for freshwater ecosystems, roots may be exposed to high rates of external radiation, accumulate some radionuclides. Whilst many species of pondweeds (*Potamogetom* spp.) occur in the Low and Sub- Arctics these are not found in the High Arctic. *Carex rostrata*, *Menyanthes trifoliata*, *Limosella aquatica* occurs within all three Arctic regions.

Phytoplankton – selected as a reference organism, the predominant primary producer in marine and freshwater ecosystems, accumulate wide range of radionuclides.

Zooplankton – selected as a reference organism, accumulate a range of radionuclides, includes larval and juvenile stages of organisms of higher trophic levels (e.g. crustaceans, fish, molluscs) which may be more radiosensitive than adult forms. Within Low and Sub-Arctic marine ecosystems, the commercially important *Pandalus borealis* (northern pink shrimp) is representative of this group; representatives are present within all three Arctic regions. Species of *Rotatoria, Cladocera* and *Copepoda* are representative of this group in freshwater ecosystems.

Benthic crustaceans - not selected as a reference organism, similarly exposure as for the more ubiquitous molluscs.

Molluscs – selected as a reference, habitat results in high rate of external exposure, accumulates a range of radionuclides. Gastropod and bi-valve species are found within both freshwater and marine ecosystems.

Polychaetes – selected as a reference organism for marine ecosystems, high external radiation doses from beta and gamma emitting radionuclides in sediment, feed by passing sediment through their gut to extract nutrients and therefore have potential for internal incorporation of radionuclides. Representative species are present within all three Arctic regions.

Insect larvae – selected as a reference organism for freshwater ecosystems instead of the polychaetes chosen for marine systems, more radiosensitive life-stage. Chironomid (non-biting midge) larvae are typical of this group and are used as indicator species for other pollutants.

Pelagic planktotrophic fish – selected as a reference organism, represent the largest biomass of fish groups, some evidence to suggest that they may be more radiosensitive to internally accumulated beta emitters than larger fish. In High and Low Arctic marine ecosystems *Boreogadus saida* (Arctic cod) whilst in the Low and Sub- Arctic *Mallotus villosus* (capelin) are typical of this group. No freshwater species is represented in the High Arctic; in the Low and Sub- Arctic *Coregonus peled* (northern whitefish) and *Coregonus laveretus* (powan) are representative of this group.

Benthic fish - selected as a reference organism for all aquatic ecosystems, habitat results in elevated exposure to radionuclides within bed sediments, may ingest comparatively high amounts of less mobile radionuclides associated with prey, accumulate mobile radionuclides. *Melanogrammus aeglefinus* (haddock), *Reinhardtius hippoglossoides* (Greenland halibut), *Pleuronectes platessa* (European plaice) and *Sebastes* spp.(redfish) are representative of this group for marine ecosystems in Low and Sub- Arctic. *Pleuronectes glacialis* (Polar plaice) and *Lycodes* spp. are representative for the High and Low Arctic. *Salvelinus alpinus* (Arctic char), present in all three Arctic regions, is representative for this group in freshwaters.

Pelagic carnivorous fish – included as a reference organism, accumulate more mobile radionuclides. *Gadus morhua* (Atlantic cod) is representative of this group for Low and Sub-Arctic marine ecosystems. In freshwater systems, *Coregonus sadinella* (Least cisco) and *Lota lota* (burbot) are present throughout all three Arctic regions; *Coregonus autumnalis* (Arctic cisco) is found in the Low and Sub- Arctic.

The selection of all three fish groups as reference organisms may seem excessive, however, we feel on the basis of current information that this is required to ensure adequate representation of possible exposure routes and radiosensitivities. When further data are collated and assessed a decision may be made to restrict the number of reference organism fish groups.

Amphibians - not selected as a reference organism, only three species found in Subarctic.

Planktotrophic mammals – not included includes as a reference organism, consideration of carnivorous mammals (see below) should provide sufficient protection for this group, many species typical of this group are endangered and have protected status.

Carnivorous mammals – included as a referenc e organism, radiosensitive, accumulation of mobile radionuclides through foodchain, a number of marine species are commercially exploited within the Arctic. *Odobenus rosmarus* (walrus) and *Erignathus barbatus* (bearded seal) are representative of this group in marine systems in all three Arctic regions, whilst *Phoca hispida* (ringed seal) occurs in the High and Low Arctic. *Mustela lutrecla* (European mink) are representative of this group in the Low and Sub Arctic freshwater ecosystems.

