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Oskarshamn and Forsmark site investigations

^{210}Pb and ^{14}C dating of sediments and peat

Accumulation rates of carbon, nitrogen and phosphorus

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WSP Environmental

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Abstract

This investigation aims at determining mass accumulation rates of organic carbon, nitrogen and phosphorus in sediments from five coastal sites and one lake, and in peat from two bogs. The sites are located in the Forsmark and Oskarshamn areas. Recent accumulation rates were determined using ^{210}Pb, and long-term rates by using ^{14}C AMS (accelerator mass spectrometry) datings.

Large portions of the bays in Forsmark are dominated by erosion or transportation bottoms. It is important to point out that the accumulation rates presented for those two sites are valid only in limited parts of these bays.

During the 20th century, accumulation rates of both dry mass and organic carbon increased over time, and are generally higher than the long term rates. The recent and historic accumulation rates of dry mass were, however, identical at two coastal sites in Oskarshamn. At the coastal sites, the long-term accumulation rates of organic carbon are higher in Oskarshamn (74–95 g C m^{-2} yr^{-1}) than in Forsmark (14 g C m^{-2} yr^{-1}). This probably reflects the local environment (e.g. hydrologic residence times). The long term nutrient accumulation rates in the two bogs were similar.

Sammanfattning

Denna undersökning syftar till att bestämma massackumulationshastigheter för organiskt kol, kväve och fosfor i sediment från fem kustlokaler och en sjö, samt i torv från två högmossar. Studieområdena är belägna kring Forsmark och Oskarshamn. Ackumulationshastigheter under 1900-talet bestämdes med ^{210}Pb, och i tusenårsperspektiv med ^{14}C AMS dateringar.

Bottnarna utanför Forsmark kan till stora delar karakteriseras som transport- eller erosionsbottnar. Det måste därför betonas att de massackumulationshastigheter som presenteras för dessa två lokaler endast är representativa för delar av dessa områden.

Undersökningen visar att ackumulationen av både sediment och organiskt kol ökat under 1900-talet, och generellt överstiger det långsiktiga medelvärdet. De moderna och de långsiktiga massackumulationshastigheterna var dock närmast identiska vid två kustlokaler utanför Oskarshamn. I kustområden är den långsiktiga kolinlagringen högre i Oskarshamn (74–95 g C m^{-2} $år^{-1}$) än i Forsmark (14 g C m^{-2} $år^{-1}$). Detta återspeglar troligen den lokala sedimentationsmiljön. Den långsiktiga inlagringen av näringsämnen var likartad i de två mossarna.

Contents

1 Introduction

This document reports the data and interpretations gained by the ^{210}Pb and ^{14}C dating of sediments and peat, which is one of the activities performed within the site investigations at Forsmark and Oskarshamn. The work was carried out in accordance with activity plans AP PS 400-06-005 and AP PF 400-06-010. In Table 1-1 controlling documents for performing this activity are listed. Activity plans are SKB's internal controlling documents.

The investigations follow the SKB activity plans, and consist of the following moments:

- Sampling and sectioning of sediment and peat cores.
- Radiological and chemical analyses.
- Calculation of mass accumulation rates.
- Interpretation and quality assessments.
- Reporting data to the SICADA database.

The sampling was performed in May and June 2006. The data are intended to be used as indata to models on nutrient fluxes in the local ecosystems.

Table 1-1. Controlling documents for the performance of the activity.

Activity plan	Number	Version
Datering av sediment i våtmark, sjö och fjärd.	AP PS 400-06-005	1.0
Bestämning av sedimentations-hastigheter i våtmark och hav.	AP PF 400-06-010	1.0

2 Objective and scope

The objective of this study was to determine recent and historic mass accumulation rates in two bogs, in one lake and at five coastal sites, located in the Forsmark and Oskarshamn areas. Accumulation rates were calculated for dry mass, organic carbon, nitrogen and phosphorus, and were based on radiologic measurements of ^{210}Pb, ^{137}Cs, ^{226}Ra and ^{14}C, as well as on chemical measurements of organic carbon, total nitrogen and phosphorus. The project also included sampling of sediments, mainly in the 0–0.5 m depth but, at one site, deeper sections were also sampled.

3 Study sites

The sediments and peats were collected within SKB's site investigation areas at Forsmark and Oskarshamn. The sampling sites are shown on the maps in Figure 3-1 and Figure 3-2. Additional information for each sampling site is compiled in Table 3-1.

At Forsmark the sediment cores were sampled in Bay Tixelfjärden and Bay Kallrigafjärden while the peat core from the peatland at Rönningarna had been collected in an earlier activity (AP PF 400-05-134).

In Tixelfjärden and Kallrigafjärden it was not very easy to find the kind of soft sediment (gyttja) that allows sampling with a gravity corer. Large portions of these bays are thus dominated by erosion or transportation bottoms and it is important to point out that the accumulation rates presented in this report are valid in limited parts of these bays only. The Quaternary deposits on the bottoms of Tixelfjärden and Kallrigafjärden have been mapped by /Ising 2005/. In Tixelfjärden the water depth at the sampling station was 5.2 m, which is approximately the greatest depth in this part of the bay. The water depth at the sampling station in Kallrigafjärden was 2.0 m. The deepest part of greater Kallrigafjärden is at least 8 m.

Figure 3-1. Sampling sites in the Forsmark area.

Figure 3-2. *Sampling sites in the Oskarshamn area.*

Table 3-1. Position of the sediment and peat cores, water depth and overview of the analyses. Note: a (core samples in this project); b (core sampled by others).

Site	Core ID code	X	Y	Water depth, m	Note	Analyses[1)] 0–0.5 m	Analyses > 0.5 m
Forsmark							
Tixelfjärden	PFM005785	6699092	1634743	5.2	a	^{210}Pb	
	PFM005791	6699092	1634743	5.2	a	C, N, P	
	PFM005863	6699092	1634743	5.2	a	Archive	
Kallrigafjärden	PFM005784	6696984	1636327	2.0	a	^{210}Pb	
	PFM005792	6696984	1636327	2.0	a	C, N, P	
	PFM005793	6696984	1636327	2.0	a		^{14}C, C, N, P
	PFM005862	6696984	1636327	2.0	a	Archive	
Rönningarna	PFM006025	6698004	1630428	–	b	^{210}Pb, C, N, P	^{14}C, C, N, P
Oskarshamn							
Granholmsfjärden	PSM007734	6368874	1549876	5.2	a	^{210}Pb	
	PSM007740	6368874	1549876	5.2	a	C, N, P	
Norrefjärd	PSM007733	6368018	1550341	2.1	a	^{210}Pb	
	PSM007739	6368018	1550341	2.1	a	C, N, P	
	PSM007743	6366018	1550341	2.1	a	Archive	
Borholmsfjärden	PSM007735	6367079	1551441	5.4	a	^{210}Pb	
	PSM007741	6367079	1551441	5.4	a	C, N, P	
	PSM006589	6367240	1551761	3.8	b		^{14}C, C, N, P
	PSM007744	6367079	1551441	5.4	a	Archive	
Frisksjön	PSM007736	6368166	1549284	2.9	a	^{210}Pb	
	PSM007742	6368166	1549284	2.9	a	C, N, P	
	PSM006571	6368223	1549474	2.7	b		^{14}C, C, N, P
	PSM007745	6368166	1549284	2.9	a	Archive	
Klarebäcksmossen	PSM007732	6370201	1543002	–	b	^{210}Pb, C, N, P	^{14}C, C, N, P

[1)] Samples analysed for ^{210}Pb were also analysed for ^{137}Cs, ^{226}Ra and ^{241}Am.

