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Sediment and carbon accumulation rates off the southern coast of Finland

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Abstract The southern coast of Finland encompasses about one third of the coasts of the Gulf of Finland. It is a mosaic of hundreds if not thousands of islands, peninsulas and bays, which also are reflected in the seabed of the coast. The sea floor is composed of a patchy and fragmented mosaic of mainly quite small basins separated from each other by thresholds of islands, peninsulas or submarine ridges. This affects transport and near bottom currents such that deposition of suspended particles is restricted to certain areas only. Linear sediment accumulation rates along the southern coast of Finland were studied from 28 cores of a sampling campaign in 2000–2004 through gamma spectrometry of ^{137}Cs. Sediment accumulation in this environment with such diverse character was found very patchy and net sedimentation rates varying from less than 0.5 cm/a to values of nearly 3 cm/a as well as mass accumulation rates from 0.5 kg/m^2/a to 8.8 kg/m^2/a were found. The sediment accumulation rates were observed to be higher in shallower water in coastal sheltered or semi-sheltered bays. Total carbon concentrations varied from 1.3 % to 12.6 % and carbon accumulation rates from 20 g/m^2/a to 355 g/m^2/a such that the highest carbon concentrations were usually found in deeper water with some distance from the coast, while the highest carbon accumulation rates were found in the coastal shallow basins where sediment accumulation was found strongest.

Keywords *• sediment • carbon • accumulation • ^{137}Cs • dating • deposition • Gulf of Finland*

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INTRODUCTION

The southern coast of Finland is located along the northern shores of the Gulf of Finland, an eastward stretching bay of the Baltic Sea. This part of the coast is composed of a mosaic of hundreds if not thousands of islands, peninsulas and bays in one of the most complex archipelagos of the world. This is reflected in the seabed of the coast such that the sea floor is patchy and composed of mainly quite small irregular basins separated from each other by thresholds of islands, peninsulas or submarine ridges. According to Kaskela *et al.* (2012) the seafloor in the northern Gulf of Finland is characterized by sea valleys, holes, sea troughs, and elevations at areas with exposed rock. This rugosity affects near bottom currents such that deposition of suspended particles is restricted to certain areas only and the accumulation has in general a patchy nature, which in fact has been reported also from the off shore Gulf of Finland (Vallius, 1999). The input of particulate matter into the water column is provided by erosion of soil and by riverine transport into the sea. Erosion from shores and shallows add to the amount of soil particles in suspension, such erosion is relatively weaker in the sheltered parts of the archipelago and stronger in the areas prone to the powers of the open sea, wind, waves and sea ice, tide is negligible in the Baltic Sea area. Even though the rivers in southern Finland and especially in the south-western Finland are rather small what comes to their water transport capacity, they add a rather large amount of suspended matter to the sea as they flow through the agricultural lands of southern Finland, where cultivation of land releases farmland soil into the streams of the catchment (Lehtoranta *et al.* 2007).

Clays of different ages and different Baltic Sea stages usually cover the bedrock of the Gulf of Finland area (Winterhalter 1992). Sometimes the bedrock crops out through the whole sediment sequence, while sometimes some of the sub seafloor stratigraphic components are missing. In the areas of recent sedimentation, the accumulation basins, the surface is typically covered with organic rich gyttja clay where the harmful substances tend to be bound due to favourable physic-chemical conditions. Thus these are the areas where the environmental studies are concentrated. As the amount of accumulating possibly harmful substances is dependent on the rate of accumulation of sedimentary particulate and organic matter it is of interest to get a picture of the magnitude of accumulation rates along the coast, which is reported in this paper.

MATERIAL AND METHODS

The Geological Survey of Finland (GTK) performed a coastal mapping program during a period from October 2000 to October 2002 as well as the field surveys of the Finnish – Russian SAMAGOL project between May 2004 and August 2004. All studies were undertaken from GTK: s research vessels *Kaita* and *Geola*, except for one core that was taken in August 2004 from Finnish Institute of Marine Research's research vessel *Aranda*. Altogether 61 sites were visited; echo sounded, and cored during the mapping program, 28 of them are presented in this study, figure 1. The results of surface chemistry of the sediments were reported by Vallius (2009). In order to give a picture on the quality of the sediments in the topmost 65 centimetres the chemistry data were compared to available sediment quality guidelines and reported (Vallius, 2015). The aim of the present study is to give a picture of the accumulation rates in the different parts of the coast based on gammaspectrometry of ^{137}Cs.

