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A carbon budget for the Aquatic Ecosystem above SFR in Öregrundsgrepen

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Abstract

The potential hazards of radionuclide release to humans and the environment is regularly evaluated in safety assessments of SFR, the final repository for radioactive operational waste. SFR handles since 1988 low and intermediate level nuclear waste from Swedish nuclear power plants, medical care attendance, industries and research laboratories and is located in the bedrock 50 meters under the seabed of Öregrundsgrepen in the southern Bothnian Sea.

This report presents a description of the aquatic ecosystem and a carbon budget for the area above SFR with the aim to include ecosystem dynamics in the present safety assessment of the repository (SAFE). The carbon budget will support SAFE by facilitating evaluations of transport and fate of radionuclides, primarily ^{14}C, in case of a release from the repository and describe the ecosystem structure and function. Furthermore, ^{14}C is the dose-dominant radionuclide in the repository which most likely will follow the general carbon flow in the ecosystem if there should be a release.

The carbon budget was based on biomasses and flow of carbon between thirteen functional groups (including POC and DOC) in the ecosystem above SFR and the results indicates that the organisms are self-sufficient on carbon and that the area exports carbon corresponding to approximately 50% of the annual primary production. The largest organic carbon pool is DOC (one and a half time larger than the total biomass) and the major functional organism groups are the macrophytes (37% of the total biomass), benthic macrofauna (36%), and the microphytes (11%). The soft bottom and phytobenthic communities seems to have important roles in the ecosystem since these communities comprise the main part of the living carbon in the studied area.

Sammanfattning

Risken för sakdor på människan och dess omgivning vid ett eventuellt utsläpp av radionuklider utvärderas regelbundet i säkerhetsanalyser för SFR, slutgiltigt förvar för radioaktivt driftavfall. SFR ligger i ett bergrum ca 50 meter under havsbotten i Öregrundsgrepen i södra delen av Bottenhavet, och tar sedan 1988 hand om låg- och medelaktivt kärnavfall från svenska kärnkraftverk, sjukvård, industrier och forskningsanläggningar.

Den här rapporten presenterar en beskrivning av det akvatiska ekosystemet och en kolbudget för området ovanför SFR med syftet att inkludera ekologiska processer i den nuvarande säkerhetsanalysen av förvaret (SAFE). Kolbudgeten ska stödja SAFE genom att underlätta bedömningen av radionukliders transport, i första hand ^{14}C, vid ett eventuellt utsläpp från förvaret och beskriva det omgivande ekosystemets struktur och funktion. Vidare är ^{14}C den dominerande radionukliden i förvaret, som vid ett eventuellt utsläpp med stor sannolikhet kommer att följa det övriga kolflödet i ekosystemet.

Kolbudgeten baserades på biomassor och kolflöden mellan tretton funktionella grupper (DOC och POC inräknade) i ekosystemet ovanför SFR och resultaten pekar på att organismerna i området är självförsörjande på kol och att området exporterar kol som motsvarar ca 50 % av den årliga primärproduktionen. Den största organiska kolreserven är löst organiskt kol (DOC) (som är en och en halv gång större än den totala biomassan) och de största funktionella organismgrupperna är makrofyterna (37 % av den totala biomassan), den bentiska makrofaunan (36 %), och mikrofyterna (11 %). Det bentiska samhället verkar vara betydelsefullt eftersom det samhället omfattar den större delen av det levande kolet i det studerade området.

Contents

1 Introduction

This study will support the SKB project SAFE (Safety Assessment of the Final Repository of Radioactive Operational Waste) by providing an ecological description of the aquatic ecosystem in form of a carbon budget for the area above SFR (final repository for radioactive operational waste). The SAFE-project is an update of the previous safety assessment of SFR and will be presented to the Swedish authorities in the end of year 2000. The SKB Reports R-98-43 and R-98-44 “Project SAFE - Prestudy“ gives an overview of the SAFE project and presents the work that has to be performed to achieve the goal of the project (Andersson et al. 1998ab).

The aim with this carbon budget is to provide background knowledge that will facilitate prediction of transport and fate of radionuclides in the coastal ecosystem in case of a release from the repository and enabling modelling of various future scenarios. The carbon budget will also help us understand the ecosystem structure and function which is an essential prerequisite when reliable assessments of ecological as well as human health risks has to be performed. For example will the ecosystem structure and function influence the transport and fate of radionuclides, concentrations in biota and thereby human exposure through e.g. fish consumption. Furthermore, ^{14}C is the dose-dominant radionuclide in the repository.

The carbon budget was based on biomasses and carbon flows between the living stocks of the functional organism groups in the aquatic environment of the area and the budget has an ecosystem approach with couplings to some abiotic factors such as water turnover, solar insolation and temperature. Other parts of the SAFE-project will study the succession from an aquatic ecosystem to a terrestrial due to the ongoing landrise, as well as the resuspension of sediments and the changes in water exchange. Studies on the flux of radionuclides from assumedly broken containers through the repository and their transport in the rock up to the biosphere will also be completed together with modelling of possible future scenarios; see further in the references above.

This study was designed as a co-operation between the Swedish Nuclear Fuel and Waste Management CO (SKB) and the Department of Systems Ecology at Stockholm University.

2 SFR and the SAFE-project

SFR is a facility for disposal of low and intermediate level radioactive waste from Swedish nuclear power plants, medical care attendance, industries and research laboratories. The repository is located in the bedrock 50 meters under the seabed in Öregrundsgrepen, 1 km off the coast near the Forsmark nuclear power plant in northern Uppland. SFR was taken into use in the beginning of 1988 and is operated by Forsmarks Kraftgrupp and SKB. The facility consists of an over ground part with office- and engineering buildings and an under ground part with five rock shelters that today can bear 60,000 m^3 waste. According to previous safety assessments, the radioactive waste kept in SFR will harm no more than the background radiation of the bedrock in 500 years. To protect the environment from an assumed release of radioactivity during this time, different barriers enclose the waste in the repository.

The potential hazards of radionuclide release to humans and the environment is regularly evaluated in safety assessments for SFR. In previous safety assessment, the biosphere had a minor role and was described in a stylised way. The technical conditions and the stability of the bedrock had the major scope and the radionuclides were assumed to enter the biosphere directly into the coastal water without taking the processes in the geosphere/biosphere interface into account. Human exposure was estimated from contaminated fish which was considered to accumulate radionuclides directly from the water and not via biomagnification. Alternatively humans were assumed to be exposed to water from wells drilled into the repository. New regulations demand that the fate of released radionuclides should be described for a realistic biosphere as well as potential effects on organisms other than man, which require a more genuine model of the biosphere (Andersson et al. 1998ab).

3 The Baltic Sea

3.1 The Baltic Sea Environment

The Baltic Sea is one of the largest brackish water seas in the world and came into existence after the ice age 15,000 years ago. Today the area of the sea is 365,000 km^2 and the mean depth only 60 meters. The Baltic Sea is connected to the North Sea through two narrow straits with only 8 and 17 meters depth. The sea consists of a series of rather shallow basins, separated by sills, and have a salinity gradient from 2 to 3‰ in the northernmost part of the Bothnian Bay to over 20‰ in Skagerack (Elmgren 1984). The salinity is fairly constant over the year in the different subareas, with the highest fluctuations in the sillarea between the Bothnian Sea and the Bothnian Bay (Kautsky 1989). The low salinity condition in the Baltic Sea has been present for the last 3000 years (Ignatus et al. 1981). Due to the reduced salinity level, the number of plant and animal species in the Baltic Sea is relatively small and consists mainly of euryhaline species (Elmgren 1984). The diversity of the macrofauna drops from 1500 species in Skagerack to about 50 in the Bothnian Bay. The micro- and meiofauna show a less drastic reduction in numbers of species, but the system is still a fairly simple biotic community compared to other marine systems of the world (Jansson & Wulff 1977a). Of the approximately 150 macroscopic algae on the Norwegian coast, only 24 remain at the Finnish coast (Kautsky 1991). It is not only the salinity that limits the biodiversity; temperature, water chemistry, annual ice-cover among other factors also influences (Kautsky 1991).