Benthos eating birds - included as a reference organism, habitat and feeding behaviour leads to elevated external exposure, may ingest comparatively high amounts of less mobile radionuclides associated with prey, accumulate mobile radionuclides. *Somateria mollissima* (common eider) and *Calidris* spp. are representative of this group in marine ecosystems of all three Arctic regions. The majority of *Calidris* spp. are summer migrants; *Somateria mollissima* is resident all year round. *Phaloropus* spp. are representative of this group in freshwater ecosystems of all three Arctic regions but are summer visitors only; *Cinclus cinclus* (dipper) is a year round resident in the Subarctic.

Fish eating birds – not included as a reference organism, no evidence to suggest they are more exposed than more radiosensitive mammals.

Fish eggs – included as a reference organism, eggs of fish laid on bed sediments (e.g. Arctic Char) will be exposed to external beta and gamma radiation, depending on egg size 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 benthic bacteria will represent a limiting case for such fish eggs. Eggs of other species may be included within zooplankton.

Selected aquatic reference organisms are summarised in Table 4.2.

Table 4.2 Summary of aquatic reference organisms.

Benthic bacteria	Molluscs	Pelagic fish (carnivorous)
Macroalgae (marine)	Polychaetes (marine)	Carnivorous mammals
Aquatic plants (freshwater)	Insect larvae (freshwater – benthos)	Benthos eating birds
Phytoplankton	Pelagic fish (planktotrophic)	Fish eggs
Zooplankton	Benthic fish	

4.3 Concluding Comments

The chosen reference organisms should be considered as a potential list to use within future evaluations within the Arctic. They may not all be applicable to any given evaluation; however, they are sufficiently broad ranging to enable assessments to be conducted throughout the different Arctic ecosystems.

The selection of appropriate reference organisms was the first stage in the development of our framework for the protection of Arctic Environments. Now that they have been selected appropriate radioecological data can be collated and dosimetric models developed. These topics will be the subject of future reports.

REFERENCES

Arctic Monitoring and Assessment Programme (AMAP) (1998) *AMAP Assessment Report: Arctic Pollution Issues*. AMAP, Oslo.

Andriyashev A.P. (1954) *Fishes of the Northern Seas.* USSR Acad. Sci. Publ. House, Moscow. (in Russian).

Barnett C. L., Beresford N. A., Self P. L., Howard B. J., Frankland J. C., Fulker M. J., Dodd B. A. & Marriott J. V. R. (1999) Radiocaesium activity concentrations in the fruit-bodies of macrofungi in Great Britain and an assessment of dietary intake habits. *Science of the Total Environment*, **231**, 67-83.

Bird G.A., Thompson C., Macdonald C., Sheppard M.I. & Sheppard S.C. (2000). *Supporting Document for the Priority Substances List Assessment of Releases of Radionuclides from Nuclear Facilities (Impact on non-human biota)* – Draft document.

Blaylock B.G. & Trabalka J.R. (1978) Evaluating the effects of ionising radiation on aquatic organisms. *Adv. Radiat. Biology*, **7**, 103-152.

Bonham K. & Welander A.D. (1961) Increase in radioresistance of fish to lethal doses with advancing embryonic development. In: *Radioecology* (Schultz V. & Klement A.W. Eds.), Reinhold Publishing Corp., New York, pp.353-358.

Brown, J. (2000) *Radionuclide uptake and transfer in pelagic food-chains of the Barents Sea and resulting doses to man and biota* . NRPA, Østerås.

Bunzl K. & Krake W. (1984) Distribution of ^{210}Pb, ^{210}Po, stable lead and fallout ^{137}Cs in soil, plants and moorland sheep of a heath. *Sci.T ot. Environ*., **39**, 143-159.

Bøhmer N., Nikitin A., Kudrik I., Nilsen T., McGovern M.H. & Zolotkov A. (2001) *The Arctic nuclear challenge*. Bellona report volume 3. The Bellona Foundation, Oslo.

