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STUDIES ON THE SINKING, DEGRADATION AND SEDIMENTATION OF ORGANIC MATTER OFF HANKO PENINSULA, ENTRANCE TO THE GULF OF FINLAND, IN 1979 (PROGRESS REPORT)

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Abstract

The present study was undertaken to obtain information on the behaviour of sinking organic matter during different production stages. An attempt is made to elucidate degradation and sedimentation of particulate matter on the basis of the C:N:P ratio of seston and of sedimented matter collected in traps at different depths. This ratio is used as an indicator of the degradation stage, and the changes that settling matter undergoes in the water column are discussed.

The average velocities of vertically moving particles were calculated using the measured concentrations and sedimentation rates.

1. INTRODUCTION

In research on Baltic Sea eutrophication, an essential step is the construction of a model for the oxygen balance of the Sea (cf. Mäkelä 1978). An obstacle to the development of such a model is the scarcity of data on the sinking and sedimentation of organic matter, and the rates of degradation in different water layers and seasons. The pycnoclines, the thermocline and the permanent halocline play important roles in these processes. Studies on such subjects were given high priority in the Baltic Sea Cooperative Research planning (ICES/SCOR, Coop. Res. nr.42, 1974).

In the northern Baltic Sea the primary production of organic matter is limited to 5-6 months. A large proportion of the organic matter is produced in spring after the break-up of the ice, when inorganic nutrients (NO_3-N, PO_4-P and SiO_4-Si) are abundant in the surface layer

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and there is enough irradiation for effective assimilation (e.g. Niemi 1975). A considerable part of the organic matter produced in spring sinks to the bottom, owing to the absence of grazers. This vernal energy input is of great importance to the benthic ecosystem (Jansson 1978).

In summer, when strong thermal stratification prevails, primary production is low. The rate of microbial degradation of organic matter is high and grazers are active. During this stage probably very little particulate organic matter is contributed from the euphotic layer to the deep benthos below 30 m. The blue-green algal blooms in late summer in the open sea produce abundant organic matter, but we do not know whether it sinks to deeper layers or is chiefly degraded in the mixed surface layer (e.g. Niemi 1976). In autumn, after deep mixing of the water column production of particulate organic matter is not substantial. The matter sinks and decomposes, and the water becomes transparent.

The aim of the present study was to obtain preliminary information on the sinking, degradation and sedimentation of organic matter during different production stages, and to follow up the regulating hydrographic and chemical factors, especially the influence of the thermocline on the sinking. The ratio of phosphorus and nitrogen to carbon in particulate organic matter may be used as an index of its stage of degradation in different water layers and different seasons.

The analyses of the material from 1979 described in the present progress report are still in a preliminary stage. Consequently, we have chiefly reported the results and probable trends; the material is still too limited to make general conclusions.

2. STUDY AREA

The study area is situated at the entrance to the Gulf of Finland, southeast of Hanko Peninsula. The sampling station, located in the sea zone (according to Häyrén 1900, 1931), lies in a small basin west of a furrow (60 m) leading from Ajax to Tvärminne Storfjärd (Fig. 1). The depth at the sampling station is about 40 m. It is surrounded by shallows, however, and during rough weather particulate matter is transported from the sublittoral benthos to the basin. The sampling station is thus not particularly suitable for sedimentation studies, but this preliminary location was chosen for practical reasons.

The hydrography (and several biological parameters) in this outer part of the Tvärminne-Pojoviken area has been studied several times

during this century (Witting 1914, Halme 1944, Granqvist 1955, Niemi 1973, 1975, Launiainen 1977); the water chemistry and carbon production have been followed since the late sixties (Niemi 1973, 1975, Lassig et al. 1978, 1980) and there are recent studies on the water chemistry and phytoplankton (Niemi & Ray 1975, 1977, Forsskåhl 1980). Abundant basic data are thus available on the hydrography, hydrochemistry and primary production of phytoplankton in the study area, but these have chiefly been collected from Tvärminne Storfjärd (Station XII) and from Ajax in the open sea. The microbial populations in the area have been studied by Väätänen (1976). He found populations typical of the open Gulf of Finland at Ajax (Fig. 1), but reported that the stations near the coast are influenced by freshwater outflows from the land. The present sampling station seems to be situated in the transition area.

The coastal waters of the Gulf of Finland are characterized by rapid displacement of the boundaries of the different water masses. The study area forms a mixing region for the following water masses:

- Baltic surface water. Especially when SE-S-SW winds drive surface water towards the Finnish coast.

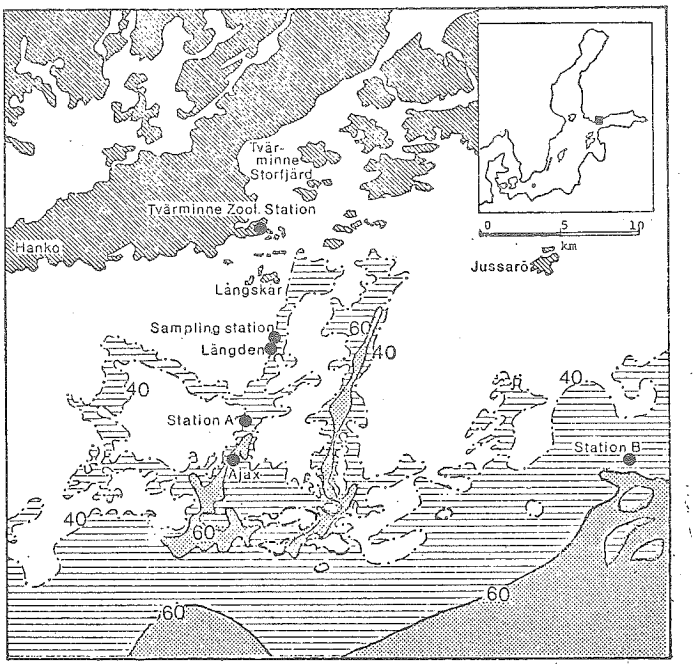


Fig. 1. Location of stations in the study area and schematic 40 m and 60 m isobaths.

- Surface water from the inner regions of the Gulf of Finland, typically flowing westward in early summer (Segerstråle 1951) and characterized by somewhat lower salinity than the surface water of the Baltic proper.
- Saline phosphorus-rich water welling up from the layers near the permanent halocline. During hard NW winds such upwelling is a familiar phenomenon in the Gulf of Finland southeast of the capes of Porkkala and Hanko (Sjöblom 1967, Voipio 1968, Niemi 1975).
- Fresh water flowing out from Pojoviken. According to Niemi (1973, 1975), the direct influence of this fresh water did not extend to the sampling area in 1968-1970, though the sampling station lies very near the transition zone. Knowledge of the water transport and connected meteorological data is essential to an evaluation of the environmental factors regulating production and sedimentation of organic matter in the study area.

The sedimenting organic matter at this sampling station comprises material of three different origins:

- Allochthonous material from the archipelago.
- Material resuspended from the nearby sublittoral or from the bottom after rough weather.
- Autochthonous material produced in the studied basin. The sampling station thus represents a coastal station, not an open-sea station. There is some influence from the sublittoral, though no direct freshwater outflows from the coast.

3. MATERIAL AND METHODS

3.1 Sampling and chemical and biological analyses

The water samples were taken with a 2-l Ruttner Sampler equipped with a mercury thermometer. The salinity was measured with an Autosal Laboratory Salinometer Model 8400. Orthophosphate, total phosphorus, nitrate, nitrite, ammonium, total nitrogen and silicate were determined by the standard methods used at the Institute of Marine Research, Helsinki (Koroleff 1976, 1979). Organic carbon was determined as total organic carbon (TOC) and particulate organic carbon (POC). TOC was measured with a Beckman Non-Dispersive Infrared Analyzer Model 865 (Perttilä & Tervo 1979). The POC samples were filtered through precombusted (500 ^{o}C, overnight). Whatman GF/C glass-fibre filters (1 µm pore size) and carbon was determined by the wet oxidation method with dichromate-sulphuric acid (Koroleff & Grönlund, 1978, with modif.).

The methods used for the determination of particulate nitrogen (PON) and particulate phosphorus (POP), were those employed for seawater samples (Koroleff, F. - In: Grasshoff, K. (ed.), Methods of seawater analyses, 2nd ed., in press). At first precombusted filters were used, as in carbon determination. However, as it was found that the filters were very easily contaminated during the ignition procedure, pretreatment was discontinued and smaller blank values were then obtained for both nitrogen and phosphorus. The filters were oxidized with potassium persulphate solution, the same method being used as in the determination of total nitrogen and phosphorus in seawater. Due to the presence of oxidizable matter there must be a tenfold excess of oxygen during persulphate oxidation. Consequently, when 4 ml of oxidizing solution is used, the total carbon content must be less than about 400 µg C/filter. The amount of filtered water varied from 250 to 500 ml. After autoclaving the samples were mixed well and cooled, and 35 ml of deionized water was added (total volume 39 ml). The samples were filtered before spectrophotometry to clear them of suspended partially decomposed filter.

Five millilitres was used for the nitrogen determination, 30 ml for the phosphorus. The reproducibility of the methods was observed to be better than $\pm$ 5 %. Work is in progress on the further development of these methods.

The total organic nitrogen in the water was calculated by subtracting nitrate-, nitrite- and ammonium nitrogen from the total nitrogen concentration. Particulate nitrogen (PON) is the same as total particulate nitrogen.

The total organic phosphorus in the water was calculated by subtracting phosphate phosphorus from the total phosphorus concentration. Particulate phosphorus (POP) is the same as total particulate phosphorus.

Phytoplankton primary production and chlorophyll *a* were determined by the staff of the Biological laboratory according to the standard methods used at the Institute of Marine Research, Helsinki: Primary production was determined by the radiocarbon method in situ (Steemann Nielsen 1952, Lassig & Niemi 1972) and chlorophyll *a* as described by the BMB (Edler 1979, see also Bruun & Grönlund 1981).

3.2 Physical measurements

In addition to the measurements of temperature and salinity made on the samples, the current velocities and directions were measured at

two stations: station A in the sea zone of the archipelago, near the sampling place, and station B, well outside the coastal region, representing conditions in the open waters of the Gulf of Finland, Fig. 1. At both stations the measuring instruments were located at depths of 10 m and 30 m the latter thus lying well below the summer thermocline. A thermistor chain was moored near the current meters at station B, extending from 8 to 33 m. Unfortunately, this chain was lost in August, so that these temperature records last only to the first maintenance time, i.e. 17.7.1979.

An automatic meteorological station on the east side of Långskär recorded wind velocity and direction, temperature and total irradiance at 30-minute intervals. Some wind vector time series were recorded at Russarö weather station (Finnish Meteorological Institute), about 6 km south of Hanko.

3.3 Sedimentation measurements

Sedimenting material was collected during the period 9.5 - 4.12.1979, on the following dates: 18.5., 30.5., 12.6., 5.7., 19.7., 2.8., 15.8., 5.9., 18.9., 4.10., 23.10., 13.11., 4.12.

The sediment traps used in this study were made from four polyethylene wash-bottles (diameter 90 mm) equipped with polypropylene

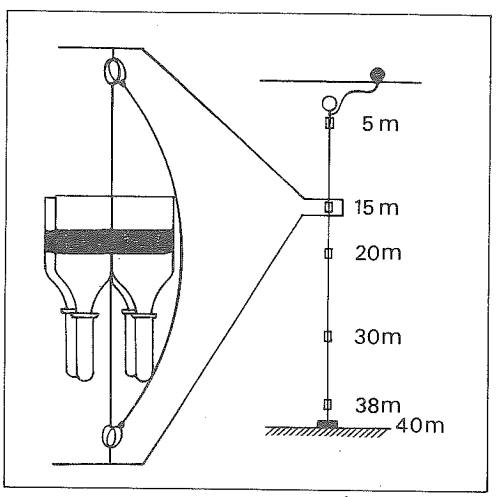


Fig. 2. The sediment traps used in this study were made from four polyethylene wash-bottles equipped with four polypropylene test-tubes. All five traps were attached to the same anchor line at the depths shown in the figure.

test-tubes (diameter 30 mm). The traps were placed at the following depths: 5, 15, 20, 30 and 38 m (the water depth was 40 m). The lifting buoy was situated at 4 m (Fig. 2). It is clear that in rough weather wave action on the buoy can be assumed to cause some disturbance in the sedimentation measurements. However, in spring and summer the weather conditions were moderate, so this disturbance was probably slight.

After sampling, most of the water in the test-tubes was decanted, and the samples were frozen within two hours. The remaining water was later evaporated in a vacuum freezer and the samples were homogenized. The dry weight of the sedimented material and its content of organic carbon, nitrogen and phosphorus were determined. The wet oxidation method using potassium dichromate and concentrated sulphuric acid (Caudette et al. 1975, with some modifications) was used to determine organic carbon. Total nitrogen and phosphorus were determined by a Kjeldahl digestion.

4. HYDROGRAPHIC CONDITIONS DURING THE STUDY PERIOD

At the beginning of the field experiment, exceptional hydrographic conditions prevailed in the study area. During the previous autumn and winter, water with a salinity well above the average had flowed into the region. After local mixing the salinity of this water mass was of the order of 6.6 to 6.9 ‰.

Thus, strong mixing readily occurred due to lack of a strong vertical salinity gradient. This can be seen in Fig. 3, which shows an almost homogeneous water column at the end of April. In early May there was an outflow of less saline water from Tvärminne Storfjärd, followed by an inflow of water with higher salinity in the bottom layers. A slight halocline formed and a thermocline then developed, so that there was a gradual change towards summer stratification. The temperatures at this time were low, however, and thus the mixing layer remained remarkably deep.

During the first half of May the winds were moderate to weak, causing fluctuations in the depth of the thermocline and occasional downwelling. During the second half of May south-west winds prevailed, with occasional strong winds from the north-east. In early June the winds were moderate, except on 9 June, when a major cyclone passed, causing strong fluctuations in the pycnoclines, followed by inertial movements in the surface layer.

The influence of the strong SW winds in June can also be seen in

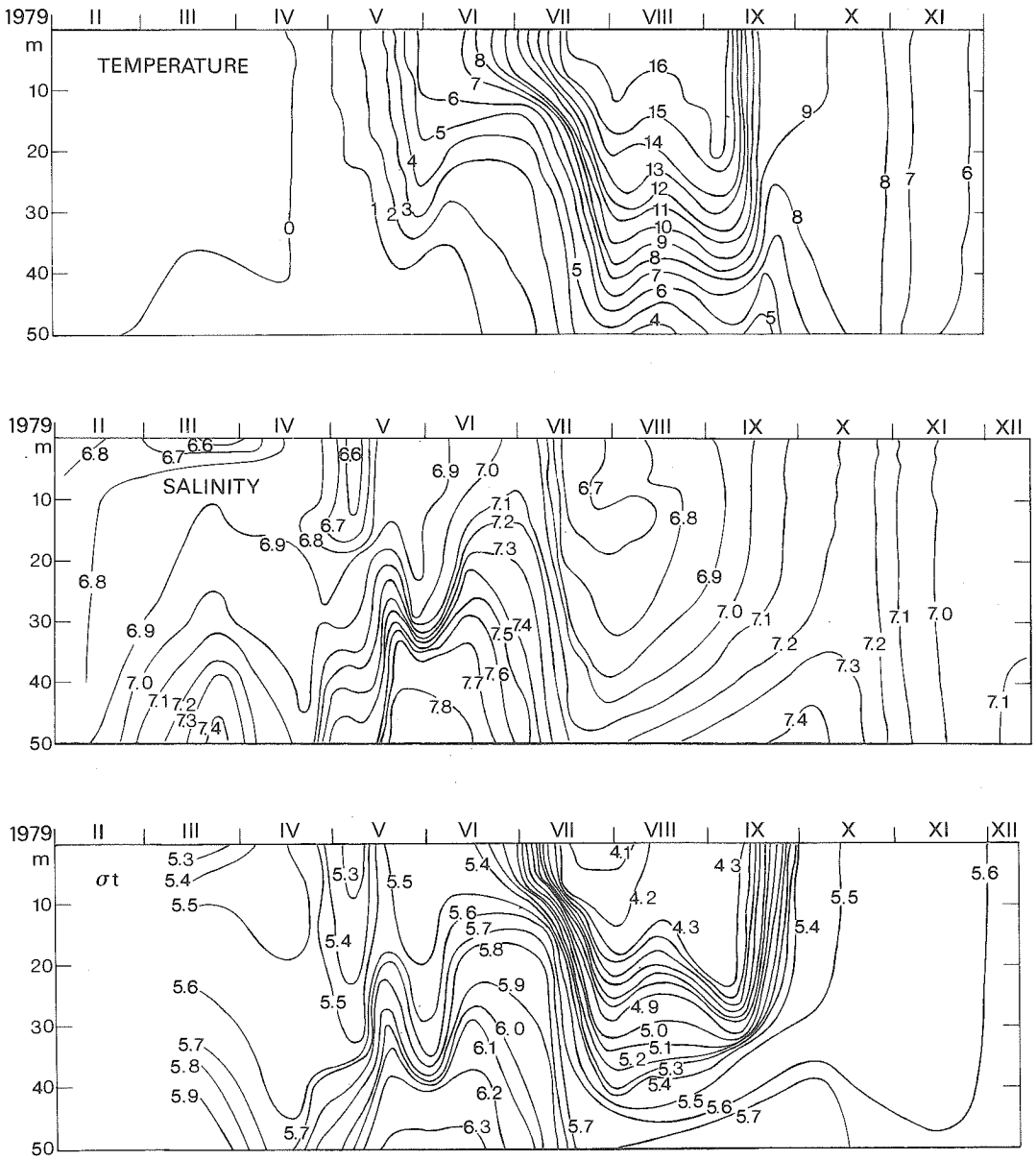


Fig. 3. Isopleths of temperature (°C), salinity (S‰) and density (T_t) during the study period at the Längden station.

the depth of the halocline. Ekman drift away from the coast in the surface layer was evidently combined with a corresponding inflow in the deeper layer, which caused a rise in the halocline.

At station A thermal stratification developed gradually until the beginning of August. In the open sea at station B, no significant changes were observed in the thermocline until mid July, when the mixed layer deepened to about 20 m. It remained at this depth until mid September. The salinity stratification continued unchanged during the period 15 July to September. On 12 September, strong mixing was initiated by a south-westerly storm within a few days the surface temperature sank to 10 ^{o}C and the stable stratification at station A almost completely disappeared. After removal of the pycnocline, mobilization of particulate matter from the surroundings was intense. This can be seen in the increased concentrations of particles in deeper layers (Table 3), and increased sedimentation rates after the storm. In the bottom layer the salinity increased somewhat till the beginning of October, when mixing penetrated down to the bottom.