3.2 Ecology of the Baltic Sea

All living organisms use energy to make and maintain the complex molecules necessary for life. Organisms can be divided into two different groups due to how they obtain their energy: primary producers (autotrophs) and consumers (heterotrophs). Primary producers get their energy from the environment, usually from the sunlight, to make their own food from carbon dioxide, water and nutrients and as they grow and reproduce they produce food for the consumers.

Most ecosystems have a number of different primary producers and many animals that eat more than just one kind of food and also change their diet as they get older and larger. The transfer of material and energy through an ecosystem usually takes place in several steps in food chains. Each step in a food chain is known as a trophic level. Most ecosystems have large, interwoven food webs instead of a simple, straight-line food chain since the structure of the systems usually is very complex. The first trophic level in an ecosystem is occupied by primary producers, the other levels by consumers. Animals living of plant material are called herbivores and other consumers are carnivores, which feeds on other animals and omnivores, which can act both as herbivores and carnivores. Some organic material is lost as waste in the transfer through the food web of producers and consumers and this material is transformed by bacteria, fungi and other decomposers through respiration and excretion into its original components: carbon dioxide, water and nutrients, which can be used by the primary producers again.

The coastal zone is the most productive environment in marine ecosystems (Kautsky & Kautsky 1995) and is usually divided into different communities. The phytobenthic community, at the seashore, has various organism belts. Close to the water surface, green and filamentous algae together with higher plants dominate. This vegetation zone is followed by the *Fucus*-belt, with bladder wrack (*Fucus vesiculosus*) and other brown algae. The deepest vegetation zone mainly consists of red algae and is followed by the *Mytilus*-belt with blue mussels (*Mytilus edulis*) (Jansson 1980). The water column is called the pelagic community and the main inhabitants here are bacterioplankton, phytoplankton, zooplankton and fish. On deeper seabeds the soft bottom community (or benthic community) is found with organisms burrowed in or attached to the sediment. The functional organism groups in this community are benthic macrofauna (invertebrates >0,5 mm), benthic meiofauna (invertebrates <0,5 mm) and benthic microfauna (mainly bacteria). Every environment has distinct characteristics that determine which organisms can live there or not. The amount of light, type of substrate and sediment, temperature, salinity, waves, currents etc affects the composition of species.

4 Description of the study area

4.1 Öregrundsgrepen

Öregrundsgrepen is shaped like a funnel between the mainland and the islands Gräsö and Örskär, figure 4-1. The western part of Öregrundsgrepen is a large ground water area with many rocks and islands and in the south eastern part there is a narrow connection with Åland Sea. South of Forsmark, the small rivers Olandsån and Forsmarksån flow into Kallrigafjärden, which is the largest freshwater outflow to Öregrundsgrepen (Persson et al. 1993; Lindahl & Wallström 1980). A 30 km long, deep channel stretches in along Gräsö Island (the singö fault) with two deep hollows; Storgrunnan (51 meters) and west of the Engelska grundet (59 meters) (Lindell & Kvarnäs 1978), which are the deepest cavities in Öregrundsgrepen. In the south the channel becomes increasingly shallow and has a depth of only 15 to 20 meters off the town Öregrund (Eriksson et al. 1977) and in the north, the channel expand and merge with the Bothnian Sea (Lindahl & Wallström 1980). The whole area is strongly influenced by the landrise, which is 0,6 cm/year (Wallström & Persson 1997). The landrise is further described in Brydsten 1999.

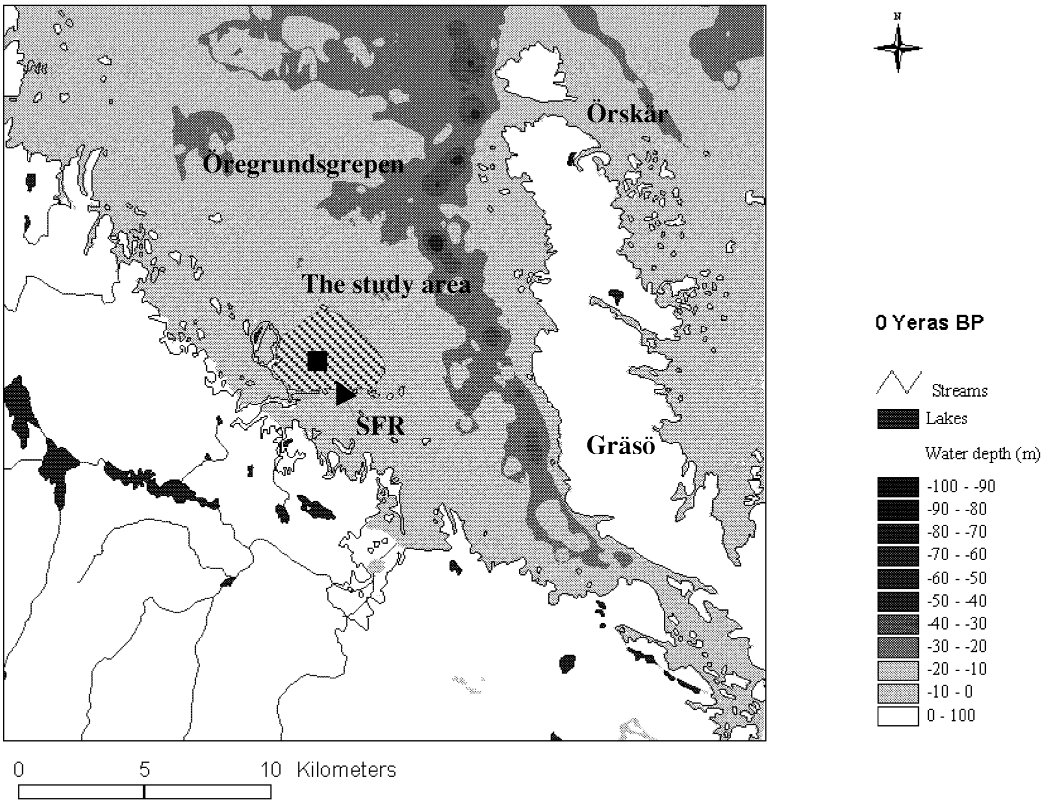


Figure 4-1. *The map shows the location of the study area in Öregrundsgrepen. Öregrundsgrepen is surrounded by the Swedish mainland in the west and by the islands Gräsö and Örskär in the east. (The backgroundmap comes from Brydsten 1999.)*

Öregrundsgrepen is a cooling water recipient for the three reactors in the Forsmark nuclear power plant. The cooling water from two of the reactors is pumped trough a long tunnel beneath the seabed into the Biotest Basin, an artificial lake, while the cooling water from the third reactor is discharged directly into Öregrundsgrepen (Persson et al. 1993).

The carbon budget is valid for the area around SFR, here called "the study area". The surface of this area is 11,5 km^2 of which 2% is land. The average water depth is approximately 10 meters with a range of 0 to 20 meters. The depth distribution is given in Table 4-1 and is based on data from Brydsten 1999.