Sampling for the mapping project was performed in the coastal area, figure 1. Standard GTK sampling procedures were used during the whole mapping project, according to which the bottom was first investigated by echo sounding at each sampling station, this in order to find the place best suitable for sampling. Often the sea floor was also examined with an underwater video camera. Sampling was performed using a twin barrel GEMAX gravity corer with an inner diameter of the core liner of 90mm. The core liner is an acrylic tube with stainless steel core cutter, which allows inspection of the core through the liner. One core from each site was split vertically in order to get the best possible sample for vertical description of the core. The other of the two cores was sliced into 10mm thick sub samples, which were transferred into plastic bags, and immediately stored in +4 degrees C. After the cruises all samples were taken ashore and sent to the chemistry laboratory of the GTK where the samples were freeze dried and sieved into < 2mm. The samples were then returned for non-destructive gammaspectrometry, after which they were sent back to the chemistry laboratory and chemically analyzed. The distribution of arsenic and the heavy metals have been reported by Vallius (2009, 2015) and the data on carbon concentrations is used in this study. The samples were also measured for weight both as wet and after freeze drying. The dry weight is used in calculations on mass accumulation rates. As the salinity in the Gulf of Finland is so low, between 3 and 9 PSU (Alenius *et al.* 1998), there is no salt correction used in the calculations.

The gammaspectrometry method used in this study is based on measurements with an EG&E Ortec ACE-2K spectrometer with a 4-inch NaI/Tl detector and on the principle of detecting the ^{137}Cs peak of the Chernobyl power plant accident in the sediment column. The method is described by Kankaanpää *et al.* (1997) in a study from the Gulf of Finland and by Mattila *et al.* (2006) in a similar study from the whole Baltic Sea. In the method the concentration curves in the cores are interpreted giving the depth of the peak of the Chernobyl accident, thus giving the thickness of sediments deposited after April 1986, giving a net

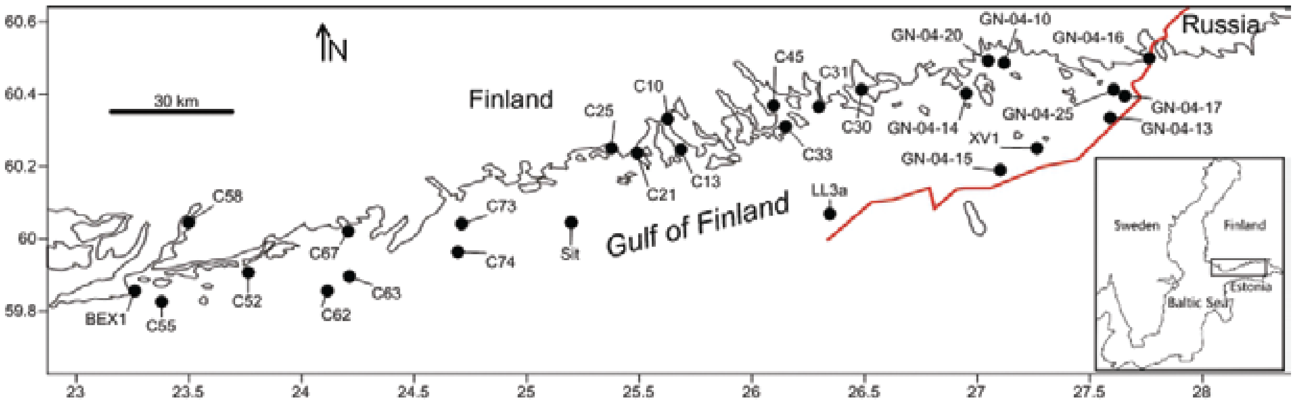

Fig. 1, Study area showing coring stations with sediment accumulation data measured (n=28). Red line indicates the border between Finland and Russia

sedimentation rate, not taking into account any possible erosional events during the time period between April 1986 and the time of sediment coring. Still it gives a good figure on the sedimentation rates in different areas. Also when compared to counts of annual varve couplets and/or triplets in some well preserved cores showing primary lamination the ^{137}Cs dating fit well with the varve counts, as described in Kotilainen *et al.* (2007). Bioturbation affects the sediment column such that the ^{137}Cs profiles are disturbed, often severely, thus such cores are not included in this study. A set of seven typical ^{137}Cs distribution curves with the year 1986 indicated is presented in figure 2.