At Oskarshamn the sediment cores were collected in Bay Granholmsfjärden, Bay Norrefjärd, Bay Borholmsfjärden and Lake Frisksjön. The peat core was collected in the bog at Klarebäcksmossen.

In Granholmsfjärden, the sampling station was located at a water depth of 5.2 m. However, the deepest part of this bay is around 18 m. In Norrefjärd, Borholmsfjärden and Frisksjön the sampling stations were located at maximum depth. It should also be mentioned that the locations of the sampling stations in Borholmsfjärden and Frisksjön are not identical to the locations where the deeper sediment cores were sampled by other workers in earlier studies.

4 Execution

4.1 General

The investigations follow the SKB activity plans AP PS 400-06-005 and AP PF 400-06-010, and consists of the following moments:

- Sampling of surface sediments at five coastal sites and one lake
- Sampling of deep sediments at Kallrigafjärden and Tixelfjärden, Forsmark.
- Core sectioning into samples suitable for analysis. Sectioning was also performed on some sediment and peat cores that were previously collected by SKB.
- Radiological measurements of ^{210}Pb, ^{137}Cs, ^{226}Ra and ^{241}Am in 14 samples per core.
- AMS ^{14}C dating on three samples per site (two samples at Kallrigafjärden).
- Chemical measurements of organic carbon, total nitrogen and phosphorus, at four depths per site.
- Calculation of age-depth models using ^{210}Pb and ^{14}C.
- Calculation of mass accumulation rates.

4.2 Field sampling

The shallow sediment cores (0–50 cm) sampled in this study were sampled using an HTH sampler (modified Kajak Corer). Using this sampler, the sediment core is collected in a polycarbonate tube with an inner diameter of 86 mm (see Figure 4-1). Generally, the top 20 cm of the cores were then sliced in 1 cm intervals. Below 20 cm the cores were sliced every 2 cm.

Figure 4-1. *Sediment cores sampled with the HTH corer (left) and the russian corer (right).*

At each station, one core was sampled for ^{210}Pb dating and one core was sampled for analysis of C, N and P. In addition, at each station one core was collected for archive use. The archive core was sliced in 2 cm sections.

At Kallrigafjärden, Forsmark, a deeper sediment core was collected using a russian corer (Figure 4-1). The intention was to collect a deep sediment core at Tixelfjärden as well. However, due to hard winds and a relatively great water depth, this was not possible on that sampling occassion.

At Bay Borholmsfjärden and Lake Frisksjön, Oskarshamn, deeper sediment cores were previously collected by other workers. These sediment cores were stored in a freezer and in this study they were sliced using a saw. The sediment samples were stored in labelled plastic bags in a freezer before analysis.

The peat had been collected earlier by other workers and stored in a freezer. In this study, the peat cores were sliced using the same saw as was used for slicing the frozen sediment cores (Figure 4-2). The peat core from Klarebäcksmossen, Oskarshamn, was 100 mm in diameter, which allowed us to slice the core in 1 cm sections within the uppermost 10 cm and in 2 cm sections below 10 cm. The peat core from Rönningarna in Forsmark had a smaller diameter and consequently the slices yielded smaller samples. The peat samples were stored in labelled plastic bags in a freezer before analysis.

4.3 Chemical and radiologic analysis

Measurements for ^{210}Pb dating were performed using gamma spectrometers at Risø National Laboratory, Denmark. Quality assurance of the analytical results is achieved through regular participation in international intercomparison exercises and proficiency tests which demonstrate that the analytical accuracy is better than 10%. The analysed nuclides were ^{210}Pb, ^{60}Co, ^{137}Cs, ^{226}Ra, and ^{241}Am. ^{14}C was analysed on bulk samples with AMS (accelerator mass spectrometry) at the Lund University, Sweden.

Organic carbon, nitrogen, phosphorus and loss on ignition were analysed by Analytica AB. Phosphorus was analysed by ICP-AES following digestion in $HNO_3 + H_2O_2$. Organic carbon was analysed according to SS-EN 13137 and loss on ignition according to SS 028113-1. Nitrogen was analysed by a LECO-method. Analytical uncertainty for C, N and P are 10%, 5% and 16%, respectively, as relative standard deviation.

***Figure 4-2**. Slicing the peat core at Forsmark (left) and at Oskarshamn (right).*

4.4 Data handling and interpretations

4.4.1 Dry density

In sediments, the dry density (gram of dry mass per cm^3 of wet sediment) was calculated on the basis of the water content and assuming a dry mass density of 2.5 g cm^{-3}:

$$\rho_d = \frac{TS}{\frac{TS}{\rho_s} + \frac{(1-TS)}{\rho_w}} \qquad 4.1$$

where ρ_d is mass of dry sediment per unit volume of wet sediment, TS is fraction of dry matter, ρ_s is density of sediment particles (clay and organic matter), ρ_w is density of water.

For peat samples, porosity was due to both water and air why this method could not be applied. Instead, the weighed dry mass was divided by the calculated original volume of each sample. The volume was calculated from the sample thickness and the diameter of the corer.

$$\rho_d = \frac{m \cdot TS}{V} \qquad 4.2$$

where m is mass of wet peat and V is the volume of peat slice.

4.4.2 ^{210}Pb data

Recent mass accumulation rates in sediments and peat cores were calculated using excess ^{210}Pb data. ^{210}Pb is a naturally occurring radioisotope with a decay constant of 0.03114 yrs^{-1}. There are two major sources of ^{210}Pb in sediments and peat, why two fractions are commonly considered:

- Supported ^{210}Pb which is formed in situ by decay of ^{226}Ra.
- Excess ^{210}Pb which is formed by decay of ^{222}Rn in the atmosphere.

In the uppermost sections, excess ^{210}Pb generally constitutes the major fraction of ^{210}Pb. Because excess ^{210}Pb is introduced at the sediment surface, but is not formed within the sediments, its activity will decay with a half-life of 22.26 years. The activity of supported lead generally shows less vertical variations, and can be estimated from measurements of ^{226}Ra assuming secular equilibrium. Thus, the activity of excess ^{210}Pb was estimated by substracting the activity of ^{226}Ra from total activity of ^{210}Pb.

There are two major theoretical models used to calculate mass accumulation rates from excess ^{210}Pb data:

1. CIC: the constant initial concentration model, where it is assumed that the mass accumulation rate is constant over time, and
2. CRS: the constant rate of supply model, where it is assumed that the flux of excess ^{210}Pb is constant over time.