Table 4-1. The depth distribution in the study area

Depth interval	Area (km^2)	Area (%) of total area
land	0,3	2,6
0– 1 meters	0,3	2,6
1– 2 meters	0,4	3,5
2– 4 meters	0,9	7,8
4– 6 meters	1,5	13,0
6–10 meters	2,8	24,3
10–15 meters	4,4	38,3
15–20 meters	0,9	7,8
photic zone (0–10 meters)	5,9	51,3
aphotic zone (10–20 meters)	5,3	46,1
sea bed (total)	11,2	97,4
sea bed and land (total)	11,5	100,0

Source: Brydsten 1999

4.2 Bottom structure

Erosion and transport bottoms are the main bottom types in Öregrundsgrepen. The sediment is very heterogeneous and mobile and consists mainly of fractions of sand and gravel with varying elements of glacial clay (Mo 1988). The sparse archipelago on the mainland side has rocky bottoms and is partly covered with coarse moraine (Sigurdsson 1987). The smaller fractions have been transported away by waves and currents and in some places there are spots with only clay remaining, usually covered with a thin layer of sand. Outside the archipelago, the bottom is almost flat except for the deep channel along Gräsö. Accumulation bottoms are found only in the channel, in parts of the Forsmarksfjärden and in the most shallow and less exposed bays (Mo 1988). The bottom above the repository have been investigated by Sigurdsson (1987) who describe that the bedrock was covered with a layer of 4 to 14 meters coarse moraine. A minor part of the area was covered with clay whose thickness varied between 0 and 4 meters, coated with sand. There were no bare rocks at all in the described area.

4.3 Water and Wind

Water movement affects the transport and dispersion of particulate and dissolved organic matter and is therefore important for the availability of nutrients for the organisms. Wave action, water turbulence, currents among other abiotic factors determine erosion and deposition areas, i.e. the distribution of hard and soft bottoms, and the sediment structure, which in turn influence the composition of the biota (Ankar 1977).

Öregrundsgrepen is influenced by a system of brackish water currents giving a stable salinity of 5 to 6‰ (Andersson & Gidhagen 1977a) which is homogenous down to 50 meters depth. That means that just about the whole area is unstratified for salinity and only the deepest parts of the Gräsö channel can have a higher salinity, around 7‰ (Persson et al. 1993).

The currents and the water exchange between Öregrundsgrepen and the western part of the archipelago are strongly influenced by winds (Wickström & Hillgren 1990). The dominating currents go south east along the mainland and north along Gräsö (Lindahl & Wallström 1980). The south east current causes lower temperature, the north higher and somewhat less saline water and currents from the south west give rise to upwellings along the mainland (Eriksson et al. 1977).

The largest water exchange is taken place in the northern part of Öregrundsgrepen (Lindahl & Wallström 1980). Of the total water transportation in the sound between Öregrund and Gräsö is 2/3 of the water going south and 1/3 going north. The average water turnover in the study area was calculated to be approximately 1,5 days (Engqvist & Andrejev 1999).

The water in the Öregrundsgrepen is naturally oligotrophic according to comparably large biodiversity, large phytoplankton biomass in spring but small in summer, a spring bloom which is dominated by diatoms and dinoflagellates and a trophogenic layer considerably thicker than 10 meters during the summer (Eriksson et al. 1977). The nutrients in the water was studied by Lindahl and Wallström (1980) and the total nitrogen content of the surface water varied between 200 and 400 mg tot-N/l and the total phosphorus content between 7 and 10 mg tot-P/l. The sechi depth in the study area was estimated to approximately 5 meters in a diving survey the by Kautsky (1998, pers.com.).

The river outflow along the mainland coast, especially from Dalälven, give rise to a lower salinity, which may explain the differences of the biotopes inside and outside Gräsö (Wærn 1952).

4.4 Temperature and Thermocline

The water temperature in Öregrundsgrepen is usually homogenous but during the summer a thermocline in water deeper than 5 meters is common. March is usually the coldest month with 1°C in the whole water column and the warmest period is July and August when the surface temperature may exceed 18°C (Eriksson et al. 1977). During the summer months a temperature difference of 4°C between the surface and the deep water is not unusual (Andersson 1974). The position of the thermocline depends on the prevailing weather. Winds from north are lowering the thermocline, while winds from south slowly raise it (Andersson & Gidhagen 1977b).

Table 4-2 gives information about some abiotic characteristics for Öregrundsgrepen. Some of them have been taken into consideration in the carbon budget.

Table 4-2. Abiotic characteristics for the study area

Characteristics	Value	Unit	Location	Source
Salinity	5-6	‰	Öregrundsgrepen	1
Water turnover	36	hours	The study area	2
Tot-Nitrogen	200-400	mgN/l	Öregrundsgrepen	3
Tot-Phosphorus	7-10	mgP/l	Öregrundsgrepen	3
Sechi depth	5	m	Öregrundsgrepen	4
POC concentration	0,35	gC/m^3	Öregrundsgrepen	5
DOC concentration	3,7	gC/m^3	Bothnian Sea	6
Annual sedimentation	65	$gC/m^2 \times year$	Bothnian Sea	6
Sedimentation rate	0,27	mm/year	Bothnian Sea	7
Annual degree days	2400	°C/year	Latitude 60° N	8
Annual light days	105	*	Latitude 60° N	8

* Number of days with a relative insolation of at least $5MJ/m^2$.

Sources:

1. Andersson & Gidhagen 1977a
2. Engqvist & Andrejev 1999
3. Lindahl & Wallström 1980
4. Kautsky (pers. com.) 1998
5. Nitchals 1985
6. Zweifel et al. 1995
7. Elmgren 1984
8. Kautsky & Kautsky 1995

4.5 Organisms in the area

The biodiversity of macrofauna and macroalgae in the area is fairly low which makes the habitats ecologically fairly simple. There are euryhaline marine species and lacustrine species as well as specifically brackish water species with their main distribution in brackish waters (Snoeijs & Mo 1987). There is a large variation in biomass and metabolic activities during the year due to the environmental features found in the area such as low average temperature, ice-cover during the winter months and large seasonal differences in temperature and insolation.

In this study the organisms in the area was divided into functional groups and the aquatic ecosystem into three different communities, which are described below.

4.5.1 The functional groups

The organisms in the area were divided into eleven different groups due to their food source and function in the ecosystem. The particulate and dissolved organic carbon pools were also included as functional groups in the carbon budget. The groups are listed and defined below:

- *Phytoplankton*: pelagic microalgae
- *Microphytes*: benthic microalgae
- *Macrophytes*: benthic macroalgae, higher plants and bryophytes
- *Bacterioplankton*: pelagic bacteria
- *Zooplankton*: planktonic animals (other than bacteria)

- *Grazers*: macrofauna (>0,5mm) mainly living in the vegetation belt and feeding on macrophytes
- *Filter feeders*: macrofauna which filter organic matter from the water
- *Benthic macrofauna*: macrofauna apart from the vegetation belt; in or attached to the sediment in the soft bottom community
- *Benthic meiofauna*: meiofauna (<0,5 mm) in/on the sea bed
- *Benthic microfauna*: benthic bacteria
- *Fish*
- *POC*: nonliving particulate organic carbon
- *DOC*: nonliving dissolved organic carbon
- *DIC*: nonliving dissolved inorganic carbon

4.5.2 The phytobenthic community

The phytobenthic community was here defined as the benthic community on the seashore down to a depth of 10 meters (i.e. the photic zone). The functional organism groups found in this community are benthic micro- and macrophytes, grazers, filter feeders, meio- and microfauna.

The benthic microphytes belong to the periphyton, which include all microorganisms living attached to substrates. The periphyton are often divided into subgroups according to the substrates they live on; e.g. epiphytic periphyton (on macrophytes), epizoic (on animals), epilithic (on stones) and epipsammic (on sand grains). Also epipelic microalgae (free living in the sediments) belong to the periphyton. In Öregrundsgrepen the epiphytic and epilithic periphyton have been studied by Snoeijs (1985 & 1986) and these results are used in this study. According to that study, the seabed in the area is covered with a layer of microalgae, mainly diatoms and to a lesser extent of blue green algae.

