Technical Report

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A transport and fate model of C-14 in a bay of the Baltic Sea at SFR

Today and in future

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Abstract

The environmental transport and fate of a hypothetical release of radioactive carbon-14 from SFR-1 (the final repository for radioactive operational waste) was investigated using an ecosystem modelling approach. The approach involved identification, quantification and dynamic modelling of the main flows and storages of carbon both in the physical environment and in the food web. Carbon-14 was in the model introduced into the food web via photosynthesising organisms. Contamination of the aquatic ecosystem above SFR-1 was then assessed assuming a release of 5.13×10^{7} Bq/year for 1,000 years. Modelling results were used to estimate steady-state C-14 concentrations in biota, exposure (Gy) of biota and dose (Sv) to humans consuming contaminated organisms both if the discharge occurred today (2000 AD) and if it occurred in the future (4000 AD). Since the modelled area is characterised by a fast water exchange, most of the discharged C-14 was flushed out of the system more or less immediately (99.8% and 98.4% at 2000 AD and 4000 AD, respectively). However, a small fraction of the discharge was assimilated by primary producers (0.18% and 2.11%), which enabled subsequent transfer of C-14 to organisms at higher trophic levels (e.g. fish, seals and humans). The exported C-14 from the area was diluted to very low concentrations in the large recipient outside. Estimated exposures were very low, and differed significantly among the studied biota (17.2×10^{-12} to 2.3×10^{-6} Gy). In general the highest exposures were observed in benthic plants and benthic grazers followed by fish and benthos. Humans consuming large quantities of locally produced food (e.g. fish, mussels and algae) will receive an exposure in case of C-14 contamination. Estimated doses to humans were approximately 10–100 nSv per year, which is significantly lower than restrictions by the authorities. The developed model was also used to evaluate implications of various assumptions concerning the route of C-14 entry in the food web and the rate of water exchange in the studied ecosystem. An assumption of C-14 entry into the food web via benthic primary producers was found to lead to increased exposures to biota (especially benthic organisms) and increased doses to humans consuming benthic organisms and fish. Reduced rates of water exchange were also observed to significantly increase C-14 exposure to both aquatic organisms and humans.

Sammanfattning

I denna studie har transport och fördelning av ett hypotetiskt utsläpp av radioaktivt kol-14 från SFR-1 (Slutgiltigt Förvar för Radioaktivt driftavfall) studerats med en systemekologisk modelleringsmetod. Med denna metod identifieras, kvantifieras och modelleras huvudsakliga flöden och reservoirer av kol, såväl i den fysiska miljön (t ex vattnet) som i näringsväven. I modellen introduceras kol-14 till näringsväven via fotosyntetiserande organismer och vid modelleringen antogs det att det akvatiska ekosystemet belastades med ett utläpp av kol-14 motsvarande 5,13 × 10^7 Bq/år under 1 000 år. Modelleringsresultaten användes för att uppskatta kol-14 koncentrationer i biota då systemet nått jämnvikt, exponering av biota (Gy) och dos till människor som konsumerat kontaminerade organismer. Modellen användes både för att bedöma konsekvenserna av ett utsläpp till dagens sekosystem (2000 AD) såväl som om det skulle ske ett om två tusen år (4000 AD). Eftersom vattenomsättningen i det modellerade området är stor, har det visat sig att den största delen av kol-14 läckaget transporteras iväg från området mer eller mindre omgående (99,8% repektive 98,4% år 2000 AD och 4000 AD). En liten del av det som släpps ut assimileras dock av primärproducerande organismer (0,18% respektive 2,11%), vilket leder till en transport av kol-14 upp genom näringsväven till organismer på högre trofinivåer (t ex fisk, säl och människa). Det C-14 som exporterades från området späddes till väldigt låga C-14 koncentrationser i den omgivande recipienten. De uppskattade exponeringarna av biota var väldigt låga och skiljde sig markant mellan de olika organismtyperna som studerades (17,2 × 10^{-12} till 2,3 × 10^{-6} Gy). Bentiska växter och betare belastades med de högsta exponeringarna, följt av fisk och benthos. Människor som konsumerar stora mändger lokalproducerad mat (t ex fisk, musslor och alger) kommer också att utsättas för radioaktivitet vid ett kol-14 utsläpp. Modelleringsresultaten uppskattade att doserna till människa till följd av konsumtion blir ca 10–100 nSv per år, vilket är betydligt lägre än de gränsvärden som satts upp av svenska myndigheter. Modellen har även använts till att bedöma konsekvenserna av olika introduktionsvägar för kol-14 in i näringsväven samt förändrad vattenomsättning i det studerade ekosystemet. Antagandet att kol-14 främst introduceras via bentiska primärproducernter visade sig leda till ökad exponering för biota (främst bentiska organismer) och ökade doser för människor som konsumerar bentiska organismer och fisk. Minskad vattenomsättning visade sig också leda till en markant ökning av kol-14 exponeringen både för akvatiska organismer och människor.

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1 Introduction

1.1 The SAFE project

This study is a part of the SKB project "SAFE" (Safety Assessment of the Final Repository for Radioactive Operational Waste, SFR-1), which has the aim to update the previous safety analysis of SFR-1 /SSR, 1987/. SFR-1 is a facility for disposal of low and intermediate level radioactive waste and is located in the bedrock beneath the seabed, 1 km off the coast near the Forsmark nuclear power plant in Northern Uppland, Sweden.

For the surface ecosystems in the area around the repository, various background information has been reported. For instance, the historic shore-level displacement and a future projection is presented by /Brydsten, 1999a/ as well as predicted future changes in sedimentation /Brydsten, 1999b/. The characteristics of present lakes and the development of future lakes in the area are described by /Brunberg and Blomqvist, 1999/ and /Brunberg and Blomqvist, 2000/ respectively and a diving survey describing the structure of the brackish water ecosystem is presented by /Kautsky et al, 1999/. A model of the water exchange in the coastal area is described by /Engqvist and Andrejev, 1999/ and variations of possible future changes by /Engqvist and Andrejev, 2000/. In /Kumblad, 1999/ an ecosystem-model of the coastal area is presented and the future changes of the ecosystem are presented in this report together with a description of a method for estimating radiation exposure to various organisms and dose to humans consuming locally produced food. The terrestrial ecosystem and the future vegetation will be presented in /Jerling et al, 2001/. The information in this report and those mentioned above will be summarised and used in final dose estimates for possible discharges from the repository.

1.2 Background and aim of this study

In SFR-1 a substantial amount of radionuclides is stored. Many of these have long half-lives and thereby pose a potential threat both to humans and to the adjacent environment for an extensive period of time. C-14 is one of the radionuclides that is of considerable interest since this isotope often is found in operational and nuclear waste repositories, e.g. in SFR-1, and has a high environmental mobility, bioavailability and a half-life of 5,730 years /Liepins and Thomas, 1988/.

The total permitted amount of radioactivity for SFR-1 is 10^{16} Bq of which 7.2×10^{12} Bq is allowed to be C-14 /Andersson, 1998a/. In the previous safety assessment of SFR-1, organic C-14 was predicted to be the radionuclide that will dominate the individual doses to humans after a few hundred years and the collective dose after 2000 years /Andersson, 1998b/. Other modelling studies than /SSR, 1987/, assessing low-level waste disposal facilities, have also indicated that C-14 may be one of the more significant contributors to the calculated radiation dose via the groundwater pathway to humans living near the site /Merill, 1986; Bandrowski, 1988/.

For a hypothetical discharge, the chemical speciation of C-14 is of importance since organic and inorganic carbon has very different physical and chemical properties. The dynamics of C-14 in surface water is of particular interest since the flux of C-14 from underground sources may contaminate ground water discharging into surface water bodies and enter aquatic food webs via uptake into autotrophic organisms such as green plants and algae /Stephenson and Reid, 1996/.

Estimates of the final composition of the C-14 in SFR-1 indicate that the main part stored is of organic speciation /Kautsky, 2000 pers. com./ but it is unknown in what chemical form the carbon isotope will enter the biosphere in case of a discharge from the repository. In this study it is assumed that the C-14 reaches the biosphere via groundwater flows in the bedrock and enters as inorganic carbon (e.g. as carbon dioxide or carbonate ions) and thereby become available for autotrophic organisms. If the C-14 instead was to enter the biosphere as organic carbon it would probably enter the food web primarily via heterotrophic bacteria, since these can utilise dissolved organic carbon /e.g. Alperin et al, 1994; Kaehler et al, 1997; Janson et al, 1999; Cherrier et al, 1999/, instead of via autotrophic organisms.

The radiological dose that humans could receive from various sources of C-14 has been the subject of many modelling exercises /e.g. Killough, 1980; McKee and Roswell, 1984; Bergström and Nordlinder, 1989; Hesböl et al, 1990; Zach and Sheppard, 1991/. Unfortunately relatively few efforts have been made to synthesise knowledge about carbon cycles into integrated conceptual or numerical whole-ecosystem models /Stephenson and Reid, 1996/. A complicating factor in radionuclide assessments is the long time scale required. Time scales of 1,000–1,000,000 years are often necessary due to the long half-lives of many radionuclides, which results in long residence times of these persistence substances in the environment. The structure and function of ecosystems often change considerably during such long time periods, which complicates extrapolation of present knowledge of ecosystem behaviour of radionuclides to future ecosystems. Particularly since it has been shown that feeding relationships and trophic conditions in an ecosystem play an important role for the exposure of contaminants in biota /e.g. Paterson et al, 1995; Russel et al, 1999/. One way of increasing the generality of the models and thereby reducing extrapolation difficulties could therefore be to base models on fundamental ecological processes, such as mass and energy transfer, which has been done in this study. This type of energy-based systems ecological modelling has successfully been used to describe and investigate ecosystem properties in a large number of ecological and ecotoxicological studies /e.g. Bartell et al, 1999; Murray and Parslow, 1999/. Naturally, since carbon is the unit of energy transfer in food webs, a model of C-14 in an ecosystem would per definition be such an energy-based model. However, a general (contaminant independent) asset of this approach is the possibility of using the large empirical data set and understanding of fundamental processes generated by ecosystem studies to extrapolate to other ecosystems in a variety of spatial and temporal scales.

In this study, two dynamic flow models that simulate discharge of C-14 from SFR-1 in the ecosystem above are presented. The models are based on an ecosystem approach where general ecological principles that identifies and quantifies the main flows and storages of energy (carbon) and C-14, both in the physical environment as well as in the food web are used. In the model a C-14 amount corresponding to 5.13×10^7 Bq/year is discharged into the modelled ecosystem during a period of 1,000 years. This magnitude of discharge was chosen to be modelled because it was the estimated maximum discharge from the repository /Lindgren et al, 2001/. The C–14 entering the biosphere follows the carbon flow in the ecosystem where it accumulates by primary producers and circulates in the food web or is exported from the system. In this model no bioaccumulation- or bioconcentration factors have been used as initial data (since the modelled flows is based on quantified carbon fluxes in the ecosystem), although bioconcentration factors have been calculated from the results to facilitate comparisons with model results from other modelling exercises.

Both models are box type carbon-flow models to which C-14 flow models are linked (Figure 1-1). These linked models describe the transport and uptake of C-14 in case of a discharge from the repository into the ecosystem. First the model was run with in-data for the present ecosystem (2000 AD) and then with in-data for the predicted ecosystem at the same location in 2,000 years (4000 AD), i.e. the same models are used with different in-data to describe the discharge at two different time periods.

1.3 Organisation of this report

This report is divided into ten sections. After the introduction, there is a short description of the study area and then a section describing how the carbon budgets were established. In section four the construction of the models is found and in section five the results of the budgets are shown. The modelling results are presented in section six, a discussion of validation of the model results in section seven and in a short discussion with conclusions in section eight. The references are listed in the last section and in Appendix the model equations as well as result tables are presented.

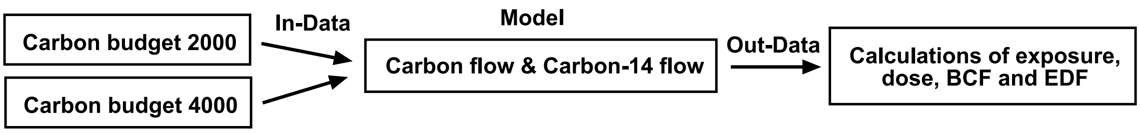

Figure 1-1. *The model in this study consists of a linked carbon flow and a C-14 flow model, where the model in-data comes from carbon budgets (representative for 2000 AD and 4000 AD respectively from the study area in Öregrundsgrepen) and the model out-data gives data for calculations of exposure to organism groups, doses etc.*

2 Description of the study area

2.1 General description of the area

Budgets and models, presented in this study, were developed for the brackish water ecosystem above the final repository for radioactive operational waste (SFR-1). The repository is located in the bedrock under the seabed in the southern part of Öregrundsgrepen, the Baltic Sea (Figure 2-1 and 2-2). The study area is almost 11.5 km^2 of which 2.4% is land. The photic zone stretches down to approximately 10 meters water depth, although a small amount of algae can be found down to a depth of 15 meters /Kautsky et al, 1999/. The retention time of the water in the area is on an annual average less than a day /Engqvist and Andrejev, 1999/.

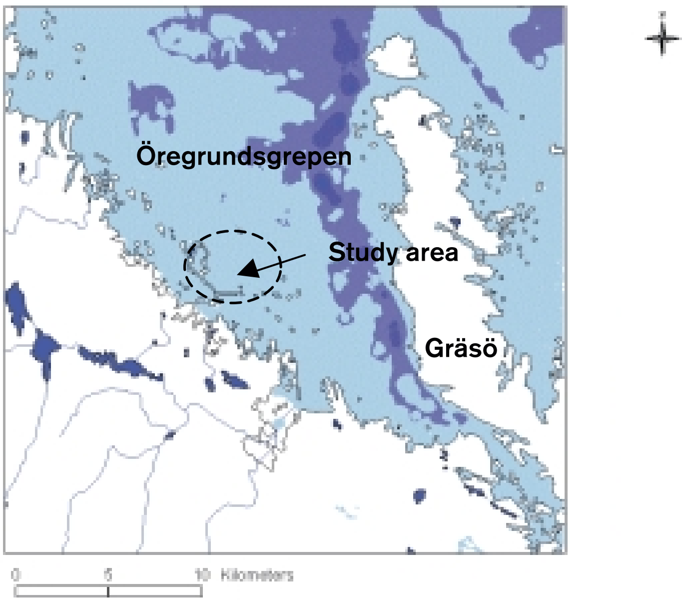

Figure 2-1. *Location of the study area in Öregrundsgrepen at 2000 AD; from /Brydsten, 1999a/.*

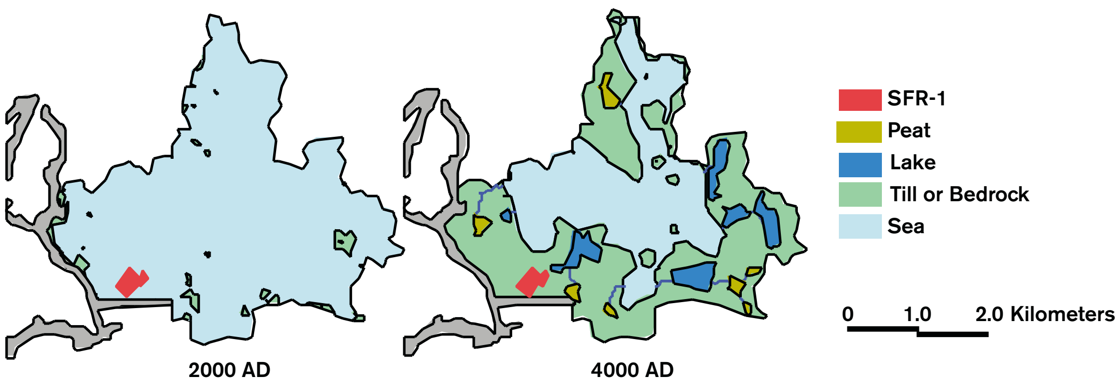

Figure 2-2. *The study area at present (2000 AD) and in future (4000 AD) in Öregrundsgrepen; from /Brydsten, 1999a/.*

Öregrundsgrepen is a relatively productive coastal area in a region of low primary production, probably due to upwellings along the mainland /Eriksson et al, 1977/. The surface water has a nutrient content of 200–400 µg/l tot-N and 7–10 µg/l tot-P /Lindahl and Wallström, 1980/. Erosion and transport bottoms dominate with heterogeneous and mobile sediment consisting mainly of sand and gravel with varying fractions of glacial clay /Mo and Smith, 1988/ and the seabed close to the mainland has some strains of rocky bottoms, which partly is covered with coarse moraine /Sigurdsson, 1987/.