Leipe *et al.* (2011) estimated the muddy sediments of the Gulf of Finland to contain 0.7 percent of inorganic carbon on average. As virtually all carbon in the Gulf of Finland is of organic origin no specific analysis for organic carbon was performed. Instead total carbon was analyzed by a LECO CNS analyzer after gammaspectrometry measurements.

RESULTS

Water depths in the studied area follow the common pattern of increasing depth with increasing distance from the coast, with small local deviations from the general rule, figure 3, table 1. The calculated net sediment accumulation rates of the present study (Fig. 4) are clearly higher in the coastal sheltered basins than in the basins of the open sea. This characteristic feature was observed also in the earlier study from the Gulf of Finland by Kankaanpää *et al.* (1997). Obviously the proximity to the coast provides for more accumulating material than in the open sea, as much of the suspended particles settle before reaching the deeper basins. Rates of sediment net accumulation vary from 0.42 cm/a up to 2.75 cm/a, having a median value of 0.87 cm/a, the lowest rate being measured in an off shore area at station LL3a and the highest at coastal station C67. Additional to net sediment accumulation rates it is interesting to also calculate sediment mass accumulation rates at the coring sites. This was done through formula $SAR = M_c/(At)$, where *SAR* is the sediment mass accumulation rate in g/cm^2/a, M_c is the cumulative mass of sediment in grams accumulated since 1986 including the sediment slice with the peak ^{137}Cs concentration. *A* is the area of the corer (63.6 cm^2) and *t* is the time in years between April 1986 and the time of coring.

When calculated to mass accumulation (SAR) rates (expressed as g/cm^2/a) the sedimentation pattern along the coast doesn't change much as the map (Fig. 5) is quite similar to the map of accumulation expressed as thickness of accumulated sediment (in cm/a) (Fig. 4). Rates of mass accumulation vary between 0.05 g/cm^2/a, and 0.88 g/cm^2/a, with a median value of 0.18 g/cm^2/a, such that the three stations with lowest rates (GN-04-13, GN-04-17 and XV1) are located along the eastern border and the station with

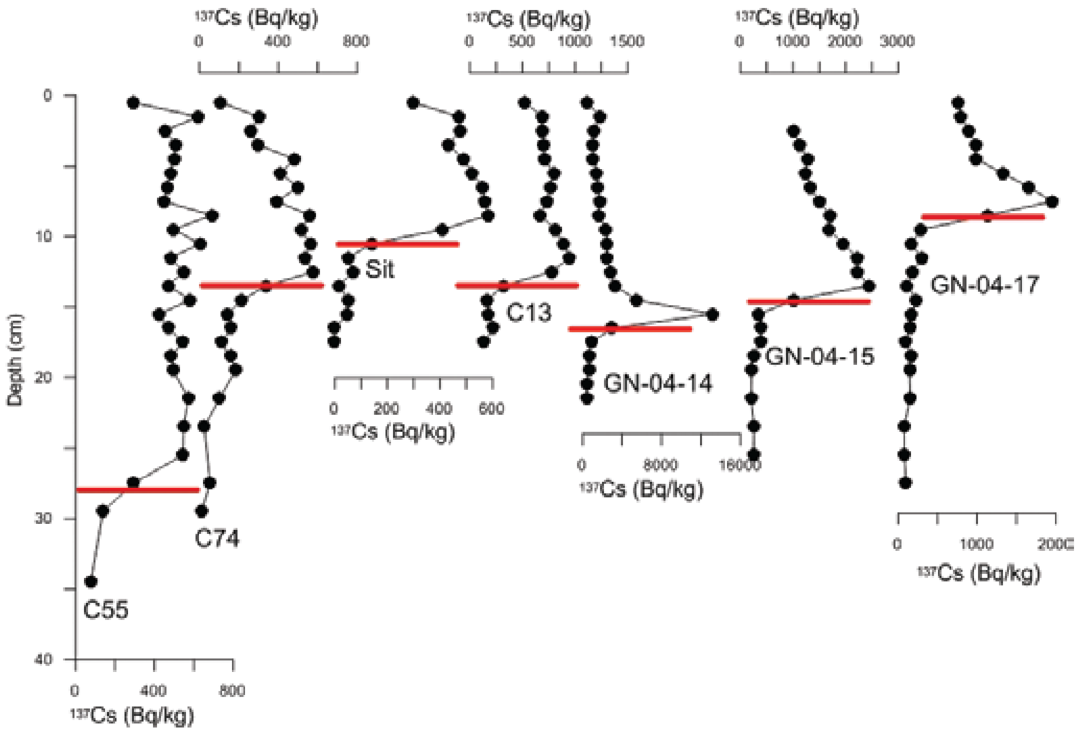

Fig. 2, ^{137}Cs activities (Bq/kg) in 7 cores along the coast from west to east, location of sites presented in Figure 1. The red lines correspond to the 1986 year cesium peak during time of sampling. Note the nearly one order of magnitude higher activity in core GN-04-14