There is a relatively high diversity and a large amount of macrophytes in the study area, (Kautsky et al. 1999a). The macrophytes were divided into annual and perennial algae, bryophytes and higher plants. The most common annual algae in the study area were *Cladophora* spp (green), *Pilayella* spp (brown), *Ectocarpus* spp (brown), *Ceramium tenuicorne* (red) and *Polysiphonia* spp (red), while *Fucus vesiculosus* (brown), *Sphacelaria arctica* (brown) and *Furcellaria lumbricalis* (red) were the most abundant among the perennial algae. The dominating higher plants were *Potamogeton filiformis* and *Ruppia marina* and the only aquatic bryophyte was *Fontinalis dalecarlia*.

The most common grazers in the area were the two gastropods *Bithynia tentaculata* (herbivore) and *Theodoxus fluviatilis* (herbivore) together with the crustaceans *Idothea baltica* (herbivore) and *Gammarus* spp (omnivore), while the dominating filter feeder was the bivalve *Cardium* spp (Kautsky et al. 1999a). According to Snoeijs and Mo (1987) were Nematodes, Acarins (of which 80-90% belonged to *Halacaridae*), Cladocerans, Copepods and Ostracods the major meiofauna taxa in the area.

4.5.3 The soft bottom community

Seabeds deeper than 10 meters, i.e. the aphotic seabeds, were defined as the soft bottom community in this study. The heterogeneous sediment, composed of sand, gravel, stone and a small fraction of organic material, is very mobile and results in a sparse biodiversity (Mo & Smith 1988). The invertebrate macrofauna (studied by Kautsky et al. 1999a) were divided into detritus feeders and carnivores due to their food source. The molluscs *Hydrobia* spp, *Macoma baltica* and the crustacea *Corophium volutator* were the most common detritus feeders while the crustacean *Mesidothea enthomon*, different polychaetes and the nemertin *Prostoma obscurum* were the dominating (by biomass) carnivorous species. The distribution of the meiofauna was assumed to be the same as in the phytobenthic community.

4.5.4 The pelagic community

The pelagic community embrace the water mass with phytoplankton, bacterioplankton, zooplankton and fish. During the spring the phytoplankton community in Öregrundsgrepen were dominated by diatoms (*Bacillariaophyceae*) and dinoflagellates (*Dinophyceae*) while the biomass in summer and autumn mainly were composed of bluegreen algae (*Cyanophyceae*) and small flagellates. The most common diatom species were *Thalassiosira* spp, *Achnanthes taeniata* and *Chaetoceros* spp while *Glenodium* spp and *Gonyaulax catenata* were the mainly occurring genera of the dinoflagellates and *Microcystis* spp and *Aphanizomenon flos-aquae* the most common bluegreen algae (Lindahl & Wallström 1980).

The zooplankton community was low of diversity since *Acartina bifilosa* and *Eurytemora affinis*, both copepods, constituted about 80% of the zooplankton biovolume. The rest were composed of cladocerans, mainly the genera *Bosmina* spp, *Podon* spp and *Evadne* spp, rotatorians with the genera *Keratella* spp and *Synchaeta* spp, ciliates with both *Tintinnida* and naked forms and also different larvae stages from benthic animals (Eriksson et al. 1977; Persson et al. 1993).

The fish fauna in Öregrundsgrepen has been studied by Neuman (1982) who found that herring, roach and perch were the most common species followed by ruffe, smelt, fourhorn sculpin, sprat and cod. This survey did not include small sized species e.g. three-spined stickleback, sand goby, common goby, bleak and minnow since the used nets had to large meshes to catch these species. This may off cause affect the species distribution. The distribution of the most abundant species is given in table 4-3.

Table 4-3. 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

4.5.5 Birds in the area

The area offers good conditions for sea birds. In Andersson et al. 1996 a compilation of bird observations are presented. The most common birds were goldeneyes, tufted ducks, gooseanders, mute-swan, mallards and eider-ducks. The sea eagle was also a frequent visitor in the area.

5 The carbon budget

The reason to make this carbon budget was to provide an ecological description for the area around SFR, such as ecosystem structure and function. This kind of knowledge is essential when reliable safety assessments of ecological and human health risks are performed. The carbon budget may also facilitate prediction of transport and fate of radionuclides in the area in case of a release from the repository and enable modelling of various future scenarios.

The carbon budget was established by coupling data from a number of studies and surveys conducted in or close to the study area, which was previously described. In fields where no studies have been done in Öregrundsgrepen, data from adjacent areas have been used. The ecosystem was divided into three different communities and the organisms into functional groups, which form the basic compartments of the budget together with dissolved and particulate carbon in the water.

5.1 Depth distribution of the functional groups

Since the photic zone in the area stretch down to approximately ten meters (Kautsky, 1998, pers. com.), the microphytes were assumed to occur on the seabed between the water surface and ten meters depth and the phytoplankton mainly in the water mass down to ten meters. The benthic meio- and microfauna together with filter feeders were supposed to be present at sea beds at all depths and the pelagic fauna; bacterioplankton, zooplankton and fish in the whole water column. The results from the diving survey by Kautsky et al. (1999a) provided biomasses of the macrophytes and the macrofauna in seven depth intervals (table 4-1) and the sum of the carbon content of the intervals were used in the budget.

5.2 Calculations

Biomasses and data for production, consumption and respiration were recalculated to match the depth distribution for each functional group and to be valid for the whole study area on an annual basis. In studies where only biomasses had been measured, respiration, production and consumption were calculated with the aid of converting factors (cf) from Kautsky (1995). Since the primary production to a great extent is dependent on solar radiation, the annual number of light-days were estimated to 105 at 60° N (Kautsky & Kautsky 1995) and used in the calculations for compensations for seasonal variations. The annual light days are the number of days per year with a relative insolation of at least 5 $MJ/m^2 \times day$. The calculation of animal respiration was also compensated for seasonal changes through consideration of temperature variations during the year. The annual degree-days were estimated to 2 400° C at 60° N (Kautsky & Kautsky 1995).

Calculations of important processes that influence the carbon flow are shown below:

- biomass (gC/m^2) = dryweight×cf for carbon content in the organism
- primary production (gC/m^2×year) = biomass×cf for prim. prod.×annual light-days
- respiration (gC/m^2×year) = biomass×cf for respiration/20×annual degree-days
- consumption (gC/m^2×year) = 3×respiration (or production+respiration).

To get data valid for the whole study area the carbon fractions were multiplied with the area for matching depth distribution for each functional group or the biomass of the functional group in the different depth intervals were summed up.

5.3 Distribution of carbon

Öregrundsgrepen is considered as a relatively productive coastal area in a region of low primary production, probably due to the upwellings along the mainland (Eriksson et al. 1977). The compilation of data made in this study indicate that the total organic carbon content in the area was approximately 707×10^3 kgC where the largest organic carbon pool was the dissolved organic carbon (DOC) with 413×10^3 kgC. The particulate organic carbon (POC) contributed to 22×10^3 kgC and the biota 272×10^3 kgC, where 53% was found in the phytobenthic community, 39% in the soft bottom and 8% in the pelagic community. Of the total biomass belonged 47% to the fauna (bacteria included) and 53% to the flora. The largest functional group was the macrophytes followed by the benthic macrofauna, microphytes, phytoplankton, benthic microfauna, fish, zooplankton, grazers, benthic meiofauna, bacterioplankton and the filter feeders which was the smallest group. The largest carbon pool in the area was though the dissolved inorganic carbon, which was more than two times larger then the total organic carbon pool. The relative distribution of carbon in the area is shown in figure 5-1 whereas the distribution of biomass, production, respiration, consumption between the functional groups can be found in figure 5-2, 5-3, 5-4 and 5-5.