Due to land rise, the area will look different in the future. In 2,000 years (4000 AD), half of the current water surface in Öregrundsgrepen will be land and the water volume will approximately be one tenth of the present. From today to 4000 AD the major change in landscape evolution will occur close to the mainland and on the east side of Gräsö. The Öregrund strait will successively narrow and close approximately 3000 AD, i.e. the island Gräsö will become a part of the mainland. About 4000 AD, the sea in the study area consists of a bay (Figure 2-2) and it is likely that the area has an estuarine environment, i.e. low salinity, a sharp developed halocline, an estuarine water circulation and a sedimentation that is controlled by water circulation. This means that the transport of particle-bound radionuclides from the SFR-1 to the open sea will decrease compared to the transport at present /Brydsten, 1999a/.

A suitable time for the future model was found to be the year 4000 AD since the study area still will be in contact with the coastal area but the "open water system" has turned into a shallow archipelago with reduced water exchange compared to at present. At 4000 AD the shoreline will be displaced 11 m below its present position /Påsse, 1996/ and the total ratio of land to water will increase from 2.4% at 2000 AD to almost 55% /Brydsten, 1999c/. The mean and maximum water depth will decrease from 10 and 18 meters respectively at 2000 AD to 3 and 8 meters at 4000 AD and the retention time of the water in the future area is estimated to an annual average of approximately eight days /Engqvist and Andrejev, 2000/.

A table with hypsographic data of the study area at present (2000 AD) and in 2,000 years (4000 AD) is shown below (Table 2-1) and a hypsographic curve is shown in Figure 2-2.

Table 2-1. Depth distribution and volume of the study area above SFR-1 (Öregrundsgrepen) at 2000 AD and 4000 AD.

Depth interval	Area (km^2)		Area (%) of total	
	2000 AD	4000 AD	2000 AD	4000 AD
Land	0.27	6.18	2.4	53.9
0–1 meters	0.29	0.86	2.6	7.5
1–2 meters	0.41	1.23	3.6	10.7
2–4 meters	0.90	1.89	7.8	16.5
4–6 meters	1.44	0.90	12.6	7.8
6–10 meters	2.84	0.41	24.8	3.6
10–15 meters	4.44	–	38.7	–
15–20 meters	0.87	–	7.6	–
Sea bed total	11.20	5.29	97.6	46.1
Area total	11.47	11.47	100.0	100.0
Photic zone	5.89	5.29	51.4	46.1
Aphotic zone	5.31	–	46.3	–
Volume (km^3)	0.11	0.0153	–	–

Source: /Brydsten, 1999c/.

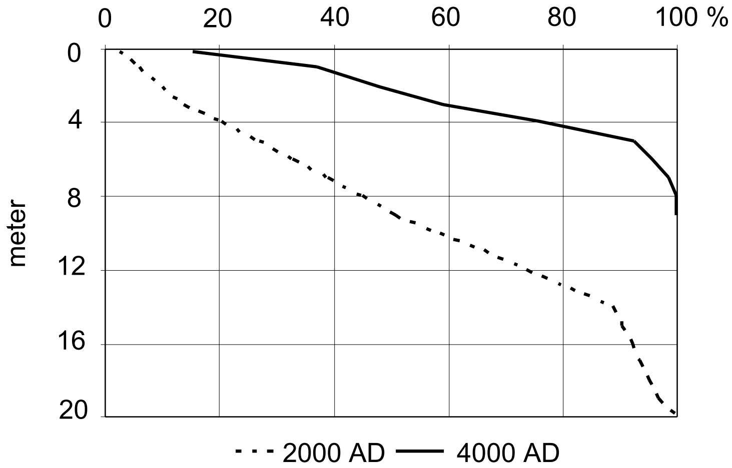

Figure 2-3. Hypsographic curve for the study area above SFR-1 (Öregrundsgrepen) at 2000 AD and 4000 AD, expressed as percentage bottom surface above a certain depth (%/m). Source: /Brydsten, 1999c/.

2.2 Flora and fauna in the study area

Several studies on flora and fauna have been carried out in the Öregrundsgrepen area and adjacent areas and many of them have been used in this model-study.

In the phytobenthic community, the benthic community in the photic zone, the seabed to a large extent is covered with a layer of micro algae, mainly diatoms, and a relatively high species diversity and large amount of macrophytes (both macro algae and phanerogames) /Kautsky et al, 1999; Snoeijs, 1985, 1986/. Herbivorous gastropods together with both herbivore and omnivore crustaceans dominate the grazing group and the most common filter feeder is a bivalve (*Cardium* spp) /Kautsky et al, 1999/. The major meiofauna taxa are nematodes, acarins, cladocerans, copepods and ostracods /Snoeijs and Mo, 1987/.

In the soft bottom community, the seabed below the photic zone, the species diversity is lower due to the heterogeneous and mobile sediment /Mo and Smith, 1988/. Organism groups in this community are macrobenthos consisting of detritus and filter feeding macrofauna along with macrofauna predators, meio- and microfauna. Among the macrobenthos, the detritus- and filter feeding bivalve *Macoma baltica* strongly dominates the biomass /Kautsky et al, 1999/. Meiofauna of the soft bottom community has not been investigated in the study area and therefore the same meiofauna data as for the phytobenthic community was used in the model development.

The organism groups in the pelagic community are phytoplankton, bacterioplankton, zooplankton and fish. During springtime, diatoms and dinoflagellates strongly dominate the phytoplankton community in Öregrundsgrepen while the plankton community in summer and autumn mainly consists of bluegreen algae and small flagellates /Lindahl and Wallström, 1980/. The zooplankton community has low species diversity. Two copepod species constitute about 80% of the zooplankton biovolume while the rest is composed of cladocerans, rotatorians, ciliates and different larvae stages from benthic animals /Eriksson et al, 1977; Persson et al, 1993/. The most common fish species in Öregrundsgrepen are herring (*Clupea harengus*), roach (*Rutilus rutilus*) and perch (*Perca fluviatilis*) /Neuman, 1982/. It should be mentioned that with the method used in that survey it was not possible to catch small sized species e.g. sticklebacks (*Gasterosteidae*) and gobies (*Gobiidae*), which may have affected the results of the species distribution.

3 Construction of the carbon budgets

Initial values for the carbon flow models originate from carbon budgets established by compiling data on biomass, production, respiration and consumption for organisms living in the area, from a number of studies conducted in or close to the previously described area. To facilitate the construction of the budgets and models as well as to get an overview of the information, the organisms were divided into functional groups (compartments), i.e. groups of organisms sharing the same ecosystem function. The compartment are compiled and described in Table 3-1, together with the source of the used data.

Data for macrophytes and macrofauna used in this study originate from a diving survey by /Kautsky et al, 1999/. That survey delivered data of the total biomass for organisms at each bottom depth interval of the study area since the organism biomass were measured along transects. The sum of the intervals for each organism group (the total macrophyte and macrofauna biomass) was used in the budget.

Table 3-1. Description of the compartments used in the carbon budget and carbon flow model and the source of data for the respective compartment.

Model compartment	Organism group(s) (source)	Definition/description
1. Plankton	Phytoplankton[1]	Pelagic micro algae (>3µm)
	Bacterioplankton[2]	Pelagic bacteria (<3 µm)
2. Zooplankton	Zooplankton[3]	Planktonic animals (other than bacteria)
3. Benthophytes	Microphytes[4]	Benthic micro algae
	Macrophytes[5]	Benthic macroalgae, phanerogams, bryophytes
4. Grazers[1]	Grazers[5]	Macrophyte grazing macrofauna (>500µm)
5. Fish	Fish[6]	Fish (both demersal and planktonic)
6. Benthos	Filter feeders[5]	Filter feeding macrofauna (> 500 µm)
	Benthic macrofauna[5]	Soft bottom living macrofauna (> 500 µm)
	Benthic meiofauna[7]	Meiofauna (3–500 µm) in/on the seabed
	Benthic microfauna[8]	Benthic bacteria (<3 µm)
7. Eagle	Eagle[9]	White-tailed eagle (modelled for individuals)
8. Eider duck	Eider duck[10]	Eider duck
9. Seal	Seal[11]	Grey seal (modelled for individuals)
10. Human	Human[12]	
11. POC	POC[13]	Nonliving particulate organic carbon
12. DIC	DIC[14]	Nonliving dissolved inorganic carbon

1. /Lindahl and Wallström, 1980/
2. /Kuparinen, 1987/
3. /Eriksson et al, 1977/
4. /Snoeijs, 1985, 1986/
5. /Kaustsky et al, 1999/
6. /Jansson et al, 1985/
7. /Ankar, 1977/
8. /Mohammadi et al, 1993/
9. /Helander, 1983/
10. /Kautsky et al, 1983; Gilek et al, 1997/
11. /Roos, 2000 pers.com./
12. /Wikberger, 2000/
13. /Nitchals, 1985/
14. /Larsson, 1999 pers.com./

For organisms other than macrophytes and macrofauna, the biomass, respiration-, production- and consumption rates were accounted for per square meter. To get values representative for the whole study area, each compartment was defined to be present at a certain depth interval of the area and multiplied with the bottom surface of the corresponding interval.

The microphytes were assumed to occur on seabeds in the photic zone while the benthic meio- and microfauna together with filter feeders were assumed to be present on sea-beds at all depths. Pelagic fauna including bacterioplankton, zooplankton and fish were assumed to be present in the whole water column and phytoplankton mainly in the water mass down to ten meters (in the photic zone).

In studies where only the biomass had been measured, respiration, production and consumption were calculated with the aid of conversion factors from /Kautsky, 1995/. All data were re-calculated to be valid on an annual basis. Since primary production to a great extent is dependent on solar radiation, the annual number of light-days was used to compensate for seasonal variations. The annual light days are the number of days per year with a relative insolation of at least 5 $MJ/m^2 \times$ day and were estimated to 105 at 60°N /Kautsky, 1993/. The animal respiration was also compensated for seasonal changes by considering temperature variations during the year. The annual degree-days were estimated to 2,400°C at 60°N /Kautsky, 1993/. The difference between consumption and respiration was assumed to be the secondary production (growth, gametes etc) and loss (faeces, death etc). The equations used in the calculations are summarised in Table 3-2.

Table 3-2. Equations used in the calculations of carbon flow variables (CF = conversion factor).

Eq	Variable	Equation	Unit
1	biomass	dry weight × CF for dry weight to carbon	gCm^{-2}
2	primary production	biomass × CF for biomass to primary production × annual light-days	$gCm^{-2}yr^{-1}$
3	respiration	biomass × CF for biomass to respiration / 20 × annual degree-days	$gCm^{-2}yr^{-1}$
4	consumption	3 × respiration	$gCm^{-2}yr^{-1}$
5	loss	consumption – respiration	$gCm^{-2}yr^{-1}$

Source: /Kautsky, 1995/.

3.1 Calculation of the carbon budget for the future ecosystem

To model the carbon flow and fate of a C-14 discharge in the future ecosystem, a separate carbon budget for 4000 AD was constructed (new initial data for the model). Data for biomass, production, respiration and consumption used in the 2000 AD budget were transformed to be applicable per square meter and then multiplied with the hypsographic data for 4000 AD (bottom surfaces of each corresponding depth interval) /Brydsten, 1999c/.

All other calculations in the two budgets were done identically and it was assumed that:

- the water visibility will remain the same at 4000 AD compared to 2000 AD,
- the organism groups will occur at the same depth intervals at 4000 AD and 2000 AD,
- the organisms will have the same abundance (biomass/m^2) and ecosystem function at 4000 AD and 2000 AD,
- the annual number of light days and degree-days will remain the same at 4000 AD compared to 2000 AD.

4 Construction of the carbon flow models

The two models developed in this study describe the circulation of carbon as well as the uptake and trophic transfer of C-14 in the ecosystem from a hypothetical discharge at 2000 AD and 4000 AD. The models were constructed in the software-modelling program STELLA (version 5.0; High Performance System Inc).

4.1 Two model sections

Both models consist of two linked model-sections (Figure 4-1), which are described in detail below. The first model-section describes the normal carbon flow in the ecosystem and is based on results from the corresponding carbon budget. The second model-section describes the amount and concentration of C-14 in the repository as well as in each compartment (Figure 4-2). Model results from the two sections present the biomass and radioactivity in each compartment as well as the flux of carbon and C-14 between the compartments. Exposure to biota, dose to human as well as bioconcentration factors (BCF:s) and ecosystem specific dose conversion factors (EDF:s) for the various compartments is then calculated. The compartments, both within as well as between the sections, are coupled with flow variables, describing the rate of the flow of carbon and C-14 respectively. All equations used in the model are shown in detail in Appendix 1 and numbered in Figure 4-2.

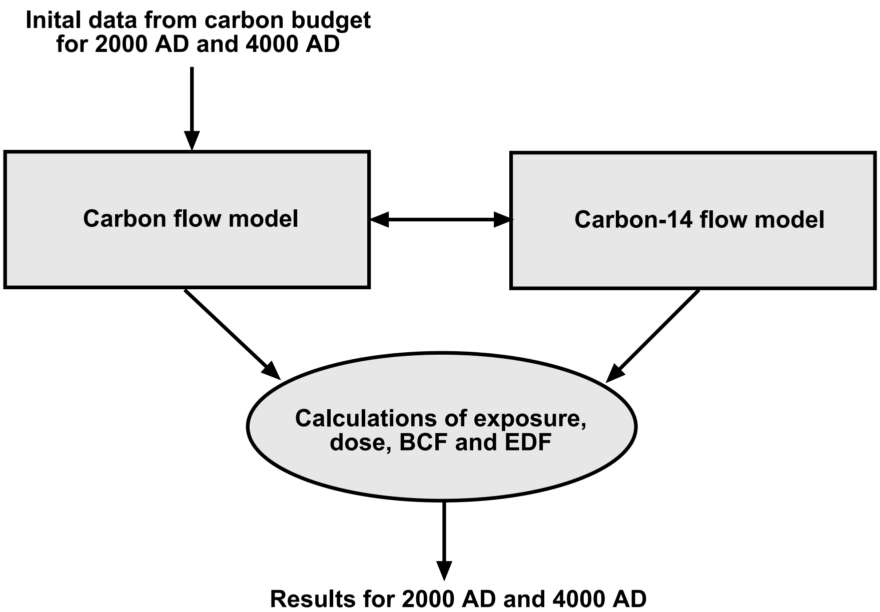

Figure 4-1. *The models are constructed of two linked model sections from which calculations of exposure, dose, bioconcentration factors (BCF:s) and ecosystem specific dose conversion factors (EDF:s) are made.*