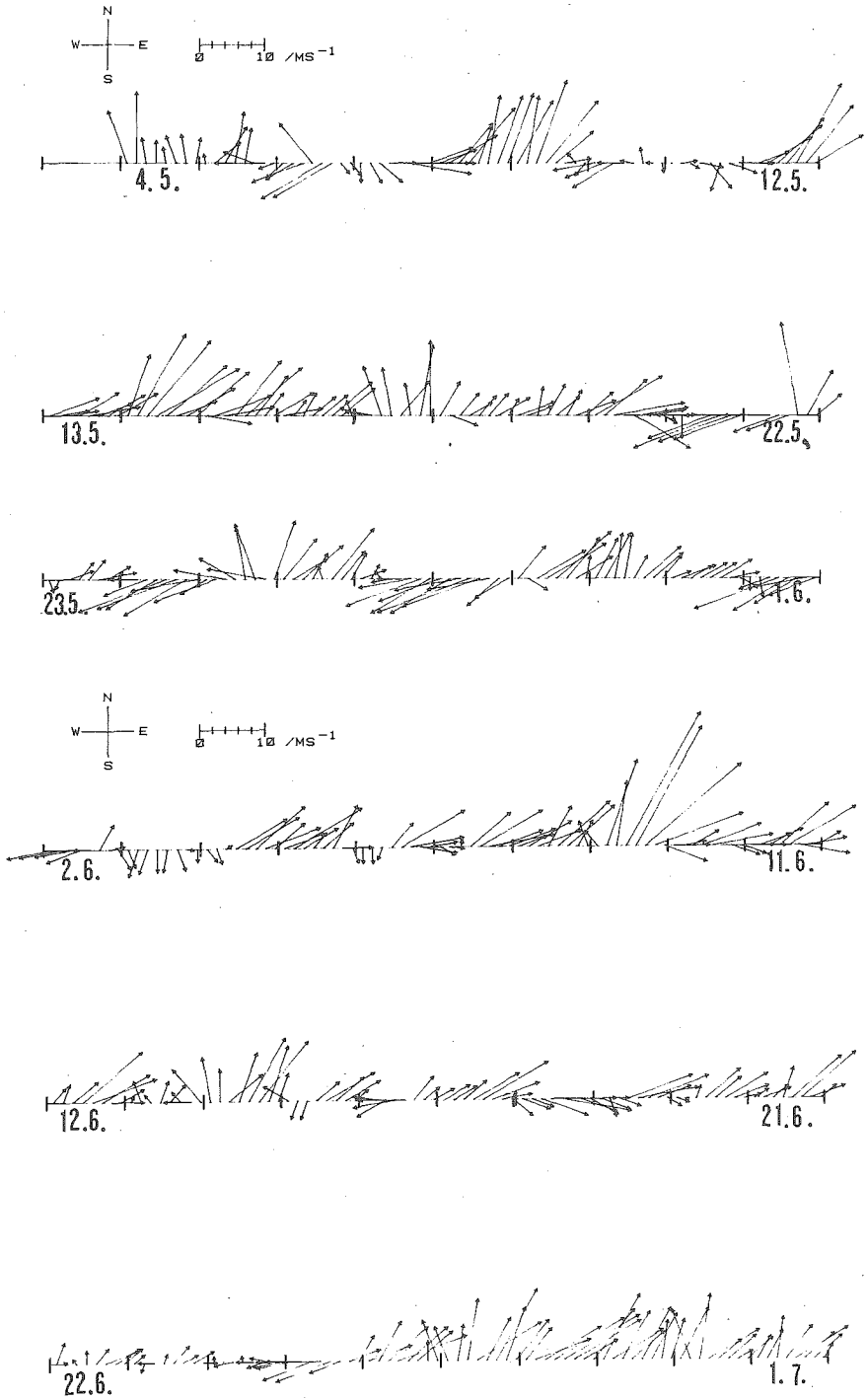
5. CURRENTS

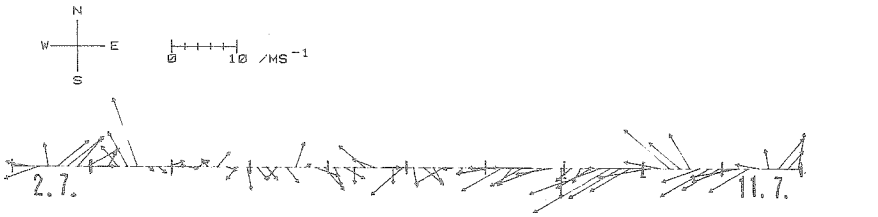
The prevailing weather conditions were typical of these seasons: relatively long calm periods interrupted by the passage of single cyclones. The wind vector time series are presented in Fig. 4. The corresponding progressive vector diagrams of current velocities are presented in Fig. 5a-c.

From late May till early June, the winds were variable, mainly east-north-east, as were also the currents in the surface layer both in the coastal region (current station A) and in the open sea (current station B). In the deep layer (30 m) the current was directed towards the coast.

Between 7 and 18 June the winds blew mainly from the west and the surface currents were directed eastward. During that period the channel in which station A was situated showed deep water flow towards Tvärminne Storfjärd, as can also be seen in the increase of the bottom salinity. Between 19 and 23 June the winds were mainly the south-west. The surface currents in both the coastal region and the open Gulf of Finland were flowing towards the south-west as a continuation of the cyclonic circulation in the Gulf of Finland. The flow in the deep layers of the channel was towards the south. From midsummer to 3 July, the wind direction remained the same, and the

Fig. 4. The wind vector time series recorded at the automatic weather station at Längden and at Russarö weather station (Finnish Meteorological Institute). Note the different scales 4.5. - 31.7. and 1.8. - 28.11.

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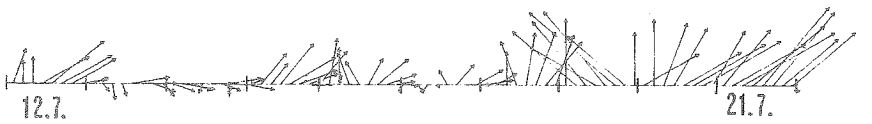
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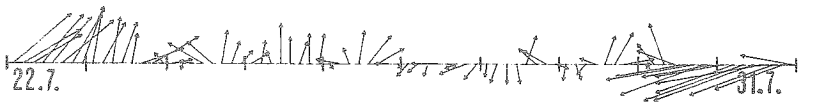
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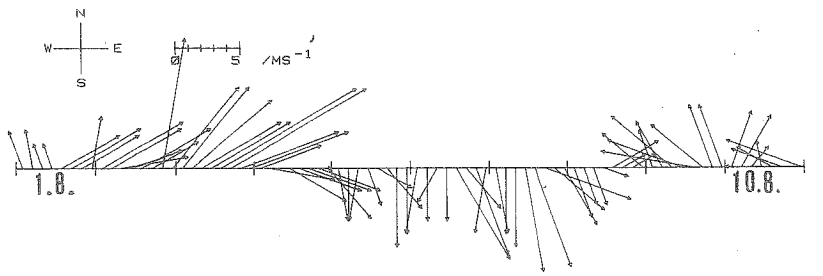
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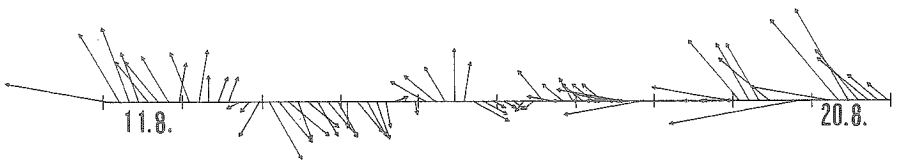
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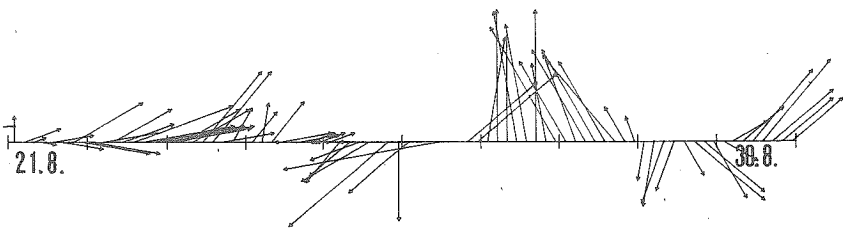
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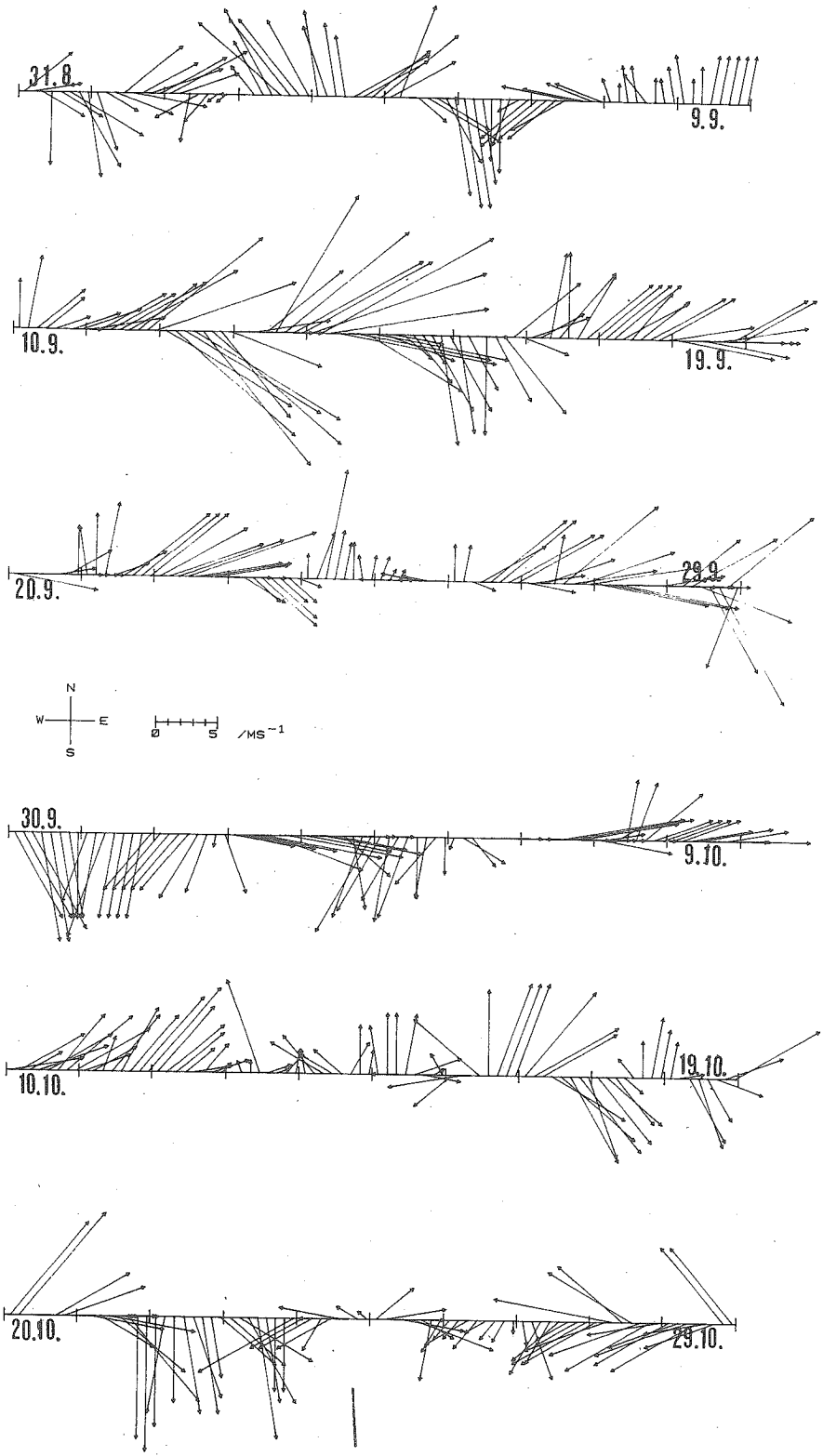
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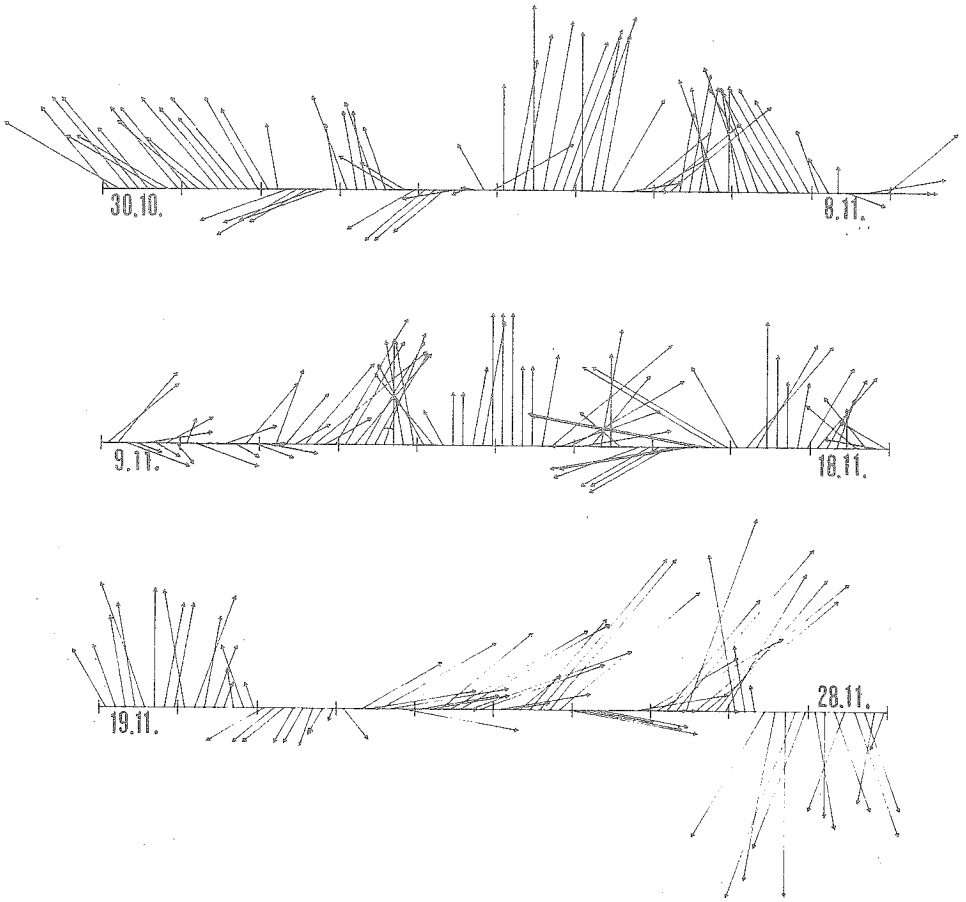

surface current in the coastal region and open sea area was directed towards the west. In the period 4 - 7 July the winds were very weak and the surface layer mainly showed inertial circulation, whereas the deep layer flowed towards the sea. Between 8 and 12 July the wind blew from the east-north-east and the surface current followed its direction closely, the deep flow also being towards the sea. On 13 - 18 July both the winds and the surface currents were again weak. During this time, however, the deep flow was directed towards Tvärminne Storfjärd. During the period 18 - 23 July there were moderate to strong SW winds, the maximum wind velocities being about 13 m/s. In the coastal region this mainly resulted in inertial circulation, but in the sea area there was a steady Ekman drift towards the south-east, and the deep flow in the channel was directed towards Tvärminne Storfjärd. After that the winds remained weak and the movement of the surface layer was west-south-west along the coast of the Gulf of Finland. During this period the flow in the deep layer was directed

Fig. 5. Progressive vector diagrams of current velocities at different observation sites. The scales in the margins denote 20 km of transport. 12-hour intervals in the vector diagrams are marked with +, the starting point with a cross.

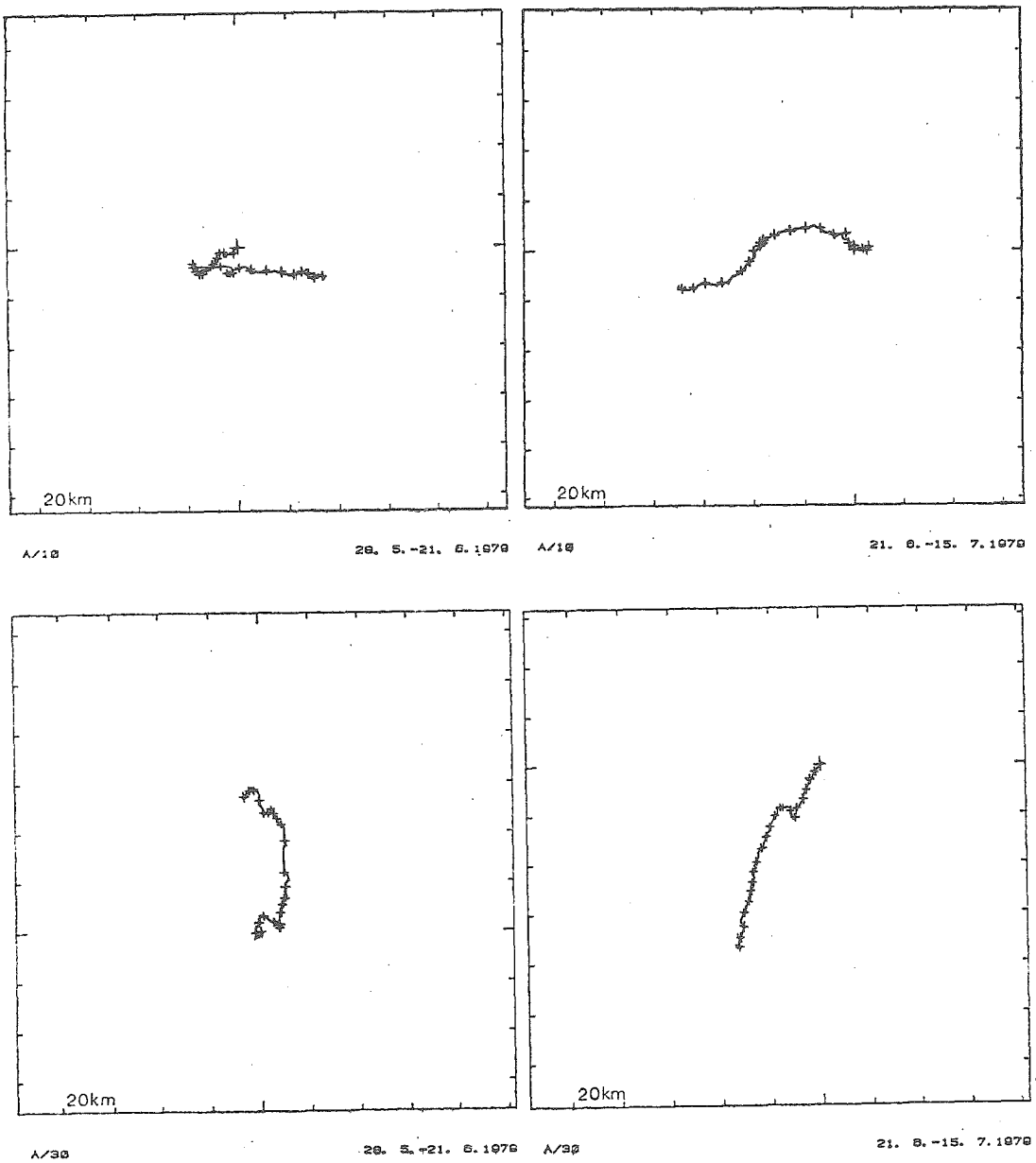

Fig. 5a. Station A, 10 m and 30 m depths, period 28.5.-15.7.1979.