The CRS method does not require constant mass accumulation rates, but actually allows for estimating the variation in sedimentation rate over time. Because such variations can commonly be assumed to occur, it is usually the preferred method /e.g. Appleby and Oldfield 1983/ and is the method employed here. It is important to recall that due to various disturbances, accumulation rates cannot always be determined using ^{210}Pb. The CRS method is briefly outlined below. In this section, all mentioning of ^{210}Pb refers to the excess fraction. The CRS method requires that the total inventory of ^{210}Pb activity can be calculated:

$$A(0) = \int_0^{\infty} C_w dz \; , \qquad 4.3$$

where A(0) is the depth integrated activity [mBq cm^{-2}], C_w is the activity per volume of wet sediment [mBq cm^{-3}], and z is the sediment depth. Continuous curves of C_w versus z were obtained by separate curve fitting of the activity per dry mass (C_d) and the dry density. In practice, it is usually sufficient to integrate between 0 and 25–45 cm. A(0) is also a measure of the depositional flux of ^{210}Pb from the atmosphere, and should in theory be roughly equal at different sites. Because of sediment focusing and input from the watershed, A(0) may nevertheless differ somewhat betwen different sites. The age *t* of a certain level *z* in the sediment is calculated as

$$t_z = 32.1 \cdot \ln\left(\frac{A(0)}{A(z)}\right), \qquad 4.4$$

where A(z) is the cumulative activity below the depth *z*. The year is then calculated as 2006–t, assuming that the sediment surface represents 2006. The mass accumulation rate MAR [g m^{-2} yr^{-1}] is calculated as

$$MAR = 32.1 \cdot \frac{A(z)}{C_d} \qquad 4.5$$

A disadvantage of the CRS model is that the activities at the base of the core generally are very uncertain. Therefore, ages and MAR at the deeper sections of a core are also very uncertain /e.g. Turner and Delorme 1995/. We have therefore chosen not to calculate ages and MARs below certain depths, although analytical data exist.

The age-depth models can in several cases be verified using ^{137}Cs as a stratigraphic marker for 1963 and 1986, when the activities peaked. At a few sites, ^{241}Am could also be detected. ^{241}Am is a stratigraphic marker for 1963 and is probably less affected than ^{137}Cs by postdepositional processes /Appleby et al. 1991/. A further check on the results can be obtained by comparing the A(0) values at different sites with what could be expected from atmospheric deposition.

4.4.3 ^{14}C data

Marine organic carbon is formed from dissolved inorganic carbon that has a ^{14}C age relative to atmospheric CO_2, why marine organic carbon commonly has a reservoir age of several hundred years. This age varies regionally due to, among other things, ocean circulation patterns. Furthermore, the organic carbon in sediments may be a mixture of both autochtonous and allochtonous origin. The allochtonous part may be of larger importance in coastal sites and lakes with large drainage areas, and where the sediment derives from erosion of more shallow bottoms. This means that the sedimentary carbon may have a certain age before deposition, and this contributes to the local reservoir age.

Several studies have attempted to derive reservoir ages for different sites in the Baltic Sea as well as for certain lakes. Reservoir ages in the range 0–1,000 years have been estimated /Hedenström and Possnert 2001, Hedenström and Risberg 2003, Risberg et al. 2005/. Obviously it is difficult to assess appropriate reservoir ages to a certain site, unless this aspect is specifically addressed e.g. by dating of macrofossils. In this study, macrofossil dating was not possible. Furthermore, the purpose with this study was not to establish detailed stratigraphical descriptions. We therefore chose to neglect correction for reservoir ages in the sediments. Bogs lack a pronounced reservoir effect. They may, however, be exposed to contamination from younger material e.g. by penetrating roots from younger layers.

The reported ^{14}C ages were converted to calendar ages BP by the use of the program CALIB 5.0 /Stuiver et al. 2005/ and are reported with one sigma range. Although the manual to CALIB recommends to publish calendar ages BP as a range rather than a single age, we use the median age for calculation of mass accumulation rates. This procedure will not affect our results, but could possibly be of relevance if detailed stratigraphical interpretations were to be made.

Long term mass accumulation rates were estimated from ^{14}C ages. For all but one station (see Section 4.4.6), three individual ^{14}C ages at different depths were determined. Because this project did not include stratigraphic investigations (pollen etc), it was not possible to validate the ^{14}C ages by independent methods. We therefore chose to calculate the long term mass accumulation rates as the slope of all ages versus cumulative mass (g/cm^2), in order to avoid presentation of variable accumulation rates that would be much more uncertain. For the peat samples, we also included the peat core surface with a cumulative mass of zero and an estimated age of –56 yr BP. For the sediments, we did not include the surface in this regression because the reservoir ages of the sediments were unknown and other studies have shown that the sediment surface may have a substantial age due to recent erosion /Risberg 2005/. For the samples where ^{14}C dating was performed, the reservoir ages tend to cancel when the slope is calculated, and can thus be neglected.

In two cases, there were apparent discontinuities in the stratigraphy and the lowermost ^{14}C ages were excluded (Klarebäcksmossen and Kallrigafjärden).

4.4.4 Accumulation rates of C, N and P

The accumulation rates of organic carbon, nitrogen and phosphorus were calculated at different levels. The uppermost levels in both sediments and peat contain labile organic matter that is progressively degraded during burial. In peat, this process may be of importance in the upper c 0.5 metre /Malmer and Wallén 2004, Beleya and Malmer 2004/. Therefore, accumulation rates in the upper sections may not represent net accumulation. The focus of this investigation is to estimate net accumulation of C, N and P, rather than to quantify the processes of accumulation and decay.

Accumulation rates were calculated as the product of C, N or P concentrations (on dry weight basis) and the dry mass accumulation rate (MAR). At Kallrigafjärden, Tixelfjärden, Norrefjärd and Granholmsfjärden, accumulation rates were calculated at three to four different depths in the upper c 40 cm, using the MARs at those levels.

At those sites where both ^{210}Pb and ^{14}C datings were performed (Kallrigafjärden, Rönningarna, Frisksjön, Borholmsfjärden and Klarebäcksmossen), accumulation rates were calculated for the base of the upper sections and as long-term averages. The long-term averages were calculated as the product of the long-term average MAR (from^{14}C) and the average concentrations of C, N or P.

4.4.5 Uncertainties

For accumulation rates based on ^{14}C, the standard error of the slope (age vs. cumulative mass) was used as a measure of the uncertainty. This error was generally larger than the uncertainty of the individual ^{14}C ages.

For the mass accumulation rate based on ^{210}Pb, the uncertainties were estimated by error propagation from the analytical uncertainty of individual ^{210}Pb activities and the dry bulk density. The uncertainty of dry bulk density was assumed to depend on the determination of dry weight, for which the laboratory gave a RSD of 2%. Conservatively, we set this value at 5%. Thus the uncertainty of MAR is:

$$\sigma_{MAR} = MAR \times \sqrt{\sum \left(\frac{\sigma_x}{x} \right)^2} , \qquad 4.6$$

where σ_x and X represent uncertainty and value of ^{210}Pb activity and dry weight.

Uncertainties of nutrient mass fluxes were estimated by error propagation following the same procedure, but adding the analytical uncertainty of C, N and P concentrations. For the long-term nutrient fluxes, the uncertainty of the nutrient concentrations was represented by the relative standard deviation of the three or four samples analysed per site, because this value was always larger than the analytical uncertainty of individual samples.