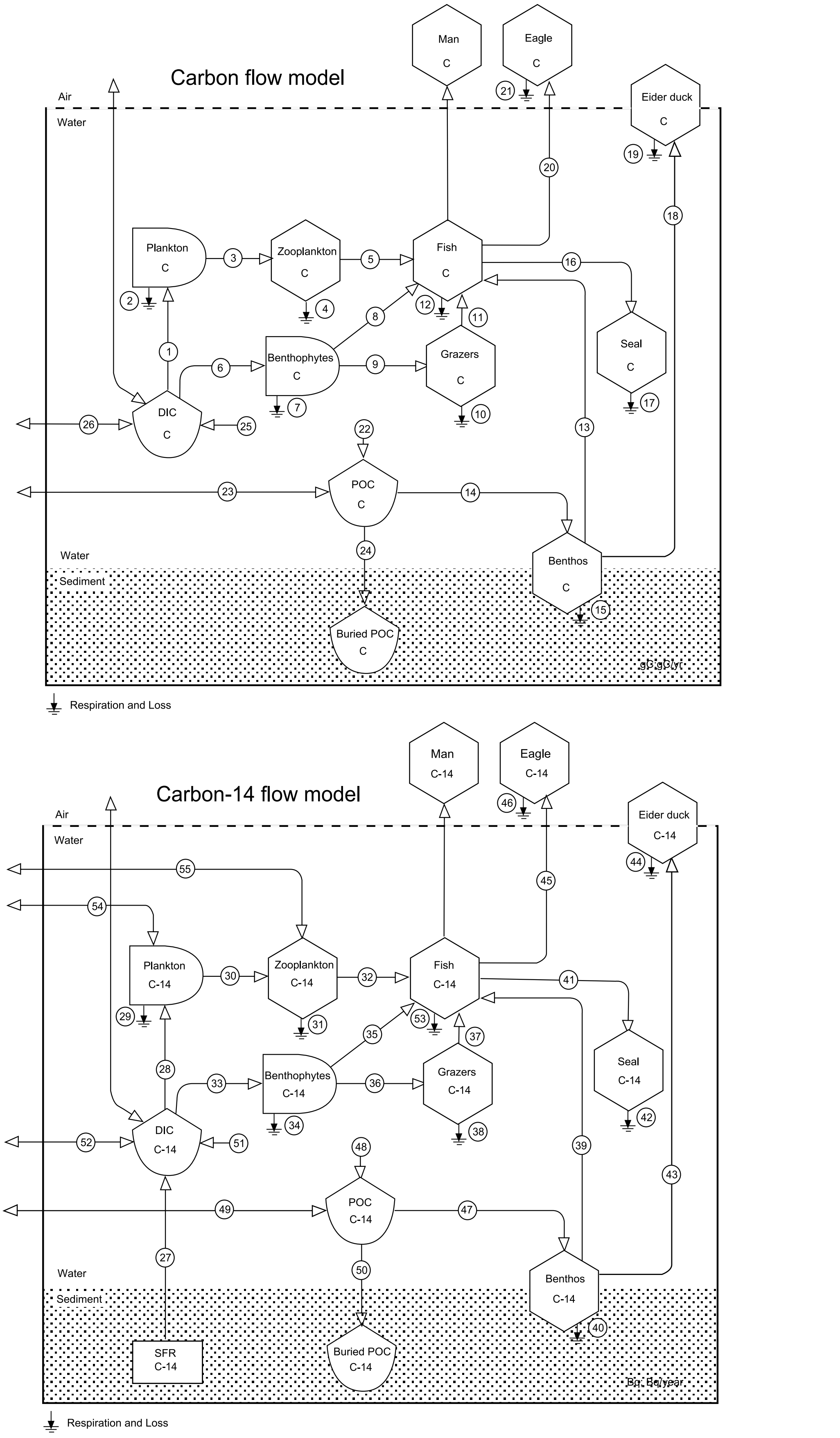

Figure 4-2. *Description of the carbon flow model and C-14 flow model. The numbers in the figure represent the equation used in the model, which are shown in Appendix 1.*

4.2 Biota compartments

Initial values for biota compartments (compartments describing organism groups) i.e. initial biomass and rates of primary production and respiration are received from corresponding budget. The rate of primary production was established by the ratio of the annual primary production and the corresponding initial annual biomass multiplied with the prevailing biomass at the certain time in the model (Eq 1 in Table 4-1). Estimations for respiration were done in the same way (Eq 2), while the consumption was assumed to be three times the respiration for all compartments except bacteria whose consumption is assumed to be two times their respiration /Kautsky, 1995/ (Eq 3). The difference between the inflow of carbon to the compartment (food consumption or primary production) and the outflow (respiration and the predation/grazing) was called loss which here include secondary production (Eq 4) and represent for instance growth and death and production of faeces or gametes. Values for primary production in the models are estimates for net production, i.e. the respiration is already subtracted. The inorganic carbon used in carbon fixation by primary producers is taken from a pool of dissolved inorganic carbon to which respired carbon dioxide from the fauna also is connected as well as the C-14 in the repository. Due to these linkages there is a recirculation of carbon (and C-14) in the system via respiration and primary production.

4.3 Description of the carbon flow model

In the carbon flow model some compartments of the budgets were fused and then coupled to other compartments in compliance with the structure of the food web in the area (Table 3-1 and Figure 4-1). Macrophytes and microphytes were fused into benthophytes and coupled to the grazers (herbivorous and omnivorous macrofauna) since they graze upon the benthophytes. These compartments were then linked to the fish compartment since the fish consume both benthophytes and grazers. The plankton compartment is a fusion of phytoplankton and bacterioplankton and was linked to the zooplankton compartment due to zooplankton grazing. The zooplankton compartment was also linked to the fish community via fish consumption. The loss from all biota compartments was collected in a 'total loss' flow variable, which feeds the compartment for particulate organic carbon (POC). The carbon content in the POC compartment is, besides the inflow rate of the total loss, dependent on the exchange of POC, which varies with the water volume, external POC-concentration and the retention time of the water (water exchange). The four soft bottom organism groups from the budget: filter feeders and benthic macro-, meio- and microfauna were fused into benthos. This compartment (benthos) was linked to the POC compartment (from which it consumes carbon). The fish were modelled to consume 80% zooplankton, 10% benthophytes, 5% benthos and 5% grazers which correspond to the distribution of the fish species in the area (Table 4-2) /Neuman, 1982/ and that species main food intake /Curry-Lindahl, 1985/.

Table 4-1. Equations used in the model to obtain ecological model variables.

Eq	Variable	Equation	Unit
1	primary production	(annual primary production / annual biomass) × prevailing biomass	$gCm^{-2}yr^{-1}$
2	respiration	(annual respiration / annual biomass) × prevailing biomass	$gCm^{-2}yr^{-1}$
3	consumption	respiration × 3 (respiration × 2 for bacteria)	$gCm^{-2}yr^{-1}$
4a	loss	primary production – respiration – predation	$gCm^{-2}yr^{-1}$
4b	loss	consumption – respiration – predation	$gCm^{-2}yr^{-1}$
5	POC burial	total loss – benthos consumption – POC exchange	$gCm^{-2}yr^{-1}$

Table 4-2. The distribution of fish species in the study area (% of the total catches in gill nets).

Herring	Roach	Perch	Ruffe	Smelt	Others
78.0%	10.0%	4.7%	3.0%	1.7%	2.6%

Source: /Neuman 1982/.

4.4 Description of the C-14 flow model

In the C-14 flow model (Figure 4-2) the circulation of discharged C-14 in to the system is modelled. The discharged radionuclide from the repository is assumed to reach the biosphere, to be bioavailable and inorganic (i.e. CO_2 or HCO_3^-) and the C-14 isotope is assumed to assimilate and circulate in the ecosystem similarly to other carbon isotopes. In the model, the C-14 source is found in the compartment C-14 in SFR-1, which is linked both with the DIC-pool (available for all primary producers) and directly with the benthic primary producers. The inflow of the radionuclide to the system can be adjusted in different model simulations, which gives the possibility to study how different pathways into the food web influence the fate of the radionuclide. The idea behind this construction is that benthic primary producers possibly can accumulate larger quantities of discharged C-14 than the pelagic since they are associated to the bottom where the radionuclide enters the ecosystem. The rate of the radionuclide inflow can also be adjusted in the model (but is constant throughout the simulations presented in this report).

The concentration of DIC-14 in the water is, in the same way as POC, dependent on the exchange of DIC-14 as well as external DIC-14 concentration, water exchange and total water volume. When C-14 accumulates in primary producers it enters the food web and will transfer from the primary producers to herbivores and omnivores and further up in the food web to the predators. The amount of C-14 in the compartments is dependent on the rate of consumption or production and the share of C-14 relative to carbon in their food source or DIC (for the plants). The outflow of C-14 from the compartments is dependent on the share of C-14 in the respective compartment and the rates of respiration and consumption/predation and the amounts of loss.

The consumption of contaminated food by eagles, eider ducks and seals also is modelled and the resulting concentrations to these groups are calculated as well as exposures, BCF:s and EDF:s in section three and four. Eagles and seals are modelled on an individual basis while eider ducks for the whole population in the area. Eagle and seal are assumed to eat from the fish-compartment and the eider ducks from benthos.

The water retention time can also be adjusted in the model in order to study how this influences the C-14 uptake in the different compartments. The water exchange is in the model coupled to the DIC and POC compartments as well as the plankton and zooplankton compartments since they also follow the movement of the water.

4.5 Description of calculations of the results

Modelling results both from the carbon flow model and the C-14 flow model are used in calculations of exposure, dose, bioconcentration factors (BCF:s) and ecosystem specific dose conversion factors (EDF:s). In Figure 4-3, the calculations of the concentration in the compartments (Bq/gC), exposure to the compartments (Gy) and dose to human consuming contaminated organisms (Sv) are conceptually described and the conversion factors used are defined in Table 4-3.

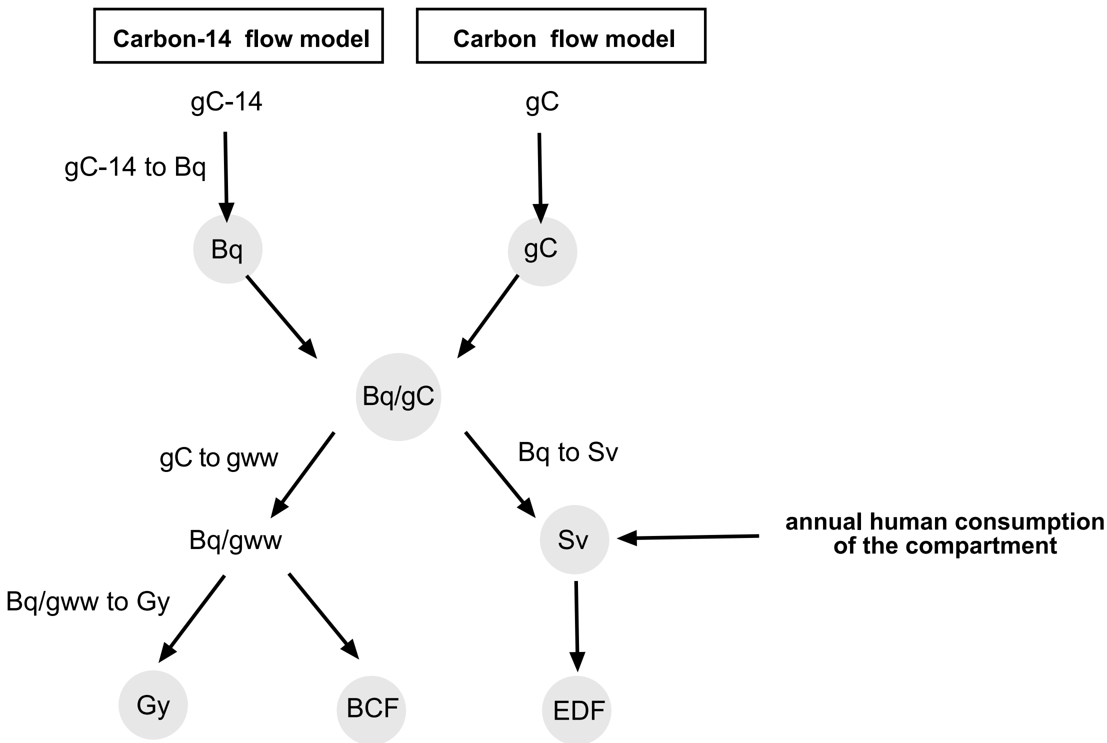

Figure 4-3. *Description of how calculations of exposure, dose to human, BCF:s, EDF:s are made. Conversion factors shown in the figure are defined in Table 4-3.*

Table 4-3. Conversion factors used in the calculations of exposure and dose to humans.

Conversion factor	Description/value	
gC-14 for a compartment	modelling result from the C-14 flow model	
gC for a compartment	modelling result from the carbon flow model	
gC-14 to Bq	1.29×10^{10} Bq/gC-14	
gC to kgww	see separate table below (varies with type of organism)	
Bq/kgww to Gy	(Bq to eV)×(eV to J)×(seconds to year)=7.57×10^{-7} (Bq/kgww)/Gy	
Bq to Sv	5.8×10^{-10}Bq/Sv /ICRP, 1996/	
annual human consumption	106 (kgC/person)	
Bq to eV (for C-14)	1.58×10^{5} Bq/eV	
eV to J	1.6×10^{-19}eV/J /Ellis, 1992/	
seconds to year	31,536,000 s/year	
Organism group	**gC to gww (gww/gC)**	**Source**
benthophytes	18.8	/Kautsky, 1995/
benthos	13.7	/Kautsky, 1995/
eagle	10.0	Estimated
fish	10.2	/Kautsky, 1995/
grazers	23.4	/Kautsky, 1995/
plankton	33.3	/Jansson and Wulff, 1979; Kautsky, 1995/
eider ducks	10.0	Estimated
seal	10.0	Estimated
zooplankton	20.0	/Jansson and Wulff, 1979; McHellar and Hobro, 1976/

4.5.1 Exposure

Exposure (in the unit gray, Gy) is the received energy per biomass wet weight (J/kgww). To transform the concentration of C-14 per gram carbon to gray, the radioactivity (Bq) was converted to joule (J) and the biomass carbon to biomass wet weight with specific conversion factors for different organisms (Table 4-3).

4.5.2 Dose to human

In the calculations of doses to humans (Sv/year) consuming contaminated organisms, the C-14 concentration of the consumed compartment was multiplied with the annual consumption for an average man (106 kgC/year) /Wikberger, 2000/ and the dose factor for ingestion of C-14 (5.8×10^{-10}) /ICRP, 1996/.

4.5.3 Bioconcentration factors (BCF:s)

A bioconcentration factor (BCF) is the ratio between the radionuclide concentration in an organism and the surrounding water. In the calculation of BCF:s, the radioactivity per kilogram wet weight in the organisms was divided by the radioactivity in the water (i.e. dissolved inorganic C-14 and particulate organic C-14) per litre. In the conversion of gram carbon (biomass) to kilogram wet weight, specific conversion factors for different organism groups were used (Table 4-3) as in the calculations of the exposure.

4.5.4 Ecosystem specific dose conversion factors (EDF:s)

Ecosystem specific dose conversion factors (EDF:s) describe the doses humans receive due to consumption of food from the area exposed to a continuous release of 1 Bq/year during 10,000 years. In this study the EDF:s were calculated by dividing the dose that humans received after consumption of food exposed to the discharge used in the model simulations in this study (5.13×10^{-7} Bq/year) by the annual C-14 discharge.

4.6 Sedimentation of C-14 in the C-14 flow models

An effort of modelling the sedimentation of C-14 was made in this study. The POC-14 pool, which is fed by the inflow of C-14 in the loss of all compartments (C-14 in total loss), has three outflows. The first is the consumption of POC-14 by benthos and the second is the POC-14 exchange through water exchange and the last one is the sedimentation or burial of POC-14 in the sediment (Eq 5 in Table 4-1). POC-14 buried in the sediment is assumed to be unavailable for further consumption or primary production by the organisms in the model. The burial of POC-14 was only modelled in a few simulations.

4.7 Air-Sea exchange of carbon dioxide (CO_2)

The exchange of carbon dioxide over the air-sea interface was studied in the Baltic Sea surface waters (Baltic Proper) by /Thomas and Schneider, 1999/. They found that the mean annual uptake of atmospheric carbon dioxide for that area was 0.9±0.09 mol CO_2/m^2. This corresponds to approximately 1.3×10^8 gC/year (or 8% of the annual primary production) for the study area at present and 1.7×10^5 gC/year (< 1%) in the future ecosystem. This information is not included in the model, which may contribute to a slight overestimation of the C-14 concentration of up to 8% in the 2000 AD model results, due to an underestimated dilution of C-14 in the DIC-pool by the atmospheric carbon dioxide. In the future ecosystem, the ignorance of CO_2-flux is negligible.

5 Results of the carbon budgets

The total biomass, primary production, respiration and consumption of the different compartments in the area at 2000 AD and 4000 AD are shown in Figure 5-1 and in Appendix 2.

5.1 Description of the main carbon flows

According to the budget, the organisms in the area are self-sufficient on organic carbon (i.e. there is a larger production than consumption of biomass) in the present ecosystem. This causes a net export of organic carbon from the area, which corresponds to approximately 35% of the total annual primary production. The most significant flow of organic carbon is a net export of remaining organic carbon after predation/consumption and respiration (e.g. detritus, gametes) produced in the phytobenthic and the pelagic communities down to the soft bottom community or away from the area.

In the budget for 4000 AD, which is an extrapolation of the carbon distribution at 2000 AD to the area at 4000 AD (described in Section 3.1), it seems like there will be a significant deficiency of dissolved inorganic carbon which probably is a sign of overestimation of the primary production in the 4000 AD budget. Probably will this affect all results from the 4000 AD model but is studied more in detail in an on-going follow-up study.