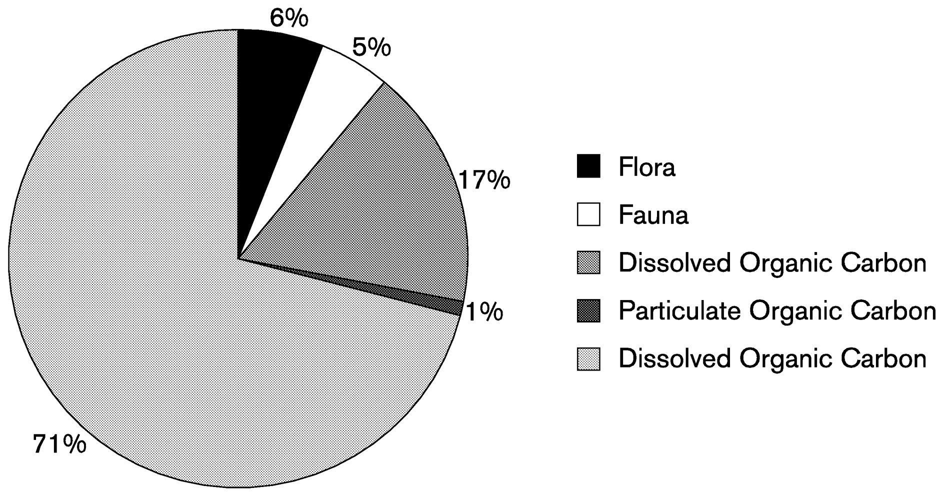


Figure 5-1. *Relative distribution (%) of carbon between Flora (including bacterioplankton), Fauna, DOC, POC and DIC in the study area; Öregrundsgrepen.*

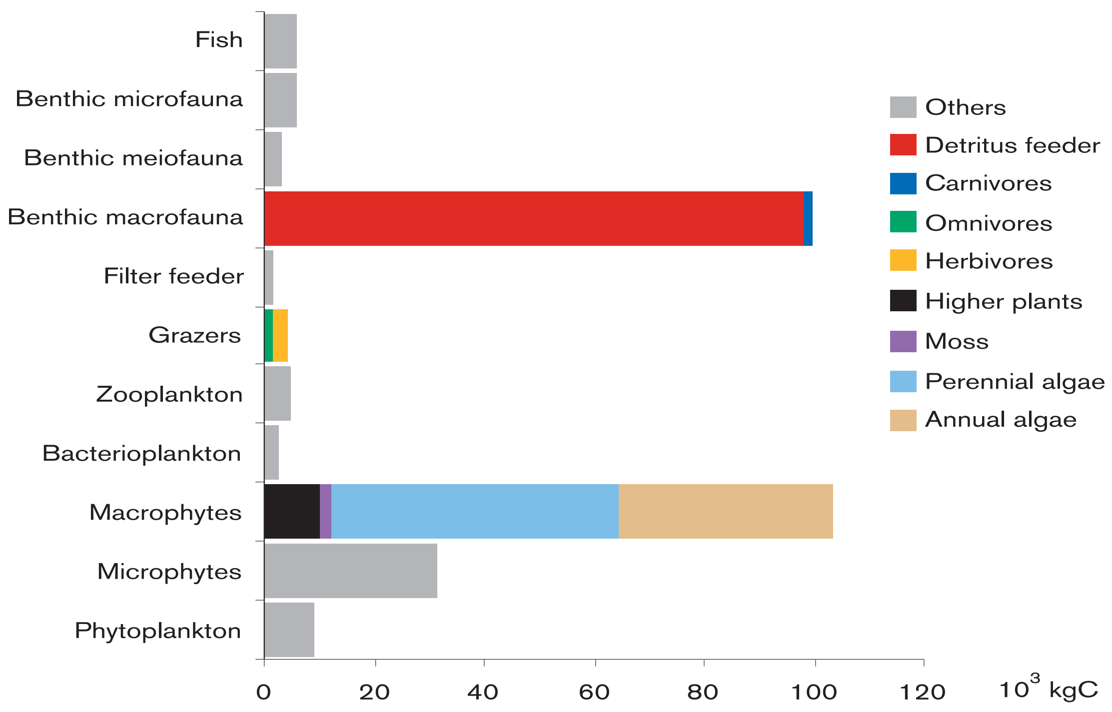


Figure 5-2. Distribution of biomass (10^3 kgC) in the study area; Öregrundsgrepen.

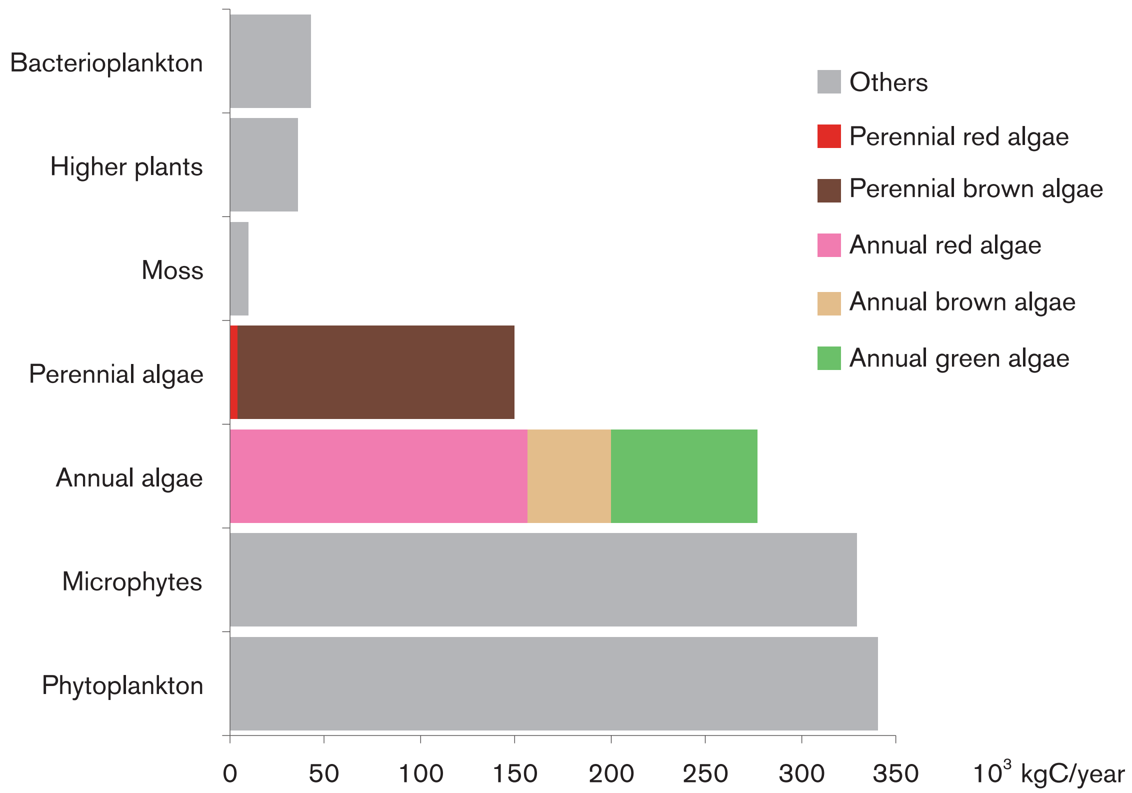


Figure 5-3. Distribution of primary production (10^3 kgC/year) in the study area; Öregrundsgrepen.