Conservation of Arctic Flora and Fauna (CAFF) (2000) CAFF Overview Report on Arctic Conservation Issues: Status and Trends of Arctic Flora, Fauna and Their Habitats. http://www.grida.no/caff/integrat.htm.

Cooley J.L. (1973) Effects of chronic environmental radiation on a natural population of the aquatic snail. *Physa heterostropha . Radiat. Res*, **54**, 130-140.

Copplestone D. (1996) *The food chain transfer of radionuclides through semi-natural habitats*. PhD. Thesis. University of Liverpool.

Copplestone D., Johnson M.A.. Jones S.R., Toal M.E. & Jackson D. (1999) Radionuclide behaviour and transport in a coniferous woodland ecosystem: vegetation, invertebrates and wood mice, *Apodemus sylvaticus*. *Sci. Tot. Environ*., **238**, 95-109.

Copplestone D., Bielby S., Jones S.R., Patton D., Daniel P. and Gize I. (2001) *Impact Assessment of ionising radiation on wildlife*. R&D Publication 128. ISBN 1 85705590. Environment Agency, Bristol.

Crossley D.A. (1963) Movement and accumulation of radiostrontium and radiocaesium in insects. In: *Radioecology* (V. Schultz & A.W. Klement Eds.) pp. 103-105. Reinhold, New York.

Engel D.W. (1967) Effects of a single and continuous exposures of gamma radiation on the survival and growth of the blue crab. *Callinectes sapidus*. *Radiat. Res*., **32**, 685-691.

Fisher N.S., Fowler S.W., Boisson F., Carroll J., Rissanen K., Salbu B., Sazykina T., Sjoelblom K-L. (1999) Radionuclide bioconcnetration factors and sediment partition coefficient in Arctic Seas subject to contamination from dumped nuclear wastes. *Environmental Science and Technology*, **33**, 1979-1982.

Gaare E. & Staaland H. (1994) Pathways of fallout radiocaesium via reindeer to man. In: *Nordic radioecology. The transfer of radionuclides through Nordic ecosystems to man.* (Dahlgaard H. Ed.) pp. 303-334. Elsevier, Amsterdam.

Gillett A.G. & Crout N.M.J. (2000) Review of ^{137}Cs transfer to fungi: importance of species, spatial scale and time. *J. Environmental Radioactivity*, **48**, 95-121.

Hanson W.C. (1967) Radiological concentration processes characterizing Arctic ecosystems. In: *Radiological concentration processes* (Åberg B. & Hungate F.P. Eds.). pp. 183-191. Pergamon Press, Oxford.

Hanson W.C., Watson D.G. & Perkins R.W. (1967) Concentration and retention of fallout radionuclides in Alaskan Arctic ecosystems. In: *Radiological concentration processes* (Åberg B. & Hungate F.P. Eds.). pp. 233-245. Pergamon Press, Oxford.

Horrill A.D., Kennedy V.H. & Howard T.R. (1990) The concentrations of Chernobyl derived radionuclides in species characteristic of natural and semi-natural ecosystems. In: *Transfer of radionuclides in natural and semi-natural environments* (Desmet, G., Nassimbeni, P. & Belli, M. Eds.). pp. 27-39. Elsevier Applied Science, London.

Howard B.J. & Wright S.M. (Eds) (in preparation). *Long-term consequences of potential radioactive contamination in the Northern areas: northern Norway*. Centre for Ecology & Hydrology, Grange-over-Sands.

Iljin G.V., Nikolaeva E.N., Borovikova O.A., Shirokolobova O.V., Ryzhov V.M., Petrov V.S., & Serova B.G. (1992) *Current ecological state of Guba Belokamenka of the Kola Bay and adjacent areas*. KSC RAS. Publ., Apatity. (in Russian).

International Atomic Energy Agency (IAEA) (1985) *Sediment K_ds and concentration factors for radionuclides in the marine environment.* Technical Report Series No. 247. IAEA, Vienna.

International Atomic Energy Agency (IAEA) (1995) *The Principles of Radioactive Waste Management.* IAEA Safety Series No 111 F. IAEA, Vienna.

International Commission on Radiological Protection (ICRP) (1975) *Report of the task group on reference man.* Publication 23. Pergamon Press, Oxford.