5.2 Distribution of biomass

The major organism groups in both the present and the future ecosystem are the macrophytes, contributing with approximately 37% of the biomass as carbon at present and 71% in future (seal, eider ducks and eagles not included). Corresponding value for macrofauna is 36% and 5% and for microphytes 11% and 13%. Comparisons of the distribution of biomass between flora and fauna indicate a change from equally occurrence on biomass basis to an environment dominated mainly by plants (86%) in the future.

The phytobenthic community contributes to the larger share of the total primary production (70% at present and 87% in the future) whereas the soft bottom community stands for the larger part of the total consumption (49% and 25%). The ranking of biomasses between the communities will not change in the future ecosystem although the distribution of biomass will change. Today, about half of the total biomass is found in the phytobenthic community, 38% in the soft bottom and 9% in the pelagic community while in the future approximately 88% of the biomass will be found in the phytobenthic community, 7% in the benthic and only 5% in the pelagic community. The dissolved and particulate organic carbon pools are not included in these comparisons.

5.3 Comparisons of the present and the future carbon budget

The land rise will cause a slight reduction of the total standing stocks and flux of carbon in the study area and the remaining biomass will be distributed differently in the future compared to at present (Figure 5-1 and Appendix 2). According to the results in this study the benthic primary producers will become more dominant in the future. This is due to the shore-level displacement, which causes a decrease of the ratio of water to land and consequently decrease both the maximum and mean depth, which probably will place the whole future study area in the photic zone and thereby favour primary producers. However, the water may also become more turbid, resulting in a lower water visibility, which would compensate or counteract a benthophytic extension. The increase of the benthophytes will occur at the cost of soft bottom consumers, especially macrofauna, as they are defined in this study. The budgets indicate that the biomass of most compartments in the phytobenthic community (macrophytes, grazers and filter feeders) will increase in the future ecosystem, while the biomass of all other compartments will decrease.

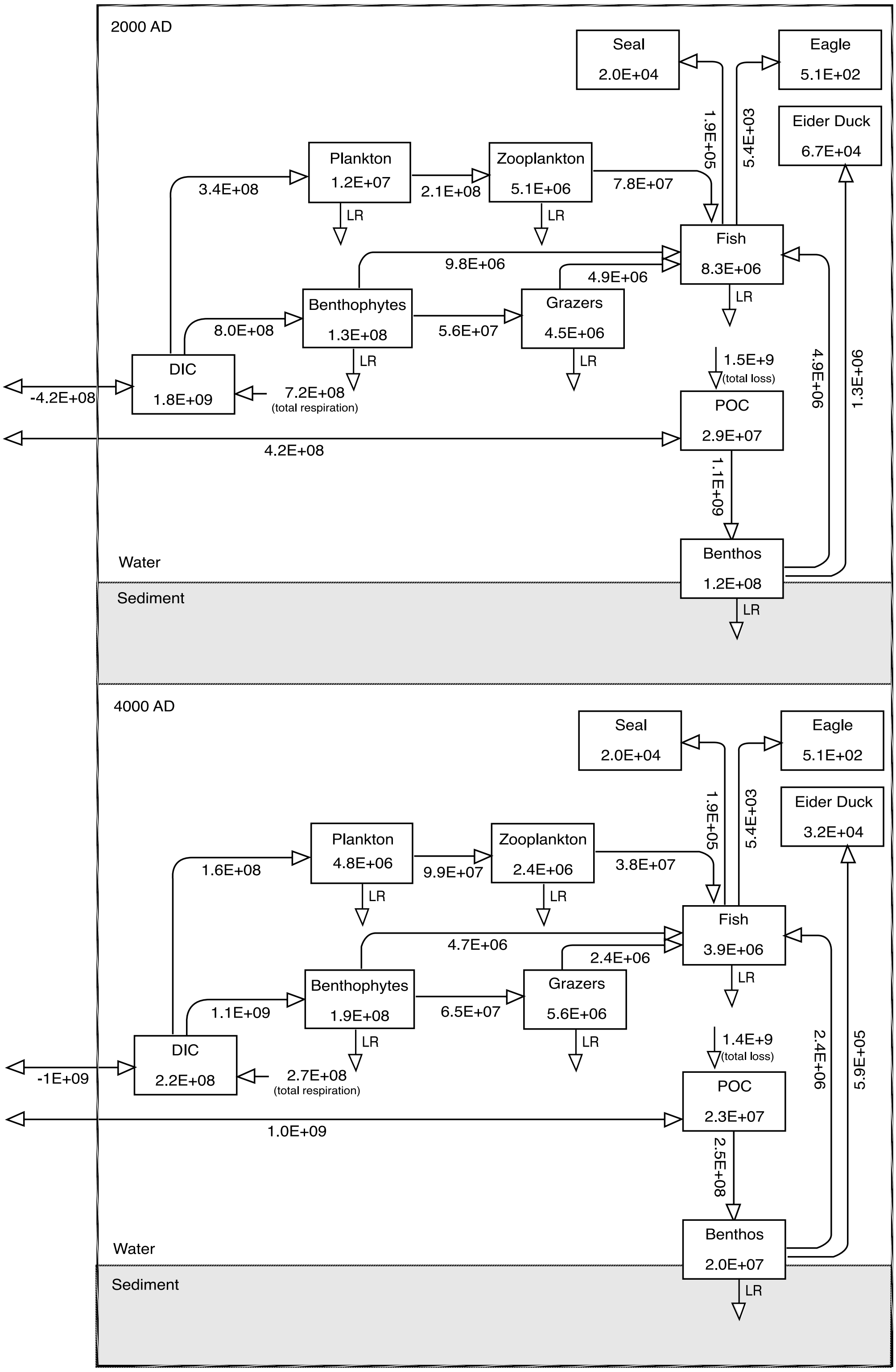

Figure 5-1. *Annual standing stocks and flux of carbon (gC and gC/year) in the study area at 2000 AD and 4000 AD. R = respiration, L = loss (i.e. primary production or consumption – respiration – predation)*

6 Results of the carbon flow models

The influence of uptake pathway and rate of water exchange on the fate of C-14 was studied by comparing various model simulations (Table 6-1). The first of three modelled uptake pathways was based on homogenous accumulation of C-14 from the DIC compartment by all plants. In the second, benthic plants accumulate C-14 directly from the discharge and the third is a combination, where equal shares of the discharge enter via the two former pathways. The influence of the water exchange was studied by comparing simulations run with normal water exchange /Engqvist and Andrejev, 1999, 2000/ with simulations run with reduced water exchange by a factor of ten or hundred. All simulations were run for a period of 2,000 years with a constant linear C-14 discharge of 5.13×10^7 Bq/year during the first 1,000 years. Simulation A to E was run for the 2000 AD and A to C for the 4000 AD model.

Data on uptake and elimination kinetics for each compartment as well as for the whole ecosystem are received by the simulation results, which describe the C-14 concentration in the compartments over time (Figure 6-1). When an open dynamic system is contaminated at a constant rate (as assumed in this study) it will take some time before the system reaches steady-state (i.e. when uptake equals loss). During the uptake phase (A) the C-14 uptake is larger than the loss in the compartments and the time to reach steady-state (B) may vary between the modelled ecosystem as a whole and the various modelled compartments because of differences in, for instance, carbon turnover and loss through water exchange. When the inflow of C-14 stops, the system enters phase C, where the loss is larger than the uptake of C-14. During this elimination phase the ecological half-life of the radionuclide in the compartments as well as in the ecosystem can be estimated.

In the model all compartments were examined for total amount of C-14 (Bq), C-14 concentration (Bq/(gC × year)). From these modelling results, exposure (Gy/year) and bioconcentration factors (BCF:s) [(Bq/kg ww)/(Bq/L)] for the compartments were calculated as well as dose to humans (Sv/year) consuming contaminated organisms and ecosystem specific dose conversion factors (EDF:s) (Sv/(Bq × year)). All of these results are presented from the steady-state phase. The results are presented both for the 2000 AD and the 4000 AD model in the following Figures (6-2–6-8) and Tables (6-2–6-4) as well as in Appendix 3 and are discussed more in detail in separate sections below.

Table 6-1. Description of the five different model simulations.

Simulation	Uptake pathway	Water exchange	Discharge duration (years)	Discharge (Bq/yr)
A	homogenous	normal	1,000	5.13×10^7
B	benthic	normal	1,000	5.13×10^7
C	mixed	normal	1,000	5.13×10^7
D	homogenous	reduced by 10	1,000	5.13×10^7
E	homogenous	reduced by 100	1,000	5.13×10^7

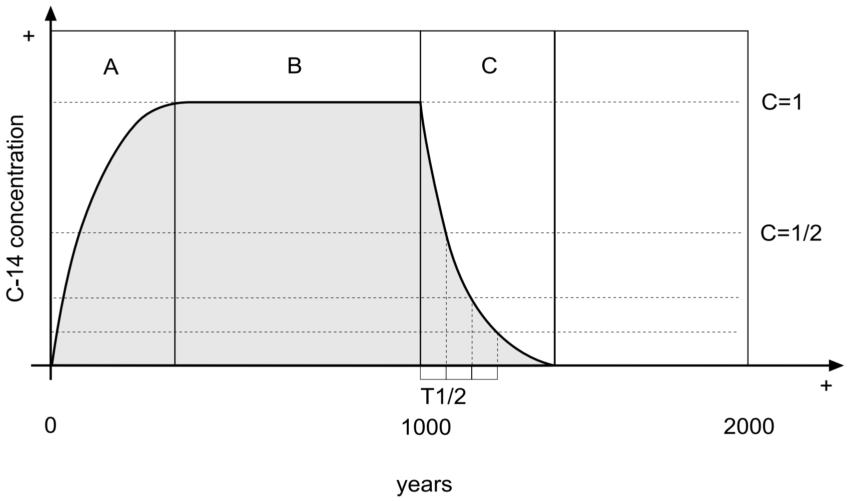

Figure 6-1. *Schematic kinetic diagram of uptake (A), steady-state (B), elimination phase (C) and ecological half-life (T1/2) of C-14 in compartments or ecosystem from a C-14 discharge during 1,000 years.*

6.1 Uptake pathways

Comparisons of results from simulation A, B and C examines the influence of uptake pathway (homogenous-, benthic- or mixed uptake) on C-14 concentrations and exposures to the biota compartments. Comparisons of the concentrations in benthophytes, benthos, fish and plankton are shown in Figure 6-2.

Discharge of C-14 into the DIC-compartment with a following homogenous uptake (simulation A) causes the lowest and most homogenous concentrations (4.7×10^{-7} to 6.7×10^{-5} Bq/gC at 2000 AD and 1.2×10^{-4} to 1.9×10^{-3} Bq/gC at 4000 AD) in biota compartments. These observed low C-14 concentrations in simulation A are caused by a significant dilution and removal through water exchange of C-14 entering the DIC pool.

In the 2000 AD model the lowest concentration was found in zooplankton. This is because of the rapid water exchange that continuously flushes away a large part of the contaminated zooplankton and simultaneously add uncontaminated organisms to both the plankton (their food source) and the zooplankton compartments, which results in reduced C-14 concentrations in these groups. The highest concentration was found in the benthophytes because that compartment constitutes an entry to the food web for the radionuclide and since they are not affected by water exchange.

In the 4000 AD model the pattern was about the same. The lowest concentration was also found in zooplankton and the highest in benthos and benthophytes.

The benthic uptake pathway (simulation B) causes very heterogeneous concentrations as well as the highest concentrations (2.5×10^{-8} to 5.4×10^{-2} Bq/gC at 2000 AD and 2.8×10^{-5} to approximately 1×10^{-1} Bq/gC at 4000 AD) compared to the other pathways in all organisms except the plankton groups. The highest concentrations are found in benthophytes and benthos and organisms feeding on them.

In simulation C, where half of the C-14 discharge enters the DIC compartment (homogenous uptake) and half the benthophytes (benthic uptake), benthophytes and grazers receives approximately 10 times higher concentrations than phytoplankton,

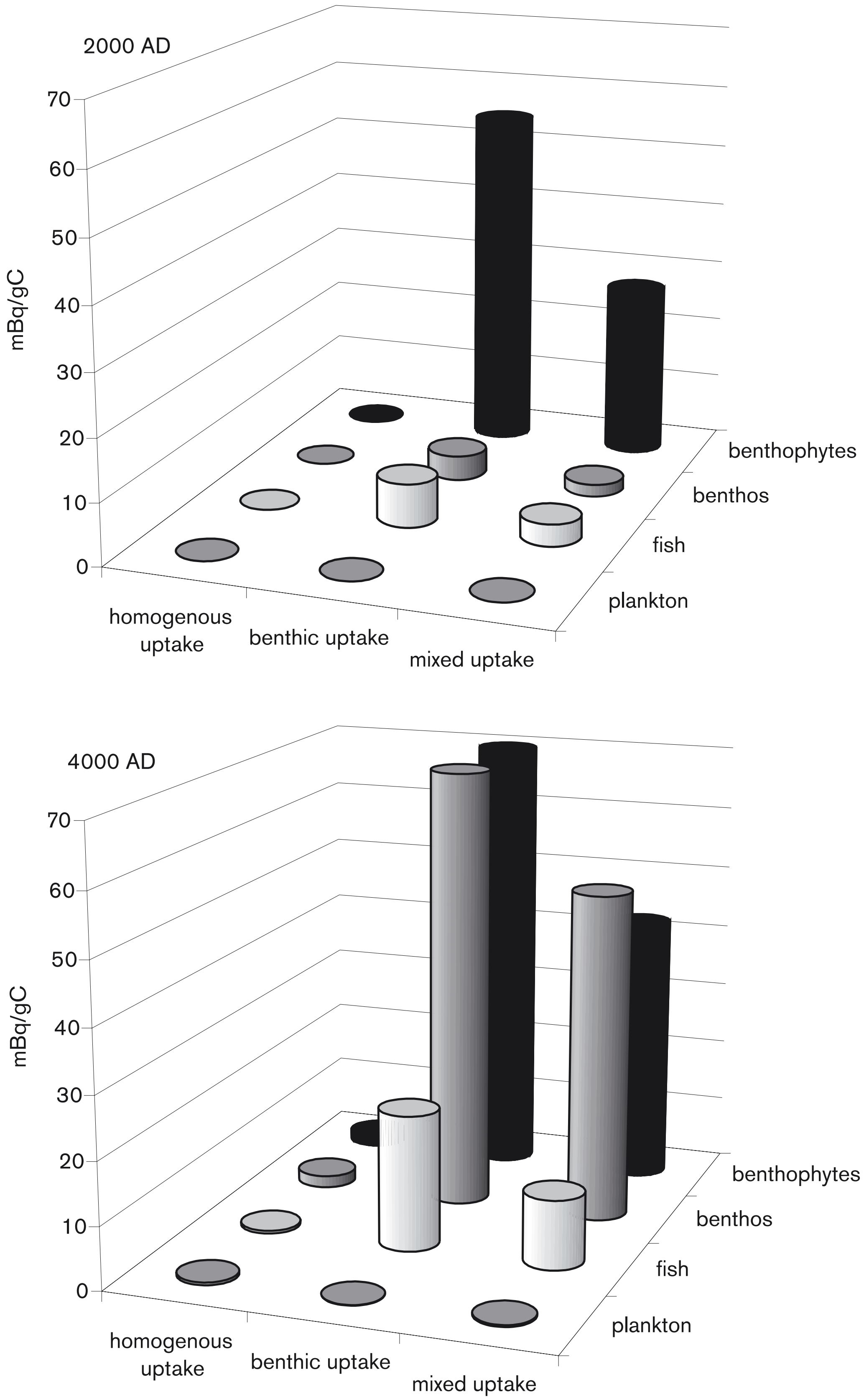

Figure 6-2. *C-14 concentration at steady-state (mBq/gC) in benthophytes, benthos, fish and plankton according to simulations with normal water exchange and homogenous uptake (A), benthic uptake (B) and mixed uptake (C) at 2000 AD and 4000 AD in the ecosystem above SFR-1.*

7 times higher concentrations than fish, eagle and seal and 150 times higher concentrations than zooplankton in the present ecosystem. The same pattern can be seen for exposure to biota (Gy) and for the future ecosystem but with smaller differences.

The benthophyte compartment contains the largest total amount of C-14 (Bq) in all three simulations both at 2000 AD and 4000 AD (except for DIC) since the benthophytes has the largest biomass both at 2000 AD and at 4000 AD.