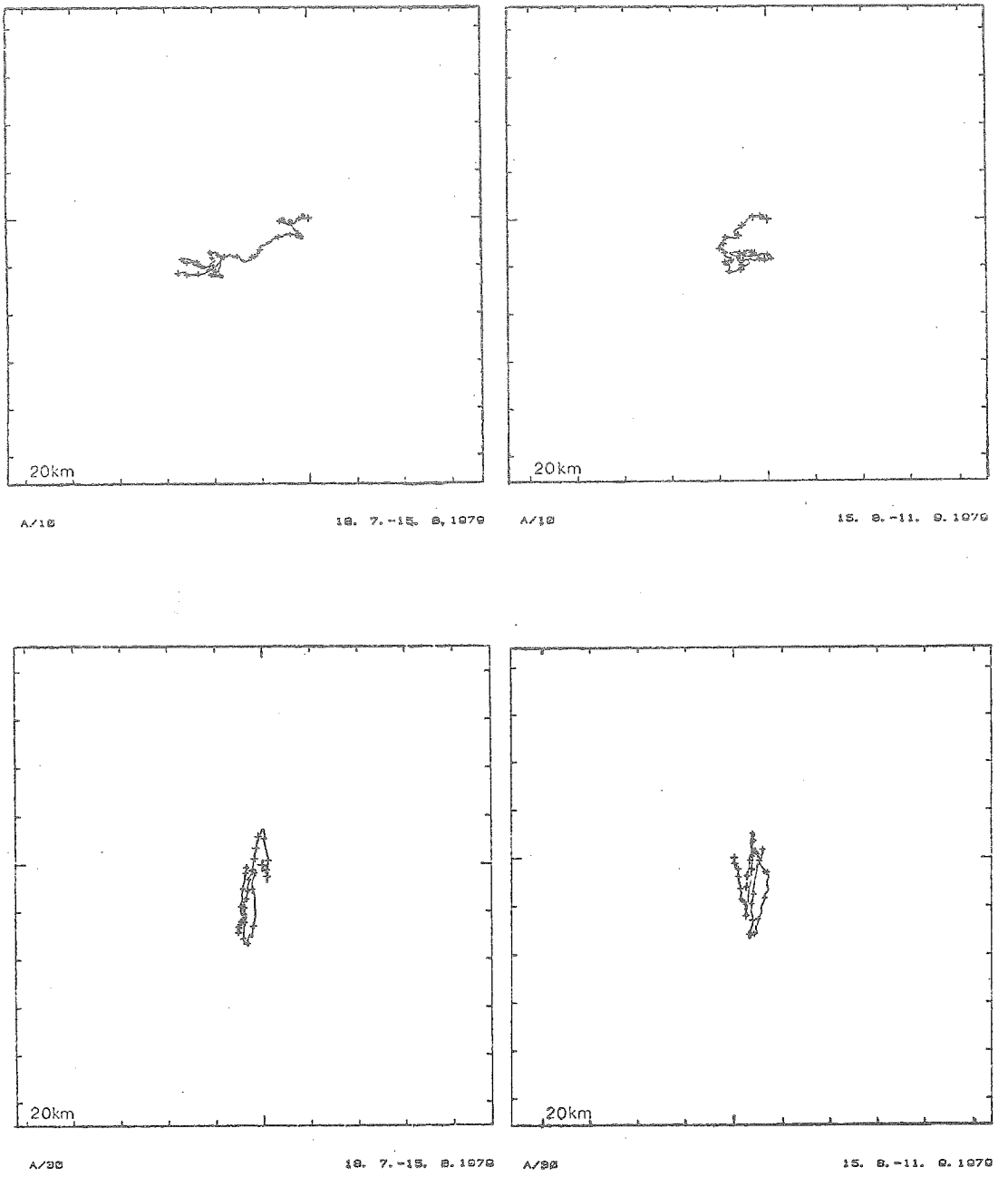

Fig. 5b. Station A, 10 m and 30 m depths, period 18.7.-15.8.1979.

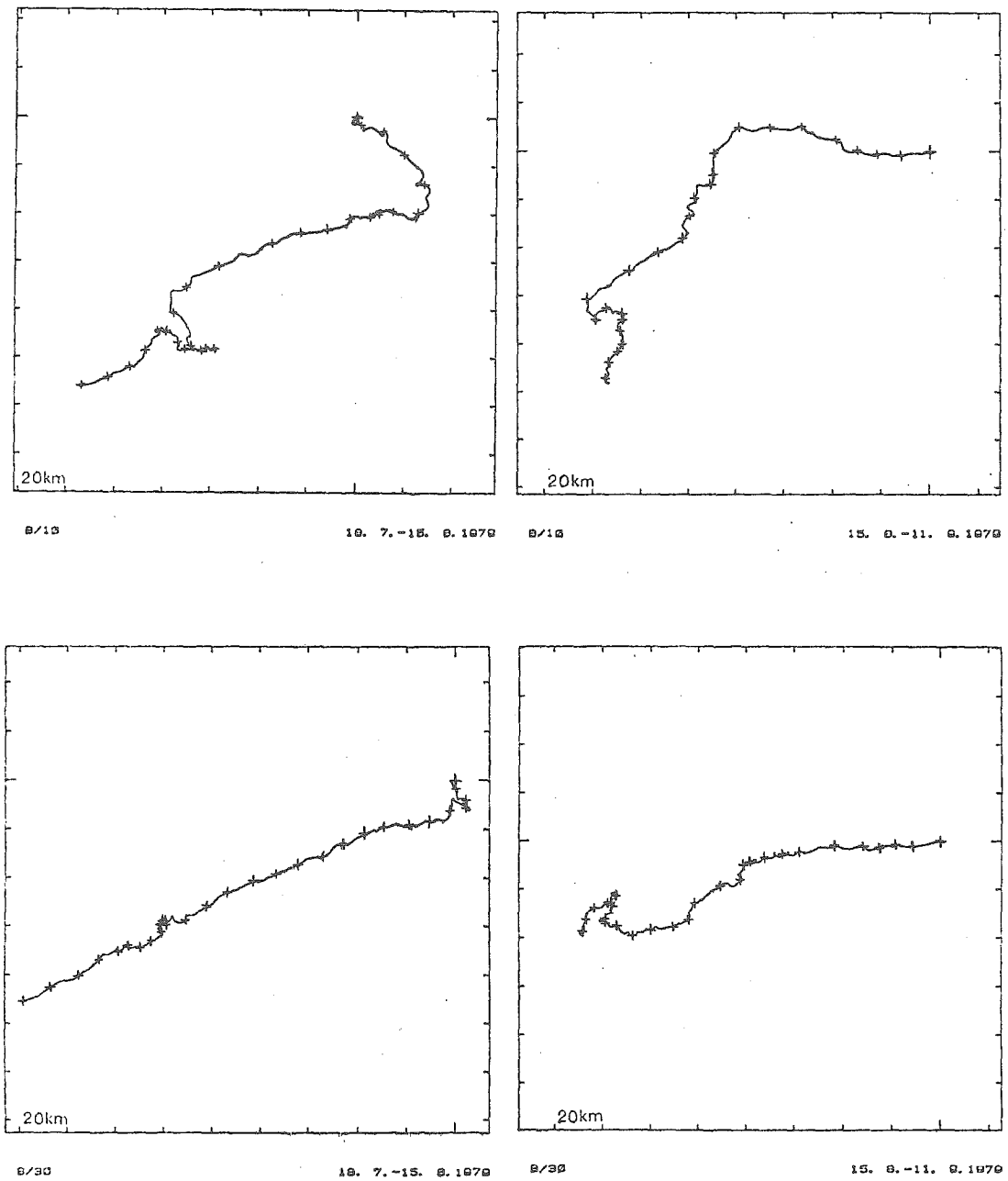

Fig. 5c. Station B, 10 m and 30 m depths, period 18.7.-15.8.1979.

towards the south. The strong winds of 18 - 23 July caused considerable baroclinicity throughout the Gulf of Finland, as is clearly evident from the hydrographic data for that period (IMR, unpubl. data). Due to the baroclinicity the homogeneous surface layer showed strong west-south-west ward flow. The circulation in the study area was thus dependent on the conditions in the open sea. The situation continued unchanged, although the winds remained weak until the end of July. During the last days of July strong east-north-eastern winds caused strong flow along the coast and seaward flow in the deep layers in the coastal region. During the first days of August SW winds caused a change in the current direction in the surface layer, while the current in the deep layer of the sea area continued to move west-south-west. During the period 5 - 8 August the winds were rather weak and the currents mainly showed a weak northerly component, including some inertial oscillations. The situation at the coastal station A remained the same until the middle of August, whereas at the outer station B the current followed the direction of the wind.

TABLE 1. Means and standard deviations of current velocity components u (due east) and v (due north) during the study period. Units: cm/s
The values in parantheses are calculated from observations covering only part of the month.
Some observations are missing for July, because of maintenance work on the measuring instruments (about 17.-18.7.).

		MAY		JUNE		JULY		AUGUST		SEPTEMBER	
		A	B	A	B	A	B	A	B	A	B
10 m	u_{mean}	(-2.94)	(-9.83)	1.08	-1.24	-4.18	-4.72	-1.01	-7.55	(0.68)	(0.71)
	SD	(3.6)	(2.3)	6.6	7.7	5.0	8.6	6.7	8.6	(5.7)	(6.4)
	v_{mean}	(-0.73)	(-4.24)	-0.04	0.14	-1.86	-2.57	-0.70	-4.18	(-0.55)	(-3.95)
	SD	(3.7)	(3.2)	4.2	6.1	4.3	7.0	4.9	7.5	(3.8)	(6.2)
30 m	u_{mean}	(-0.22)	-	-0.94	-	-0.88	-7.47	0.18	-7.97	(-0.16)	(-2.6)
	SD	(2.6)	-	3.1	-	2.6	(6.9)	3.3	5.9	(3.3)	(6.0)
	v_{mean}	(1.66)	-	1.09	-	-2.47	(-3.46)	-0.73	-3.12	(1.55)	(-0.04)
	SD	(4.6)	-	5.9	-	5.6	(5.4)	8.9	5.4	(10.0)	(6.5)

On the basis of the conditions described above, some general remarks can be made concerning the currents (Fig. 5 and Table 1).

- At station A, where the bulk of the observations were made, the currents in the deep layers were mainly directed northward, i.e. towards the coast, or southward, towards the Baltic Proper.
- In the surface layer at the same station, the current did not always follow the direction of the wind. It is probable that the proximity of the coast causes some local eddies, which behave in their own way.
- At station B the currents varied much less than at the inner station. The surface currents followed the wind direction more closely, with some major exceptions, which are mainly due to the circulation in the whole of the Gulf of Finland. In the deep layer (30 m), the current direction was mainly west-south-west, following the circulation in the Gulf. It can thus be seen that the variability of the currents at station B can be understood only against the background of the general circulation pattern in the western Gulf of Finland. Occasional storms of short duration caused considerable inertial movements, observable in both the current measurements and the thermocline variations; for example during the storm of 9 June, the oscillation in the thermocline depth reached a maximum amplitude of approximately 6 m (Fig. 6). The oscillation was damped down, however, within 2 to 3 cycles. Variable winds also caused a set of internal waves, which can clearly be detected in the thermistor chain observations (Fig. 6). The considerable variations in the currents and the oscillations in the thermocline will, of course, create difficulties in the interpretation of the sedimentation observations.

6. PRIMARY PRODUCTION, CHLOROPHYLL AND INORGANIC NUTRIENTS

In winter low chlorophyll *a* values showed that the level of primary production remained low until mid April (Fig. 7). However, the decreasing NO_3-N and PO_4-P concentrations in early April indicate that the vernal phytoplankton production had an early start. The maximum of the vernal phytoplankton bloom (Fig. 7) was observed in late April, when the primary production of carbon rose above 1 $g\,m^{-2}d^{-1}$. Depletion of NO_3-N in the mixed surface layer in late April caused the end of the vernal maximum. Since there was still plenty of PO_4-P (>10 mg m^{-3}) at that time, this supports the observations made by Niemi (1975) in 1968-1970 that the duration of the vernal high production stage seems to be regulated by nitrate nitrogen. The time

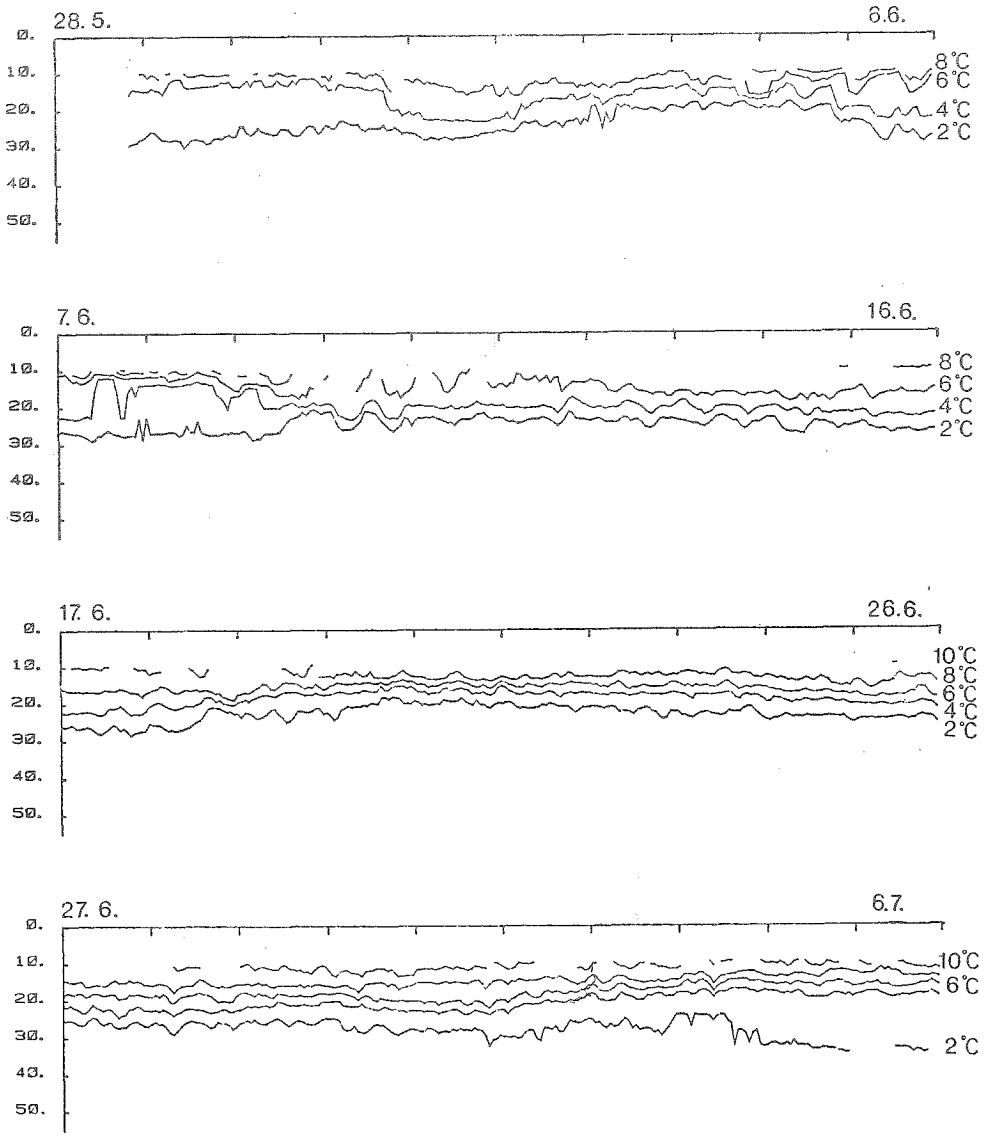

Fig. 6. Variation of the temperature as measured by a thermistor chain at Station B (22.5.-6.7.1979).