Table 1 Data on coring sites with sediment and carbon accumulation, between years 2000 and 2004

Site	Longitude (dec deg) WGS 84	Latitude (dec deg) WGS 84	Water depth (m)	Sampling date (yyyymmdd)	Peakdepth (cm)	Accumulation rate (cm/a)	Mass acc. rate (SAR) ($g/cm^2/a$)	TC (%)	TC acc. rate (CAR) ($g/m^2/a$)
BEX1	23.2588	59.85615	34	20010405	24.0	0.93	0.45	no data	-
C10	25.6263	60.3297	13	20011010	37.0	2.40	0.88	2.6	227
C13	25.6855	60.2460	30	20011010	13.5	0.87	0.20	5.4	108
C21	25.4903	60.2357	19	20011011	12.5	0.81	0.24	4.9	117
C25	25.3750	60.2508	13	20011012	37.0	2.40	0.80	4.0	318
C30	26.4883	60.4110	11	20011003	24.0	1.55	0.42	5.0	210
C31	26.2963	60.3655	15	20011003	10.0	0.65	0.14	6.6	92
C33	26.1522	60.3107	30	20011008	22.0	1.42	0.32	6.3	201
C45	26.0967	60.3692	13	20011008	37.0	2.40	0.51	3.1	156
C52	23.7620	59.9051	23	20020910	22.0	1.33	0.23	7.7	176
C55	23.3790	59.8240	46	20020911	28.0	1.71	0.31	7.9	244
C58	23.4968	60.0463	24	20020912	10.5	0.64	0.10	5.3	53
C62	24.1160	59.8576	54	20020916	14.0	0.85	0.16	1.3	20
C63	24.2117	59.8952	45	20020916	7.0	0.43	0.09	6.6	59
C67	24.2074	60.0198	22	20020917	45.0	2.75	0.63	5.6	355
C73	24.7120	60.0417	41	20020919	16.5	1.00	0.18	6.4	115
C74	24.6936	59.9633	53	20020919	13.0	0.80	0.13	10.0	129
GN-04-10	27.1213	60.4876	17	20040524	15.5	0.86	0.17	5.8	99
GN-04-13	27.5914	60.3357	39	20040526	12.0	0.67	0.06	10.6	64
GN-04-14	26.9524	60.4012	20	20040527	17.0	0.94	0.10	10.0	100
GN-04-15	27.1005	60.1883	64	20040527	14.5	0.81	0.10	11.7	117
GN-04-16	27.7629	60.4990	16	20040531	18.0	1.00	0.18	9.0	162
GN-04-17	27.6572	60.3969	44	20040531	9.0	0.50	0.05	6.8	34
GN-04-20	27.0510	60.4923	13	20040602	16.5	0.92	0.17	6.6	112
GN-04-25	27.6053	60.4107	40	20040828	8.5	0.47	0.09	12.6	113
Sit	25.1985	60.0462	52	20001004	10.5	0.73	0.09	8.4	76
XV1	27.2650	60.2490	60	20040829	10.3	0.56	0.06	9.8	59
LL3a	26.3289	60.0777	63	20040830	7.5	0.42	0.39	no data	-
MEDIAN			30		15.0	0.87	0.18	6.6	114