6.2 Water exchange

The influence of the water exchange on the uptake of C-14 in the compartments can be evaluated by comparing the modelling results from simulation A, D and E, where simulations with homogenous uptake pathway and normal water exchange is compared with those with homogenous uptake pathway and water exchanges that are reduced 10 and 100 times. This comparison has been done for fish for the 2000 AD model and is shown in Figure 6-3.

At higher rates of water exchange, the discharged C-14 is removed quicker from the area than at lower rates of water turn-over, which causes lower concentrations. This pattern is the same for all compartments but they are influenced to various extent.

When the water exchange is reduced, the compartments need both longer times to reach steady state as well as longer elimination periods to reduce the C-14 concentrations to 50% of the steady state levels. The elimination rate is extended because the reduced water exchange increases the amount of C-14 available for re-uptake (respired C-14) by primary producing organisms. Changed water exchange influences the concentrations of C-14 in biota more during homogenous uptake than when benthic uptake is assumed. Differences in concentrations between bottom dwelling and pelagic compartment increase at decreased water exchange. For instance, the difference in concentration between fish and benthophytes is 13% at normal water exchange and increases to 31% when the water exchange was reduced by a factor ten.

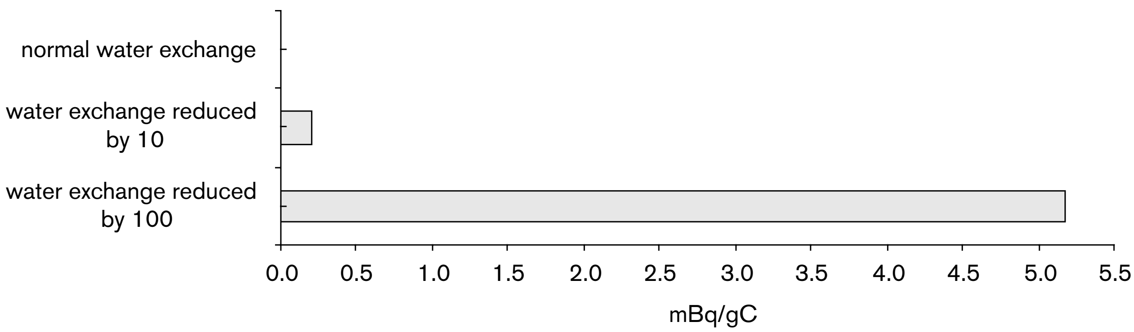

***Figure 6-3.** The influence of the water exchange on the C-14 concentration (mBq/gC) in fish. Comparison of simulations with homogenous uptake pathway and normal water exchange (A), water exchange reduced by 10 (D) and by 100 (E) at 2000 AD in the ecosystem above SFR-1.*

6.3 Amount and duration of discharge

The magnitude and length of the radionuclide discharge from the repository will naturally influence the C-14 exposure of the organisms. The relation of amount and duration of the discharge and the exposure is linear, which makes recalculations of the modelling results possible as long as all compartments have reached steady-state (this may not be the case for shorter discharges).

6.4 Exposure to biota

The model results for exposure to the organism groups, gives an opportunity to evaluate absorbed doses to other biota than humans from a discharge from SFR-1.

The estimated exposures change with the different discharge pathways and the magnitude of water exchange in the same way as for concentrations as mentioned above. The exposures are generally very low and well below the suggested dose limits. The exposures to some selected organisms according to the five simulations are shown in Figure 6-4 and 6-5.

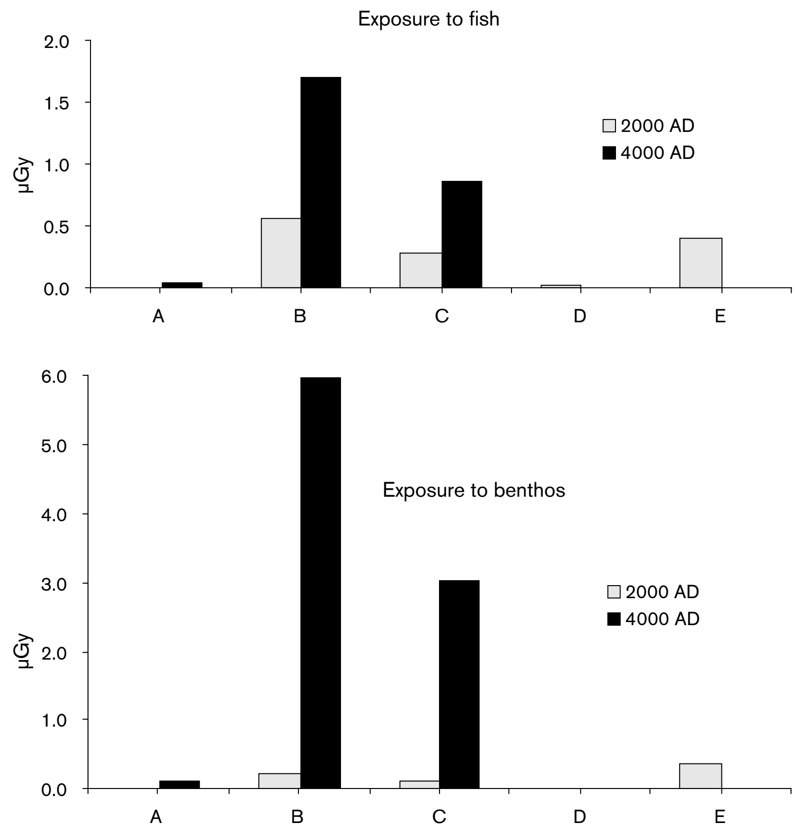

Figure 6-4. *Exposure (µGy) to fish and benthos in simulation with homogenous uptake and normal water exchange (WE) (A), benthic uptake and normal WE (B), mixed uptake and normal WE (C), homogenous uptake and WE reduced by 10 (D) and homogenous uptake and WE reduced by 100 (E) in the ecosystem above SFR-1 at 2000 AD and 4000 AD. (Note the different scales.)*

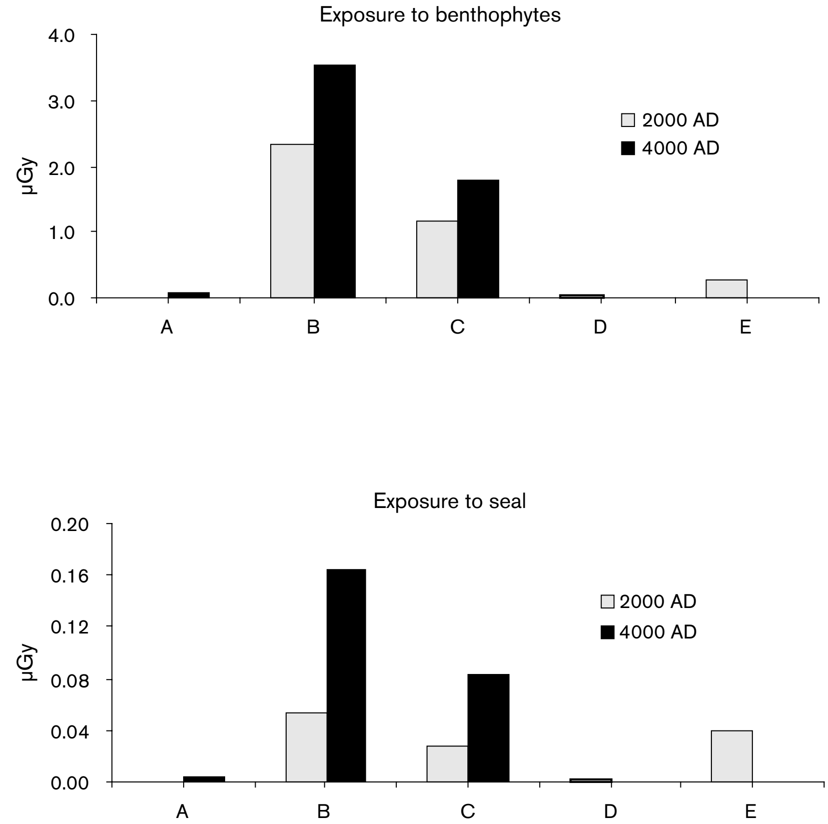

Figure 6-5. *Exposure (µGy) to seal and benthophytes in simulation with homogenous uptake and normal water exchange (WE) (A), benthic uptake and normal WE (B), mixed uptake and normal WE (C), homogenous uptake and WE reduced by 10 (D) and homogenous uptake and WE reduced by 100 (E) in the ecosystem above SFR-1 at 2000 AD and 4000 AD. (Note the different scales.)*

In simulations with normal water retention time and a homogenous uptake (A), the exposure to fish amounts to approximately 71 nGy in the present ecosystem and 0.36 nGy in the future. Uptake via the benthic pathway (B) causes higher exposures to all compartments except plankton and zooplankton. In the present ecosystem the exposure to fish will be approximately 554 nGy and 1,700 nGy in the future. The exposures becomes highest for compartments that receive high C-14 concentrations and have low water contents since the exposure is a measurement based on received energy per mass wet weight (J/kgww).

6.5 Dose to humans

Humans consuming large quantities of locally produced food (e.g. fish, mussels and algae) contaminated by discharged C-14 will be exposed to radiation in case of a discharge. It is reasonable to assume that for people living in the area, 2.8% of their annual consumption is fish originating from the area /Karlsson et al, 2001/. Using this assumption, a human will receive approximately 10 nSv/year (according to simulation with mixed uptake and normal water exchange, C). The dose would increase about 3 times if the C-14 discharge and consumption takes place in the future ecosystem instead of the present. However, this is well below the dose limits suggested by the Swedish radiation protection authority /SSI, 1998/.

Consumption of benthic organisms would give the highest doses to humans, especially consumption of benthic algae. The highest doses would be received if benthic algae that have accumulated C-14 via the benthic uptake pathway (B) would be consumed in the future ecosystem at reduced water exchange rate.

In Table 6-2 the annual doses to humans consuming contaminated organisms from the area are shown. These modelled doses are based on the assumption that all (or 2.8% for fish[b]) of the annual consumption comes from the respective compartment.

Table 6-2. Annual doses to humans consuming contaminated organisms from the area above SFR-1 at 2000 AD and 4000 AD.

Dose to humans[a] (Sv)	2000A	2000B	2000C	2000D	2000E
benthophytes	4.2×10^{-9}	3.4×10^{-6}	1.7×10^{-6}	4.1×10^{-8}	4.1×10^{-7}
benthos	3.1×10^{-10}	2.5×10^{-7}	1.2×10^{-7}	1.9×10^{-8}	3.9×10^{-7}
eagle	5.6×10^{-10}	4.3×10^{-7}	2.2×10^{-7}	1.3×10^{-8}	3.2×10^{-7}
fish	5.6×10^{-10}	4.3×10^{-7}	2.2×10^{-7}	1.3×10^{-8}	3.2×10^{-7}
grazers	1.1×10^{-10}	8.6×10^{-8}	4.3×10^{-8}	1.1×10^{-9}	1.0×10^{-8}
plankton	3.5×10^{-10}	1.9×10^{-11}	1.9×10^{-10}	2.1×10^{-8}	4.1×10^{-7}
eider duck	8.7×10^{-12}	6.9×10^{-09}	3.5×10^{-9}	5.3×10^{-10}	1.1×10^{-8}
seal	1.6×10^{-11}	1.2×10^{-8}	6.1×10^{-9}	3.6×10^{-10}	8.9×10^{-9}
zooplankton	2.9×10^{-11}	1.5×10^{-12}	1.5×10^{-11}	9.8×10^{-9}	3.6×10^{-7}
fish[b]	1.6×10^{-11}	1.2×10^{-8}	6.1×10^{-9}	3.6×10^{-10}	8.9×10^{-9}
	4000A	**4000B**	**4000C**		
benthophytes	9.4×10^{-8}	5.1×10^{-6}	2.6×10^{-6}		
benthos	1.2×10^{-7}	6.3×10^{-6}	3.2×10^{-6}		
eagle	5.2×10^{-12}	2.5×10^{-10}	1.3×10^{-10}		
fish	2.9×10^{-8}	1.3×10^{-6}	6.8×10^{-7}		
grazers	2.4×10^{-9}	1.3×10^{-7}	6.6×10^{-8}		
plankton	2.6×10^{-8}	6.1×10^{-9}	1.6×10^{-8}		
eider duck	3.3×10^{-9}	1.8×10^{-7}	9.0×10^{-8}		
seal	8.0×10^{-10}	3.7×10^{-8}	1.9×10^{-8}		
zooplankton	7.4×10^{-9}	1.7×10^{-9}	4.5×10^{-9}		
fish[b]	8.0×10^{-10}	3.7×10^{-8}	1.9×10^{-8}		

[a] If all of the consumed food during a year would be the respective organism group.
[b] If 2.8% of the consumed food during a year would be fish from the area.

6.6 Distribution and transfer in the food web

Since the model is of mass balance type it was possible to analyse the fate of a C-14 discharge in the whole ecosystem. In Figure 6-6 and 6-7, the steady-state distribution and the transfer in the food web have been compiled for simulation A at 2000 AD and 4000 AD.

Since the modelled area is characterized by a large water exchange, most of the discharged C-14 was flushed out from the system more or less immediately (99.8% at 2000 AD and 98.4% at 4000 AD) and further 0.02% (0.15%) was lost at the air-sea interface (Figure 6-7). However, a small fraction of the discharge was assimilated by primary producers (0.18% and 2.1% respectively), which enabled subsequent transfer of C-14 at higher trophic levels. Approximately 4% (21%) of the assimilated C-14 was annually re-circulated within the system via the respiration route. Loss from the organism compartments (e.g. growth, death and production of faeces or gametes) was the dominant biological route of C-14 flow in the system (6.65×10^4 and 1.23×10^7 Bq/year, respectively). Since loss was assumed to feed the POC compartment 91% (59%) of this loss was exported annually from the system via water exchange of POC. A further 10% (42%) of the C-14 in loss was consumed annually by benthos and approximately 0.25% (2%) was buried in the sediment each year. The exported matter is diluted to much lower concentrations in the larger recipient outside than the C-14 concentrations caused by the C-14 that stays in the area /Karlsson et al, 2001/.