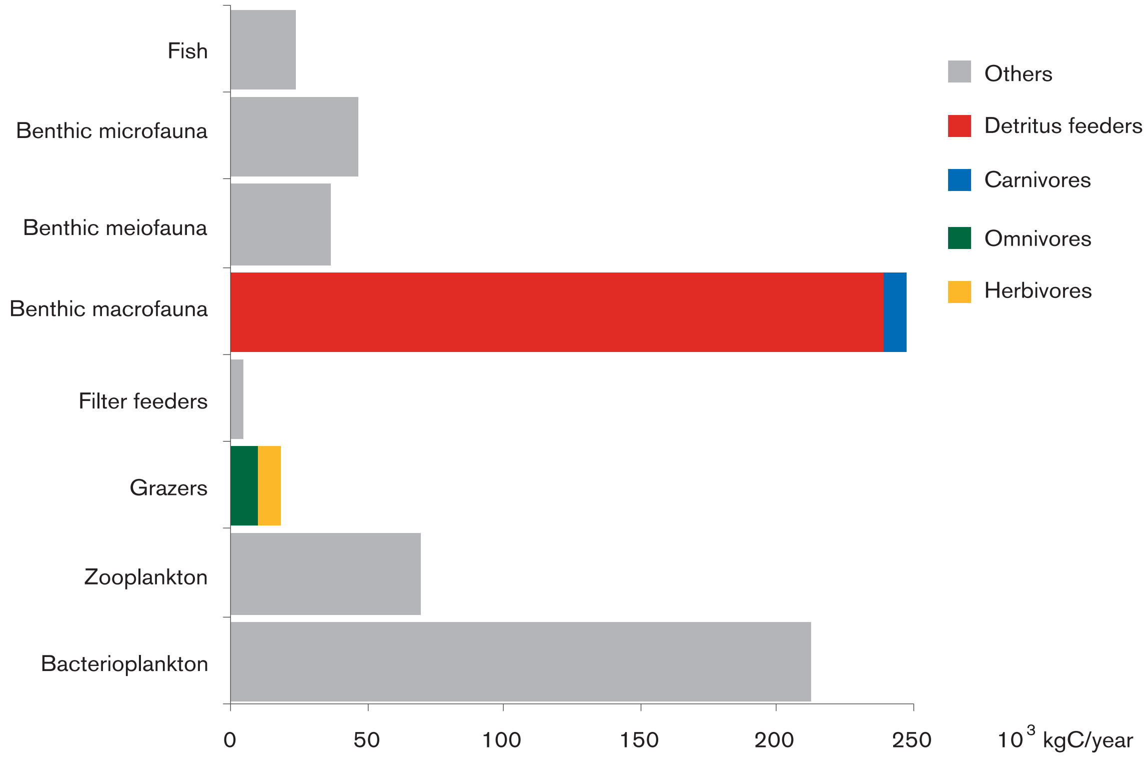


Figure 5-4. *Distribution of respiration (10^3 kgC/year) in the study area; Öregrundsgrepen.*

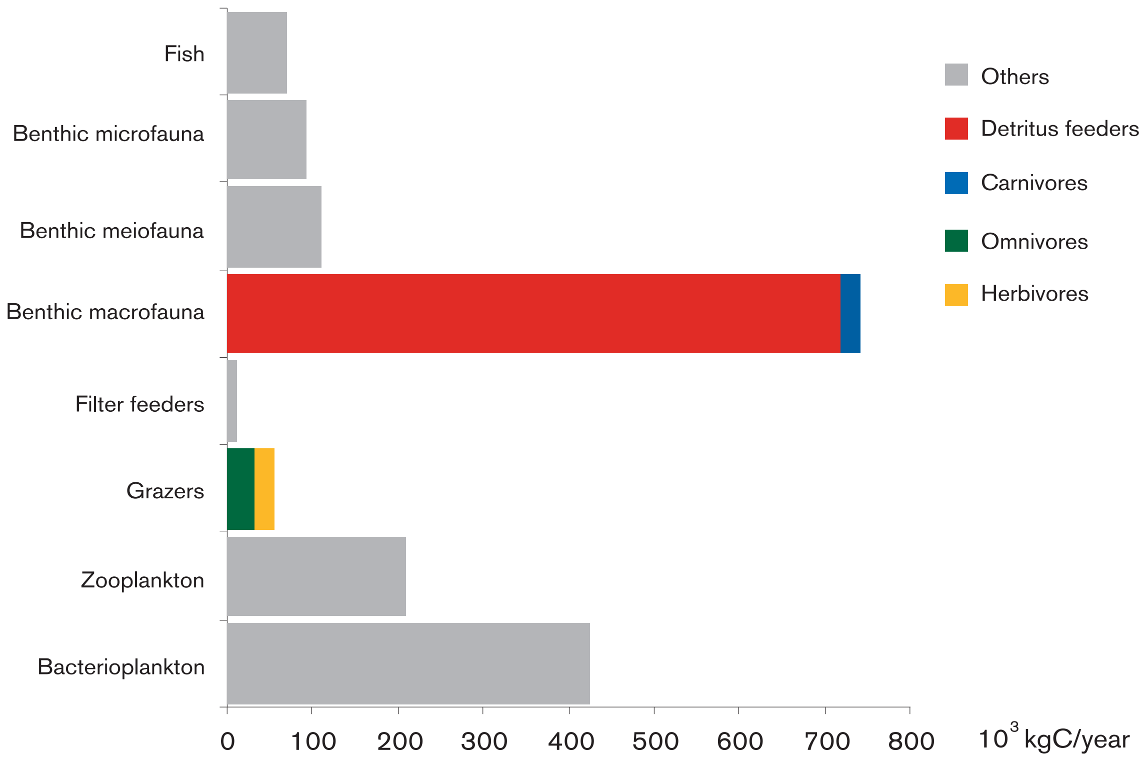


Figure 5-5. *Distribution of consumption (10^3 kgC/year) in the study area; Öregrundsgrepen.*

5.4 The food web and flow of carbon

The flow of carbon between the functional groups are shown in figure 5-6 which is based on data compiled in this study. This data are also shown in table 5-1. In the sections below, the different compartments in the ecosystem are described.

5.4.1 Dissolved Organic Carbon (DOC)

The largest pool of organic carbon in the ecosystem was DOC (413×10^3 kgC) and most of this carbon is in the Baltic Sea of allochtonous origin due to freshwater inputs (Kuparinen & Heinänen 1993). The annual carbon turnover of DOC in the area was approximately 100×10^6 kg carbon/year due to the water turnover of 1,5 day.

DOC mainly comes from zooplankton excretion and sloppy feeding together with extracellular products from phytoplankton metabolism (Vegter & de Vischer 1984). Bacterioplankton is the only organisms that can utilise DOC (Azam et al. 1983) and since the bacterial metabolism is dependent on DOC, their production rate is coupled to the rate of primary production and zooplankton metabolism (Vegter & de Vischer 1984). Most of the DOC found in the Baltic Sea consists however mainly of compounds that not very easily can be utilised by the bacteria (Bölter 1981).

5.4.2 Particulate Organic Carbon (POC)

The POC pool in the study area was determined to 22×10^3 kgC which is a number that only cover the nonliving fraction of the particulate organic carbon. (The living fraction constitutes of bacterio-, phyto- and zooplankton and is described in the next section.) The annual turnover of POC in the area is less than one tenth of the DOC-turnover.

A large contributor to this carbon fraction is the zooplankton sloppy feeding since their released organic carbon is equally divided between the DOC and POC pools (these figures are assumed to be representative for protozooplankton) (Caron et al. 1985).

5.4.3 Bacterio-, Phyto- and Zooplankton

Bacterioplankton biomass and production represent a significant part of the total planktonic biomass and production in the open Baltic Sea (Heinänen 1992a). In this study the bacterioplankton biomass was found to contribute to 18% of the total planktonic biomass, the phytoplankton to 53% and the zooplankton to 29%. The annual planktonic primary production, i.e. the sum of phytoplankton (72%) and bacterioplankton (28%), constituted to almost 40% of the total primary production in the area, eventhough these groups just make up 8% of the total primary producing biomass. In other surveys concerning the Baltic proper, the corresponding figure for the planktonic primary production was twice as high, which can be explained with the generally lower phosphorus concentration in the Bothnian Sea compared to the Baltic proper (Persson et al. 1993). Almost 41% of the planktonic primary production were grazed by zooplankton while the other phyto- and bacterioplankton consumers probably consume the rest. A comparison of phyto- and bacterioplankton primary production in this budget indicates that the bacterial primary production was almost 33% of the total planktonic primary production. In a similar comparison made by Larsson (1986) for coastal areas of the Baltic Sea the corresponding figures were 10 to 20%. In an investigation by Heinänen (1991) the bacteria accounted for 13% of the net primary production and the corresponding figure for this study was the same (12,6%).