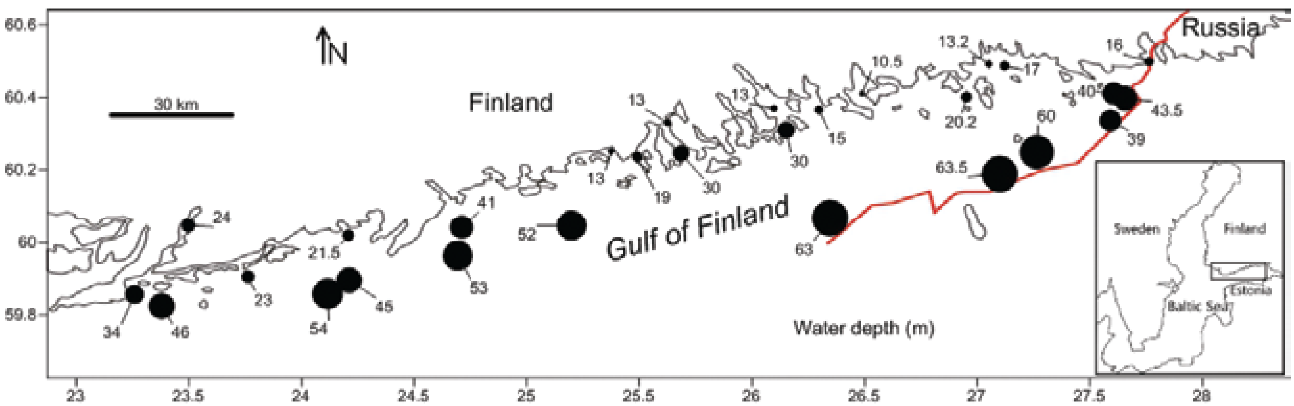

Fig. 3, Water depths at the coring sites (m)

highest accumulation rate C10 is a rather shallow inner coastal basin.

As it is interesting to know the percentage of organic carbon in the accumulating matter the total carbon contents (TC) in the surface slices (0-1 cm) of the collected cores is used as a measure of organic matter. TC in the sediment surface of the research area varies between 1.3 and 12.6 percent, with median value of 6.6 %, and the concentrations tend with a few exceptions to be higher with increasing distance

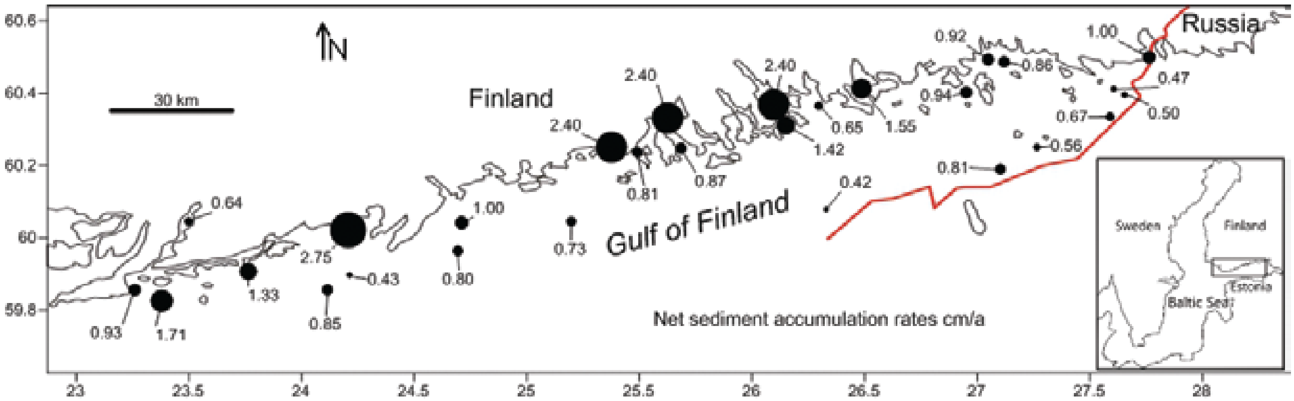

Fig. 4, Net sediment accumulation rates in the coastal zone expressed as cm/a.

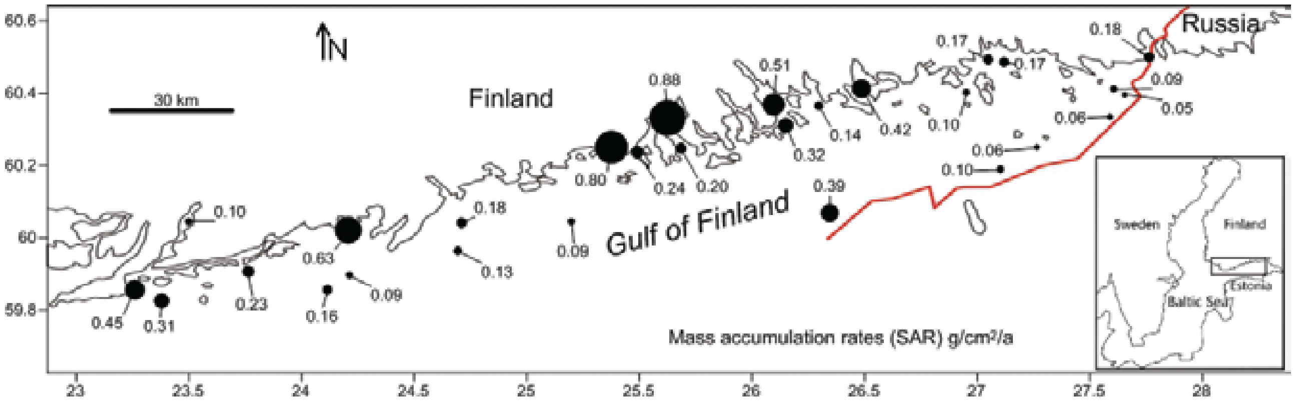

Fig. 5, Mass sediment accumulation rates (SAR) in the coastal zone expressed as g/cm²/a.