International Commission on Radiological Protection (ICRP) (1977) *Recommendations of the International Commission on Radiological Protection.* Publication 26. Pergamon Press, Oxford.

Jones B.E.V. (1989) Radiocaesium uptake in reindeer on natural pasture. *Sci. Tot. Environ.*, **85**, 207-212.

Karaban R.T., Mishenkov N.N., Spirin D.A., Prisre B.S. & Alexsakhin R.M. (1980) The effects of acute gamma-irradiation on forest trees at different seasons. *Dokl. Akad. Nauk SSSR*, **252**, 766-768.

Kuzin, A.M. (1986) *Structural metabolic theory in radiobiology.* Nauka Publishers, Moscow (in Russian).

Kålås J.T., Bretten S., Brykjedal I. & Njåstad O. (1994) Radiocesium (^{137}Cs) from the Chernobyl reactor in Eurasian Woodcock and earthworms in Norway. *J. Wildl. Manage.*, **58**, 141-147.

Lowe V.P.W. & Horrill A.D. (1991) Caesium concentration factors in wild herbivores and the fox (*Vulpes vulpes* L). *Environmental Pollution*, **70**, 93-107.

Marshall J.S. (1966) Population dynamics of *Daphnia pulex* as modified by chronic radiation stress. *Ecology*, **47**, 561-571.

Maslov V.I., Maslova K.I. & Verkhovskaya I.N. (1967) Characteristics of the radioecological groups of mammals and birds of biogeocoenoses with high natural radiation. In: *Radiological concentration processes* (Åberg B. & Hungate F.P. Eds.). pp 561-571. Pergamon Press, Oxford.

Matishov G.G. (Ed.) (1989) *Ecology and Bioresources of the Kara Sea*. USSR Acad.Sci. Kola Sci.Center Publ.House, Apatity. (in Russian).

Natural Environment Research Council (NERC) (1993) Radiocaesium in natural systems – A UK coordinated study. *J. Environ. Radioactivity*, **18**, 133-149.

O'Brien R.D. & Wolfe L.S. (1964) Nongenetic effects of radiation. In: *Radioactivity and insects*. Volume **23**. Academic Press, New York.

Pendleton R.C., Lloyd R.D., Mays C.W. & Church B.W. (1964) Trophic level effect on the accumulation of caesium-137 in cougars feeding on mule deer. *Nature*, **204**, 708-709.

Pentreath R.J. (1977) Radionuclides in marine fish. *Oceanogr. Mar. Biol. Annual Review*, **15**, 365.

Pentreath R.J. (1999) A system for radiological protection of the environment : some initial thoughts and ideas. *Journal of Radiological Protection*, **19**, 117-128.

Pentreath R.J. & Woodhead D.S. (1988) Towards the development of criteria for the protection of marine fauna in relation to the disposal of radioactive wastes into the sea. In: *Radiation Protection in Nuclear Energy* Vol.2. pp 213-243. IAEA, Vienna.

Pentreath R.J. & Woodhead D.S. (2000) A system for environmental protection: reference dose models for fauna and flora. In: *10th Int. Congress IRPA*, 14-19 May 2000, Hiroshima, Japan, P-4b-228.

Pentreath R.J. & Woodhead D.S. (in press) A system for protecting the environment from ionising radiation: Selecting reference fauna and flora, and the possible dose models and environmental geometries that could be applied to them. *Sci. Tot. Env.*

Pokarzhevskii A. D. & Krivolutzkii D.A. (1997) Background concentrations of Ra-226 in terrestrial animals. *Biogeochemistry*, **39,** 1-13.

Rissanen K., Ikaheimonen T.K., Matishov D. & Matishov G. (1997) Radioactivity levels in fish, benthic fauna, seasl and seabirds collected in the northwest Arctic of Russia. *Radioprotection – Colloques*, **32**, 323-331.

Rose K.S.B. (1992) Lower limits of radiosensitivity in organisms excluding man. *Journal of Environmental Radioactivity*, **15,** 113-133.

Rudge S.A., Jonson M.S., Leah R.T. & Jones S.R. (1993a) Biological transport of radiocaesium in a semi-natural grassland ecosystem. 2. Small mammals. *J. Environ. Radioactivity,* **19**, 199-212.