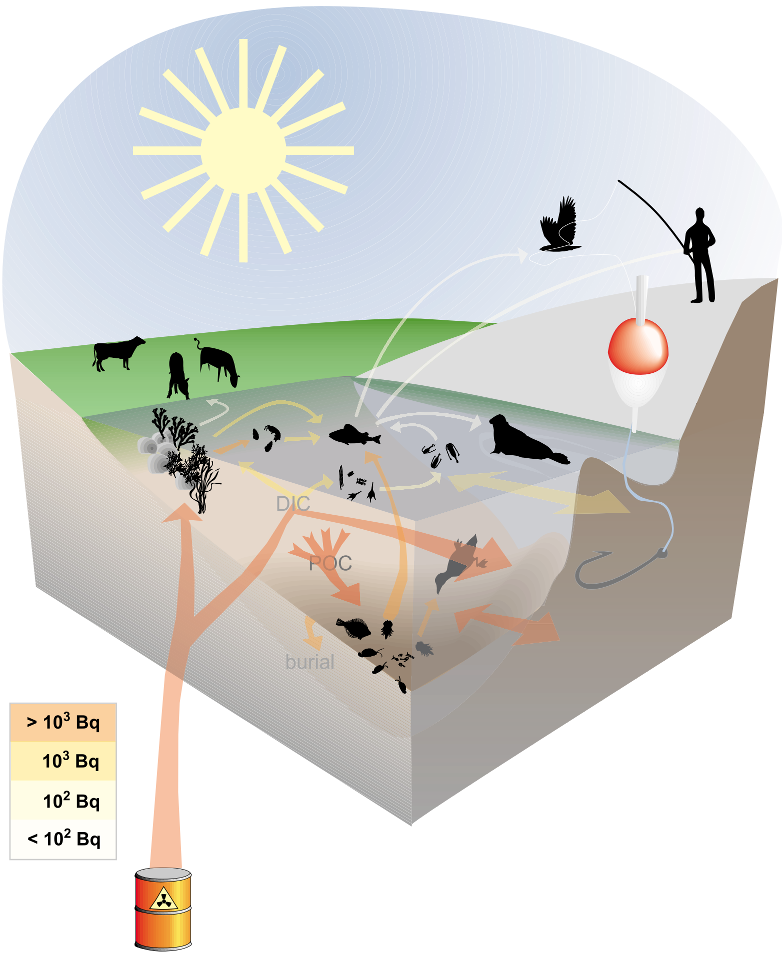

Figure 6-6. *Annual transfer of C-14 in the food web (Bq/year) of the study area (Öregrundsgrepen) at 2000 AD for simulation A.*

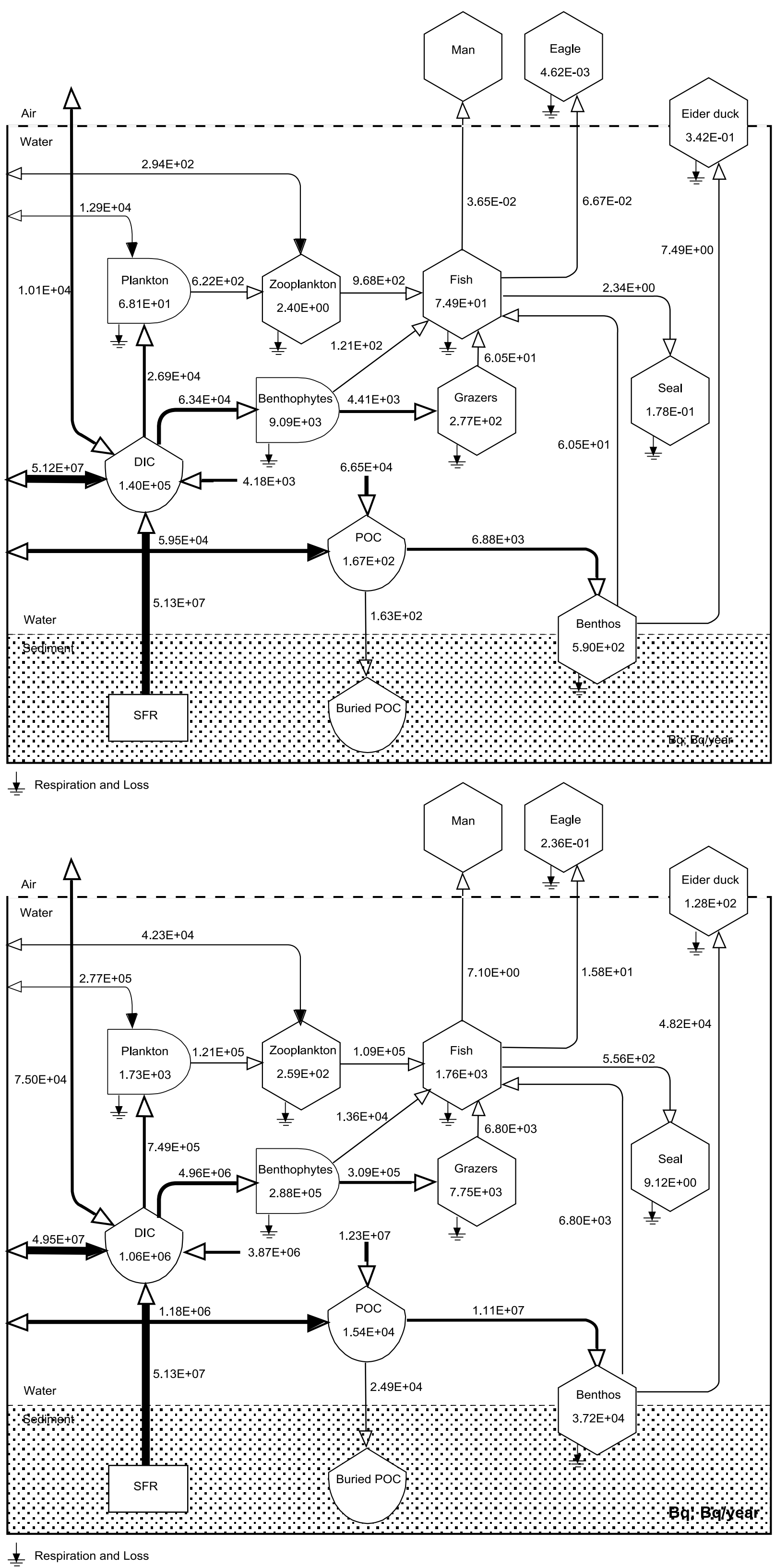

Figure 6-7. *Annual distribution and transfer of C-14 in the food web (Bq and Bq/year) of the study area (Öregrundsgrepen) at 2000 AD and 4000 AD, according to simulation A.*

The relative distribution of the C-14 between the compartments in the ecosystem at steady-state is very unequal. The largest share is found in the DIC compartment, which amounts to approximately 94.3% at 2000 AD and 82.2% at 4000 AD. The biota compartments that receive the highest loads are benthophytes (5% and 12%), benthos (0.21% and 3.3%) and plankton (0.10% and 0.77%). The main reason for finding the largest amounts of C-14 in the benthophytic compartments is that these organisms dominate the biomass.

6.6.1 Total radioactivity in the ecosystem

A comparison of the total radioactivity at steady-state in the area, i.e. the sum of the radioactivity in all compartments, for all simulation in the present as well as in the future ecosystem are shown in Figure 6-8. The ecosystem accumulates the largest amount of radioactivity in case of a discharge similar to simulation B or E for 2000 AD (approximately 10 MBq) and simulation B for 4000 AD (approximately 20 MBq). The total radioactivity is generally higher in the future ecosystem compared to the present and increases markedly at benthic C-14 uptake (simulation B).

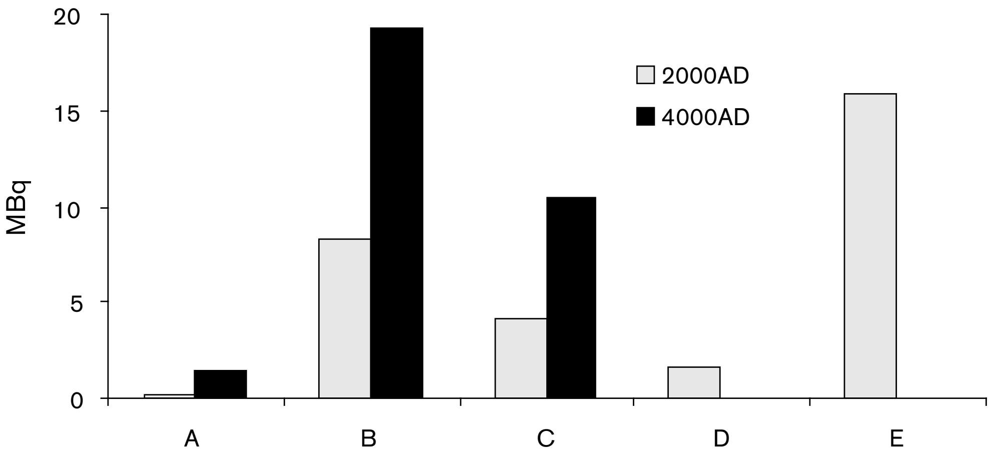

Figure 6-8. *Comparison of the total radioactivity in the system between simulation with homogenous uptake and normal water exchange (WE) (A), benthic uptake and normal WE (B), mixed uptake and normal WE (C), homogenous uptake and WE reduced by 10 (D) and homogenous uptake and WE reduced by 100 (E) at 2000 AD and 4000 AD.*

6.7 Ecological half-life in the ecosystem

The ecological half-lives of C-14 in the compartments, i.e. the time needed for elimination of 50% of the total amount of C-14 in the compartment from steady-state, were calculated for all compartments and the ecosystem for all simulations at both 2000 AD and 4000 AD (Table 6-3).

The half-life varied between the compartments as well as for the whole ecosystem between the various simulations (Table 6-1). The shortest ecological half-lives were found for pelagic compartments (DIC, POC, plankton and zooplankton) for all simulations, except for benthic uptake (simulation B), in both models and the longest for those that consume benthophytes and benthos.

The ecosystem ecological half-lives was shortest at homogenous uptake and normal water exchange (simulation A), 188 days at 2000 AD and 213 days at 4000 AD, and longest when the water exchange was reduced by 100 (simulation E), 292 days at 2000 AD, and B (352 days at 4000 AD).

Table 6-3. Ecological half-life (days) of C-14 in the compartments and the ecosystem for simulation with homogenous uptake and normal water exchange (WE) (A), benthic uptake and normal WE (B), mixed uptake and normal WE (C), homogenous uptake and WE reduced by 10 (D) and homogenous uptake and WE reduced by 100 (E) at 2000 AD and 4000 AD.

Ecological half-life (days)	2000A	2000B	2000C	2000D	2000E
benthophytes	279	284	279	289	367
benthos	303	328	328	297	434
fish	330	339	339	281	351
grazers	313	313	312	322	403
eagle	330	339	339	281	351
eider duck	303	284	328	297	367
seal	330	339	339	281	351
plankton	184	323	192	196	277
zooplankton	185	325	193	201	287
DIC	184	323	192	193	272
POC	260	288	285	254	389
ecosystem	188	287	281	200	292
	4000A	**4000B**	**4000C**		
benthophytes	346	340	339		
benthos	327	404	404		
fish	298	406	405		
grazers	382	375	374		
eagle	298	406	405		
eider duck	346	404	404		
seal	298	406	405		
plankton	196	408	253		
zooplankton	200	413	257		
DIC	192	404	248		
POC	294	372	371		
ecosystem	213	352	344		

6.8 Bioconcentration factors (BCF)

Bioconcentration factors, BCF:s, calculated in this study describe the ratio between the C-14 concentration in the organisms (per biomass wet weight) and in the water. Model results used in these calculations are steady-state concentrations. BCF:s for all simulations at both 2000 AD and 4000 AD are compiled in Table 6-4.

Large variations were found both between the compartments within each simulation as well as between simulations and models, indicating that processes such as uptake route, transport through the food web, and rate of water exchange influence the ratio significantly. In simulation with homogenous uptake and normal water exchange (A) at 2000 AD, the BCF:s varies between approximately 10 to 1,140 (Bq/kgww)/(Bq/L), where the lowest BCF are found for zooplankton, benthos and eider duck and the highest for benthophytes, grazers and plankton. At reduced rates of water exchange the BCF:s become more homogenous and generally somewhat higher, while the BCF:s become much more heterogeneous when the benthic uptake pathway is assumed in the model. The pattern is the same for the 4000 AD model although the BCF:s generally are higher.

Table 6-4. Bioconcentration factors [(Bq/kgww)/(Bq/L)] for the organism groups for simulation with homogenous uptake and normal water exchange (WE) (A), benthic uptake and normal WE (B), mixed uptake and normal WE (C), homogenous uptake and WE reduced by 10 (D) and homogenous uptake and WE reduced by 100 (E) at 2000 AD and 4000 AD.

Bioconcentration factor [(Bq/kgww)/(Bq/l)]	2000A	2000B	2000C	2000D	2000E
benthophytes	1.0×10^{3}	8.1×10^{5}	4.1×10^{5}	1.0×10^{3}	1.0×10^{3}
benthos	5.5×10^{1}	4.4×10^{4}	2.2×10^{4}	3.4×10^{2}	7.0×10^{2}
eagle	7.2×10^{1}	5.6×10^{4}	2.8×10^{4}	1.7×10^{2}	4.1×10^{2}
fish	7.3×10^{1}	5.7×10^{4}	2.9×10^{4}	1.7×10^{2}	4.2×10^{2}
grazers	1.1×10^{3}	9.2×10^{5}	4.6×10^{5}	1.1×10^{3}	1.1×10^{3}
plankton	1.5×10^{2}	8.0×10^{0}	7.9×10^{1}	9.0×10^{2}	1.8×10^{3}
eider duck	4.0×10^{1}	3.2×10^{4}	1.6×10^{4}	2.4×10^{2}	5.1×10^{2}
seal	7.2×10^{1}	5.6×10^{4}	2.8×10^{4}	1.7×10^{2}	4.1×10^{2}
zooplankton	7.5×10^{0}	4.0×10^{-1}	3.9×10^{0}	2.5×10^{2}	9.4×10^{2}
	4000A	**4000B**	**4000C**		
benthophytes	4.1×10^{2}	2.2×10^{4}	1.1×10^{4}		
benthos	3.7×10^{2}	2.0×10^{4}	1.0×10^{4}		
eagle	6.6×10^{1}	3.1×10^{3}	1.6×10^{3}		
fish	6.7×10^{1}	3.1×10^{3}	1.6×10^{3}		
grazers	4.6×10^{2}	2.5×10^{4}	1.3×10^{4}		
plankton	2.0×10^{2}	4.7×10^{1}	1.3×10^{2}		
eider duck	2.7×10^{2}	1.5×10^{4}	7.4×10^{3}		
seal	6.6×10^{1}	3.1×10^{3}	1.6×10^{3}		
zooplankton	3.4×10^{1}	7.9×10^{0}	2.1×10^{1}		

BCF:s derived in this study also change with time during the uptake end elimination phase (data not shown), demonstrating that it is important to consider whether the system has reached steady-state or not when transfer factors are used as initial data in models.

In a parallel dose assessment model study by /Karlsson et al, 2001/ BCF:s were used as initial values. The BCF for fish used in the coastal module of that study was 2,000 (Bq/kgww)/(Bq/l), which is about ten times lower than the derived BCF for fish in simulation with mixed uptake and normal water exchange (C) at 2000 AD in this study.

6.9 Ecosystem specific dose conversion factors (EDF)

In /Karlsson et al, 2001/ the environmental fate of released radioactivity was modelled by using six different modules (well, lake, running waters, coastal area, agricultural land and peat bog) to improve existing models and applying site-specific data to biosphere model calculations. For each module, ecosystem specific dose conversion factors, EDF:s, for various radionuclides were calculated. In this study analogous factors have been retrieved. EDF:s are values that estimate the dose to a human that consumes locally produced food that have been exposed to a continuous C-14 discharge of 1 Bq/year during 10,000 years from SFR-1. The EDF:s for consumption of the organisms in the area corresponding to 100% of the annual food consumption are listed in Appendix 3.

EDF:s calculated in the same way as the in /Karlsson et al, 2001/, i.e. that of the total annual humans consumption, 2.8% is coastal fish, are approximately 5 times lower than in /Karlsson et al, 2001/, that is 2.48×10^{-19} Sv/Bq compared to 1.13×10^{-18} Sv/Bq.

7 Validation of the model results

7.1 Validation of time step in model iterations

The time step used in the model simulations was 0.002 years (runge kutta 4, fixed step size). In the time step validation, the time step was gradually lowered from 0.002 till 0.0008 years and the modelling results were compared for each time step. Since the modelling results did not change with decreased time step size it could be concluded that the models are stable.

7.2 Validation of the carbon budget

The carbon budget for the present ecosystem has been compared with various budgets from the vicinity (Askö region), which show both similarities and differences. In a budget for the benthic ecosystem by /Ankar and Elmgren, 1978/ the macrofauna biomass is about five times lower than in this budget whereas the meiofauna data is about the same. The phythobenthic community has been compared with a budget for a *Fucus*-community /Jansson et al, 1982/, which shows large similarities in estimations of macrophytic, microphytic, grazers as well as filter feeder biomass. However, when comparing the pelagic community with plankton system budgets /Mc Kellar and Hobro, 1976; Larsson et al, 1986/, the budget in this study has consequent lower values, which partly can be explained with seasonal variations since the other two studies describe the plankton community during the spring bloom and this an annual mean. /Jansson and Wulff, 1977/ present an ecosystem analysis of a shallow sound in the Askö region that describes energy storage and flows that are in the same magnitude as this study.

The carbon budget in this study has also been compared with a study of the carbon flows in food webs of the Bothnian Sea by (Sandberg et al, 2000). These two budgets are however not completely comparable since this study refer to a coastal area (11.5 km^2) and the study by /Sandberg et al, 2000/ to the whole Bothnian Sea (79,000 km^2) where the coastal area represent only a very small part. The estimates of typical coastal organisms, such as benthic primary producers and grazers differ very much due to this as well as data for zooplankton. The respiration and consumption of zooplankton in this carbon budget is approximately one third of the other budget even though the biomass is 50% higher. The benthic macrofauna follow the same pattern in biomass although the respiration and consumption is about the same. Estimations of biomass as well as respiration and consumption for the other functional groups, pelagic producers, bacterioplankton, benthic meiofauna and fish, are about the same.