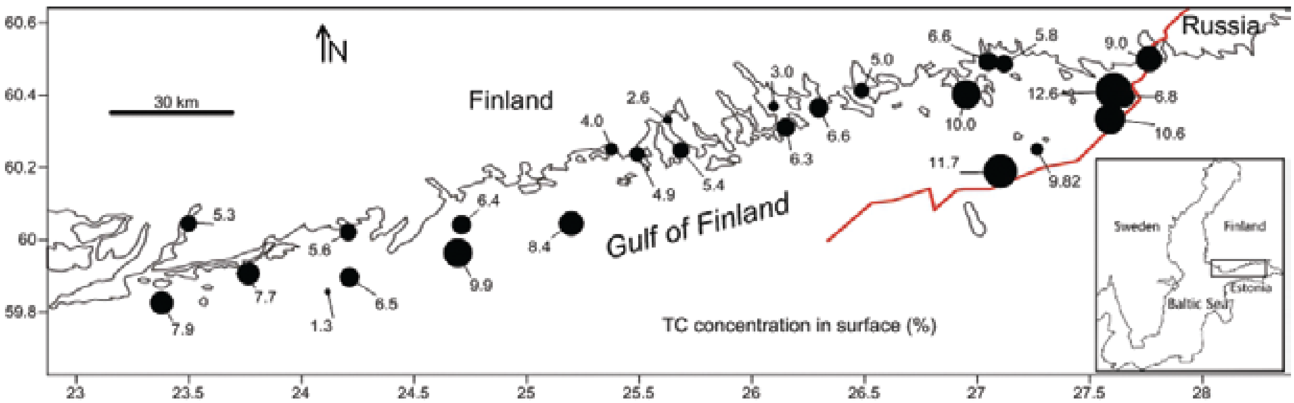

Fig. 6, Total carbon (%) content in the surface sediments (0-1 cm)

from the coast, figure 6. However, when calculating carbon accumulation rates (CAR), the figure changes considerably. If determining the rates as a function of carbon concentration in the surface of the sediment with relation to the calculated mass accumulation rates as *CAR = (TC*SAR*100)*, where *CAR* is the carbon accumulation rate in g/m^2/a, *TC* is the total carbon concentration (%), and *SAR* is the sediment mass accumulation rate (g/cm^2/a) we get the annual accumulation of carbon per square meter (g/m^2/a) at the coring sites, which gives a figure that the carbon accumulation rates are highest in coastal sheltered accumulation basins. It is, however, important to bear in mind that carbon is not trapped in the sediment column similar to heavy metals, but instead the concentrations decrease down core as carbon is decomposed, remobilized and partly used by benthic biota and only a part is trapped in the sediment column, as seen in figure 7, which shows as an example total carbon concentrations in 4 cores from the coastal area. High carbon concentrations in the surface sediments don't correlate with high CAR in the same area. Instead carbon concentrations are diluted in areas of high sediment accumulation as carbon accumulation rates there are high but accumulation of particulate sedimentary matter is even higher with a dilution of