Rudge S.A., Jonson M.S., Leah R.T. & Jones S.R. (1993b) Biological transport of radiocaesium in a semi-natural grassland ecosystem. 1. Soils, vegetation and invertebrates. *J. Environ. Radioactivity,* **19**, 173-198.

Seeger R. (1982) Toxische Schwermetalle in Pilzen. *Deuche Apotheker Zeitung*, **122**, 1835-1844.

Shekhanova I.A. (1983) *Radioecology of fish*. Publ. House "Light and Food Industry", Moscow.

Stonehouse B. (1989) *Polar Ecology*. Blackie and Son, Glasgow.

Strand P., Balonov M., Aarkrog A., Bewers M.J., Howard B.J. Salo A. & Tsaturov Y.S. (1997) *Arctic pollution issues: Radioactive contamination*. NRPA, Østerås.

Strand, P. & Larsson, C.M. (2001) Delivering a Framework for the protection of the environment from ionising radiation. In: *Radioactive pollutants impact on the environment* (Bréchignac F. & Howard B.J. Eds.) EDP Sciences, Les Ulis.

Strand P., Beresford N., Avila R., Jones S. & Larsson C-M. (2001) *Identification of candidate reference organisms from a radiation exposure pathways perspective*. Deliverable of the FASSET project. Swedish Radiation Protection Institute, Stockholm.

Thomas P. A. & Gates T. E. (1999) Radionuclides in the lichen-caribou-human food chain near uranium mining operations in northern Saskatchewan, Canada. *Environmental Health Perspectives*, **107**, 527-537.

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) (1996) *Effects of radiation on the environment.* United Nations Scientific Committee on the Effects of Atomic Radiation, Report to the General assembly, Annex 1. United Nations, New York.

United States Department of Energy (USDOE) (2000) *A graded approach for evaluating radiation doses to aquatic and terrestrial biota*. (Proposed standard). UDOE, Washington, D.C.

Whicker F.W. & Schultz V. (1982) *Radiecology: Nuclear Energy and the environment*. Vol. 1. CRC Press, Inc., Boca Raton.

Woodwell G.M. & Rebuck, A.L. (1967) Effects of chronic gamma radiation on the structure and diversity of an oak-pine forest. *Ecol. Monogr*. **37**, 53-69.

Woodwell G.M. & Whittaker R.H. (1968) Effects of chronic gamma irradiation on plant communities. *Q. Rev. Biol.*, **43**, 42-55.

Yardin M.R., Kennedy I.R. & Thies J.E. (2000) Development of high quality carrier materials for field delivery of key micro-organisms used as bio-fertilisers and bio-pesticides. *Radiat. Phys. Chem*., **57**, 565-568.

Zenkevich L.A. (1963) *Biology of the USSR Seas*. USSR Acad. Sci. Publ. House, Moscow (in Russian).

APPENDIX 1
Derivation of species lists

Species lists were derived for terrestrial, freshwater and marine environments in the Arctic from books, published papers and Internet web sites. Temperate ecosystem species whose range extends into the Arctic because of warmer climates associated with ocean currents such as the North Atlantic Drift have been excluded. The sources used are listed below.

Species list for vertebrates, terrestrial and freshwater plants, bryophytes and macrolichens can be considered to be virtually complete; these record most observed species. Only those plant species that are widely distributed within the Arctic, that could be easily identified and that have a clear taxonomy have been included. Hence, for some species of lichens and bryophytes it was necessary to include them as plant genera or aggregated groups. However, it was not possible to include species of fungi, bacteria, etc.; general sources of information for these organisms were not available (some localised surveys exist but may not be representative of the whole Arctic), and taxonomic classifications have yet to be completed (in fact, different physiological strains are likely to be more important than differences between species). Similarly, the identification of Arctic terrestrial and freshwater invertebrates to species level was difficult as most of the available information is based on single collecting expeditions that are difficult to extrapolate to the whole Arctic. Therefore, Arctic invertebrates were identified only to functional type (e.g. spiders, aphids, moths, butterflies, etc.). All freshwater fish that spend part of their life cycle in freshwater (e.g. salmon) were included. Marine organisms found in the Barents, Kara, White and Greenland Seas including the northern part of the Norwegian Sea were included; for phytoplankton, species commonly found in the Kola Bay are listed and were typical of species found in Low Arctic marine areas; predominant zooplankton species were included.