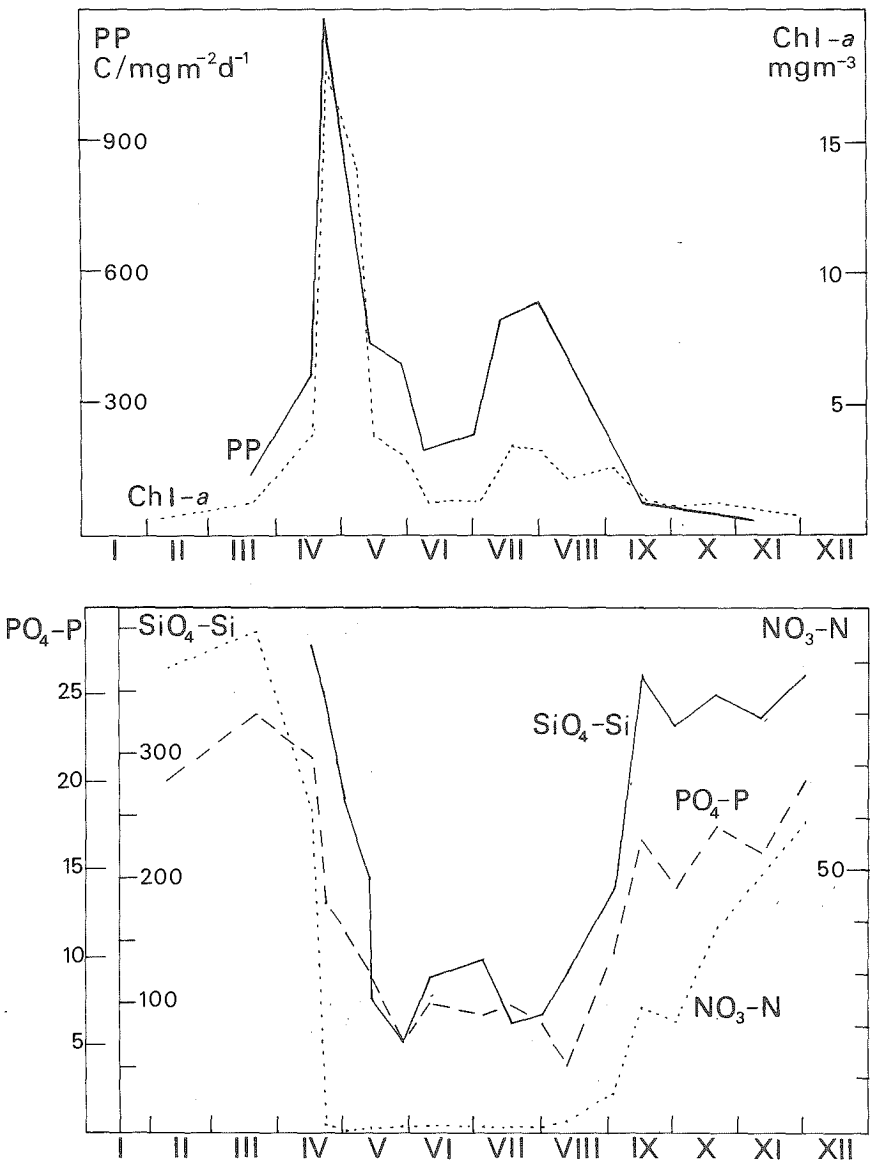

Fig. 7. The primary production (PP) and chlorophyll *a* (IMR, biol.lab.) compared with the inorganic nutrients NO_3-N(mg m^{-3}), PO_4-P (mg m^{-3}) and SiO_4-Si (mg m^{-3}) in the surface layer ($\bar{X}$,0–15 m) at Längden.

of the SiO_4-Si minimum indicates that the production of diatoms had largely ended by late May. This is also in agreement with the results from 1968-1970. During the growing season in the present study, the PO_4-P level did not fall below 5 mg m^{-3}. No measurable amount of NO_3-N was found in the mixed surface layer before late August, when mixing caused by rough weather transported inorganic nutrients from the winter water (and perhaps from layers near the permanent halocline) into the euphotic layer, markedly increasing its level of nutrients.

The vernal maximum of primary production was followed by a summer minimum in June (primary production of carbon 200-250 mg $m^{-2}d^{-1}$. In late July and early August another production peak occurred (ca. 700 mg $m^{-2}d^{-1}$) caused by nanoplankton and blue-green algae. The smallness of the biomass (estimated as chlorophyll *a*) in relation to the fairly high level of primary production gave a high activity coefficient during this production stage (cf. Niemi 1975).

No autumnal diatom peak was observed this year owing to absence of stability in the water column, a prerequisite for effective phytoplankton production in autumn (cf. Niemi & Ray 1977, Hällfors & Niemi 1981). Rough and cloudy weather causing circulation of phytoplankton below the critical depths for production (Sverdrup 1954) explains the unusually low production from September on.

The following different stages of production of organic matter could be discerned in 1979:

- Winter stage in late March; little or no production
- Vernal stage from early April to mid May; high production
- Summer minimum stage of production of organic matter; high activity coefficient.
- Late summer stage characterized by nanoplankton and occasionally dominant heterocystous blue-green algae in late July early August; relatively high production.
- Autumnal stage from September on characterized by gradually decreasing production of organic matter. No autumnal diatom peak.

When these results are compared with those for the years 1968-1970 (Niemi 1973, 1975), there is a good agreement in the pattern of phytoplankton production and the levels and seasonal fluctuations of inorganic nutrients, except for the rather high level of phosphate phosphorus in the surface layer in the summer of 1979. This increase in the phosphorus concentration seems to be connected with

hydrographic changes during the seventies (e.g. Nehring 1979, Fonselius 1980, Lassig et al. 1980, Perttilä et al. 1980 and Voipio 1980) and upwelling of phosphorus-rich water from the halocline at the entrance to the Gulf of Finland.

7. CHEMICAL COMPOSITION OF SESTON

Total particulate organic matter consists of two parts: the living part made up of planktonic organisms and microbes, and the non-living part made up of detritus. The term seston covers the living plankton together with detritus and inorganic particles. Particulate organic nitrogen is often used as a basis for the determination of the amount of proteins. Therefore the C:N ratio supplies some general information on the composition of suspended organic matter. The more protein compounds present, the smaller the C:N ratio will be, as a result of the higher nitrogen content. Proteins are more rapidly decomposed in water than higher molecular carbohydrates and lipids (Rheinheimer 1975). Thus the C:N ratio increase, when plankton degrades to detritus (Lenz 1977).

Concentrations of particulate organic carbon, nitrogen and phosphorus are given in Table 2 and Fig. 8. The maximum values were

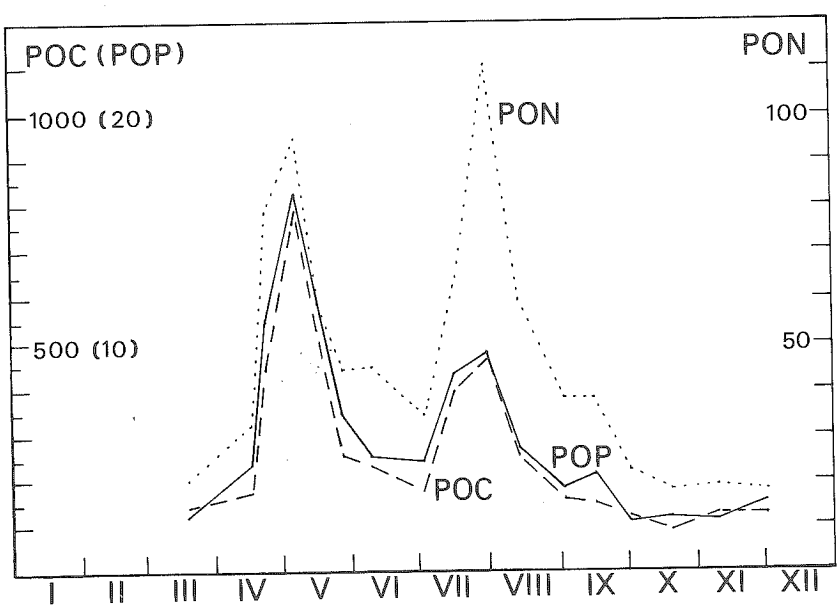

Fig. 8. The concentrations (mg m^{-3}) of particulate organic carbon (POC), particulate nitrogen (PON) and particulate phosphorus (POP) in the surface water ($\bar{X}$ 0-10 m) at Längden.

TABLE 2. Particulate organic carbon (POC), particulate nitrogen (PON) and particulate phosphorus (POP), mg m^{-3}.

POC

depth (m)	22.3.	18.4.	24.4.	8.5.	16.5.	29.5.	11.6.	4.7.	18.7.	1.8.	14.8.	4.9.	18.9.	4.10.	23.10.	13.11.	4.12
0	230	135	465	810	405	245	270	170	400	790	330	160	190	120	95	90	155
6	120	185	410	815	580	270	220	180	420	335	260	155	135	95	95	145	110
10	80	215	475	825	520	235	185	160	370	270	165	170	130	145	90	115	145
20	75	115	425	580	295	125	200	95	240	180	105	155	260	155	125	-	115
30	100	65	375	450	195	165	230	105	305	140	115	140	185	110	75	90	110
40	80	75	215	290	215	230	155	170	255	155	125	260	290	125	95	110	145
50	150	105	175	455	150	240	245	335	370	320	285	380	310	160	125	110	135

PON

depth(m)																	
0	28	27	70	99	60	44	44	32	62	210	69	40	57	18	19	15	20
6	17	32	80	87	62	52	41	33	70	73	60	37	30	24	17	22	19
10	16	39	89	107	55	39	57	37	55	64	48	39	28	24	17	19	18
20	8	17	78	87	46	34	58	24	37	38	25	38	42	21	18	18	16
30	-	8	76	77	38	40	59	19	40	27	22	23	31	21	19	17	16
40	11	7	39	57	39	56	47	31	37	29	27	47	39	19	18	19	18
50	21	7	32	42	32	44	33	62	55	51	41	72	49	26	22	23	20

POP

depth (m)																	
0	3.7	5.0	11	15	8.1	7.0	5.1	5.5	8.7	13	5.7	4.2	6.9	1.9	2.6	2.1	3.2
6	2.2	4.3	11	16	9.0	7.8	5.5	4.7	9.4	8.4	5.5	3.3	3.1	2.6	2.6	2.6	3.2
10	1.2	5.3	11	20	7.7	6.1	4.5	5.4	6.0	6.4	4.1	3.3	3.1	2.5	2.6	2.7	2.8
20	.93	2.8	11	14	5.6	4.7	4.4	2.9	3.1	4.7	2.5	3.4	3.3	1.8	2.5	2.7	3.0
30	-	1.5	11	13	4.6	6.4	4.4	3.1	3.8	5.5	2.5	2.3	4.9	2.3	2.9	2.7	3.2
40	1.9	1.9	5.0	12	5.3	9.0	3.7	6.1	5.9	5.2	4.7	6.9	6.7	3.0	2.8	2.9	4.1
50	4.3	1.5	5.0	11	3.7	7.7	6.8	12	11	10	6.8	12	8.7	5.5	4.4	3.7	4.5

encountered in early May and late July - early August in the surface layer in connection with high production of phytoplankton. Low values were found in mid May in the inflow saline water in the near-bottom layer. After the turnover in early October, the POC, PON and POP concentrations were low owing to low production of phytoplankton and biodegradation of particulate organic matter. During the growing period from late April to late August, POP made up a large percentage of the total phosphorus, but its proportion decreased rapidly after mixing of the water column from early September on (Figs. 9 and 10). The same applies to POC and PON (Fig. 9), although their percentage of total carbon and total nitrogen are evidently smaller (cf. Leppänen & Tamelander 1981).

Fig. 11 shows the ratios between the concentrations of POC, PON and POP in the surface ($\bar{X}$, 0-10 m) and winter water ($\bar{X}$, 30-40 m). The ratios were great during the high production in spring and early August, but low during the low production of phytoplankton in June and July and also after the mixing from early September on. In autumn the

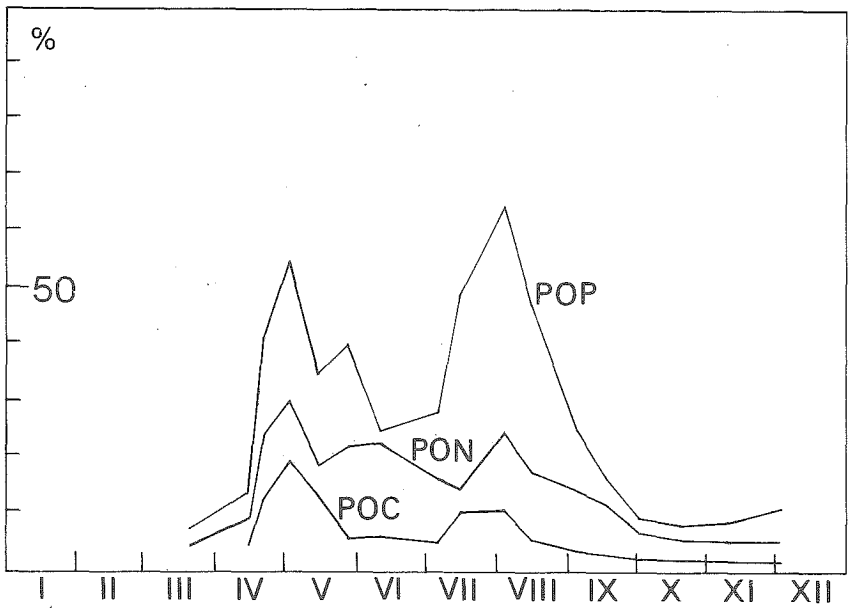

Fig. 9. POC, PON and POP expressed as percentages of total C, N and P, respectively, in the surface layer.

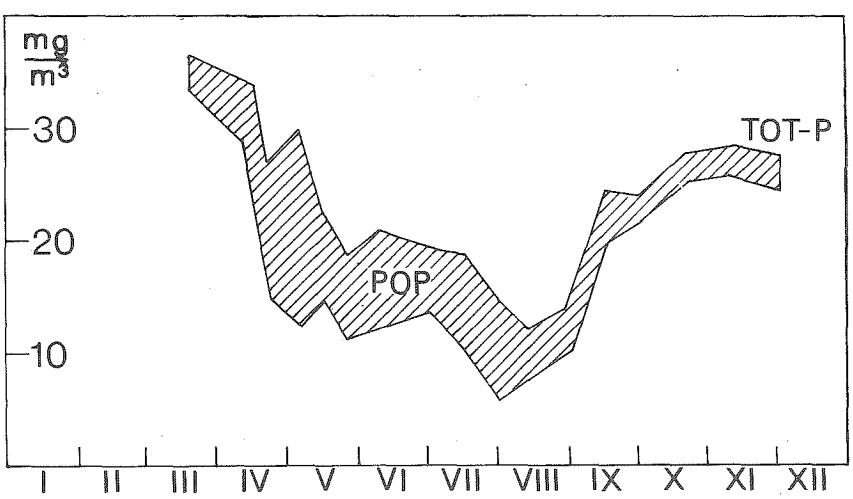

Fig. 10. The concentrations of total phosphorus and particulate phosphorus (> 1 µm) in the surface water during the study period.

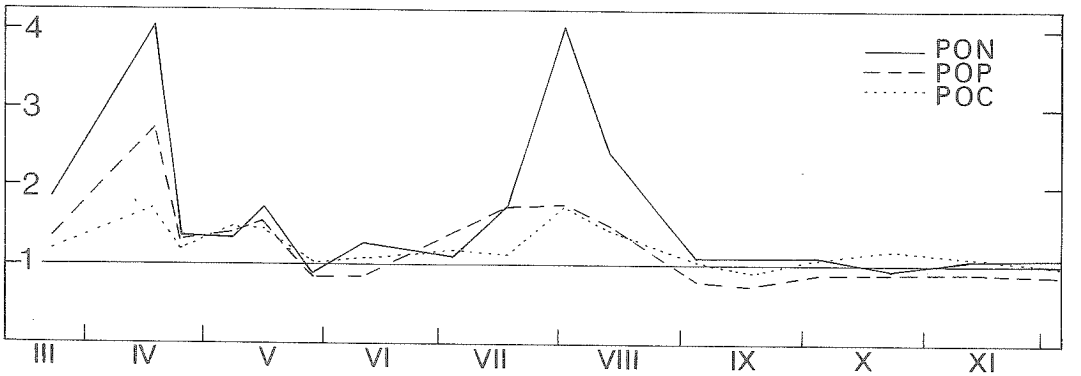

Fig. 11. The ratios between the concentrations of POC, PON and POP in the surface (0-10 m) and winter water (30-40 m).

POP values were higher near the bottom than in the surface layer. The contrast between the high PON ratios in April and early August and the low summer and autumn values possibly shows that the nitrogen in the organic matter passes rapidly into solution in the deep layer. The difference between the corresponding POP values is not so great perhaps owing to the presence in the deep layer of resuspended particles containing ferric phosphates.

In general, the C:N:P ratios of the seston show no clear trends (Tables 4 and 5). A low C:N ratio occurred during the blue-green algal stage, possibly indicating fixation of molecular nitrogen. The highest N:P values were found in summer (July-August), the lowest after the spring bloom and after the autumnal turnover. No significant trends were found in the C:P ratios.

8. SEDIMENTATION DATA

The total sedimentation of particulate matter and carbon (sampled in traps) in different depth layers are given in Fig. 12 and Table 3. In the upper layer (0-15 m) the sedimentation rate decreased from May, reaching a minimum in July (<10 mg C $m^{-2}d^{-1}$) during the low production stage of phytoplankton. In August the sedimentation rate increased in connection with the late summer production peak of phytoplankton (Fig. 7). Notwithstanding the low phytoplankton production, high sedimentation values were recorded from September on. The high values near the bottom indicate that this was due to stormy weather causing resuspension of matter, probably from the bottom and the sublittoral.

TABLE 3. Sedimentation as dry weight and organic carbon.

$gdwm^{-2}d^{-1}$

depth	9.5.-18.5	30.5.	12.6.	5.7.	19.7.	2.8.	15.8.	5.9.	18.9.	4.10.	23.10.	13.11.	4.12.
5	.71	.20	.26	.13	.09	.27	.34	.44	1.2	1.4	2.2	10	9.0
15	.74	.36	.80	.29	.08	.27	.45	.55	2.7	3.9	5.0	34	35
20	-	-	-	-	.12	.36	.74	.85	4.3	5.1	5.8	40	43
30	1.8	.81	3.1	.89	.51	1.2	1.7	1.0	35	8.6	8.1	63	51
38	2.7	.97	6.6	1.6	2.4	5.0	5.2	6.0	110	16	14	73	57

$mgCm^{-2}d^{-1}$

depth	9.5.-18.5.	30.5.	12.6.	5.7.	19.7.	2.8.	15.8.	5,9,	18.9.	4.10.	23.10.	13.11.	4.12.
5	85	26	25	8	8	20	17	26	69	63	105	430	360
15	87	28	75	24	5	19	28	35	140	200	245	1410	1390
20	-	-	-	-	10	24	51	52	210	250	280	1660	1850
30	235	105	255	65	37	81	115	64	1540	420	390	2520	2060
38	355	95	470	89	130	275	195	345	5220	785	650	2640	2380

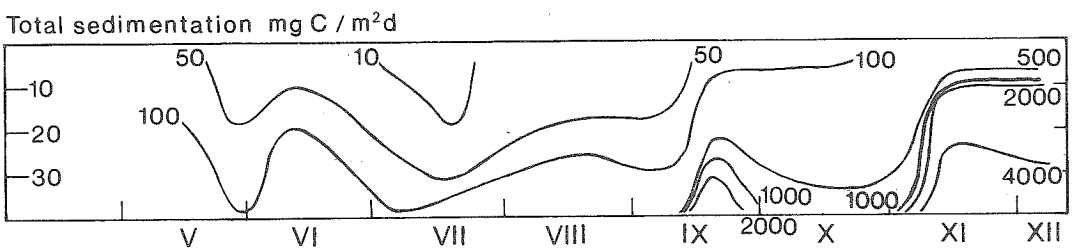

Fig. 12. Schematic diagram of total sedimentation measured as organic carbon. Strong mixing began in September, causing extensive resuspension from the bottom.