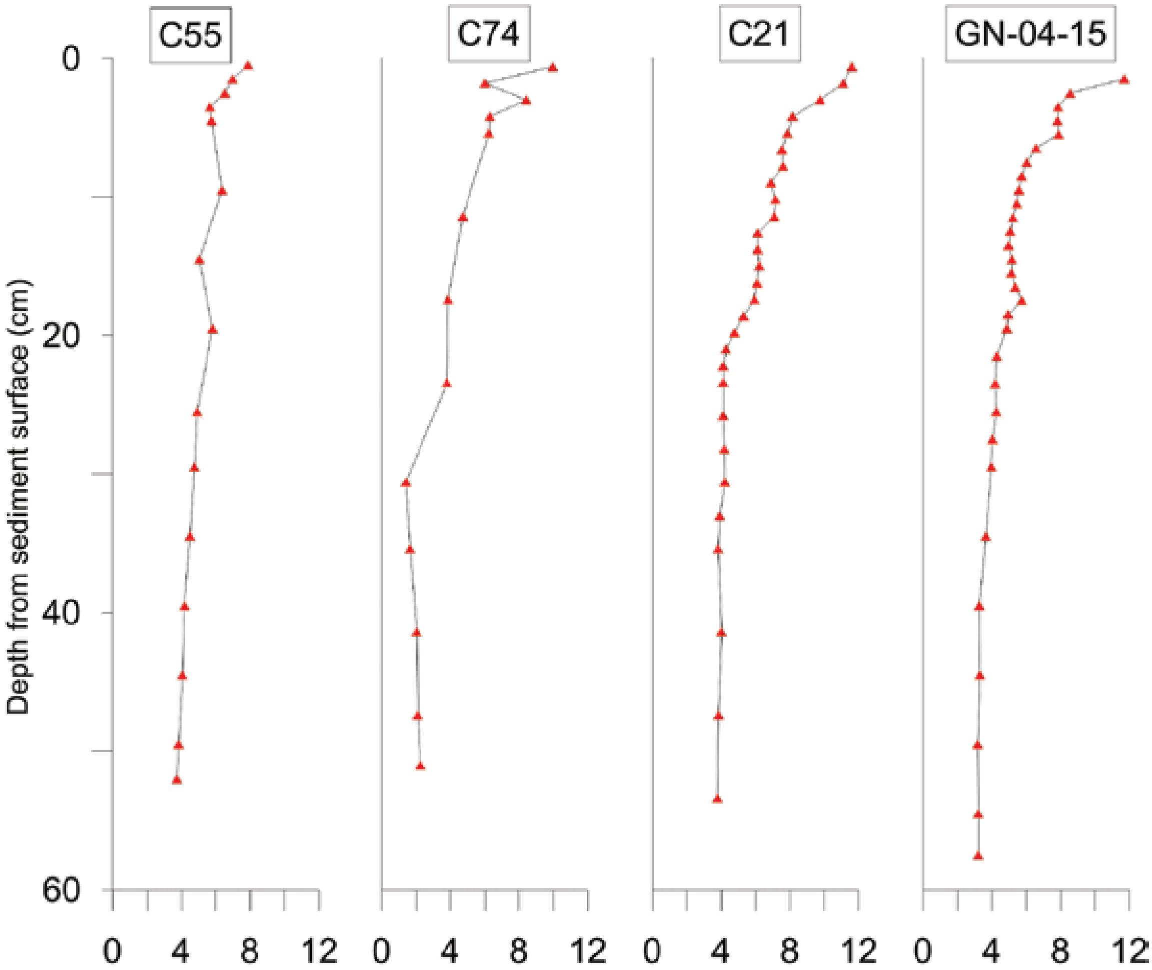

Fig. 7, Total carbon concentrations (%) in 4 cores along the coast (for locations see Figure 1)

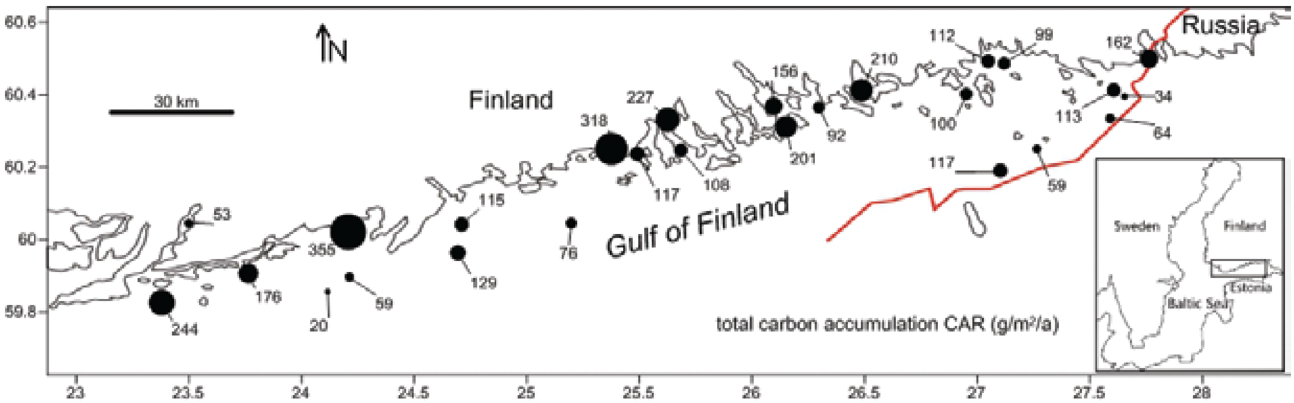

Fig. 8, Carbon accumulation rates at coastal stations (g/m²/a)

carbon concentrations as a result. The CAR rates vary between 20 g/m²/a and 355 g/m²/a, with median value of 114 g/m²/a, such that the highest rates are found in the coastal basins, figure 8.