7.3 Validation of the results from the C-14 flow model

Validation is a process that tests selected parameters with an independent set of data. Since environmental assessment models for long-term assessment of nuclear fuel waste management system cannot be validated, the relative distribution of C-14 in the compartments according to the model was compared with field measurements of C-14 in biota and water around the Sellafield reprocessing plant in Great Britain /Cook et al, 1998/. When comparing the concentrations in biota and water per discharged Bq to the water, this C-14 model generates slightly lower concentrations in fish and benthic organisms as well as in the water (DIC), but higher in seaweed (Table 7-1). This might be due to the high water exchange rate in the study area and the high abundance of benthic primary producers, which area able to accumulate an extensive amount of discharged C-14.

Table 7-1. Ratio of C-14 concentration (Bq/gC) per annual discharge (10^{-13} Bq/year) in biota and DIC in the area around Sellafield, UK, /Cook et al, 1998/ and in this study (homogenous uptake and normal water exchange, simulation A) at 2000 AD.

	DIC	Seaweed	Mussel/benthos	Fish
/Cook et al, 1998/[1]	24	7.1	1.3	6.8
This study[2]	15	13	0.98	1.8

[1]Annual discharge: 2 TBq (varied between approximately 0.5 to 12.4 TBq per year during 1967–1995).
[2]Annual discharge: 51.3 MBq.

8 Discussion and summary

8.1 Results in short

8.1.1 Carbon dynamics

The bay described in this study is shallow and has its main bottom surface in the photic zone. Consequently, more than half of the total biomass is made up by organisms in the phytobenthic community, 39% to soft bottom organisms and only 8% to pelagic. In the future ecosystem, even a larger share will be found in the phytobenthic community since the whole seabed will be located in the photic zone. When it comes to maintenance of the biomass, the area is self-sufficient on carbon at present. According to the assumptions made in the model, the future ecosystem seems to be carbon limited, i.e. have a larger need for dissolved inorganic carbon than what is available. This tells us that the biomasses of at least primary producers (but probably all functional groups) most likely are overestimated which affects all results in the 4000 AD model.

8.1.2 Fate of C-14 in the ecosystem

According to the model, discharged C-14 from SFR-1 would accumulate in plants and animals in the aquatic ecosystem, especially in benthic dwelling organisms such as macroalgae and benthos. The large water exchange in the area will however rapidly dilute and export a large fraction of the discharge, which results in very low concentrations and an ecosystem half-life of C-14 of approximately 188 (213) days at homogenous uptake and normal water exchange (A) at 2000 AD (4000 AD).

8.1.3 Determining factors

The most important factor determining the exposure to benthophytes and grazing organisms seems to be the uptake pathway of C-14. The concentrations in these compartments in simulation with benthic uptake and normal water exchange (B) are approximately 25% higher than for simulation with homogenous uptake and reduced water exchange by 100 (E). For the other compartments, the water exchange has higher or equal influence as the uptake pathway.

8.1.4 Comparison of the present and the future ecosystem

Compared to the present ecosystem, future (4000 AD) organisms are estimated to receive higher exposures in equivalent simulations. The increase is however not very large except for simulation A where the future ecosystem gets remarkably higher exposures compared to the present. Thus, the exposure to the environment would increase if a discharge of C-14 from SFR-1 would take place in an ecosystem similar to the modelled future ecosystem than in one similar to the present.

8.2 The ecosystem modelling approach

The aim with this study was to develop a transport and fate model of discharged C-14 into a coastal ecosystem, which could be used in the safety-assessments of nuclear waste facilities, such as SFR-1.

On the basis of results received in this study, it can be summarised that the ecosystem mass balance approach that was adopted, enabled settlements of some of the problems identified in other modelling surveys. For instance, it was possible to analyse and numerically describe the fate of the discharged C-14 in the whole ecosystem, i.e. predict the amount in the various compartments, the amounts re-circulated in the system, the magnitudes of the flows between the compartments and from the system as well as the amount buried in the sediment. Apart from generating the estimates of the fate and persistence of hypothetical C-14 releases it was possible address other important questions connected with safety assessment of the facility (e.g. importance of environmental factors and modelling of various routes of C-14 entry into the food web). It soon became clear that the water exchange rate in this particular area was an extremely important abiotic factor, both because a large fraction of the discharge left the system immediately with the export of C-14 in DIC and plankton but also since the high productivity in the area caused a large export of secondary produced biomass from the area. The effect water exchange had on the C-14 concentrations in biota and the time needed to reach steady state was also shown to be very important. Another advantage with the adopted approach was shown to be the possibility to model various routes for uptake and follow transport patterns through the food web. Because of the uneven distribution of biomass in the ecosystem, it would be difficult to predict bioconcentrations successfully with other methods, since dilution of the C-14 by biomass would be difficult to compensate for.

Since the model is of large-scale mass balance type with dynamics on an annual basis, many generalisations, simplifications and estimations had to be made. For instance, the food web structure used in the model was simplified, especially the pelagic microbial food web, but also the interactions between the organisms in the soft bottom community, which has resulted in un-detailed descriptions of many carbon flows. Furthermore, since the initial data were annual averages excluding important natural between-year fluctuations and other sources of biological variability, modelling results must be considered to be approximate. The framework of the model is however based on well-known ecological processes and interactions, and the initial data are collected from local studies often with a high resolution. Sensitivity analysis of for instance fish biomass indicate that an over- or underestimation of 30% of the biomass would cause an increase or decrease of less than one percent of the dose to humans consuming the contaminated fish from the area.

Many carbon flows and storages of importance may change considerable in 2,000 years owing to a various environmental and biological factors that have not been considered in this study. Therefore, the results of the prospective model (4000 AD) should be evaluated with large caution. For instance, the implications future changes in salinity or eutrophication status have not been evaluated. An increased salinity would probably favour the blue mussel, *Mytilus edulis*, which is a very effective filter feeder. This would contribute to an increased filtration of the water and thereby increase the transport of particulate matter in the water down to the bottom and consequently lead to a different fate of discharged radonuclides.

As mentioned in a previous section, the discharge was assumed to reach the biosphere as an inorganic and bio-available form. If the C-14 is introduced into the biosphere with organic speciation the molecules would probably enter the food web anyway but via benthic bacteria, which would mineralise the molecules and partly respire them (to the DIC-compartment) and partly enable trophic transfer through meiofauna to higher trophic levels.

The ecosystem modelling approach adopted in this study requires a comprehensive knowledge of the carbon dynamics in the ecosystem. This implies that it can be quite resource demanding to assemble the necessary input data for the model. However, once established the model is constructed in such a way that it can be rescaled to other geographical areas and to changes in ecosystem structure and function if the initial data are available. The model may with complementation of some element-specific characteristics, such as differences in uptake processes of the element compared to carbon and active accumulation and excretion rates (other than consumption and production of e.g. faeces) be used for other radionuclides. It also enables sensitivity analyses for various processes to evaluate how other radionuclides than C-14 compared to carbon may flow through the system /Næslund et al, in preparation/.

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Appendix 1

The equations used in the model sections are listed below and numbers in front of the equations shows where in the models they are used, see Figure 4-2. The initial values for both models can be found in Appendix 2.

CARBON FLOW MODEL

Benthophytes

benthophytes (t) = benthophytes (t–dt) + (benthophyte production – grazing – benthophyte loss – benthophyte fishgrazing) × *dt*

6 benthophyte production = (initital benthophyte production)/(initial benthophyte biomass) x benthophytes
9 grazing = grazer respiration × 3
7 benthophyte loss = benthophyte production – grazing – benthophyte fishgrazing
8 benthophyte fishgrazing = total fish consumption × fish share of benthophytes

Grazers

grazers (t) = grazers (t–dt) + (grazing – grazer respiration – grazer loss – grazer predation) × *dt*

9 grazing = grazer respiration × 3
10 grazer respiration = grazers × (initial grazer respiration/initial grazer biomass)
10 grazer loss = grazing – grazer respiration – grazer predation
11 grazer predation = total fish consumption × fish share of grazer predation

Plankton

plankton (t) = plankton (t–dt) + (plankton production – zooplankton grazing – plankton loss) × *dt*

1 plankton production = initial plankton production/(initial plankton biomass) × plankton
3 zooplankton grazing = zooplankton respiration × 3
2 plankton loss = plankton production – zooplankton grazing

Zooplankton

zooplankton (t) = zooplankton(t–dt) + (zooplankton grazing – zooplankton respiration – zooplankton loss – zooplankton predation) × *dt*

3 zooplankton grazing = zooplankton respiration × 3
5 zooplankton predation = total fish consumption × fish share of zooplankton
4 zooplankton respiration = zooplankton × (initial zooplankton respiration/initial zooplankton biomass)
4 zooplankton loss = zooplankton grazing – zooplankton respiration – zooplankton predation

Fish

fish (t) = fish(t–dt) + (grazer predation + benthophyte fishgrazing + zooplankton predation + benthos predation – fish respiration – fish loss) × *dt*

8 benthophyte fishgrazing = total fish consumption × fish share of benthophytes
5 zooplankton predation = total fish consumption × fish share of zooplankton
13 benthos predation = total fish consumption × fish share of benthos
11 grazer predation = total fish consumption × fish share of grazer predation
12 fish respiration = fish × (initial fish respiration/initial fish biomass)
12 fish loss = grazer predation + zooplankton predation + benthos predation + benthophyte fishgrazing – fish respiration
fish share of benthophytes = 0.1
fish share of benthos = 0.05
fish share of grazer predation = 0.05
fish share of zooplankton = 0.8

Benthos

benthos (t) = benthos(t–dt) + (benthos consumption – benthos respiration – benthos loss – benthos predation) × *dt*

14 benthos consumption = benthos respiration × 3
15 benthos respiration = benthos × (initial benthos respiration)/(initial benthos biomass)
15 benthos loss = benthos consumption – benthos respiration – benthos predation
13 benthos predation = total fish consumption × fish share of benthos

Seal
seal (t) = seal(t–dt) + (seal consumption – seal respiration – seal loss) × dt
16 seal consumption
17 seal respiration = seal consumption / 3
17 seal loss = seal consumption – seal respiration

Eider duck
eider duck (t) = eider duck(t–dt) + (eider duck consumption – eider duck respiration – eider duck loss) × dt
18 eider duck consumption
19 eider duck respiration = eider duck consumption / 3
19 eider duck loss = eider duck consumption – eider duck respiration

Eagle
eagle (t) = eagle (t–dt) + (eagle consumption – eagle respiration – eagle loss) × dt
20 eagle consumption
21 eagle respiration = eagle consumption / 3
21 eagle loss = eagle consumption – eagle respiration

POC
POC (t) = POC(t–dt) + (total loss – benthos consumption – POC exchange) × dt
22 total loss = benthos loss + fish loss + grazer loss + benthophyte loss + plankton loss + zooplankton loss
14 benthos consumption = benthos respiration × 3
23 POC exchange = water exchange × c POC water exchange × (POC concentration – external POC concentration) × total water volume
POC concentration = POC / total water volume
water exchange = number of water-exchanges per year
external POC concentration = initial POC / total water volume
c POC water exchange = 1
24 POC-burial = total loss– benthos consumption – POC exchange

DIC
DIC (t) = DIC (t–dt) + (total respiration – total primary production – DIC diffusion – DIC exchange) × dt
25 total respiration = benthos respiration + fish respiration + grazer respiration + zooplankton respiration
1,6 total primary production = benthophyte production + plankton production
26 DIC diffusion = 0
26 DIC exchange = water exchange × (DIC concentration – external DIC concentration) × total water volume
DIC concentration = DIC / total water volume
external DIC concentration = initial DIC / total water volume

C-14 FLOW MODEL

C14 in DIC
C14 in DIC (t) = C14 in DIC (t–dt) + (inflow from SFR + C14 in total respiration – C14 from DIC) × dt
27 inflow from SFR = C14 in SFR-1 / discharge duration × (1 – discharge direction)
51 C14 in total respiration = (benthos respiration × share of C14 in benthos + fish respiration × share of C14 in fish + grazer respiration × share of C14 in grazers + zooplankton respiration × share of C14 in zooplankton)
28,33,52 C14 from DIC = C14 in to benthophytes via DIC + C14 in to plankton via DIC + DIC14 diffusion + DIC14 exchange
52 DIC14 diffusion = 0
52 DIC14 exchange = water exchange × (share of C14 in DIC – external DIC14 concentration) x total watervolume
external DIC14 concentration = 0
share of C14 in DIC = C14 in DIC / DIC

C14 in Benthophytes
C14 in benthophytes (t) = C14 in benthophytes (t−dt) + (C14 in to benthophytes via DIC − C14 from benthophytes) × dt
33 C14 in to benthophytes via DIC = share of C14 in DIC × benthophyte production
34,35,36 C14 from benthophytes = share of C14 in benthophytes × (grazing + benthophyte loss + benthophyte fishgrazing)
initial value for C14 in benthophytes = 0
share of C14 in benthophytes = C14 in benthophytes / benthophytes

C14 in Plankton
C14 in plankton (t) = C14 in plankton (t−dt) + (C14 in to plankton − C14 from plankton − C14 plankton exchange) × dt
28 C14 in to plankton = share of C14 in DIC × plankton production
29,30,54 C14 from plankton = share of C14 in plankton × (plankton loss + zooplankton grazing) + C14 plankton exchange
C14 plankton exchange = C14 in plankton × c plankton exchange × water exchange
initial value for C14 in plankton = 0
share of C14 in plankton = C14 in plankton / plankton
c plankton exchange = 1

C14 in Grazers
C14 in grazers (t) = C14 in grazers (t−dt) + (C14 in to grazers − C14 from grazers) × dt
36 C14 in to grazers = share of C14 in benthophytes × grazing
37,38 C14 from grazers = share of C14 in grazer × (grazer loss + grazer predation + grazer respiration)
initial value for C14 in grazers = 0
share of C14 in grazers = C14 in grazers / grazers

C14 in Zooplankton
C14 in zooplankton (t) = C14 in zooplankton (t−dt) + (C14 in to zooplankton − C14 from zooplankton − C14 zooplankton exchange) × dt
30 C14 in to zooplankton = share of C14 in plankton × zooplankton grazing
31,32,55 C14 from zooplankton = share of C14 in zooplankton × (zooplankton loss + zooplankton predation + zooplankton respiration) + C14 zooplankton exchange
C14 zooplankton exchange = C14 in zooplankton × water exchange × c zooplankton exchange
c zooplankton exchange = 1
initial value for C14 in zooplankton = 0
share of C14 in zooplankton = C14 in zooplankton / zooplankton

C14 in Benthos
C14 in benthos (t) = C14 in benthos (t−dt) + (C14 in to benthos − C14 from benthos) × dt
47 C14 in to benthos = share of C14 in POC × benthos consumption
39,40,43 C14 from benthos = share of C14 in benthos × (benthos loss + benthos fish predation + benthos
respiration + benthos eider ducks predation)
initial value for C14 in benthos = 0
share of C14 in benthos = C14 in benthos / benthos

C14 in Fish
C14 in fish (t) = C14 in fish (t−dt) + (C14 in to fish − C14 from fish) × dt
32,35,37,39 C14 in to fish = (share of C14 in zooplankton × zooplankton predation) + (share of C14 in benthos × benthos predation) + (share of C14 in benthophytes × benthophyte fish grazing) + (share of C14 in grazers × grazer predation)
41,45,53 C14 from fish = share of C14 in fish × (fish loss + fish respiration + fish seal predation + fish eagle predation)
initial value for C14 in fish = 0
share of C14 in fish = C14 in fish / fish

C14 in Eagle
C14 in eagle (t) = C14 in eagle (t−dt) + (C14 in to eagle − C14 from eagle) × dt
45 C14 in to eagle = C14 in eagle consumption
46 C14 from eagle = share of C14 in eagle × (eagle loss + eagle respiration)
C14 in eagle consumption = share of C14 in fish × eagle consumption

C14 in Eider ducks

C14 in eider ducks (t) = C14 in eider ducks (t–dt) + (C14 in to eider ducks – C14 from eider ducks) x dt

43 C14 in to eider ducks = C14 in eider ducks consumption

44 C14 from eider ducks = share of C14 in eider ducks × (eider ducks loss + eider ducks respiration)

C14 in eider ducks consumption = share of C14 in benthos × eider ducks consumption

C14 in Seal

C14 in seal (t) = C14 seal (t–dt) + (C14 in to seal – C14 from seal) × dt

41 C14 in to seal = C14 in seal consumption

42 C14 from seal = share of C14 in seal × (seal loss + seal respiration)

C14 in seal consumption = share of C14 in fish × seal consumption

C14 in POC

C14 in POC (t) = C14 in POC (t–dt) + (C14 in to POC – C14 from POC) × dt

48 C14 in to POC = (benthophyte loss × share of C14 in benthophytes) + (plankton loss × share of C14 in plankton) + (zooplankton loss × share of C14 in zooplankton) + (benthos loss × share of C14 in benthos) + (fish loss × share of C14 in fish)

47,49,50 C14 from POC = share of C14 in POC × (benthos consumption + max (0, POC exchange) + POC-14 burial)

initial value for C14 in POC = 0

share of C14 in POC = C14 in POC / POC

C14 in POC exchange = share C14 in POC × max (0, POC exchange)

50 POC-14 burial = C14 in to POC – share of C14 in POC × benthos consumption – POC exchange

C14 in SFR-1

DIC14 in SFR-1 (t) = DIC14 in SFR-1 (t–dt) + (inflow from SFR) × dt

27 inflow from SFR = C14 in SFR-1 / discharge duration × (1 – discharge direction)

DIC14 in SFR-1 = total amount of C14 in SFR-1

Appendix 2

Annual standing stocks and flux of carbon (gC and gC/year) in the ecosystem above SFR-1 at 2000 AD and 4000 AD which also are used as initial data in the models. The share (%) of the carbon compartments at 4000 AD compared to 2000 AD are also presented.