4.4.6 Nonconformities

The activity plan PF 400-06-010 was followed with a few deviations:

1. Recent accumulation rates in the peat core from Rönningarna (PFM006025) could not be established, because the section 0–0.1 m was lacking.
2. A deeper core for ^{14}C dating could not be sampled in Tixelfjärden, due to the strong winds prevailing at the sampling occassion.
3. In Kallrigafjärden, ^{14}C datings were only performed on two samples because the sediment above the clay was only c 70 cm deep.
4. Due to the smaller diameter of the peat core at Rönningarna, the amount in each sample was not sufficient for analysing organic carbon. The concentration of organic carbon was therefore calculated from loss on ignition (LOI), using the strong relationship between LOI and organic carbon in the peat core from Klarebäcksmossen.

The activity plan PS 400-06-005 was followed with one deviation:

1. The samples for analysis of C, N and P in Granholmsfjärden were lost. New samples were taken from the archived core (PSM007740) in November 2006.

5 Results and discussion

The results that are presented in this report are stored in the SICADA data base, and are traceable by the Activity Plan number (AP PS 400-06-005 and AP PF 400-06-010).

5.1 Density and stratigraphy

The densities of the sediment and peat samples were calculated according to equation 4.1 and 4.2, respectively. The dry bulk dry densities are shown in Figure 5-1.

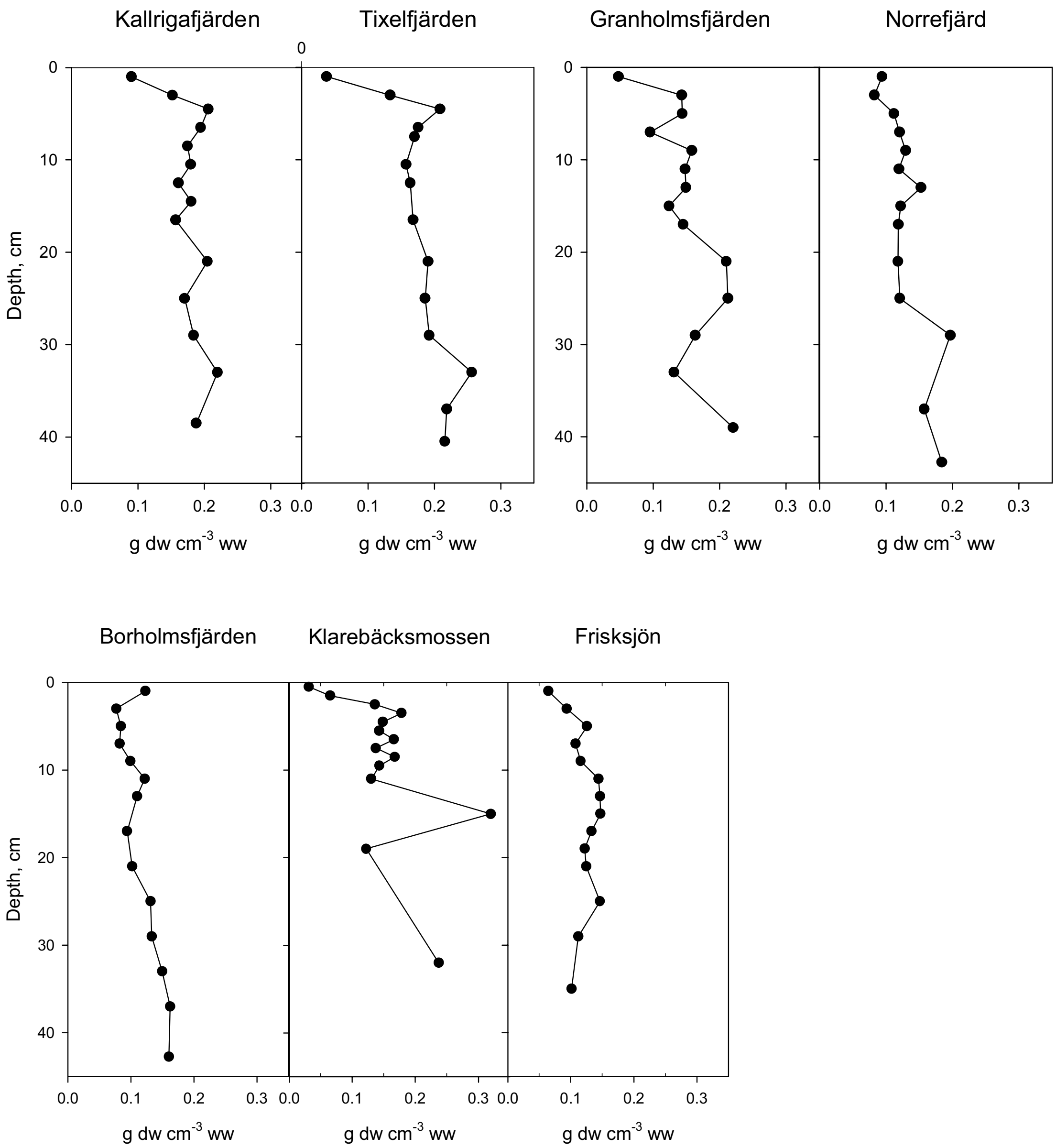

Figure 5-1. Dry bulk densities. Because the peat core from Rönningarna was not complete, dry bulk densities are not shown.

Below a short description of each core follows. The descriptions are intended to highlight some main stratigraphical characteristics rather than to constitute a comprehensive stratigraphical record.

Tixelfjärden, Forsmark

- PFM005785: Length 44 cm. Well oxidized 0–4 cm, gradual transition to reducing conditions 4–10 cm, reduced below 10 cm. Hair-like plant remains around 40 cm. Used for ^{210}Pb dating.
- PFM005791: Length 41 cm. Similar as above. Used for analysis of C, N, P.
- PFM005863: Length 34.5 cm. As above but with hair-like remains at 30–37 cm. Sliced in 2 cm sections and stored as an archive core.

Kallrigafjärden, Forsmark.

- PFM005784: Length 41 cm. Well oxidized at 0–3 cm with slightly degraded organic matter. Gradual transition to reducing conditions 3–8 cm, reduced below 8 cm. Hair-like plant remains around 35 cm. Gas bubbles (Ø 2–3 cm) scattered throughout the reduced zone. Used for ^{210}Pb dating.
- PFM005792: Length 38 cm. As above but without gas bubbles. Used for analysis of C, N, P.
- PFM005862: Length 41 cm. As above. Sliced in 2 cm sections and stored as an archive core.
- PFM005793: Length 200 cm. Gyttja 0–70 cm, sandy gyttja 70–73 cm, sandy gravel with gyttja 73–76 cm, laminated clay with light grey and dark grey sections 76–105 cm (see Figure 5-2). Used for ^{14}C dating.

Rönningarna, Forsmark.

- PFM006025: Three sections labelled 0.1–1.0 m, 0.97–1.97 m and 1.5–2.5 m, respectively. Peat 0.1–1.0 m, peat 0.97–1.41 m, empty 1.41–1.46 m, peat 1.46–1.89 m, clay 1.89–1.97 m. Third section not sampled.
  This core lacked the 0–10 cm section, why a complete inventory of ^{210}Pb could not be established. Calculation of the cumulative ^{210}Pb activity confirmed that a major part of the inventory was missing. It was therefore not possible to calculate recent mass accumulation rates at this site.

Granholmsfjärden, Oskarshamn.