Comparison of the sedimentation in the euphotic layer (15 m) and the sedimentation in the winter water at 30 m reveals certain trends (Fig. 13). The production peaks in May and early August are reflected by high values in the euphotic layer. The peaks in the winter water in May and June may also be connected with resuspension of bottom material by influxes of saline water (cf. the salinity and density diagrams, Fig. 3). The strong increase in the whole water column from September on is connected with stormy weather, which caused vigorous resuspension of matter from the bottom. The carbon content of the sedimented material decreased from May to late autumn (Fig. 13). The lowest values occurred from September on, after resuspension of

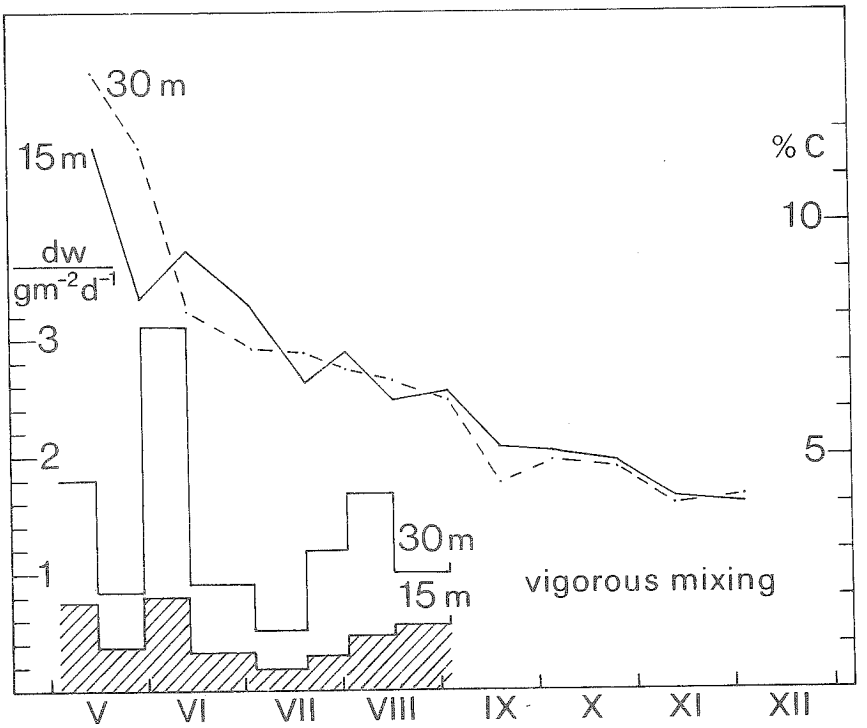

Fig. 13. Dry weight (columns) and organic carbon content (lines) of the sedimented material in the 15 m and 30 m traps. The dry weight is omitted from September on, because of strong resuspension from the bottom.

material from the bottom. The decrease shows the importance of the vernal production peak for the energy input to the pelagic and benthic ecosystem.

The C:N:P ratios of the material in the sediment traps are seen in Tables 4 and 5. From mid May to mid July a weak decreasing trend can be observed in the N:P ratios. From early August the ratio increased in connection with the production of nitrogen fixing blue-green algae, but reached low values (7:1) again in November. No clear vertical differences were observed. The same trends emerged in the C:P ratio. From mid May the ratio decreased to low values in mid July, but increased again during the late summer production peak. From early September on the ratio clearly decreased. During the production peaks there is a vertical decrease from the surface.

The C:N ratio of the matter collected by the sediment traps is significantly higher than that measured at the same time on the particulate matter (seston) in the water. The reason is probably

TABLE 4. C:N:P ratios (atomic) of particulate matter in water, seston and traps. Surface layer (0-15 m).

Period	Water	Seston	Traps
I	-	158:21:1	-
II	771:47:1	121:15:1	198:13:1
III	851:39:1	98:17:1	122:11:1
IV	1484:91:1	122:25:1	138:14:1
V	1900:70:1	112:17:1	73: 9:1

C:N ratios (atomic) of particulate matter in water, seston and traps. Surface layer (0-15m).

Period	Water	Seston	Traps
I	-	8:1	-
II	16:1	8:1	15:1
III	22:1	6:1	11:1
IV	16:1	5:1	10:1
V	27:1	7:1	8:1

Periods: I -Winter stage (-31.3.)
II -Vernal stage (1.4.-15.5.)
III -Summer minimum stage (16.5.-15.7.)
IV -Late summer stage (16.7.-15.9.)
V -Autumnal stage (16.9.-)

that the partly decomposed matter in the sediment traps contains fewer living particles than the seston. The conditions in the traps possibly increase decomposition, causing greater nitrogen loss. Whether the increasing bacterial activity and biomass in the sediment traps are important or not, remains an open question.

9. COMPOSITION OF SEDIMENTED MATTER IN TRAPS

The material caught in the traps consisted chiefly of unidentifiable organic matter and diatom frustules. A microscopical study was made on only two samplings by M. Forsskåhl (cf. Forsskåhl & Sundberg 1981).

TABLE 5. C:N:P ratios of particulate organic matter (seston) and material in sediment traps.

seston

depth	22.3.	18.4.	24.4.	8.5.	16.5.	29.5.	11.6.	4.7.	18.7.	1.8.	14.8.	4.9.	18.9.	4.10.	23.10.	13.11.	4.12.
0	161:17:1	70:12:1	109:14:1	139:15:1	129:16:1	90:13:1	136:19:1	80:13:1	119:16:1	157:36:1	150:27:1	99:21:1	70:18:1	164:21:1	94:16:1	110:16:1	125:14:1
6	141:17:1	111:16:1	96:16:1	132:12:1	167:15:1	89:15:1	106:17:1	99:16:1	116:17:1	103:19:1	122:24:1	122:25:1	113:21:1	94:20:1	94:14:1	144:19:1	89:13:1
10	171:29:1	105:16:1	111:18:1	107:12:1	175:16:1	99:14:1	106:28:1	77:15:1	159:20:1	109:22:1	104:26:1	134:26:1	108:20:1	149:21:1	89:14:1	110:16:1	134:14:1
20	208:19:1	106:13:1	100:16:1	107:14:1	136:18:1	69:16:1	117:29:1	84:18:1	200:26:1	99:18:1	108:22:1	117:25:1	204:28:1	158:26:1	129:16:1	15:1	100:12:1
30	-	113:12:1	88:15:1	89:13:1	110:18:1	67:14:1	135:30:1	88:14:1	207:23:1	66:11:1	108:19:1	158:22:1	98:14:1	124:20:1	66:14:1	86:14:1	89:11:1
40	109:13:1	102: 8:1	111:17:1	63:11:1	105:16:1	66:14:1	109:28:1	72:11:1	112:14:1	77:12:1	69:13:1	97:15:1	112:13:1	107:14:1	107:14:1	98:14:1	92:10:1
50	90:11:1	182:10:1	91:14:1	107: 8:1	105:19:1	81:13:1	93:11:1	72:11:1	87:11:1	83:11:1	108:13:1	81:13:1	92:12:1	75:11:1	75:11:1	77:14:1	78:10:1

traps

depth (m)	18.5.	30.5.	12.6.	5.7.	19.7.	2.8.	15.8.	5.9.	18.9.	4.10.	23.10.	13.11.	4.12.
5	206:13:1	170:13:1	132:13:1	114:11:1	62: 9:1	147:13:1	158:18:1	119:13:1	90:11:1	80: 9:1	75: 9:1	67: 7:1	65: 9:1
15	189:13:1	181:13:1	116:11:1	111:11:1	90: 9:1	124:13:1	145:13:1	137:13:1	70: 9:1	83: 9:1	80: 9:1	62: 7:1	62: 9:1
20	-	-	-	-	124:13:1	106:11:1	127:13:1	121:13:1	67: 9:1	80:11:1	77: 9:1	67: 7:1	70: 9:1
30	163:13:1	119:13:1	101: 9:1	90: 9:1	88: 9:1	90: 9:1	96:11:1	106:13:1	57: 4:1	75: 9:1	77: 9:1	65: 7:1	67: 9:1
38	137:13:1	93:11:1	85:11:1	70:11:1	80: 9:1	88:11:1	54: 9:1	77: 9:1	62: 7:1	70: 9:1	75:11:1	54: 7:1	65: 9:1

The biogenic material in the samples of 5 September consisted chiefly of organic matter, intact diatoms and frustules, and a few blue-green algae, but unexpected no thecate dinoflagellates. At 5 m living diatoms (esp. *Nitzschia* sp.) were abundant and unexpectedly many benthic species were present. In the deeper traps there were fewer living diatoms. In the deepest trap, at 38 m, living individuals were few, but there were many frustules of various species, especially *Achnanthes taeniata* and *Chaetoceros holsaticus* (resting spores), species abundant during the vernal diatom bloom. It is possible that the abundant specimens of *Nitzschia longissima* in the trap at 5 m represent individuals living at the bottom of the traps.

The material in the sample of 18 September showed the influence of rough weather and mixing of the water column. Besides late summer phytoplankton species and frustules of littoral diatoms, the traps contained abundant frustules of the planktonic spring diatom *Achnanthes taeniata*, which must have been resuspended from the sediments. No thecate dinoflagellates occurred in the traps.

10. CALCULATION OF THE SEDIMENTATION RATE OF ORGANIC MATTER DURING DIFFERENT STAGES OF PRODUCTION

The rate of sedimentation was evaluated from changes in concentrations in time and space, using observations made at station A.

According to the equation of diffusion, the material balance can be written as

$$\frac{\partial c}{\partial t} = k \frac{\partial^2 c}{\partial z^2} + \frac{\partial T}{\partial z} - \frac{\partial S}{\partial z} \qquad (1)$$

where c = concentration
k = vertical diffusion coefficient
T = advective flux of matter
S = sedimentation flux.

Since the frequens of concentration measurements was not sufficient for determining the advective flux, an effort was made to estimate the balance without it and to determine it as a residual term from the order of magnitude. The calculation is necessarily a very crude one, owing to the small number of sampling depths, the long time scales involved and the possibility of considerable errors in the measurement of the rate of sedimentation.

In order to obtain comparable data on sedimentation and concentration changes, eq. 1 was integrated from the surface to the depth of the sampling device. The resulting equation is

$$\frac{\partial}{\partial t} \int c\,dz = k \left.\frac{\partial c}{\partial z}\right|_d + T_d - S_d \qquad (2)$$

The procedure was tested for the depths 15, 20 and 30 m by calculating the vertical diffusion coefficient k from the available data. The results of this calculation (Table 6) show that the order of magnitude of the diffusion coefficient is not inconsistent with the results of direct determination in weakly stratified environments (observations at the depth of 15 m), but in the deeper layers, due to the uncertainties mentioned, the results show random behaviour. Naturally, the consistency may be accidental, but it is tempting to assume that this indicates lack of importance of the advective term especially in the surface layer. As was mentioned in previous sections, the currents at station A varied considerably, and therefore with the time scales involved it can be assumed that the advection may not be very significant. It seems to be necessary to try to modify the sampling procedure considerably in future experiments in order to obtain more consistent estimates of the mass balance in Eq. 1.

The highly random variations below the thermocline also show that

TABLE 6. Coefficients of eddy diffusivity k (cm^2/s) calculated from eq. 2. Lacking values indicate the inflection point in the vertical concentration gradient.
x) POC increased.

Period	15 m	20 m	30 m
8.-16.5.	1.7	-	-
16.-29.5.	3.0	-	-0.8
29.5.-11.6.	4.9	-	-
11.6.-4.7.	0.3	-	-0.4
4.-18.7.	-2.0 x)	-	-
18.7.-1.8.	-0.5 x)	0.6	-2.4
1.-14.8.	2.6	2.2	-3.8
14.8.-4.9.	1.0	-0.5	-0.8
4.-18.9.	1.3	-	93
18.9.-4.10.	18.5	-	-

the sedimentation rate at that depth is strongly influenced by the mobilization of material from the bottom. The sampling depth was some 10 metres above the bottom, but the irregularity of the bottom together with current fluctuations causes turbid water and a consequent increase in the rate of sedimentation.

11. DISCUSSION

Despite their preliminary nature, the measurements made in 1979 give some information about the representativenes of the sampling station and study area and about the sedimentation and degradation of organic matter.

The sampling station represents a coastal area. It is influenced by coastal currents differing from those in the open sea. Moreover, the nearby shallows probably contribute a surplus of seston to the sediment traps. The occasional marked inflows of deep water and exceptional hydrographic conditions caused by the proximity of the channel will also sometimes disturb the sedimentation measurements at the sampling station. Thus, the present results cannot correspond directly to the conditions in the open sea.

Sedimentation measurement with traps probably include several sources of error. The main problems are resuspension from the bottom and deficiencies in the sampling equipment. Since these sedimentation measurements were started, some methodological studies have been made on the efficiency of different types of traps (Blomqvist & Håkansson 1979, Hargrave & Burns 1979, Bloesch & Burns 1980 and Gardner 1980). It appears that our sedimentation results (without resuspension) may be underestimates, because the height/ opening ratio of the trap was too low. Our trap type was changed later on, but unfortunately the loss of two trap series in spring 1980 made it impossible to compare the results obtained with the different trap types.

Although only rough estimates, the results indicate that between 9.5. and 5.9. the sedimentation of organic carbon at 30 m was 106 mg $m^{-2}d^{-1}$. This means that during this period, when the weather conditions were moderate and the effect of resuspension was slight, the sedimentation totalled ca 12 gCm^{-2}. The primary production in this area in 1979 was estimated at 78 gCm^{-2} (Bruun & Grönlund 1981).

The production and sedimentation can be devided among the following

subperiods, table 7 (the primary production data according to J.-M. Leppänen, IMR).

TABLE 7. Primary production, sedimentation and sedimentation expressed as a percentage of primary production at the sampling station in 1979. x) 9.5 - 31.5.

Period	Primary production mg C $m^{-2}d^{-1}$	Sedimentation mg C $m^{-2}d^{-1}$	Sedimentation as % of production
1.4.-31.5.	419	161 x)	38
1.6.-31.8.	415	96	23
1.9.-4.12.	105	vigorous mixing	-

It is possible that the sedimentation maximum in spring occurred before the start of sampling and the sedimentation percentage was greater than 38 %. Since no sedimentation data can be given for the period 5.9.-4.12., the total annual sedimentation cannot be calculated. However, the results show that vernal production and sedimenting material are important to the bottom ecosystem, as they were shown to be earlier in Askö Bay (cf. Hobro et al. 1975).

Using the measured concentrations and sedimentation rates it is possible to make simple calculation of the average velocity of vertically moving particles. This calculation showed considerable variation with time and depth. In the spring and summer the sedimentation velocity in the surface layer varied between 1 and 20 cm d^{-1}, revealing the influence of turbulence in the surface layer. Below the thermocline at 20 m depth, the average velocity was 40 to 80 cm d^{-1}. At 30 m it ranged from 60 to 120 cm d^{-1}, which probably represents the value for dead biomass descending evenly in undisturbed conditions. Exceptionally high velocities, of the order of 10 to 20 m d^{-1}, were recorded in late autumn, indicating the presence of heavy resuspended material in the sediment samples.

It is very difficult, however, to determine sinking velocities for a heterogeneous group of particles.

Settling velocities of 0.24 - 2.32 m d^{-1} were obtained for three different size ranges of particulate organic carbon by Burns & Rosa (1980), who also give some settling velocities for different

phytoplankton species. The measurements were made in Lake St. George, Canada. Smayda (1970) has also made and collected estimates of the sinking rates of different organisms, and has found that diatom sinking behaviour is influenced by colony formation. For example, the mean sinking rates varied from 0.79 to 3.21 md^{-1} *(Bacteriastrum hyalinum)* and from 0.13 to 0.73 md^{-1} *(Skeletonema costatum)*. The velocities calculated from the Tvärminne material match these results.

Some earlier sedimentation studies have been made in the Baltic Sea area, e.g. in Askö, where the primary production was estimated at 130 $gCm^{-2}y^{-1}$ in 1977 and the sedimentation at 40-50 $gCm^{-2}y^{-1}$ or about 30-40 % of the primary production (Elmgren et al. 1979). The water depth was 40 m and sedimentation was measured at 20 m depth.

In the southern Baltic Sea, Kiel Bight, where the primary production was reported to be 158 gCm^{-2} for 1973 (von Bodungen 1975), the sedimentation was estimated at 40 $gCm^{-2}y^{-1}$ (Zeitzschel 1965, depth 26 m, trap 1 m above the bottom), and 22-61 $gCm^{-2}y^{-1}$ (Smetacek 1980, depth 20 m, two traps, 15 m and 18 m). For Eckernförde Bight (depth 30 m) the following sedimentation rates are reported: 15 $gCm^{-2}y^{-1}$ (10 m) and 31 $gCm^{-2}y^{-1}$ (20 m) (Hendrikson 1976), 19.62 $gCm^{-2}y^{-1}$ (10 m) and 45.26 $gCm^{-2}y^{-1}$ (18 m) (Iturriaga 1979). Being from different years and different stations, the values are not completely comparable, but they give a rough idea of the approximate ratio between sedimentation and primary production: for Kiel Bight in general 30-40 % (Smetacek 1980).

If the primary sedimentation of organic material from the upper layer in the Tvärminne area is assumed to have been negligible from September on, when there was strong mixing in the whole water column, the matter sedimented in 1979 may be estimated at about 20 % of the annual primary production. Since the primary production was unusually low in that autumn, the level of the annual sedimentation was somewhat lower than if an autumnal diatom maximum had occurred.

Actually, only one part of the material that sinks to the bottom is buried in the sediment. Most of it is used by bottom animals and microbes, or moved by bottom currents to deeper sedimentation basins. Pustelnikov (1974) has estimated that of the total organic matter produced annually in the euphotic zone of the whole Baltic Sea (300 gCm^{-2}) only about 1.5 % reaches the bottom and 0.06 % is buried in the sediments.

According to Perttilä & Tervo (1979), the average C:N:P atomic ratio in the sea water for the whole Baltic Sea is roughly 2000:80:1.

They also noted that the C:P and N:P ratios varied greatly from one area to another, but that the C:N ratio (23-25) was almost constant. Carlberg (1972) reported that the Baltic Sea C:P ratio varied from 433 to 2000. Our results are presented in Table 4: The C:P ratio ranged from 771 (vernal stage) to 1900 (autumnal stage), the C:N ratio from 16 (vernal stage) to 27 (autumnal stage). The N:P ratio was 47-39 in the vernal and summer minimum stages and 91-70 in the late summer and autumnal stages.