	Biomass (gC)			Production/loss (gC/year)				
	2000	4000	%	2000		4000		%
Phytoplankton	9.3E+06	4.4E+06	47%	3.4E+08	a	1.6E+08	a	47%
Bacterioplankton	2.6E+06	3.6E+05	14%	2.2E+08	b	1,0E+08	b	20%
Zooplankton	5.1E+06	2.4E+06	47%	1.4E+08	b	6.6E+07	b	47%
Fish	8.3E+06	3.9E+06	47%	5.4E+06	c	2.5E+06	c	46%
Microphytes	3.1E+07	2.8E+07	90%	3.3E+08	a	3.0E+08	a	91%
Macrophytes[d]	1.0E+08	1.6E+08	160%	4.7E+08	a	7.6E+08	a	162%
Grazers	4.5E+06	5.6E+06	124%	3.7E+07	b	4.3E+07	b	116%
Filter feeders	1.7E+06	2.5E+06	147%	8.8E+06	b	1.2E+07	b	136%
Benthic macrofauna	1.0E+08	1.0E+07	10%	4.9E+08	b	5.5E+07	b	11%
Benthic meiofauna	3.1E+06	1.5E+06	48%	7.3E+07	b	3.7E+07	b	51%
Benthic microfauna	1.2E+07	5.6E+06	47%	1.0E+08	b	4.7E+07	b	47%
Eagle[e]	5.1E+02	5.1E+02	100%	5.2E+03	b	5.2E+03	b	100%
Eider ducks	6.7E+04	3.2E+04	48%	8.7E+05	b	3.9E+05	b	45%
Seal[e]	2.0E+04	2.0E+04	100%	1.3E+05	b	1.3E+05	b	100%
Total	2.8E+08	2.2E+08	81%	1.9E+09	b	3.6E+08	b	20%

	Respiration (gC/year)			Consumption (gC/year)		
	2000	4000	%	2000	4000	%
Bacterioplankton	2.1E+08	1.0E+08	48%	4.3E+08	2.0E+08	47%
Zooplankton	7.0E+07	3.3E+07	47%	2.1E+08	9.9E+07	47%
Fish	3.3E+07	1.6E+07	48%	9.8E+07	4.7E+07	48%
Grazers	1.9E+07	2.2E+07	116%	5.6E+07	6.5E+07	116%
Filter feeders	4.2E+06	5.9E+06	140%	1.3E+07	1.8E+07	138%
Benthic macrofauna	2.5E+08	2.7E+07	11%	7.4E+08	8.2E+07	11%
Benthic meiofauna	3.7E+07	1.8E+07	49%	1.1E+08	5.5E+07	50%
Benthic microfauna	9.8E+07	4.6E+07	47%	2.0E+08	9.3E+07	47%
Eagle[e]	1.8E+02	1.8E+02	100%	5.4E+03	5.4E+03	100%
Eider ducks	4.3E+05	2.0E+05	47%	1.3E+06	5.9E+05	45%
Seal[e]	6.3E+04	6.3E+04	100%	1.9E+05	1.9E+05	100%
Total	7.2E+08	2.7E+08	37%	1.9E+09	6.6E+08	36%

	Amount (gC)			Turnover (gC/year)		
	2000	4000		2000	4000	
POC	2.7E+07	6.6E+05	2%	8.2E+09	3.1E+07	0.5%
DIC	1.8E+09	2.5E+08	14%	6.5E+11	1.2E+10	2%

[a] Primary production (phytoplankton primary production includes bacterioplankton primary production).
[b] Loss = consumption – respiration – predation (Loss from primary producers i.e. primary production – grazing is not shown in the table).
[c] Fish secondary production (production of fish meat that actually can be consumed, e.g. by man)
[d] Includes macroalgae, phanerogames and aquatic bryophytes.
[e] Results for eagle and seal are valid for individuals of the respective animal.

Appendix 3

Radioactivity (Bq), concentration (Bq/gC), exposure (Gy), dose to human consuming food from the area (Sv), bioconcentration factor [(Bq/kgww)/(Bq/l)] and ecosystem specific dose conversion factor (Sv/Bq) for biota, DIC and POC in the ecosystem above SFR-1 at steady state in the 2000 AD and 4000 AD ecosystem (simulation A to E).

Radioactivity (Bq)	**2000A**	**2000B**	**2000C**	**2000D**	**2000E**
benthophytes	9.09E+03	7.36E+06	3.68E+06	9.06E+04	8.96E+05
benthos	5.90E+02	4.69E+05	2.35E+05	3.60E+04	7.46E+05
fish	7.49E+01	5.84E+04	2.92E+04	1.72E+03	4.28E+04
grazers	2.77E+02	2.24E+05	1.12E+05	2.76E+03	2.73E+04
DIC	1.40E+05	7.44E+03	7.39E+04	1.38E+06	1.25E+07
POC	1.67E+02	1.33E+05	6.66E+04	1.57E+04	1.46E+06
eagle	4.62E–03	3.60E+00	1.80E+00	1.06E–01	2.64E+00
eider duck	3.42E–01	2.72E+02	1.36E+02	2.09E+01	4.33E+02
seal	1.78E–01	1.39E+02	6.95E+01	4.10E+00	1.02E+02
plankton	6.81E+01	3.61E+00	3.59E+01	4.05E+03	7.97E+04
zooplankton	2.40E+00	1.27E–01	1.26E+00	8.07E+02	2.97E+04
total	1.51E+05	8.25E+06	4.20E+06	1.54E+06	1.58E+07

Concentration (Bq/gC or Bq /l)	**2000A**	**2000B**	**2000C**	**2000D**	**2000E**
benthophytes	6.77E–05	5.48E–02	2.74E–02	6.74E–04	6.67E–03
benthos	5.05E–06	4.02E–03	2.01E–03	3.08E–04	6.39E–03
eagle	9.05E–06	7.06E–03	3.53E–03	2.08E–04	5.17E–03
fish	9.05E–06	7.06E–03	3.53E–03	2.08E–04	5.17E–03
grazers	6.15E–05	4.98E–02	2.49E–02	6.13E–04	6.06E–03
DIC	7.91E–05	4.19E–06	4.16E–05	7.87E–04	7.79E–03
POC	5.74E–06	4.57E–03	2.29E–03	3.51E–04	7.27E–03
plankton	5.73E–06	3.04E–07	3.02E–06	3.41E–04	6.70E–03
eider duck	5.05E–06	4.02E–03	2.01E–03	3.08E–04	6.39E–03
seal	9.05E–06	7.06E–03	3.53E–03	2.08E–04	5.17E–03
zooplankton	4.74E–07	2.51E–08	2.50E–07	1.59E–04	5.87E–03
water	1.27E–06	1.27E–06	1.27E–06	1.26E–05	1.26E–04

Exposure (Gy)	**2000A**	**2000B**	**2000C**	**2000D**	**2000E**
benthophytes	2.87E–09	2.32E–06	1.16E–06	2.86E–08	2.83E–07
benthos	2.93E–10	2.33E–07	1.17E–07	1.79E–08	3.71E–07
eagle	6.85E–11	5.34E–08	2.67E–08	1.58E–09	3.91E–08
fish	7.10E–10	5.54E–07	2.77E–07	1.63E–08	4.06E–07
grazers	2.10E–09	1.70E–06	8.50E–07	2.09E–08	2.07E–07
plankton	1.37E–10	7.27E–12	7.21E–11	8.15E–09	1.60E–07
eider duck	3.82E–11	3.04E–08	1.52E–08	2.33E–09	4.84E–08
seal	6.85E–11	5.34E–08	2.67E–08	1.58E–09	3.91E–08
zooplankton	1.89E–11	1.00E–12	9.95E–12	6.36E–09	2.34E–07

Dose to human[a] (Sv)					
	2000A	**2000B**	**2000C**	**2000D**	**2000E**
benthophytes	4.16E−09	3.37E−06	1.69E−06	4.14E−08	4.10E−07
benthos	3.10E−10	2.47E−07	1.24E−07	1.90E−08	3.93E−07
eagle	5.56E−10	4.34E−07	2.17E−07	1.28E−08	3.18E−07
fish	5.56E−10	4.34E−07	2.17E−07	1.28E−08	3.18E−07
grazers	1.06E−10	8.57E−08	4.29E−08	1.05E−09	1.04E−08
plankton	3.52E−10	1.87E−11	1.85E−10	2.09E−08	4.12E−07
eider duck	8.69E−12	6.91E−09	3.46E−09	5.31E−10	1.10E−08
seal	1.56E−11	1.21E−08	6.08E−09	3.58E−10	8.90E−09
zooplankton	2.91E−11	1.54E−12	1.53E−11	9.80E−09	3.61E−07
fish[b]	1.56 E−11	1.21 E−08	6.08E−09	3.58E−10	8.90E−09
Ecosystem specific dose factor (Sv/Bq)					
	2000A	**2000B**	**2000C**	**2000D**	**2000E**
benthophytes	8.11E−17	6.57E−14	3.29E−14	8.08E−16	7.99E−15
benthos	6.05E−18	4.81E−15	2.41E−15	3.69E−16	7.66E−15
eagle	1.08E−17	8.45E−15	4.23E−15	2.49E−16	6.20E−15
fish	1.08E−17	8.45E−15	4.23E−15	2.49E−16	6.20E−15
grazers	2.06E−18	1.67E−15	8.36E−16	2.06E−17	2.03E−16
plankton	6.86E−18	3.64E−19	3.61E−18	4.08E−16	8.03E−15
eider duck	1.69E−19	1.35E−16	6.75E−17	1.03E−17	2.14E−16
seal	3.04E−19	2.37E−16	1.19E−16	6.98E−18	1.73E−16
zooplankton	5.68E−19	3.01E−20	2.99E−19	1.91E−16	7.04E−15
Bioconcentration factor [(Bq/kgww)/(Bq/l)]					
	2000A	**2000B**	**2000C**	**2000D**	**2000E**
benthophytes	1.01E+03	8.14E+05	4.08E+05	1.00E+03	9.99E+02
benthos	5.47E+01	4.35E+04	2.18E+04	3.35E+02	6.97E+02
eagle	7.15E+01	5.57E+04	2.79E+04	1.65E+02	4.12E+02
fish	7.30E+01	5.69E+04	2.85E+04	1.68E+02	4.20E+02
grazers	1.14E+03	9.20E+05	4.61E+05	1.14E+03	1.13E+03
plankton	1.51E+02	7.99E+00	7.94E+01	8.99E+02	1.78E+03
eider duck	3.99E+01	3.17E+04	1.59E+04	2.44E+02	5.09E+02
seal	7.15E+01	5.57E+04	2.79E+04	1.65E+02	4.12E+02
zooplankton	7.49E+00	3.97 × 10−01	3.94E+00	2.53E+02	9.35E+02

[a] If all of the consumed food during a year would be the respective organism group.
[b] If 2.8% of the consumed food during a year would be fish from the area.

Radioactivity (Bq)	4000A	4000B	4000C
benthophytes	2.88E+05	1.57E+07	8.00E+06
benthos	3.72E+04	2.02E+06	1.03E+06
fish	1.76E+03	8.21E+04	4.19E+04
grazers	7.75E+03	4.23E+05	2.15E+05
DIC	1.06E+06	2.47E+05	6.56E+05
POC	1.54E+04	8.34E+05	4.25E+05
eagle	2.36E–01	1.10E+01	5.63E+00
eider duck	1.28E+02	6.97E+03	3.55E+03
seal	9.12E+00	4.25E+02	2.17E+02
plankton	1.73E+03	4.02E+02	1.07E+03
zooplankton	2.59E+02	6.02E+01	1.60E+02
total	1.42E+06	1.93E+07	1.04E+07

Concentration (Bq/gC or Bq /l)	4000A	4000B	4000C
benthophytes	1.53E–03	8.36E–02	4.25E–02
benthos	1.90E–03	1.03E–01	5.24E–02
eagle	4.63E–04	2.16E–02	1.10E–02
fish	4.63E–04	2.16E–02	1.10E–02
grazers	1.38E–03	7.55E–02	3.85E–02
DIC	2.20E–03	5.12E–04	1.36E–03
POC	2.08E–03	1.13E–01	5.76E–02
plankton	4.30E–04	9.99E–05	2.65E–04
eider duck	1.90E–03	1.03E–01	5.24E–02
seal	4.63E–04	2.16E–02	1.10E–02
zooplankton	1.20E–04	2.78E–05	7.36E–05
water	7.06E–05	7.07E–05	7.07E–05

Exposure (Gy)	4000A	4000B	4000C
benthophytes	6.49E–08	3.54E–06	1.80E–06
benthos	1.10E–07	5.97E–06	3.04E–06
eagle	3.51E–09	1.64E–07	8.35E–08
fish	3.63E–08	1.70E–06	8.66E–07
grazers	4.72E–08	2.58E–06	1.31E–06
plankton	1.03E–08	2.39E–09	6.34E–09
eider duck	1.44E–08	7.79E–07	3.97E–07
seal	3.51E–09	1.64E–07	8.35E–08
zooplankton	4.76E–09	1.11E–09	2.94E–09

Dose to human[a] (Sv)	**4000A**	**4000B**	**4000C**
benthophytes	9.41E–08	5.14E–06	2.62E–06
benthos	1.17E–07	6.33E–06	3.22E–06
eagle	5.24E–12	2.45E–10	1.25E–10
fish	2.85E–08	1.33E–06	6.78E–07
grazers	2.38E–09	1.30E–07	6.62E–08
plankton	2.64E–08	6.14E–09	1.63E–08
eider duck	3.26E–09	1.77E–07	9.02E–08
seal	7.97E–10	3.72E–08	1.90E–08
zooplankton	7.35E–09	1.71E–09	4.53E–09
fish[b]	7.97E–10	3.72E–08	1.90E–08

[a] If all of the consumed food during a year would be the respective organism group.
[b] If 2.8% of the consumed food during a year would be fish from the area.

Ecosystem specific dose factor (Sv/Bq)	**4000A**	**4000B**	**4000C**
benthophytes	1.83E–15	1.00E–13	5.10E–14
benthos	2.27E–15	1.23E–13	6.28E–14
eagle	1.02E–19	4.77E–18	2.43E–18
fish	5.55E–16	2.59E–14	1.32E–14
grazers	4.64E–17	2.53E–15	1.29E–15
plankton	5.15E–16	1.20E–16	3.18E–16
eider duck	6.36E–17	3.45E–15	1.76E–15
seal	1.55E–17	7.25E–16	3.70E–16
zooplankton	1.43E–16	3.33E–17	8.82E–17

Bioconcentration factor [(Bq/kgww)/(Bq/l)]	**4000A**	**4000B**	**4000C**
benthophytes	4.08E+02	2.22E+04	1.13E+04
benthos	3.68E+02	1.99E+04	1.02E+04
eagle	6.56E+01	3.05E+03	1.56E+03
fish	6.69E+01	3.12E+03	1.59E+03
grazers	4.59E+02	2.50E+04	1.27E+04
plankton	2.03E+02	4.70E+01	1.25E+02
eider duck	2.69E+02	1.45E+04	7.41E+03
seal	6.56E+01	3.05E+03	1.56E+03
zooplankton	3.38E+01	7.85E+00	2.08E+01

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