- PSM007734: Length 40.5 cm. Oxidized 0–5 cm, reduced below 5 cm. Very loose (mostly water) 0–6 cm. Gas bubbles below 20 cm, smell of H_2S. Used for ^{210}Pb dating.
- PSM007740: Length 40 cm. As above. Sliced in 2 cm sections. Used for analysis of C, N, P.

Figure 5-2. *Sediments from Kallrigafjärden. The transition from gyttja to clay (left). To the right is a close-up of the laminated clay. Also seen are the layers with sandy gyttja and sandy gravel with gyttja.*

Norrefjärd, Oskarshamn.

- PSM007733: Length 42 cm. Oxidized 0–1 cm. Plants on the surface, root-like plant remains at 36–40 cm. Used for ^{210}Pb dating.
- PSM007739: Length 34 cm. Used for analysis of C, N, P.
- PSM007743: Length 41 cm. As above. Sliced in 2 cm sections and stored as an archive core.

Borholmsfjärden, Oskarshamn.

- PSM007735: Length 43.5 cm. Well oxidized 0–5 m. Reducing conditions below 6 cm. Very loose (mostly water) 0–6 cm, fairly loose 6–12 cm. Gas bubbles below 22 cm. Grass-like or hair-like plant remains at 28–30 cm. Used for ^{210}Pb dating.
- PSM007741: Length 40 cm.Used for analysis of C, N, P.
- PSM007744: Length 42 cm. Looks like PSM007735 but with the grass-like layer at 22–26 cm (most pronounced at 24–26 cm). Sliced in 2 cm sections and stored as an archive core.
- PSM006589: Five sections labelled 0–1 m, 1–2 m, 2–3 m, 3–4 m and 4.68–5.68 m, respectively. Gyttja at 0–4.70 m. Clay with decomposed organic material below 4.70 m. Used for ^{14}C dating.

Frisksjön, Oskarshamn.

- PSM007736: Length 36.5 cm. No oxidized layer on top (the sediment is brownish black throughout the core). Not as loose as the coastal sediments. Used for ^{210}Pb dating.
- PSM007742: Length 33.5 cm. As above. Used for analysis of C, N, P.
- PSM007745: Length 34.5 cm. Sliced in 2 cm sections and stored as an archive core.
- PSM006571: Five sections labelled 0–1 m, 1–2 m, 2–3 m, 3–4 m and 3.68–4.68 m, respectively. Gyttja throughout the core. Used for ^{14}C dating.

Klarebäcksmossen, Oskarshamn

- PSM007732: Four sections labelled 0–1 m, 1–2 m, 2–3 m and 3–4 m, respectively, on which the date 060202 appears. The core consists of peat from 0 to 3.7 m, where a gradual transition to more clay-rich peat occurs. At 0.35–0.40 m a layer of sand and gravel occurs.

5.2 ^{210}Pb and ^{137}Cs

The activities of ^{210}Pb and ^{137}Cs versus depth are shown in Figure 5-3. The derived age-depth models are also given in Appendix 1. Most ^{210}Pb profiles indicate a mixed surface layer, followed by declining activites at depth. The presence of mixed surface layers is not surprising, because most sediments are sampled in fairly shallow environments where wave induced mixing may occur. Also the peat core at Klarebäcksmossen displays a comparably homogenous ^{210}Pb profile in the upper 10 cm. This pattern is commonly observed in peat cores /e.g. Rausch et al. 2005/.

The values of A(0) (see Section 4.4.2) is a measure of the cumulative ^{210}Pb inventory and should ideally equal the atmospheric deposition of ^{210}Pb divided by 0.03114. The A(0) values obtained were 375–1,300 mBq cm^{-2} (Appendix 1), which is in the expected range. Tixelfjärden had the highest value, suggesting that this site accumulates sediments from a larger area. The A(0) in Klarebäcksmossen was c 800 mBq cm^{-2}, which is in perfect agreement with two of the local coastal sites. A(0) may vary due to, inter alia, local uranium content in the bedrock /Oldfield and Appleby 1984/. The uranium content in the bedrock is relatively high in regions close to Klarebäcksmossen (geophysical maps at www.sgu.se). Although the A(0) in

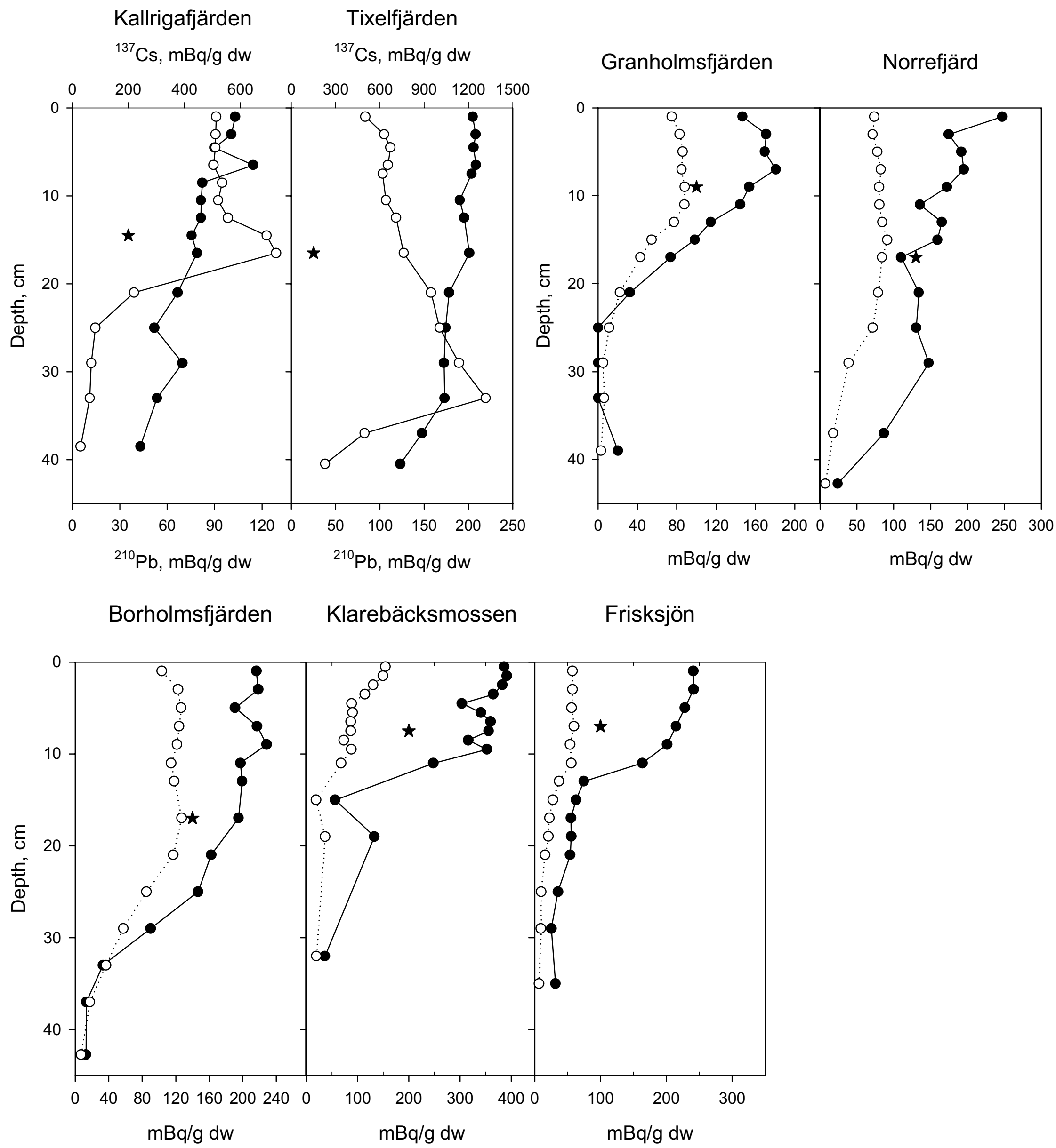

Figure 5-3. *Activities of excess ^{210}Pb (black) and ^{137}Cs (white) in sediments and peat from the Forsmark and Oskarshamn region. Note that in the two upper left graphs, the activities of ^{137}Cs are shown on separate axes. The approximate position of 1986 is denoted with a star.*