COMPARISON OF RESULTS WITH OTHER STUDIES

As demonstrated earlier by Kankaanpää *et al.* (1997) also the result of this study reveal that gammaspectrometry of ^{137}Cs from surface sediment cores provides a good tool for understanding the sedimentary environment of the Gulf of Finland. When comparing the results of present study with the results of Kankaanpää *et al.* (1997) it can be clearly seen that the data of the present study is based on coastal cores, as the sediment accumulation rates are higher in the present study. Many of the cores in this study were collected in rather sheltered areas where sediment accumulation is promoted by riverine transport from land added up by material from coastal erosional areas. Median sediment accumulation rates of the present study are 1.5 to almost 2 times higher than in the study by Kankaanpää *et al.* (1997), as net sediment accumulation of present study is 0.87 cm/a compared to 0.49 cm/a by Kankaanpää *et al.* (1997) and sediment mass accumulation rate of the present study is 0.18 g/cm^2/a compared to 0.12 g/cm^2/a in the study by Kankaanpää *et al.* (1997). Median TC values by Kankaanpää *et al.* (1997), 6.9 %, are very close to the median of the present study, 6.6%. When comparing the present data with the data reported by Mattila *et al.* (2006) the data presented here are in general higher. Mattila *et al.* (2006) report for the Gulf of Finland a median sediment net accumulation value of 0.56 cm/a (0.87 in this study), and a median sediment mass accumulation value of 0.069 g/cm^2/a (0.18 in this study). Thus the median net accumulation rate value of the present study is only slightly higher while the median mass accumulation rate value of the present study is about 2.5 times greater than the rates by Mattila *et al.* (2006). The median values of the two studies are still in rather good agreement with each other, taking into account that the cores of the present study represent coastal areas only and in many cases sheltered or semi-closed inner bays with higher accumulation than average. Kankaanpää *et al.* (1997) did not report carbon accumulation rates but Leipe *et al.* (2011) reported accumulation of particulate organic carbon (POC) in the whole Baltic Sea. A comparison between the carbon results of the present study and the carbon data of Leipe and co-authors gives much higher values for the present study. Leipe *et al.* (2011) reports an average POC value of 4.09 % (0.7% inorganic C) in comparison to a median value of 6.6 in the present study, and a total POC deposition rate of 35 g/m^2/a compared to 114 g/m^2/a in the present study. However, Leipe *et al.* (2011) used the sediment mass accumulation rate values by Kankaanpää *et al.* (1997) and Mattila *et al.* (2006) which mainly represent off shore sediments and are thus on a clearly lower level than the one in the present study. Together with a clearly lower TC value the calculations by Leipe *et al.* obviously give clearly lower carbon accumulation rate for the Gulf of Finland sediments. Even though there is a small amount of inorganic carbon (0.7% according to Leipe *et al.* 2011) in the Gulf of Finland sediments this does not affect the calculations that much, and in fact there are no known sources of inorganic carbon in the northern Gulf of Finland sediments, thus, as a matter of fact, the inorganic carbon fraction is probably much lower in the northern Gulf of Finland than what Leipe *et al.* (2006) reported. Also when looking at the POC accumulation map of Leipe *et al.* (2011) the northern coast of the Gulf of Finland is clearly highlighted with much higher POC accumulation rates than anywhere else in the Baltic Sea, with maximum rates exceeding 70 g/m^2/a. If higher sediment mass accumulation rates would have been used by Leipe *et al.* (2011) the carbon accumulation rates in that study would match well with the rates reported in the present study.

CONCLUSIONS

This study demonstrates that there are large differences in the sediment and carbon accumulation rates along the southern coast of the Gulf of Finland, reflecting the patchy character of the seafloor and the effect of riverine input. Information on accumulation patterns, together with knowledge on such sediment dynamics as erosion and transportation, is important in marine spatial planning when dealing with issues such as plans for dredging, dumping and sea floor infrastructures. The heterogenic nature of the Gulf of Finland thus makes marine spatial planning an issue of utmost importance in the area.

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