Protozooplankton, which are the smallest zooplankton, are the main consumers of pelagic bacteria (Fenchel 1982) but the standing stock and growth rate of bacterioplankton in the Bothnian Sea seems to be controlled by available resources, such as inorganic nutrients and carbon, rather than by predators (Heinänen 1992b). Larger zooplankton are inefficient harvesters of such small particles as bacteria (Sherr & Sherr 1984) and mainly consume phytoplankton and smaller zooplankton. The main predators upon zooplankton are the filter feeders and fish where the former mainly filtrates the smaller fraction while the latter prefer the larger zooplankton.

5.4.4 Micro- and Macrophytes

Microphytes are an important food source for both meiofauna and certain macrofauna species. The dominating groups consuming benthic diatoms are gastropods, oligochaetes, gammarids and chironmids (Snoeijs & Mo 1987), which were defined as grazers in this study. The microphytes contributed to 25% of the total annual primary production and approximately 21% of the primary producing biomass. Corresponding values for the macrophytes were 36% and 71%. The biomass of the macrophytes was the largest (37%) among the functional groups in the area and the dominating groups within the macrophytes were algae (annual 37%, perennial 51%, moss 2% and higher plants 10%). As seen in figure 5-3 the annual algae are the main contributors to the annual primary production (59%) among the macrophytes.

5.4.5 Sediment and Benthic microfauna

The sediment represents a highly heterogeneous and complex environment, consisting of organic and inorganic particles, surrounded by interstitial water. The benthic microfauna (mainly bacteria) are attached to particle surfaces or are free floating in the interstitial water (Meyer-Reil 1986). Bacteria are basic components of the benthic food chain both since they are an important food source for the benthic fauna (Meyer-Reil 1986) and since microbial activities in the surface of the sediment can mobilise nutrients and drastically alter the chemistry of the water column (Bell et al. 1983). The bacterial biomass in the mud of the Bothnian Sea has been investigated by Mohammadi et al. (1993) which reports a biomass of approximately 1 gC/m^2. Based on Mohammadi et al's data the corresponding figure for the whole study area was 6×10^3 kg carbon. Their total respiration and consumption were comparably large compared to their biomass (figure 5-4 and 5-5).

5.4.6 Benthic meiofauna

The meiofauna, invertebrate animals smaller than 0,5 mm, lives in the surface layer of the sediment and are both detritus feeders and grazers upon microphytes. For instance are nematodes and harpacticoid copepods the most important grazers on diatoms (Admiraal et al. 1983). The role of the meiofauna in the system should not be underestimated. The relation between macro- and meiofauna in the Askö area were found to be 8:1 in dryweight and 2:1 in annual secondary production (Ankar & Elmgren 1978). In the Luleå archipelago Kautsky et al. (1981) found corresponding values of 4,5: 1 in dry weight and 1:1 in annual secondary production. The relations between the two groups in this budget were approximately 18:1 (gC) and 4:1 (gC).

5.4.7 Macrofauna

The macrofauna, invertebrates larger than 0,5 mm, were divided into grazers, filter feeders and benthic macrofauna.

The biomass of the grazers (herbivores and omnivores) was 4% of the total macrofauna biomass. They mainly feed on macrophytes but also on microphytes and their annual consumption were 56×10^3 kg carbon/year, which corresponded to 12% of the annual macrophytic primary production or 17% of the microphytic production.

The filter feeders, which have the smallest biomass in the area with only 2% of the macrofauna biomass, satisfy their carbon demand by filtering organic matter from the water, i.e. phytoplankton, bacterioplankton, small zooplankton and POC. The reasons to the small influence of this group on the total carbon flow probably rely on the low abundance of *Mytilus edulis* in the area.

The benthic macrofauna group consists of both carnivores and detritus feeders and is the second largest functional group in the area with 94% of the macrofauna biomass. The dominating species was *Macoma baltica*, which can act both as a filter feeder and a detritus feeder depending on the prevailing conditions. *M. baltica* was in this study defined as a detritus feeder and constituted approximately 96% of the biomass in this group. The rest were mainly made up of *Hydrobia* spp, *Corophium volutator* and *Mesidothea enthemon*.

5.4.8 Fish

The data for the fish group were obtained from a survey in the northern Baltic Proper by Jansson et al. (1985). According to these data the fish have a relatively small impact on the total carbon flow. There are many investigations on fish done in Öregrundsgrepen by the Institute of coastal research in Öregrund but their data were difficult to access due to the measurement methods. The biomasses were mostly presented in form of numbers per catch or share of different species per catch that made recalculations to biomass expressed in gC/m^2 questionable.

Ankar (1977) presents data from the Askö-Landsort area which corresponded to 2×10^3 kgC for the whole study area which was in the same magnitude (6×10^3 kgC) as the data from the study by Jansson et al 1985. The reason to use the figures from Jansson et al was that their data were based on a diving survey, which included both large and small fishes (33 different species). The biomass of fish in Ankar's report were most likely underestimated due to inaccurate fishing methods used by Aneer and Westin (1977), according to Ankar himself.

Table 5-1. Biomass, primary production, respiration, consumption, secondary and faecal production for the functional groups and in the three different communities together with the distribution of nonliving carbon in the coastal ecosystem in the study area; Öregrundsgrepen

Functional group/ Community	Biomass (10^3 kgC)	Prim. prod. (10^3 kgC/ year)	Respiration (10^3 kgC/ year)	Consumption (10^3 kgC/year)	Secondary (10^3 kgC/ year)	Source and Location
Phytoplankton	9	504 I, II	–	–	–	1 & 4
Macrophytes	103	473 II	–	–	–	2
Microphytes	31	329 II	–	–	–	3
Bacterioplankton	3	III	213	426	213	4
Zooplankton	5	–	70	209	139	5
Grazers	4	–	19	56	37	2
Filter feeders	2	–	4	13	9	2
Benthic macro-fauna	100	–	247	741	494	2
Benthic meiofauna	3	–	37	111	74	6
Benthic microfauna	6	–	46	93	47	7
Fish	6	–	23	70	47	8
Total	272	1,306	659	1,719	1,060	–
Phytobenthic community	142	802	44	109	65	2, 3, 6, 7
Benthic community	107	–	309	905	596	2, 6, 7
Pelagic community	23	504	306	705	399	1, 4, 5, 8
Total	272	1,306	659	1,719	1,060	–
Form of nonliving carbon			10^3 kgC	Carbon turnover	10^6 kgC/ year	–
Annual sedimentation			728	–	–	9
Dissolved Organic Carbon (DOC)			413	DOC	100	9
Particulate Organic Carbon (POC)			22	POC	5	10
Dissolved Inorganic Carbon (DIC)			1,777	PIC	430	11