Klarebäcksmossen appears somewhat high compared to certain recent measurements in Finnish bogs (86–173 mBq cm^{-2} /Rausch et al. 2005/) and earlier Swedish data (120–240 mBq cm^{-2} /El-Daoushy 1986/), values in this range have been published from other bogs (e.g. 400–780 mBq cm^{-2} /Le Roux 2005/). We are not aware of more representative and recent Swedish data to further evaluate this dataset.

The activities of ^{137}Cs are much higher at the two coastal sites from Forsmark (Tixelfjärden and Kallrigafjärden) than in sediments from the Oskarshamn region. This may reflect the fact that northern Uppland was much more influenced by the Chernobyl accident than the southeastern part of Sweden. The approximate position of the year 1986 is denoted with stars in Figure 5-3. There is a fairly good agreement between 1986 and ^{137}Cs at several sites. However, the ^{137}Cs profiles generally do not display pronounced peaks that can be used as stratigraphic markers for 1962 or 1986. This may primarily be due to the mixing of the uppermost sediments, as is also reflected in the ^{210}Pb data. Mixing is a well-known problem when dating surficial sediments in shallow environments. Neither does ^{137}Cs adsorb as strongly as ^{210}Pb in sediments or peat, and cesium may therefore be subject to postdepositional migration in sediments /e.g. Davis et al. 1983, Appleby et al. 1991/. Furthermore, in regions that received large influx of ^{137}Cs during the 1986 Chernobyl accident, the 1963 peak is frequently obliterated due to downward diffusion of ^{137}Cs from the 1986 peak /e.g. Appleby et al. 1991/. ^{241}Am was detected at a few levels in sediment from Tixelfjärden and Klarebäcksmossen. The age-depth models for these two sites (Appendix 1) were supported by the ^{241}Am peak in 1963.

The peat core from Klarebäcksmossen displays progressively increasing ^{137}Cs activites toward the surface. This is not in agreement with the ^{210}Pb derived age-depth model. Possibly, ^{137}Cs substitutes for potassium in biogeochemical processes, is accumulated in plant roots and transported upwards in the profile.

5.3 ^{14}C

^{14}C ages and the corresponding calibrated ages are shown in Table 5-1. Ages increase progressively with depth at all sites, indicating that major disturbance of the sedimentation has not occurred. An earlier investigation at Borholmsfjärden found evidence of strongly disturbed sedimentation /Risberg 2002/.

At Kallrigafjärden, there is a large age interval between the two closely spaced samples. The lower sample was taken in a sandy gravel layer just above the glacial clay, and probably represents a period when sedimentation just started due to progressively more sheltered sedimentation conditions. The upper sample is probably more representative of the sedimentation that has occurred during the last centuries, why the lower sample was omitted from the calculations of accumulation rates.

The lowermost sample in Klarebäcksmossen is sampled from below the peat layers, which was clearly revealed by the organic carbon content. Therefore, this layer was not included in the calculation of the MARs.

Table 5-1. ^{14}C ages, calibrated years BP and ages AD/BC. Uncertainties are given as standard deviations at one sigma.

Site	Depth, cm	^{14}C-age BP	cal yrs BP	age AD/BC
Kallrigafjärden	68–70	500 ± 50	530 ± 25	1,420 AD
Kallrigafjärden	73–76	1,670 ± 50	1,570 ± 51	380 AD
Rönningarna	100–102	680 ± 50	620 ± 57	1,330 AD
Rönningarna	150–154	935 ± 50	855 ± 60	1,100 AD
Rönningarna	187–190	1,655 ± 50	1,570 ± 52	380 AD
Frisksjön	193–198	2,555 ± 50	2,640 ± 105	700 BC
Frisksjön	293–298	3,035 ± 50	3,270 ± 65	1,300 BC
Frisksjön	431–436	3,715 ± 50	4,060 ± 81	2,100 BC
Borholmsfjärden	293–298	3,070 ± 50	3,300 ± 59	1,350 BC
Borholmsfjärden	455–460	3,500 ± 50	3,790 ± 110	1,800 BC
Borholmsfjärden	553–558	3,880 ± 50	4,340 ± 63	2,400 BC
Klarebäcksmossen	196–198	3,940 ± 50	4,370 ± 73	2,400 BC
Klarebäcksmossen	296–298	7,640 ± 50	8,420 ± 36	6,470 BC
Klarebäcksmossen	396–398	8,790 ± 50	9,800 ± 103	7,850 BC

5.4 Carbon, nitrogen and phosphorus

The concentrations of C, N and P are shown in Appendix 2. The coastal sediments from Forsmark contain lower levels of organic carbon and nitrogen than do the coastal sediments from Oskarshamn. This probably reflects that the bays in Oskarshamn are more sheltered and enclosed than more open sites in Forsmark. Frisksjön contains the highest levels of organic carbon. In peat, roughly 50% of dry mass is organic carbon. The nitrogen levels are in the same range in sediment and peat, whereas the phosphorus levels are slightly lower in the peat than in the sediments.

In sediments, most sites show slightly declining levels downwards in the cores. The samples are, however, fairly distant in Rönningarna, Frisksjön, Broholmsfjärden and Klarebäcksmossen, why these patterns not should be considered as trends.

5.5 Accumulation rates of dry mass

The average mass accumulation rates (MAR) are presented in Table 5-2. It must be noted that the time period for the long-term fluxes differ between the sites, but all represent mainly preindustrial times.

5.5.1 Sediments

The mass accumulation rates in the upper c 40 cm decline with depth at all sites except Frisksjön. This pattern is commonly observed in recent sediments. The total range of recent MARs is within a factor 2.8. The lowest MAR was found in Granholmsfjärden, which also agrees with the lowest ^{210}Pb inventory (Section 5.2). This may very well reflect the fact that this site was not at the deepest point in the basin, where MAR most probably is higher. The two coastal sites in Forsmark displayed the highest and almost identical MARs. The recent MARs are in perfect agreement with previous measurements on the Swedish coast (400–1,900 g m^{-2} yr^{-1}) and in Swedish lakes (30–950 g m^{-2} yr^{-1}) /El-Daoushy 1986/.

The agreement between long-term average mass accumulation rates and the average during the last c 100 yrs is striking at Frisksjön and Borholmsfjärden (Table 5-2). At Kallrigafjärden, the MAR appears to have increased during the last c 500 years.