The C:N:P ratio for the particulate matter and plankton in the Baltic Sea has been studied earlier. According to Voipio (1973), the ratio for the plankton is approximatively 101:19:1 (in organic matter taken with a 150-µm net, which chiefly collects zooplankton). Sen Gupta (1973) obtained the ratio 154:13:1 (see also Sen Gupta and Koroleff 1973). The plankton net used for phytoplankton had a mesh size of 25 um and that for zooplankton a mesh of 150 µm. After collection, the plankton samples were filtered through a glass-fibre filter (GF/C) without suction or pressure. For organic matter collected on a glass fibre filter (1-µm pore size) a C:N value of 8.8 is reported for the Baltic Proper (Ehrhardt 1969). The C:N:P value used for oceanic plankton is 106:16:1 (Fleming 1940). According to our results, the C:P ratio varied from 98 (summer minimum stage) to 158 (winter stage, 22 March). The N:P value was highest (25) during the late summer stage of phytoplankton production, lowest (15) during the vernal bloom. The C:N value varied from 5 to 8, the minimum occurring in late summer and the maximum in winter and during the vernal stage (Tables 4 and 5).

The Baltic Sea bottoms sediments have been studied by Gripenberg (1934) and Niemistö & Voipio (1974) among others. According to Gripenberg, the C:N value for the North Baltic Sea, including the Åland and Archipelago Seas, was 10.5 (atomic ratio). The same value is reported by Niemistö & Voipio for two cores from the Gotland Deep. The C:P atomic ratio varied between 230 and 318 for samples from the uppermost 10 cm layer. These values give a rough C:N:P ratio of 270:26:1 for Baltic Sea bottom sediments. When compared with the values for seston, our results from the sediment traps showed some degradation of organic matter. The C:P ratio varied from 73 (autumnal stage) to 198 (vernal stage), and the N:P ratio from 9 to 14; the C:N ratio was highest (15) in spring, the minimum (8) being reached in autumn. Comparison of the values from the bottom sediments with our results from the traps shows that the matter in the traps is

chemically different from the bottom sediments. The C:P and N:P ratios in the traps are markedly lower than in the sediment, which indicates that the loss of phosphorus from the bottom is greater than that of carbon and nitrogen. The variation of the C:N ratio in the traps (8 - 15) covered the mean (10) for the bottom sediments.

12. CONCLUSIONS

Although the analyses of the material are preliminary, the ratios between carbon, nitrogen and phosphorus in particulate matter in seston and traps show some interesting trends:

- The C:N ratios increased markedly after the phytoplankton production peaks, indicating that nitrogen passed rapidly into solution from decomposing organic material.
- The C:N ratio was remarkably low in the surface layer during the blue-green algal blooms, possibly indicating that assimilation of molecular nitrogen was more intense than that of carbon (cf. Rinne et al. 1979).
- In autumn, when production had apparently decreased, the values for particulate phosphorus were greater than expected in the deep water and the whole water column. Vigorous resuspension of bottom sediments took place during that period and the high content of particulate phosphorus points to the occurrence of inorganic phosphorus bound to particles, as ferric phosphates or other compounds (cf. Voipio 1969). Thus nitrogen and phosphorus show different behaviour in the water phase.

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ABUNDANCE, BIOMASS, SPECIES COMPOSITION OF PHYTO- AND ZOOPLANKTON AND THEIR INTERRELATIONS AT THE ENTRANCE TO THE GULF OF FINLAND IN 1979

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Abstract

Detailed studies of abundance, biomass and species composition of phyto- and zooplankton were made offshore in the Tvärminne archipelago, south coast of Finland, in 1979. Trophic interactions between the phytoplankton and zooplankton populations are presented and used to estimate their role in the transfer of the organic matter.

During the growth period the phyto- and zooplankton dynamics followed the seasonal cycle characteristic of this area. The zooplankton standing stock was markedly low during the vernal phytoplankton bloom so that a great part of the organic matter produced by phytoplankton sedimented without being consumed by zooplankton. From June until September, there was an increased consumption of phytoplankton-produced organic matter by the zooplankton.

Phyto- and zooplankton sedimentation is discussed in relation to the sedimentation of other organic matter, and some information on the species composition of the phytoplankton in the sediment traps is also included.

1. INTRODUCTION

Plankton abundance, biomass and species composition have been studied by the Institute of Marine Research (IMR) at the entrance to the Gulf of Finland, off Tvärminne Zoological station, since 1966 (zooplankton) and 1972 (phytoplankton). In 1979 an investigation on sinking, degradation and sedimentation of organic matter was begun in this area. The results for 1979 are presented by Laakkonen et al. (1981).

Mikaela Forsskåhl is responsible for the phytoplankton data and Anneli Sundberg for the zooplankton data. The discussion was prepared by the two authors in cooperation.

2. MATERIAL AND METHODS

Plankton samples were taken during the ice-free period at the sampling station Längden. Its location is described by Laakkonen et al. (1981: Fig. 1), who have also presented hydrographical data for the study period. Chemical data and chlorophyll *a* values are presented by Leppänen & Tamelander (1981) and primary production measurements by Bruun & Grönlund (1981).

Integrated phytoplankton samples from 0-10 m were taken from the same water samples as those for the determination of primary production and chlorophyll *a*. The phytoplankton samples were stored in dark glass bottles and preserved with Lugol-AA solution (Hällfors et al. 1979). A qualitative net sample, mesh size 25 µm, was also taken with a vertical haul of ca. 10-0 m.

The quantitative phytoplankton analyses were made using the Utermöhl technique and phase contrast. The biomass was calculated using mean cell volumes (unpublished, Institute of Marine Research (IMR). The carbon content of the diatoms was calculated according to Edler (1977) and that of all the other groups according to the Baltic Marine Biologists (Edler 1979). Hällfors' (1979) nomenclature is used. The sample taken on 18 September was only analysed qualitatively, because rough weather in mid-September had mixed the water and resuspended material from the bottom.

Sedimented material from two subperiods, 15 August - 5 September and 5 September - 18 September, was examined microscopically. The material in one test tube from each depth (see Laakkonen et al. 1981) was preserved with formalin and analysed by species. The traps were placed at 5, 15, 20, 30 and 38 m.

The zooplankton samples were taken at the same time as the phytoplankton samples. The microzooplankton fraction was not sampled. Vertical hauls were made with a Hensen net (Steuer 1910), mesh size 150 µm, from 25 m to the surface. The volume of each haul was assumed to be 10 m^3. The samples were preserved in 4 % formalin, subsampled with the Folsom plankton sample splitter (McEven et al. 1954), analysed to species level and counted. For the copepods the sex and developmental stages were also determined. The unit *Acartia* spp. comprises *A. bifilosa*, *A. longiremis* and *A. tonsa*. The results for the three species are combined, since it was not possible to separate their nauplii and copepodid stages 1-3. The biomass was calculated using the mean volumes of the individuals (unpublished, IMR). The density of zooplankton was considered to be 1 g m^{-3}. The carbon content was estimated as 5,2 % of the wet weight (Mullin 1969). The zooplankton production values were calculated according to Ackefors (1972).

3. RESULTS

3.1. Phytoplankton abundance, biomass and species composition

The total number of phytoplankton units counted, the biomass and the carbon content are presented in Fig. 1. The contributions to the total biomass of the phytoplankton groups Cyanophyceae, Dinophyceae, Bacillariophyceae, Cryptophyceae and flagellates are presented in Figs. 2 and 3.

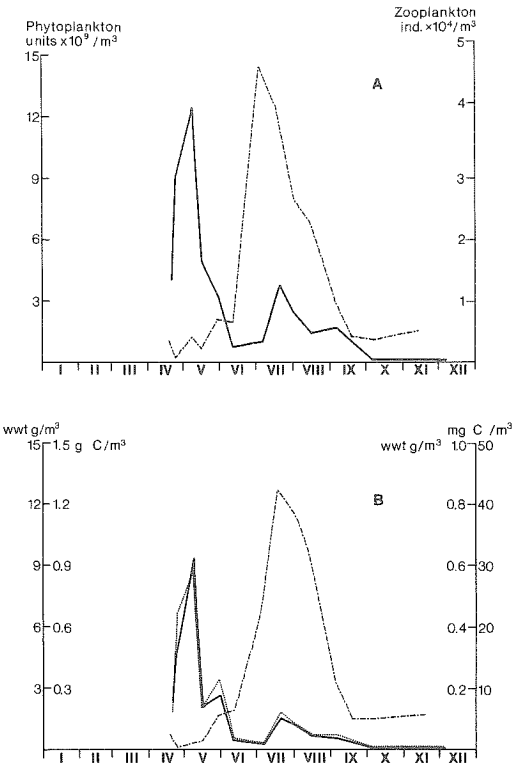

Fig. 1 A Abundance of phytoplankton, units/m^3 (———), and of zooplankton, ind./m^3 (– – – –).

B Phytoplankton biomass, g/m^3 (———), and carbon content, g C/m^3 (·····). Zooplankton biomass in g/m^3 and in mg C/m^3 (– · – · –).

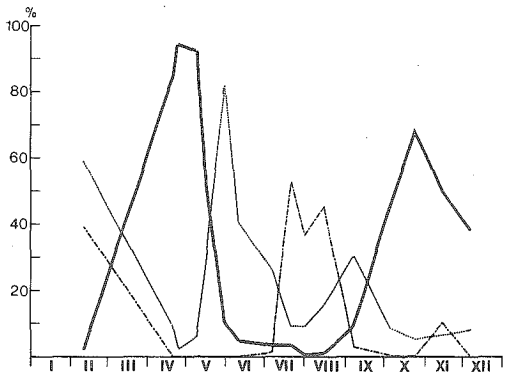

Fig. 2. Phytoplankton group proportions (of the total biomass): Bacillariophyceae (———), Dinophyceae (·····) and Cyanophyceae (-·-·-·).

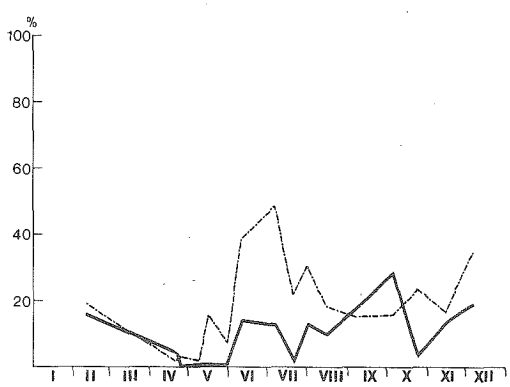

Fig. 3. Phytoplankton group proportions (of the total biomass): Cryptophyceae (———) and flagellates (-·-·-·-·).

In 1979 the vernal phytoplankton bloom started after the breakup of the ice in mid-April and lasted until early May (Fig. 1). Diatoms contributed 90 % of the number of units counted to the total biomass. Dinoflagellates increased in number in mid-May and reached a maximum in late May (Fig. 2). The diatoms *Achnanthes taeniata, Chaetoceros holsaticus* and *C. wighamii* were present during the whole diatom maximum. In April cold-water species were also frequent: *Melosira arctica, Nitzschia cylindrus, N. frigida* and *Navicula vanhoeffenii*. The diatoms *Thalassiosira baltica* and *Skeletonema costatum* occurred in late May, when dinoflagellates, chiefly *Gonyaulax catenata* together with *Protoperidinium bipes* and *P. granii*, accounted for ca. 80 % of the phytoplankton biomass.

During the summer minimum stage, small dinoflagellates, *Glenodinium* spp., cryptomonads, the chrysomonads *Calycomonas ovalis* and *C. wulffii* and other small flagellates, were abundant and together contributed 35 - 90 % to the total biomass (Fig. 3). In Mid-July the blue-green alga *Gomphosphaeria* sp. was frequent and made up 50 % of the phytoplankton biomass (Fig. 2).

In late summer, the nitrogen-fixing blue-green algae *Anabaena lemmermannii, Aphanizomenon flos-aquae* and *Nodularia spumigena* were most abundant and accounted for 40-50 % of the biomass (Fig. 2). *Achroonema* sp. and *Gomphosphaeria* sp. occurred only sparsely. The rest of the biomass consisted of dinoflagellates, crytpmonads, euglenoids (*Eutreptiella* sp.) and other flagellates. Besides *Glenodinium* spp., the dinoflagellates *Dinophysis acuminata* and *D. norvegica* were present.

In early September, the only blue-green algae still observed were *Aphanizomenon flos-aquae* and *Gomphosphaeria* sp., and they accounted for only 3 % of the biomass, the rest being made up by the same groups as in August. In early October, the phytoplankton biomass had declined to less than 0.1 mg/dm^3 (Fig. 1). It consisted of diatoms (40 %), cryptomonads (30 %), dinoflagellates (9 %) and small flagellates (15 %). Later in the autumn diatoms formed the greater part of the biomass (Fig. 2). Autumnal species were *Actinocyclus octonarius, Chaetoceros danicus, Coscinodiscus granii, Melosira arctica* and after November also *Skeletonema costatum*. The contributions of flagellates and cryptomonads remained important (Fig. 3).

3.2. Composition of phytoplankton in sediment traps

In the sediment traps at 5 m and 15 m depth, living cells were abundant only after the first subperiod. Many benthic species were very frequent, such as *Nitschia cf. actinastroides, N. longissima* and *Synedra* sp. A few

of the following species were also found: *Gomphonema* sp., *Diploneis* sp., *Lichomophora* sp. and *Rhoicosphaenia curvata*. No cells or heterocyst of nitrogen-fixing blue-green algae were observed, and only small amounts of *Achroonema* sp., *Gomphosphaeria* sp. and *Oscillatoria* sp. In the deeper traps very few living cells were found and the material consisted mainly of undefinable organic matter, frustules of *Achnanthes* and resting spores of *Chaetoceros*.

3.3. Zooplankton abundance, biomass, species composition and production

The abundance of the zooplankton varied during the study period from 800 ind./m^3 in late April to 48 000 ind./m^3 in early July (Fig. 1). In late April the groups Copepoda (93 %), Cladocera (1 %) and 'others' (6 %) were present (Fig. 4). The last group included planktonic larvae of the bottom fauna, *Balanus improvisus (larvae)*, *Fritillaria borealis* and *Pleurobrachia pileus*. In early July the zooplankton consisted of the following groups: Rotatoria (54 %), Cladocera (9 %), Copepoda (34 %) and 'others' (3 %).

The zooplankton biomass, mg C/m^3, and the contributions of the different groups are presented in Fig. 5.

During the vernal phytoplankton bloom the zooplankton standing stock was markedly low. The mean biomass was 1 mg C/m^3. Copepods contributed more than 90 % to the total biomass in April and early May. In late May their contribution was 55 %, the rest of the biomass was made up by the group 'others'. *Acartia* nauplii and copepodid stages 1-3, and *Pseudocalanus elongatus* copepodids 4-5 predominated. The group 'others' consisted of *Pleurobrachia pileus* and *Fritillaria borealis*.

In June the zooplankton biomass had risen to 6.7 mg C/m^3 and copepods composed 97 % of the total biomass. Adult *Acartia* spp. and *Pseudocalanus elongatus* nauplii and copepodids predominated. In early and mid-July, when the biomass reached 22.5 mg C/m^3 and 42.3 mg C/m^3, respectively, the same copepods were still dominant. The rortifers *Synchaeta* spp. (especially *S. baltica* and *S. monopus*) made up 14 % of the total biomass and the cladocerans *Evadne nordmanni* and *Podon polyphemoides*, 10 %.

In August the biomass decreased to ca. 35 mg C/m^3. The most frequent copepods were *Acartia*, *Eurytemora hirundoides*, *Temora longicornis* and cyclopids. The rotifers *Keratella quadrata quadrata* and *K. quadrata platei* occurred sparsely, as did also the caldocerans *Bosmina coregoni maritima* and *Podon intermedius*.

In early September the total biomass had declined to 11 mg C/m^3. The copepods *Acartia* spp. and *Pseudocalanus elongatus* were the dominant species. *Centropages hamatus* was also observed.

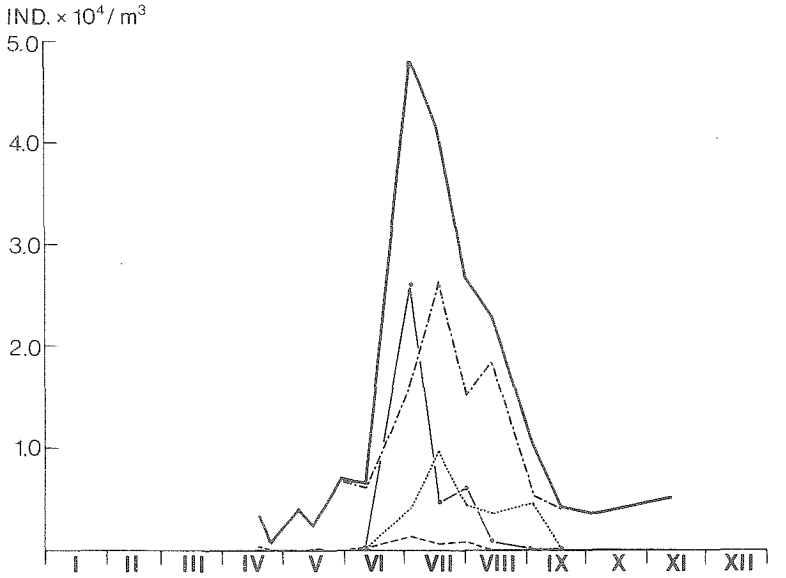

Fig. 4. Zooplankton abundance. ind./m^3 (———), and abundance of the different groups: Rotatoria (—•—), Cladocera (·····), Copepoda (– – –) and 'others' (– – – –).