Where possible information about the distribution and habitat of Arctic species was also included within the species lists. Species were identified as being present in High, Low and Sub- Arctic areas, and their geographical distribution was also recorded. The period of residency was also included for birds and mammals to identify resident Arctic species (which may move between different Arctic environments during the year) and those that migrate to non-Arctic areas for some part of the year. All species were allocated to one type of ecosystem - terrestrial, freshwater or marine - using habitat information. In some cases it was necessary to be pragmatic. For example, polar bear was identified as being in the marine ecosystem as they spend the majority of their life on sea ice; similarly, lapwing were identified as being part of the terrestrial ecosystem even though they migrate to coastal areas during the winter. It must be remembered that the absence of distribution information for any species, especially for some plants, invertebrates and micro-organisms, may only indicate a lack of information and may not confirm the absence of an organism from an area.

Freshwater Fish

Wheeler A. (1978) *Key to the Fishes of Northern Europe*. Warne, London.

Mammals

Corbet G.B. (1978) *The Mammals of the Palaearctic Region: a taxonomic review*. Cornell University Press and The British Museum (Natural History), London.

Macdonald D. & Barrett P. (1993) *Collins Field Guide: Mammals of Britain and Europe*. HaperCollins, London.

Birds

Harrison C. (1982) *An Atlas of the Birds of the Western Palearctic*. Collins, London.

Hagemeijer W.J.M. & Blair M.J. (Eds.) (1997) *The EBCC Atlas of European Breeding Birds: Their distribution and abundance.* T & A.D Poyser, London.

Vascular Plants

Hulten E. (1968) *The Flora of Alaska and Neighbouring Territories*: A manual of the vascular plants. Stanford, California.

Nilsson O. (1986) *Nordisk fjällflora*. Bonniers, Stockholm.

Polunin N. (1959) *Circumpolar Arctic Flora*. Oxford University Press, London.

Rønning O.I. (1996) *The Flora of Svalbard*. Norwegian Polar Institute, Oslo.

Bryophytes

Elvebakk A. & Prestrud P. (1996) *A Catalogue of Svalbard Plants, Fungi, Algae and Cyanobacteria*. Norsk Polarinstitutt, Oslo.

Hallingbäck T. & Holmåsen I. (1985) *Mossor: en fälthandbok*. Interpublishing, Stockholm.

Paton J.A. (1999) *The Liverwort Flora of the British Isles*. Harley Books, Colchester.

Smith A.J.E. (1978) *The Moss Flora of Britain & Ireland*. Cambridge University Press, Cambridge.

Smith A.J.E. (1990) *The Liverworts of Britain & Ireland*. Cambridge University Press, Cambridge.

Lichens

Elvebakk A. & Prestrud P. (1996) *A Catalogue of Svalbard Plants, Fungi, Algae and Cyanobacteria*. Norsk Polarinstitutt Oslo.

Purvis O.W., Coppins B.J., Hawksworth D.L., James P.W. & Moore D.M. (1992) *The Lichen Flora of Great Britain and Ireland*. Natural History Museum Publications, London.

Terrestrial and freshwater invertebrates

Bale J.S., Hodkinson I.D., Block W., Webb N.R., Coulson S.J. & Strathdee A.T. (1997) Life strategies of Arctic terrestrial invertebrates. In: *Ecology of Arctic Environments*. (Woodin S.J. & Marquess M. Eds.) Blackwell Science, Oxford.

Birkemoe T., Coulson S.J. & Sømme L. (in press) Species characteristics, life cycles and population dynamics of enchytraeids (Oligochaeta) from the high Arctic.

Bøcher J. (1988) The Coleoptera of Greenland. *Meddedelser om Grønland Biosciences*, **26**, 1-100.

Chernov Y.I. (1985) *The Living Tundra*. Cambridge University Press, Cambridge.

Coulson S.J. (2000) A review of the terrestrial and freshwater invertebrate fauna of the High Arctic archipelago of Svalbard. *Norwegian Journal of Entomology*. **47**, 41-63.

Danks H.V. (1981) *Arctic Arthropods*. Entomological Society of Canada, Ottawa.