5.5.2 Peat

The recent MAR (^{210}Pb) in Klarebäcksmossen decreases slightly downwards and is c 8 times higher than the long-term MAR, which however represents a very long time span. Many other studies on bogs have also found varying accumulation rates that rapidly decrease with depth in the uppermost layers /e.g. Bindler 2003, Shotyk et al. 2005/. The recent MARs in the Klarebäcksmossen is slighly higher than other measurements of recent accumulation rates in Scandinavian bogs or mires (peak values in g m^{-2} yr^{-1}: 220 /Bindler 2003/, 600 /Rausch et al. 2005/).

The long-term MARs are almost identical at Klarebäcksmossen and Rönningarna and are similar to other Scandinavian bogs /e.g. Turunen et al. 2002, Beleya and Malmer 2004/. The relatively large difference in accumulation rates between the 20th century (^{210}Pb) and the Holocene (^{14}C) was also noted by /Shotyk et al. 2005/.

Table 5-2. Average mass accumulation rates [g m^{-2} yr^{-1}] during the 20th century (^{210}Pb) and during longer time scales (^{14}C). For the long term accumulation rates, uncertainties are given as standard errors of the slope.

Site	^{210}Pb, average	^{210}Pb range	Average long term (^{14}C)	Statistics for long term MAR	long term period, cal yrs BP
Kallrigafjärden	1,070	500–1,500	250 ± 125 [a]		0–500
Tixelfjärden	1,080	200–1,900			
Rönningarna			69 ± 18 [a]	r^2 = 0.88, p = 0.06	0–1,600
Frisksjön	410	300–600	400 ± 30	r^2 = 0.99, p = 0.047	2,600–4,060
Borholmsfjärden	680	470–1,000	680 ± 100	r^2 = 0.98, p = 0.09	3,300–4,400
Norrefjärd	740	200–1,100			
Granholmsfjärden	380	200–650			
Klarebäcksmossen	450	300–600	56 ± 6 [a]	r^2 = 0.99, p = 0.07	0–8,400

a. The surface was included in deriving accumulation rates.

5.6 Accumulation rates of C, N and P

The accumulation rates of C, N and P are presented in Table 5-3. It must be noted that the time periods for the long-term fluxes differ between the sites, but all represent mainly preindustrial times.

5.6.1 Sediments

At Kallrigafjärden, Tixelfjärden, Norrefjärd and Granholmsfjärden, accumulation rates decreased with depth between 0 and 40 cm. The uppermost layers may not represent net accumulation. As a comparison, accumulation rates of organic carbon in different basins of the open Baltic Sea (not coasts) range from c 10 to 70 g C m^{-2} yr^{-1} during the past c 60 years /Emeis et al. 2000/. Our coastal sites show slightly higher recent values, which could be expected at coastal sites.

The long-term accumulation rates of organic carbon are significantly higher in Oskarshamn (74–95 g C m^{-2} yr^{-1}) than in Forsmark (14 g C m^{-2} yr^{-1}). This may reflect the fact that the sites in Oskarshamn are more similar to lakes than at the open bays outside Forsmark. Long-term fluxes from the open Baltic Sea during Holocene range from c 5–30 g C m^{-2} yr^{-1} /Emeis et al. 2003/.

5.6.2 Peat

The accumulation rate of organic carbon is estimated to c 137 g C m^{-2} yr^{-1} during the first half of the 20th century (33–35 cm), whereas that of nitrogen is 2.7 g N m^{-2} yr^{-1}. Most studies on carbon accumulation in peatland focus on the long-term accumulation, but a recent compilation of apparent accumulation rates over the last 100–200 years give a range of 30–120 g C m^{-2} yr^{-1} /Turunen 2003/. The value at Klarebäcksmossen appears therefore somewhat too high, which also the MAR indicated (Section 5.5.2). However, carbon accumulation rates in peatlands are known to depend on many factors, e.g. the depth of the water table, vegetation changes, and nitrogen deposition. We do not have the detailed knowledge on the recent history of these aspects for Klarebäcksmossen.

The long-term carbon accumulation rate is similar at Rönningarna (38 ± 11 g C m^{-2} yr^{-1}) and Klarebäcksmossen (29 ± 4 g C m^{-2} yr^{-1}) which is in the expected range of c 20–50 g C m^{-2} yr^{-1} /e.g. Turunen et al. 2002, Malmer and Wallén 2004/.

Table 5-3. Accumulation rates of phosphorus, nitrogen and organic carbon. Long term averages are shown in bold.

Depth, cm	**Organic carbon accumulation rate [g C m^{-2} yr^{-1}]**		**Phosphorus accumulation rate [g P m^{-2} yr^{-1}]**		**Nitrogen accumulation rate [g N m^{-2} yr^{-1}]**	
	Average	SD	Average	SD	Average	SD
Kallrigafjärden						
2–4	101	13	1.69	0.31	13.0	1.3
16–18	71	14	0.85	0.20	9.0	1.7
32–34	38	7	0.30	0.06	3.8	0.6
0–70	**14**	**7**	**0.20**	**0.10**	**1.6**	**0.8**
Tixelfjärden						
2–4	118	15	3.00	0.53	15.3	1.4
10–12	92	12	1.55	0.28	12.6	1.2
16–18	67	9	0.95	0.17	8.3	0.8
32–34	13	2	0.17	0.04	1.6	0.2
Rönningarna						
0–190	**38**	**11**	**0.02**	**0.01**	**1.1**	**0.3**
Frisksjön						
20–22	79	14	0.63	0.13	6.3	0.9
188–431	**74**	**13**	**0.36**	**0.13**	**9.3**	**1.7**
Borholmsfjärden						
20–22	67	8	0.86	0.15	7.8	0.7
280–560	**95**	**18**	**0.49**	**0.07**	**13.6**	**2.1**
Norrefjärd						
2–4	151	22	1.82	0.35	19.3	2.2
10–12	151	22	1.66	0.32	18.1	2.2
20–22	108	16	1.13	0.22	12.5	1.5
32–34	47	7	0.40	0.08	5.6	0.6
Granholmsfjärden						
2–4	78	10	1.25	0.23	9.1	0.9
10–12	45	7	0.67	0.13	4.9	0.6
20–22	26	3	0.38	0.07	3.0	0.3
36–38	28	4	0.30	0.05	3.4	0.3
Klarebäcksmossen						
33–35	137	17	0.18	0.03	2.7	0.2
0–300	**29**	**4**	**0.03**	**0.005**	**0.9**	**0.4**