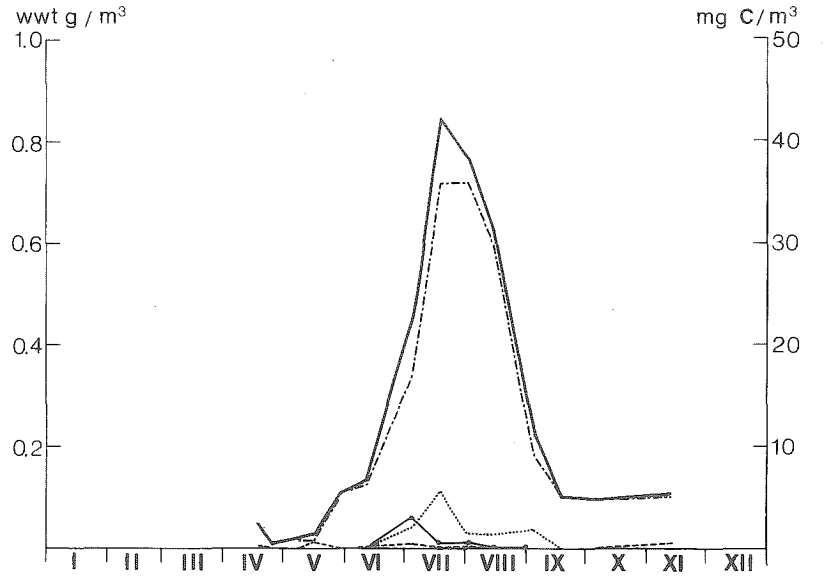

Fig. 5. Zooplankton biomass, g/m^3, and carbon content, mg C/m^3 (———), and biomasses of the different groups: Rotatoria (—•—), Cladocera (·····), Copepoda (– – –) and 'others' (– – – –).

The annual production maximum of the cladocerans then occurred. *Bosmina coregoni maritima*, *Evadne nordmanni* and *Podon intermedius* made up 17 % of the zooplankton biomass.

In October the total biomass was only 4.9 mg C/m^3 and copepods predominated (98 %). In November the situation was the same, but the group 'others', included *Pleurobrachia pileus*, Polychaeta larvae, Lamellibranchiata larvae and *Fritillaria borealis*, made up 10 % of the total biomass.

In 1979 the annual zooplankton production was 4.3 g C m^{-2}. This value is at the same production level as previously (cf. Niemi, A. 1980). During the spring bloom the zooplankton production was less than 10 mg C $m^{-2}d^{-1}$. The maximum production occurred during July and August, about 50 mg C $m^{-2}d^{-1}$. Rotifers and cladocerans had some importance for the biomass production in summer, but during the rest of the study period the dominant contribution was made by copepods.

4. DISCUSSION

During the study period the phytoplankton production (Bruun & Grönlund 1981), and the phyto- and zooplankton dynamics followed the annual cycle characteristic of this area (Lassig & Viljamaa 1973, Forsskåhl 1980, Niemi, A. 1980).

During the spring bloom in mid-April to mid-May primary production averaged 700 mg C $m^{-2}d^{-1}$, while zooplankton production averaged less than 10 mg C $m^{-2}d^{-1}$. This indicates that the spring bloom was utilized very little by the zooplankton. Large scale sedimentation of the vernal phytoplankton bloom is a regular feature in areas with low overwintering zooplankton populations (Smetacek et al. 1978); as much as 40 - 50 % of the phytoplankton spring bloom can reach the benthos (Hobro et al., Ref. Elmgren 1978).

In June the primary production values decreased to 220 mg C $m^{-2}d^{-1}$. From June until September the phytoplankton production was about 600 mg C $m^{-2}d^{-1}$, and the zooplankton production was about 50 mg $m^{-2}d^{-1}$. The phytoplankton production was thus utilized more by the zooplankton during this period. From the beginning of September the production of both phytoplankton and zooplankton decreased. In the autumn the phytoplankton seemed to be utilized effectively by the zooplankton.

The role of phytoplankton and zooplankton in the food web is still incompletely known, which makes it difficult to calculate the transfer of energy from the trophic level to another. During the study period, the ratio between the phytoplankton and zooplankton production was 18:1

(the average primary production was 78 g C $m^{-2}a^{-1}$ and the secondary production 4.3 g C $m^{-2}a^{-1}$), which indicates a low production by the herbivores utilizing phytoplankton. Particles of detritus are an important source of food for the zooplankton (Poulet 1974, Lenz 1977) and this increases the ratio to an unknown degree. Another reason for the high ratio is the mesh size of the net used, which catches only part of the smallest size groups. According to Ackefors et al. (1978), the corresponding ratios for the northern and southern Baltic Sea are 10:1 and 9:1, respectively, but they used a net with a mesh size 90 µm.

In the study area, the zooplankton standing stock in 1979 developed after the vernal maximum in late May. Rotifers, the first group that developed, increased rapidly in number in June. At that time, the diatom *Skeletonema costatum*, cryptomonads and small flagellates were abundant and were presumably suitable food for this zooplankton group. According to Bakker (1979), the reproductive capacity of the rotifers is significantly correlated with algal densities, crytomonads being the main food. He noted that the feeding relation *Synchaeta* - *Cryptomonas* was significantly stronger than that for *Synchaeta* and the diatom *Skeletonema*.

At the beginnig of August cladocerans became common, especially the herbivorous *Bosmina*, which is known to feed on nanoplankton. The blue-green algal bloom in July-August was apparently not grazed upon the zooplankton; it is assumed that these phytoplankton species do not provide food for any zooplankton group (cf. Hernroth & Ackefors 1979).

According to Poulet (1973, 1974, 1978), the copepods *Pseudocalanus minutus*, *Oithona similis*, *Eurytemora herdmani*, *E. affinis*, *Temora longicornis*, *Acartia tonsa* and *A. clausi* can ingest particles of wide size range. Evidence for large-particle selectivity has been occurred for a variety of copepod species feeding upon mixed phytoplankton (Mullin 1963, 1966, Richman & Rogers 1969). Mayzaud & Poulet (1978) found that the herbivorous genera *Acartia*, *Eurytemora*, *Pseudocalanus*, *Oithona* and *Temora* can utilize food particles with diameters between 1.5 and 150 µm.

After the rough weather in mid-September the phytoplankton and zooplankton species compositions changed abruptly. Most of the above-mentioned copepod genera were observed in the autumn. They could probably utilize both the rather big centric diatoms and the flagellates, which may be one of the reasons for the small phytoplankton biomass.

In the study area, the relation of the phyto- and zooplankton production to the amount of material found in the sediment traps followed the annual pattern reported by Smetacek et al. (1978) and Smetacek (1980). The rate of phytoplankton sedimentation is high, probably at its highest, after the vernal bloom, when the zooplankton stock is small. Later, during the summer minimum stage, the phytoplankton sedimentation is markedly reduced by vigorous zooplankton grazing. According to Laakkonen et al. (1981:Fig. 10) the amounts of organic matter found in the sediment traps were high in May-June, decreased in June-July and then gradually increased. The increase in the amount of the sedimented material coincided with the blue-green algal bloom. However, no microscopically recognizable blue-green algal material was observed in the trap material. Fallon & Brock (1979), who studied blue-green algal sedimentation in fresh water, found that the blue-green algae disappear very rapidly while sedimenting out of the water, due to decomposition. That this probably occurred in our study area is indicated by the observations of Laakkonen et al. (1981), who found that the C:N ratios increased markedly after the phytoplankton production peaks and who attributed this to nitrogen passing rapidly into solution from decomposing organic material.

Smetacek (1980) reports that after the zooplankton decline in late summer the autumnal phytoplankton bloom appeared to sink out of the water column. Autumnal phytoplankton blooms are rare in the study area and in other parts of the northern Baltic Sea (Niemi & Ray 1977). No such bloom was observed in the autumn of 1979.

The large amounts of benthic diatom species found in the traps near the surface were not observed in the corresponding phytoplankton samples. Consequently these species cannot have sedimented into the traps but evidently developed there. The traps situated in the surface layer probably formed a suitable growing environment, where these could increase rapidly in number.

Acknowledgements

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COMPOSITION OF PARTICULATE MATTER AND ITS RELATION TO PLANKTON BIOMASS IN THE TROPHOGENIC LAYER OFF TVÄRMINNE, AT THE ENTRANCE TO THE GULF OF FINLAND

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Abstract

The biological and chemical composition of particulate matter in the trophogenic layer of Tvärminne archipelago was studied during 1981. The composition of particulate matter and the contribution of particulate organic carbon, nitrogen and phosphorus to the total organic matter fluctuated according to the succession of plankton population. Most of the nitrogen recycling in the euphotic layer during the growth period took place between particulate organic and dissolved inorganic nitrogen while most of the dissolved organic nitrogen was in biologically inactive form causing long turn-over time for total nitrogen. The balance between the different forms of phosphorus suggests that total phosphorus recycled more completely than total nitrogen.

1. INTRODUCTION

The particulate matter in the trophogenic layer of the pelagic ecosystem consists of several living and non-living components with different carbon and nutrient content changing with the seasonal phytoplankton succession. Several studies have been published on the biological components, phytoplankton, zooplankton and microbes of the Gulf of Finland (e.g. Niemi, Å., 1973, Niemi, Å. & Ray 1975, 1977, Väätänen 1976, Niemi, A., 1980, Forsskåhl 1980, Forskåhl & Sundberg 1981). There are few reports on the chemical composition of the particulate matter (Sen Gupta & Koroleff 1973, Voipio 1973, Blashchishin & Pustelnikov 1977, Koroleff & Grönlund 1978). The different biological and chemical parameters are seldom studied simultaneously to determine the composition of organic matter in the different trophic levels of the ecosystem (cf. Lahdes et al. 1981).

In the present work the seasonal succession of particulate matter and its biological and chemical composition (carbon, nitrogen, phosphorus) in the trophogenic layer off Tvärminne, at the entrance to the Gulf of Finland, were studied during one growth period in 1981.

2. MATERIAL AND METHODS

The samples were taken at a station situated near Längden lighthouse in the sea zone off Tvärminne archipelago in 1981. The depth of the sampling area is ca. 40 m. A more detailed description of the area is given by Lassig et al. (1978, 1980) and Laakkonen et al. (1981).

The water samples were taken with a Ruttner sampler from the surface layer, 0-10 m, where practically all the net primary production in this area takes place (Niemi 1975, Bruun & Grönlund 1981).

The phytoplankton biomass was determined from integrated samples, (0-10 m), according to the methods recommended by Baltic Marine Biologist (Edler 1979). The zooplankton biomass was determined from net hauls, 25 - 0 m, by microscopic counting and using the mean volumes of the individual organisms. The mesh size of the Hensen net (Fraser 1968) was 150 µm. The carbon content of the zooplankton biomass was calculated according to Mullin (1969).

The chlorophyll *a* values (phaeophytin *a* not taken into account) are the means of samples from 0, 2, 4, 6, 8 and 10 m. Chlorophyll *a* was determined fluorometrically as recommended by Baltic Marine Biologist (Edler 1979). Water samples (100 ml) were filtered on Whatman GF/C glass-fibre filters. Acetone (90 %) was used as solvent.

The samples for total particle amount (TPA) and total particle counts (TPC) determination were taken from 0, 2, 4, 6, 8 and 10 m and preserved in 4 % formalin. TPA and TPC were then determined using a Coulter Counter TA II particle counter with an aperture of 200 µm.

The values for dissolved, total and particulate nitrogen, phosphorus and carbon are integrated means of the samples from 0, 2, 6 and 10 m.

Total nitrogen, total phosphorus and NO_3^--N, NO_2^--N, NH_4^+-N, PO_4^--P, SiO_4^--Si were determined according to Koroleff (1976, 1980).

The samples for determination of particulate organic carbon (POC), nitrogen (PON) and phosphorus (POP) were filtered on Whatman GF/C glass-fiber filters and analysed by a technique described by Laakkonen et al. (1981). It is possible that the analytical method used in some cases may underestimate the POP and PON values and thus the values for dissolved organic phosphorus (DOP) and dissolved organic nitrogen (DON) will be overestimated (Laakkonen et al. 1981). DOP was calculated by subtracting PO_4^--P and POP from total P, and DON by subtracting NO_3^--N, NO_2^--N, NH_4^+-N and PON from total N.

Dissolved inorganic carbon (DIC) was calculated according to Buch (1945). Total organic carbon (TOC) was determined from deep-frozen water

samples using a Beckman infrared carbon analyzer (Perttilä & Tervo 1979). Dissolved organic carbon (DOC) was calculated by subtracting POC from TOC. The negative DOP values in late summer are obviously an artefact caused by an analytical error; they indicate that the amount of DOP in the trophogenic layer was very small.

The plankton data have been analysed by Forsskåhl & Sundberg (1981) and the values for POC, PON and POP are from Laakkonen et al. (1981). They are used here with the permission of the authors without further reference.

3. GENERAL BIOLOGICAL FEATURES OF THE TROPHOGENIC LAYER

The ice cover disappeared in mid April. At that time the amount of particulate matter was low and the concentration of inorganic nutrients was high (Figs. 1-4). Phytoplankton biomass then increased rapidly (Fig. 3), incorporating the main part of inorganic nutrients into their particulate organic forms (Figs. 1 and 2). The vernal phytoplankton bloom ended when practically no dissolved nitrogen was left in the trophogenic layer. The

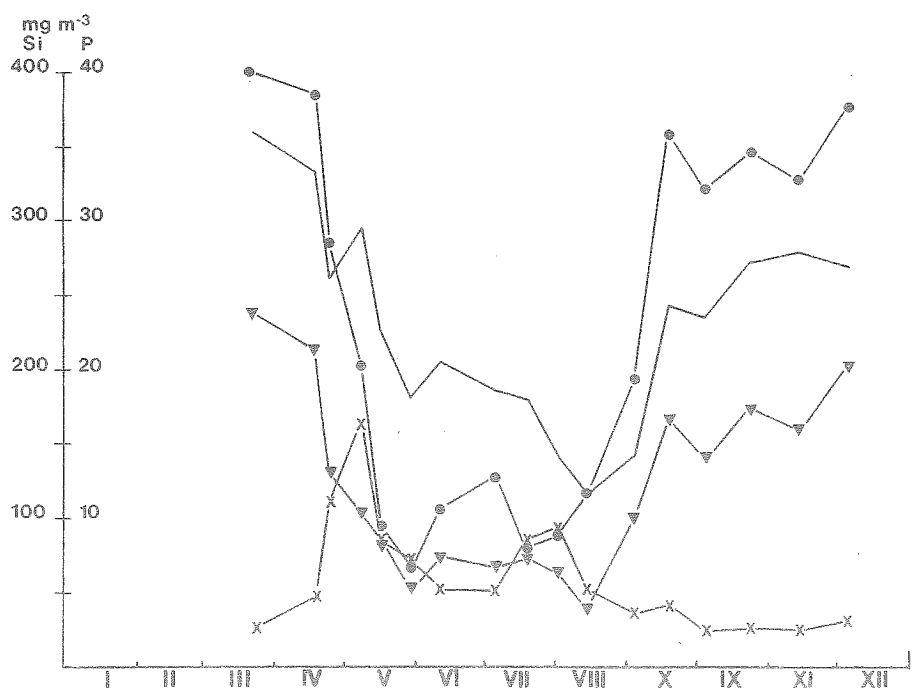

Fig. 1. Mean concentrations of total phosphorus (continuous line), PO_4-P (-▼-), particulate organic phosphorus (-x-) and SiO_4-Si (-●-) in the trophogenic layer in 1979. The Si scale refers to SiO_4-Si, the P scale refers to phosphorus compounds.

amount of particulate matter then decreased rapidly through sedimentation (Laakkonen et al. 1981). Zooplankton biomass increased steadily after the vernal bloom reaching its maximum in mid-summer (Fig. 3). The contribution of N_2-fixing blue-green algae to phytoplankton biomass was also highest in mid-summer causing the annual maximum of PON.

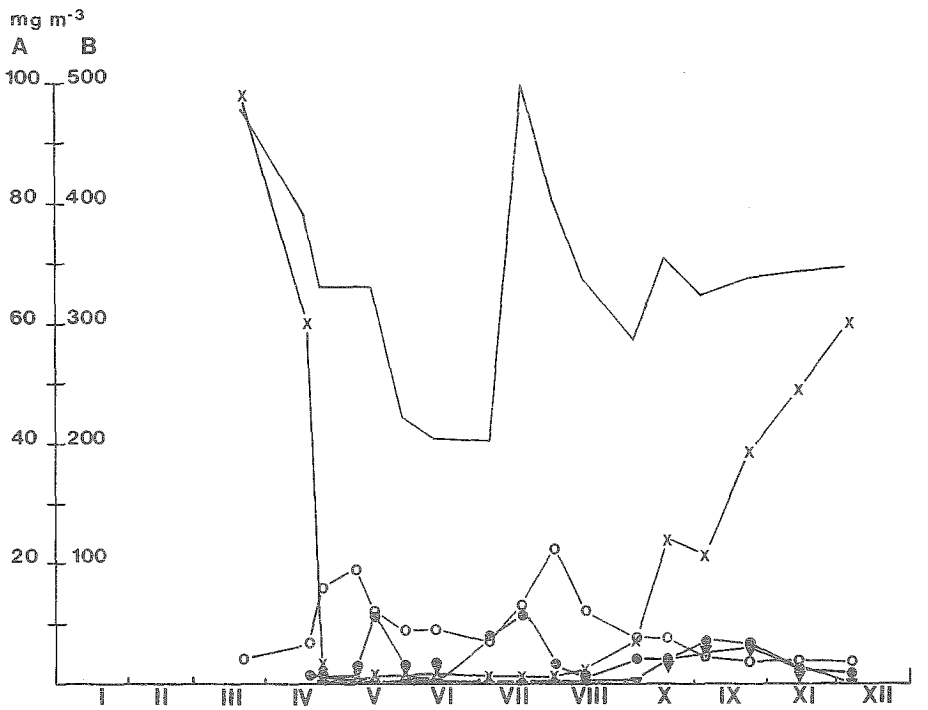

Fig. 2. Mean concentrations of total N (continuous line), NO_3-N (-x-), NO_2-N (-▽-), NH_3-N (-●-) and particulate organic nitrogen (-o-) in the trophogenic layer in 1979. The B scale refers to total nitrogen and particulate organic nitrogen; the A scale refers to all other compounds.

At the beginning of September a stormy period broke down the thermal stratification of the water column. Large amounts of particulate material were stirred up from the bottom and resuspended in the trophogenic layer (Fig. 4). During the autumn the water was thoroughly mixed, and the convection extended below the critical depth of phytoplankton production. Because of the circulation and the decreasing irradiation, the net primary production remained low despite increasing amounts of inorganic nutrients. The plankton biomass thereby fell to its winter minimum level.