Gorny M. & Grum L. (1993) *Methods in Soil Zoology*. Elsevier, Amsterdam.

Heath J. & Emmett A.M. (1983) *The Moths and Butterflies of Great Britain and Ireland.* Vol 10. Harley Book, Colchester.

Hodkinson I.D., Coulson S.J., Harrison J.A. & Webb N.R. (in press). What a wonderful web they weave: spiders, nutrient capture in early ecosystem development in the High Arctic - some counter intuitive ideas on community assembly. *Oikos*.

Kozlov M.V. & Jalava J. (1994) Lepidoptera of the Kola Peninsula, northwestern Russia. *Entomolgica Fennica* , **5**, 65-85.

Neuvonen S., Rossolimo T. & Ryrholm N. (1995) Monitoring methods for terrestrial invertebrates in Arctic terrestrial ecosystems. In:*Biological Methods for use in Monitoring the Arctic* (Olsen K.V. Ed.). Nordic Council of Ministers, Copenhagen.

Sømme L & Block W. (1991) Adaptations to alpine and polar environments in insects and other terrestrial arthropods. In: *Insects at Low Temperatures*. (Lee R.E & Denlinger D.L. Eds.) Chapman & Hall, London.

Strathdee A.T., Bale J.S., Block W., Coulson S.J., Hodkinson I.D. & Webb N.R. (1993) Effects of temperature elevation on a field population of Acyrthosiphon svalbardicum (Hemiptera: Aphididae) on Spitsbergen. *Oecologia* **96**, 457-465.

Traugott-Olsen, E. & Schmidt Nielsen, E. (1977) *The Elachistidae (Lepidoptera) of Fennoscandia and Denmark*. Scandinavian Science Press, Klampenborg.

Webb N.R., Coulson S.J., Hodkinson I.D., Block W., Bale J.S. & Strathdee A.T. (1998) The effects of experimental temperature elevation on populations of cryptostigmatic mites in high Arctic soils. *Pedobiologia* **42**, 298-308.

Wolff N.L. (1971) Lepidoptera. *Zoology of Iceland* **3**, 1-193.

Marine organisms

Arctic Monitoring and Assessment Programme (AMAP) (1998) AMAP Assessment Report: Arctic Pollution Issues. AMAP, Oslo.

Andriyashev A.P. (1954) *Fishes of the Northern Seas.* USSR Acad. Sci. Publ. House, Moscow. (in Russian).

Frovola E.A. (1997) Ecological status of the Kola Bay benthos. In: *Ecological situation and protection of flora and fauna in the Barents Sea*. pp. 121-125. KSC RAS. Publ., Apatity. (in Russian).

Gilyarov M.S. (Ed.) (1986) *Biological Encyclopedia*. Soviet Encyclopedia Publishers, Moscow. (in Russian).

Iljin G.V., Nikolaeva E.N., Borovikova O.A., Shirokolobova O.V., Ryzhov V.M., Petrov V.S., & Serova B.G. (1992). *Current ecological state of Guba Belokamenka of the Kola Bay and adjacent areas*. KSC RAS. Publ., Apatity. (in Russian).

Marti, Yu.Yu. (1980). *Migration of sea fishes.* Pishevaya Promyshlennost Press, Moscow. (in Russian).

Matishov G.G. (Ed.) (1989) *Ecology and Bioresources of the Kara Sea*. USSR Acad. Sci. Kola Sci.Center Publ.House, Apatity. (in Russian).

Matishov G.G (1992). *Anthropogenic destruction of ecosystems.* Kola Sci. Center Publ. House, Apatity. (in Russian).

Rass T.S. (1965) *Fish resources of the USSR European Seas and means of their replenishment through acclimatization.* Nauka, Moscow. (in Russian).

Yesipov V.K. (1952) *Fishes of the Kara Sea*. USSR Acad. Sci. Zool. Inst. Publ. House, Leningrad. (in Russian).

Zenkevich L.A. (1963) *Biology of the USSR Seas.* USSR Acad. Sci. Publ. House, Moscow (in Russian).

Zemskoy V.A. (Ed.) (1980) *Album of sea mammals of the USSR*. Food Industry, Moscow. (in Russian).