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Appendix 1

Mass accumulation rates and ages-depth relationships from ^{210}Pb

Depth, cm	MAR g/m²/yr	MAR Uncertainty	mm/yr	Uncertainty mm/år	Year
Granholmsfjärden		A(0) = 375 mBq cm^{-2}			
0–2	647	73	7.0	0.87	2003
2–4	573	49	5.2	0.52	2000
4–6	509	39	4.1	0.38	1995
6–8	451	44	3.3	0.37	1990
8–10	399	37	2.7	0.29	1983
10–12	350	42	2.3	0.30	1975
12–14	305	34	1.9	0.23	1967
14–16	264	23	1.6	0.16	1956
16–18	228	34	1.4	0.21	1944
20–22	200	17	1.1	0.12	1916
Norrefjärd		A(0) = 800 mBq cm^{-2}			
0–2	1,012	104	11	1.25	2004
2–4	1,066	109	11	1.21	2002
4–6	1,109	98	10.4	1.06	2001
6–8	1,137	84	10	0.90	1999
8–10	1,146	99	9.7	0.97	1997
10–12	1,135	123	9.3	1.10	1995
12–14	1,103	104	8.7	0.93	1992
14–16	1,053	81	8.1	0.74	1990
16–18	989	111	7.4	0.91	1987
20–22	834	88	6.0	0.70	1981
24–26	668	68	4.6	0.53	1974
28–30	510	38	3.4	0.31	1964
36–38	255	33	1.5	0.21	1930
Borholmsfjärden		A(0) = 740 mBq cm^{-2}			
0–2	997	76	9.7	0.89	2004
2–4	920	67	9.4	0.83	2002
4–6	837	62	8.8	0.79	2000
6–8	772	56	8.2	0.72	1997
8–10	718	53	7.6	0.68	1995
10–12	673	50	7.0	0.63	1992
12–14	635	48	6.5	0.59	1989
16–18	573	42	5.5	0.48	1983
20–22	525	40	4.6	0.42	1975
24–26	489	37	3.9	0.35	1965
28–30	471	50	3.4	0.40	1955
32–34	490	60	3.3	0.44	1944
36–38	603	228	3.9	1.47	1934

Depth, cm	MAR g/m²/yr	MAR Uncertainty	mm/yr	Uncertainty mm/år	Year
Klarebäcksmossen		A(0) = 800 mBq cm^{-2}			
0–1	597	43	19	1.68	2005
1–2	594	42	9.1	0.79	2004
2–3	580	43	4.3	0.38	2002
3–4	560	43	3.1	0.29	1999
4–5	537	38	3.6	0.31	1996
5–6	514	37	3.6	0.32	1993
6–7	492	36	3.0	0.26	1990
7–8	470	34	3.4	0.30	1987
8–9	449	33	2.7	0.24	1984
9–10	430	31	3.0	0.26	1981
10–12	388	28	3.0	0.26	1975
14–16	343	24	1.1	0.09	1963
18–20	315	22	2.6	0.22	1950
31–33	465	33			
Frisksjön		A(0) = 400 mBq cm^{-2}			
0–2	462	37	6.5	0.60	2003
2–4	410	35	4.5	0.44	1999
4–6	362	30	3.4	0.33	1993
6–8	325	28	2.7	0.27	1987
8–10	303	25	2.4	0.23	1979
10–12	294	24	2.2	0.21	1971
12–14	295	48	2.1	0.37	1963
14–16	303	41	2.2	0.32	1955
16–18	315	48	2.3	0.36	1947
18–20	330	32	2.4	0.26	1940
20–22	348	49	2.6	0.39	1933
24–26	390	147	3.1	1.18	1921
28–30	444	230	3.9	2.01	1910
34–36	548	110	5.3	1.10	1899
Kallrigafjärden		A(0) = 530 mBq cm^{-2}			
0–2	1,512	126	14	1.4	2005
2–4	1,481	127	9.8	1.0	2003
4–5	1,435	186	8.1	1.1	2000
6–7	1,390	136	7.5	0.8	1998
8–9	1,330	119	7.0	0.7	1995
10–11	1,290	155	6.8	0.9	1992
12–13	1,220	115	6.7	0.7	1989
14–15	1,170	102	6.7	0.7	1986
16–17	1,100	197	6.6	1.2	1983
20–22	993	87	6.4	0.6	1977
24–26	865	113	6.0	0.8	1970
28–30	700	216	5.5	1.7	1960
32–34	601	82	4.9	0.7	1946

Depth, cm	MAR g/m²/yr	MAR Uncertainty	mm/yr	Uncertainty mm/år	Year
Tixelfjärden		A(0) = 1,300 mBq cm^{-2}			
0–2	1,882	200	28	3.3	2005
2–4	1,838	140	15	1.3	2004
4–5	1,780	136	11	1.0	2002
6–7	1,690	131	9.5	0.9	2000
7–8	1,650	125	9.3	0.8	1999
10–11	1,500	116	8.2	0.8	1995
12–13	1,420	109	7.8	0.7	1993
16–17	1,220	95	7.4	0.7	1988
20–22	1,019	78	7.2	0.7	1982
24–26	830	64	6.7	0.6	1974
28–30	615	48	6.1	0.6	1963
32–34	364	26	5.4	0.5	1944

Concentrations of loss on ignition, organic carbon, nitrogen and phosporus

Site	Depth cm	Dry weight, %	LOI, % dw	P, % dw	N-tot, % dw	TOC, % dw
Kallrigafjärden	2–4	13.9	16.7	0.114	0.88	6.9
Kallrigafjärden	18–20	16.3	15.4	0.078	0.82	6.4
Kallrigafjärden	34–36	15	18.3	0.061	0.77	7.8
Kallrigafjärden	65–68	19.1	14.4	0.080	0.64	5.7
Tixelfjärden	2–4	12.4	15.2	0.163	0.83	6.4
Tixelfjärden	10–12	14.4	15.2	0.103	0.84	6.1
Tixelfjärden	18–20	14.7	14.5	0.085	0.74	6.0
Tixelfjärden	34–36	19.7	13	0.075	0.69	5.5
Rönningarna	26–28	10.4	99.2	0.031	0.99	56
Rönningarna	60–65	7.8	99.8	0.007	0.38	57
Rönningarna	146–150	10	97.2	0.019	1.27	55
Rönningarna	185–187	7	87.8	0.044	3.88	50
Frisksjön	20–22	9.4	42.8	0.18	1.8	22.5
Frisksjön	188–193	14.7	30.2	0.0765	1.9	15.1
Frisksjön	288–293	23	39.7	0.127	2.5	20.0
Frisksjön	426–431	21.4	40.0	0.0657	2.6	20.7
Borholmsfjärden	20–22	10.2	27.4	0.17	1.5	12.8
Borholmsfjärden	288–293	21.6	33.2	0.061	2.3	16.7
Borholmsfjärden	450–455	23.7	28.9	0.080	2	13.8
Borholmsfjärden	548–553	26.4	24.8	0.076	1.7	11.6
Norrefjärd	2–4	7.8	31.3	0.17	1.8	14
Norrefjärd	10–12	8.8	29.1	0.147	1.6	13
Norrefjärd	20–22	9.8	28.0	0.136	1.5	13
Norrefjärd	32–34	12.8	28.3	0.109	1.5	13
Klarebäcksmossen	33–35	13.6	81.1	0.058	0.9	46
Klarebäcksmossen	194–196	15.8	95.8	0.047	1.8	56
Klarebäcksmossen	294–296	20.4	95.4	0.047	2.1	54
Klarebäcksmossen	392–394	21.1	22.1	0.016	1.1	11
Graneholmsfjärden	2–4	6	30.9	0.220	1.6	13.7
Graneholmsfjärden	10–12	8.8	27.9	0.190	1.4	12.9
Graneholmsfjärden	20–22	11.8	26.4	0.190	1.5	12.9
Graneholmsfjärden	36–38	15.9	28	0.150	1.7	14