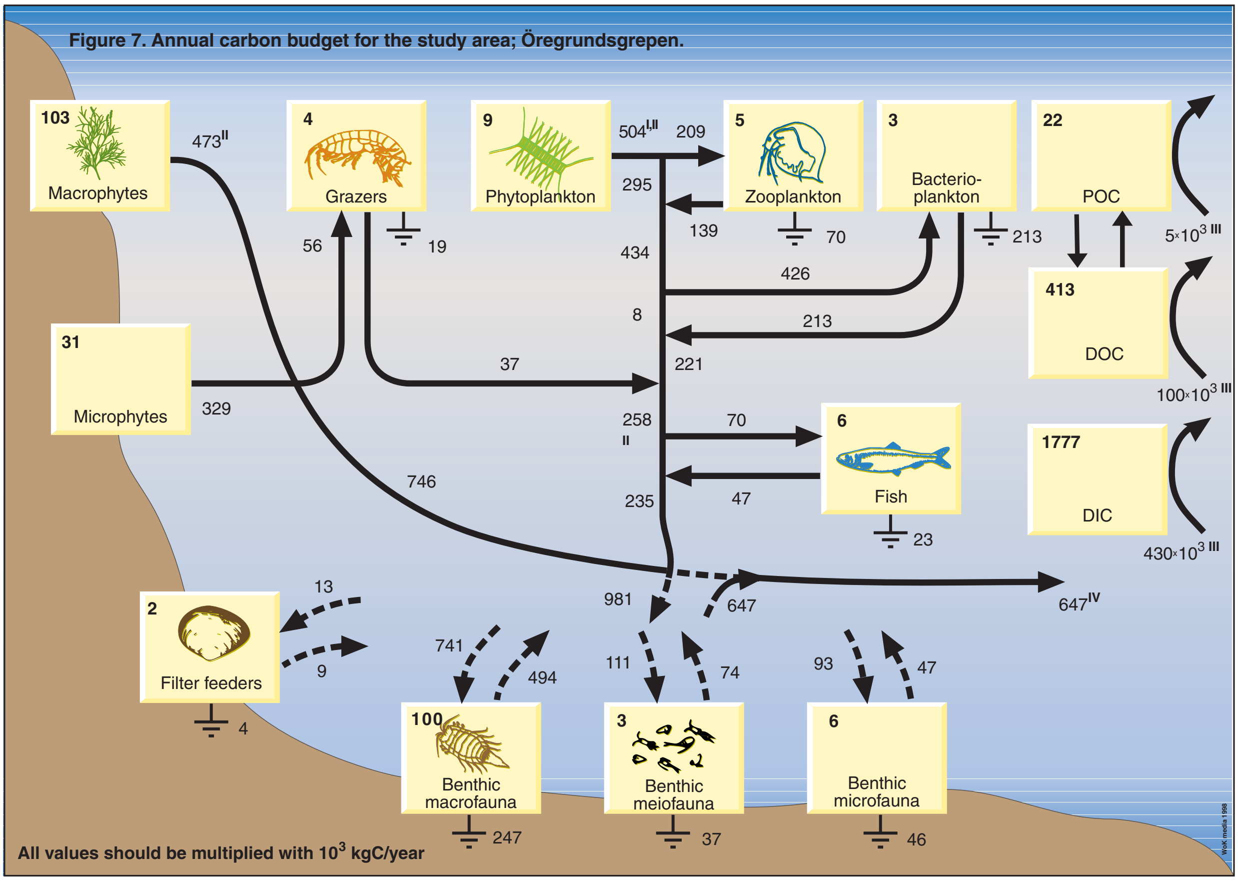
I) Includes all planktonic primary production

II) Netproduction (Grossproduction-Respiration)

III) A bacterioplankton production of 164 is included in the phytoplankton primary production

Sources:

1. Lindahl & Wallström 1980; Öregrundsgrepen
2. Kautsky et al. 1999a; Öregrundsgrepen
3. Snoeijs 1985 & 1986; Forsmark
4. Kuparinen 1987; Tvärminne
5. Eriksson et al. 1977; Öregrundgrepen
6. Ankar 1977; Askö-Landsort
7. Mohammadi et al. 1993; Bothnian Sea
8. Jansson et al. 1985; Northern Baltic Sea
9. Zweifel et al. 1995; Bothnian Sea
10. Nitchals 1985; Öregrundsgrepen
11. Larsson 1999 (pers. com); Baltic Sea



I) Includes all planktonic primary production – (Bacterioplankton 33% and Phytoplankton 67%)

II) Netproduction (grossproduction-respiration)

III) Annual POC- and DOC-turnover

IV) Amount of carbon exported from the area

Figure 5-6. *Annual carbon budget for the study area; Öregrundsgrepen.*

6 Discussion

This compilation of distribution and flow of carbon describes the ecosystem structure and function in the area above SFR. The budget envince that the organisms in the area are self-sufficient on carbon i.e. the primary production exceed the consumption of biomass, which lead to a net export of carbon, corresponding to 50% of the annual primary production. The amount of exported produced carbon (674×10^3 kg carbon/year) is however almost neglectable compared to the DOC- and POC-turnover (almost 300×10^3 kg carbon/day).

The results from the budget also indicates that the coastal ecosystem may act as a filter in the land sea interface by e.g. processing and storage of carbon in the tissues of relatively long-lived components of the phytobenthic and soft bottom communities. This will most likely also apply for many contaminants, such as radionuclides.

One of the most significant carbon flows is the sedimentation (or export) from the phyto-benthic community (mainly in form of exceeding benthic primary production) to the soft bottom community and further away from the area. Since the grazers consume only approximately 7% of this fraction of primary production, would probably a great deal of a potential release of radionuclides from the repository (that are bioavailable and possible to incorporate in primary production, e.g. $^{14}CO_2$), be exported from the area or temporarily be stored in long-lived macroalgae.

Another important flow of carbon is the sedimentation from the pelagic community, which correspond to approximately 64% of the planktonic primary production. But, due to the relatively large water exchange (1,5 days) would $^{14}CO_2$, fixed by planktonic primary producers, rather quick be transported from the area and dilute in Öregrunds-grepen and the Bothnian Sea.

The major functional organisms groups in the area are the macrophytes (37% of the biomass), the benthic macrofauna (36%) and the microphytes (11%). The largest organic carbon source is though the DOC-pool, which is approximately one and a half time larger than the total biomass. In the studied area more than half of the total biomass are found in the phytobenthic community, 39% in the soft bottom and 8% in the pelagic community (DOC and POC are not included). The biomass is close to equally divided between the fauna and the flora where the flora is mainly found in the phytobenthic community and the main part of the animals in the soft bottom community. The phytobenthic community contribute to the larger share (61%) of the primary production whereas the larger part of the consumption is taken part in the soft bottom community (53%).

Comparisons with other carbon budgets (from the Askö area) show both similarities and differences. In a budget for the benthic ecosystem by Ankar & 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 show large similarities in estimations of macrophytic, microphytic, grazers as well as filter feeder biomasses. However, when comparing the pelagic community with plankton system budgets (Mc Kellar & Hobro 1976; Larsson et al 1986;), this budget has consequent lower numbers, which partly can be explained with seasonal variations since the other two budgets describes the plankton community during the spring bloom and this an annual mean. Jansson & Wulff (1977b) present an ecosystem analyses of a shallow sound in the Askö region that describes energy storages and flows that are in the same range as this study.

Data in this report should be seen as approximate and should primarily be applied for this large scale view of the ecosystem since fluctuations and variability in biological systems are common and necessary estimations, assumptions and simplifications have been made which most likely affect the specific interactions and processes.

A weakness of the budget is the simplifications made in food web structure, especially in the soft bottom community, which have lead to a somewhat coarse disintegration of the carbon flow. There are unfortunately rather large uncertainties in the quantification and configuration of the planktonic community (bacterio-, phyto- and zooplankton) in the budget, which may have resulted in an underestimation of their role in the ecosystem. The framework of the budget is however adequate, based on data from studies made in the area and with a good (species) resolution. This reasonable rigid framework likely lead to that small differences (or bad estimations and errors) in the input data would not obscure or cause any big differences in the main carbon flows.

The carbon budget may be used to explore implications of possible future changes in the ecosystem. For example, in the area of interest in this study, it is important to evaluate the consequences of changes in salinity, temperature, landrise and species composition. The study makes the basis for a dynamic carbon-14 flow model (using the software Stella) as well as a carbon-14 budget for the study area (Kautsky et al. 1999b). The Stella-model will be used as a base for the construction of a dynamic carbon-14 flow model and, if possible, for other radionuclides as well.

7 Acknowledgement

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