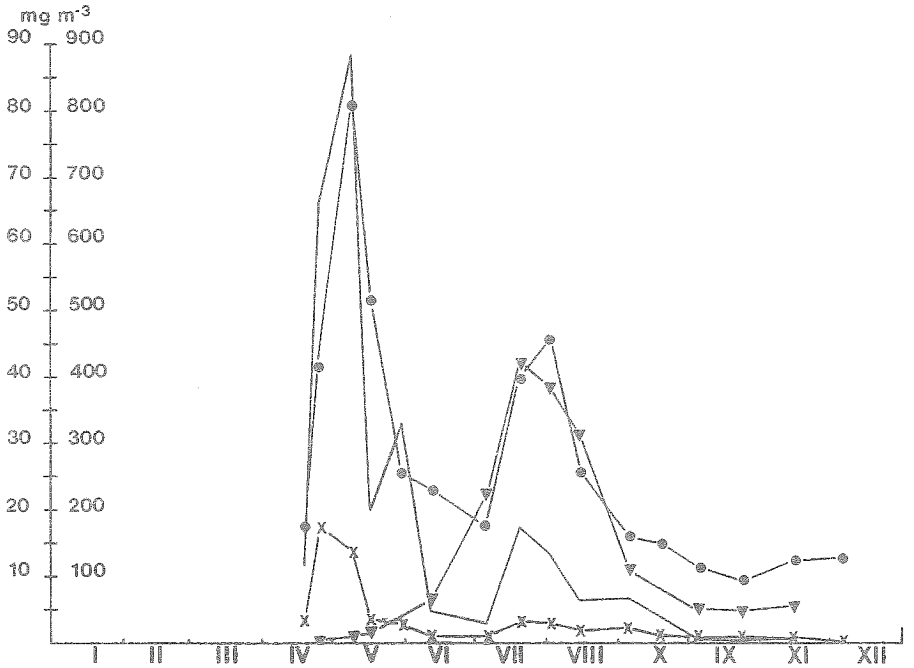

Fig. 3. The annual fluctuation of phytopalnkton biomass (continuous line), zooplankton biomass (-▽-), chlorophyll *a* (-x-) and POC (-●-) in the trophogenic layer in 1979. The left scale refers to chlorophyll *a* and zooplankton biomass, the right scale refers to phytoplankton biomass and particulate organic carbon.

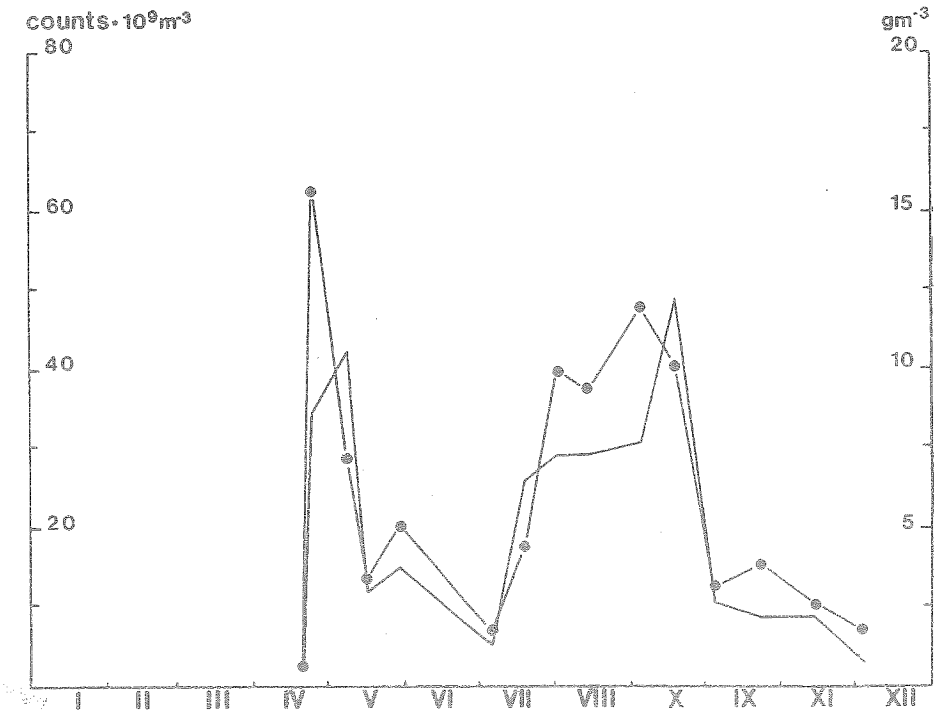

Fig. 4. Mean values for total particle amount (continuous line) and total particle number (-●-) in the trophogenic layer in 1979.

4. RESULTS

4.1. Composition of particulate matter

During the vernal bloom, phytoplankton biomass (expressed as wet weight) accounted for almost 90 % of the total particulate amount (TPA, Fig. 5). The bulk of POC was also contributed by living phytoplankton except on the May 16, when the diatom bloom was replaced by dinoflagellate bloom (Forsskåhl & Sundberg 1981) and large amounts of detritus from the diatom maximum were still present. The percentage values exeeding 100 (Fig. 6) were probably resulted from an overestimation of living phytoplankton biomass using the microscopic method (cf. Kononen 1981), and possibly from the incomplete oxidation of large amounts of organic matter in the POC analysis (Laakkonen et al. 1981). In the summer, the contribution of phytoplankton to TPA and to POC varied from ca. 10 % to ca. 40 % (phytoplankton summer minimum) and from ca. 20 % to ca. 40 % respectively. The large contribution of phytoplankton to POC on September 4 was probably caused by the low carbon content of the resuspended detritus (Figs. 6 and 7).

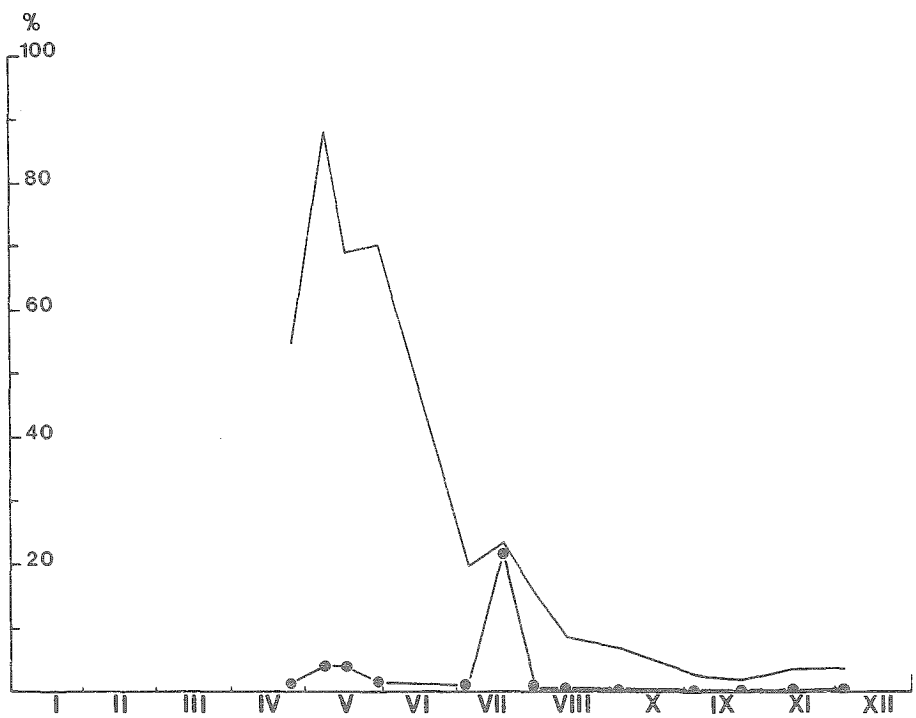

Fig. 5. Percentage contributions of phytoplankton biomass (wet wt.) to total particle amount (continuous line) and phytoplankton counts to total particle number (dotted line) in the trophogenic layer in 1979.

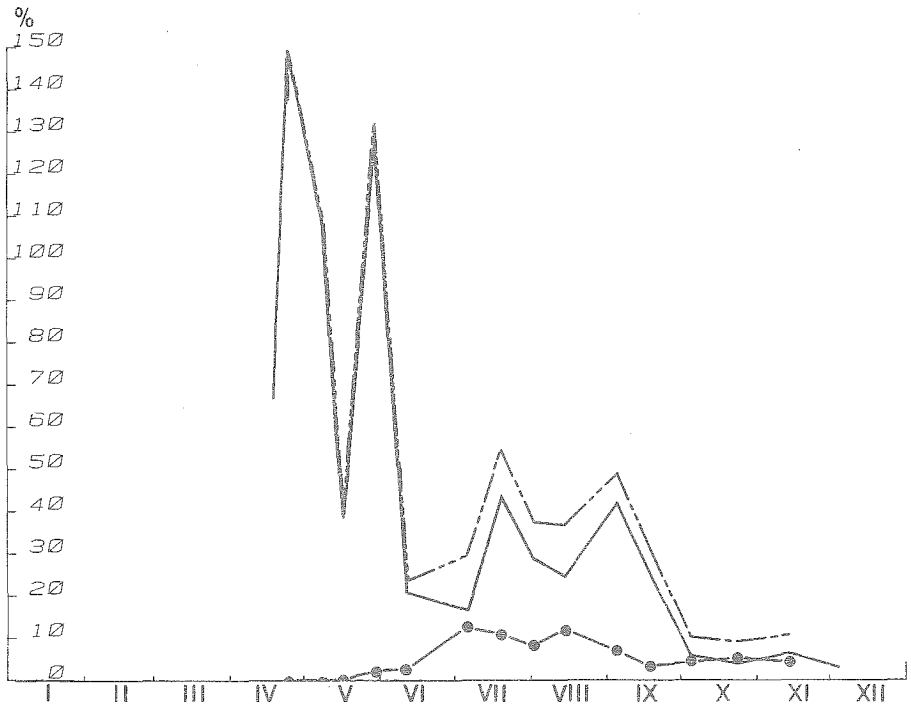

Fig. 6. The percentage contributions of phytoplankton (continuous line), zooplankton (dotted line) and total plankton (broken line) to particulate organic carbon in the trophogenic layer in 1979.

The highest carbon contribution to the total particle amount (TPA) was observed during the vernal phytoplankton bloom and in early July when the zooplankton biomass made its greatest contribution to POC (Fig 6). The contribution of zooplankton to TPA is slightly underestimated due to the aperture used in the Coulter Counter (200 µm). However, zooplankters bigger than 200 µm were not abundant in this area (Forsskåhl & Sundberg 1981). Zooplankton seldom contributed more than 10 % to the POC (Fig. 6). The zooplankton percentages may be too high, because the POC values are the means taken from 0-10 m samples while those of zooplankton are calculated from samples obtained by net hauls of 25-0 m. The sampling always took place in the forenoon when at least most of the largest zooplankters are situated below the 0-10 m layer due to their diel migration (e.g. Lassig & Niemi 1978).

4.2. Carbon

The amount of DIC was fairly constant throughout the study period. The proportion of TOC to total carbon was about 20 % and deviated little (Table 1).

Table 1. Total carbon (TC), dissolved inorganic carbon (DIC), total organic carbon (TOC), dissolved organic carbon (DOC) and particulate organic carbon (POC) in the trophogenic layer in 1979. TOC is shown as a percentage of TC, and DOC and POC as percentages of TOC.

	g m^{-3}				mg m^{-3}	%		
Date	TC	DIC	TOC	DOC	POC	DOC/TC	DOC/TOC	POC/TOC
18.4.	33.7	28.8	4.9	4.7	175	14	96	4
24.4.	22.7	18.7	4.0	3.6	440	18	90	10
8.5.	22.6	17.8	4.8	4.0	815	21	83	17
16.5.	22.8	18.4	4.4	3.9	515	19	88	12
29.5.	22.0	18.0	4.4	4.1	255	20	93	7
11.6.	22.9	18.5	4.4	4.2	230	19	95	5
4.7.	22.7	18.9	3.8	3.6	175	17	95	5
18.7.	21.7	17.4	4.3	3.9	395	20	95	5
1.8.	22.4	17.5	4.9	4.4	460	22	90	10
14.8.	23.0	17.6	5.4	5.1	260	23	94	6
4.9.	22.8	18.1	4.7	4.5	160	21	96	4
18.9.	24.2	19.1	5.1	5.0	150	21	97	3
4.10.	27.9	19.5	8.4	8.3	115	30	98	2
23.10.	25.4	19.5	5.9	5.8	94	23	98	2
13.11.	25.9	19.1	6.8	6.7	125	26	98	2
4.12.	26.1	19.2	6.9	6.7	130	26	98	2

The TOC (3.8-8.4 g m^{-3}) tended to increase towards the end of the study period (Table 1). DOC made up the greater part of TOC (> 80 %) throughout the study period. The proportion of POC was low (2-17 % of TOC); its highest percentages were observed during the biomass maxima.

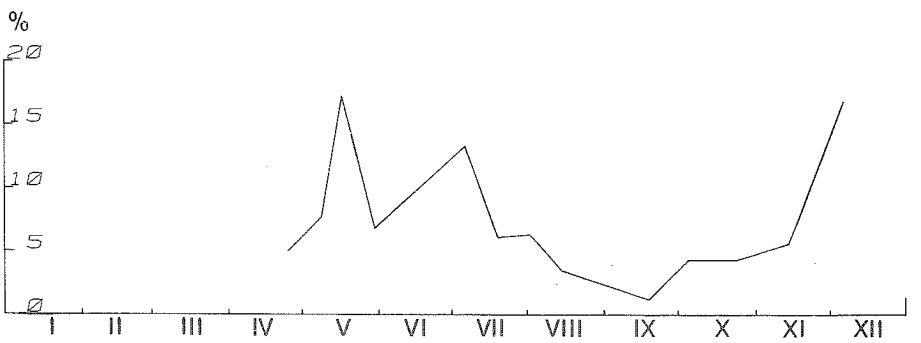

Fig. 7. Percentage contribution of particulate organic carbon to total particle amount in the trophogenic layer in 1979.

4.3. Nitrogen and phosphorus

Throughout the study period, most of the total N (usually > 70 %, Table 2) was in the form of dissolved and suspended organic compounds (DON). The contribution of PON to totan N was ca. 20 % during the growth period. Before the vernal phytoplankton maximum and in the autumn, the inorganic nitrogen was mostly in the form of NO_3^--N. During the summer, the fluctuations of inorganic nitrogen were related to the fluctuations of NH_4^+-N (Fig. 2).

Table 2. Dissolved inorganic nitrogen (DIN), particulate organic nitrogen (PON), dissolved organic nitrogen (DON), dissolved inorganic phosphorus (DIP), particulate organic phosphorus (POP), and dissolved organic phosphorus (DOP) expressed as percentages of total nitrogen and of total phosphorus in the trophogenic layer in 1979.

Date	DIN %	PON %	DON %	DIP %	POP %	DOP %
18.4.	17	8	75	62	14	24
24.4.	1	24	75	51	43	7
8.5.	1	29	70	33	55	11
16.5.	7	18	75	35	36	39
29.5.	2	20	79	26	39	35
11.6.	1	22	76	36	25	39
4.7.	18	17	66	31	46	23
18.7.	11	13	76	39	48	13
1.8.	3	27	69	-	-	-
14.8.	2	18	80	28	44	28
4.9.	9	13	78	49	25	25
18.9.	13	11	76	69	17	14
4.10.	18	7	76	60	10	30
23.10.	23	5	72	63	10	28
13.11.	19	6	75	55	9	36
4.12.	19	5	76	75	12	14

The contribution of POP to total P was clearly higher and more variable than the corresponding nitrogen contribution (Table 2). Contrary to the N situation, the contribution of inorganic P was high throughout the growing period, making up ca. 1/3 of total P.

5. DISCUSSION

The vernal phytoplankton maximum consisted of two blooms (cf. Fig. 3): during the first bloom diatoms made up the bulk of the phytoplankton biomass and during the second bloom dinoflagellates were the dominant group (Forsskåhl & Sundberg 1981).

At the beginning of the vernal production stage 18.4.-24.4. the phytoplankton biomass increased by 90 mg C $m^{-3}d^{-1}$. The rate of decrease in dissolved inorganic silicate concentration was 12 mg $m^{-3}d^{-1}$, 1.3 mg $m^{-3}d^{-1}$ in inorganic phosphorus and 11 mg $m^{-3}d^{-1}$ in inorganic nitrogen ($NO_3^+ + NO_2^- + NH_4^+$-N). After this stage, most of the inorganic nitrogen was bound in the phytoplankton biomass which limited further growth of the phytoplankton population. During the next 14 days, the phytoplankton biomass increased by 16 mg C $m^{-3}d^{-1}$. The rate of decrease for phosphate phosphorus was 0.2 mg $m^{-3}d^{-1}$ and 5.8 mg $m^{-3}d^{-1}$ for silicate. The amount of inorganic nitrogen increased slightly during that period due to an NH_4^+-N increase indicating the start of decomposition and grazing and the end of the diatom bloom (c.f. Forsskåhl & Sundberg 1981). The next phase of the vernal bloom was dominated by dinoflagellates (Forsskåhl & Sundberg 1981). The phytoplankton biomass increased by 10 mg C $m^{-3}d^{-1}$. This second bloom saw a decrease in phosphate and silicate rate of 0.3 mg $m^{-3}d^{-1}$ and 2 mg $m^{-3}d^{-1}$ respectively. The inorganic nitrogen originated from the decomposing diatom bloom and was predominantly in the form of NH_4^+-N. The decrease in inorganic nitrogen concentration was 4.2 mg $m^{-3}d^{-1}$.

During the fast growing stage of the diatom bloom, the ratios of phytoplankton carbon increase and inorganic nutrients decrease were $\Delta C:\Delta N:\Delta Si:\Delta P$ = 188:19:11:1 by atomic ratio. When the calculations are done using the increase of POC, PON and POP the ratios were $\Delta C:\Delta N:\Delta P$ = 123:19:1, which approximates the uptake ratios of phytoplankton found in the North Sea during the vernal bloom (Weichart 1980). The dinoflagellate bloom was not seen by an increase in POC, PON and POP because the amount of detritus was high and its sedimentation decreased these values (Laakkonen et al. 1981). The inorganic nitrogen was predominantly in the form of NH_4^+-N due to the decomposition of organic matter. The ratios of changes for inorganic nutrient concentrations to the phytoplankton biomass were, at this stage, $\Delta C:\Delta N:\Delta Si:\Delta P$ = 84:11:7:1. During the first stage of the diatom bloom, the decrease of inorganic nutrients and the increase of particulate organic nutrients estimate the nutrient incorporation ratios. The nutrients then, are not growth limiting and disintegration and grazing are of minor importance. However, during the second phase, when the dinoflagellates predominate, disintegration of algal cells, decomposition and grazing cause remineralisation of nutrients. Therefore the decrease in inorganic nutrients during the dinoflagellate bloom does not directly explain the incorporation of nutrients into the phytoplankton biomass.

After the vernal period, when most of the nutrients were sedimented from the euphotic layer (Laakkonen et al. 1981), the primary production rate depended on the nutrient recycling above the thermocline caused by bacterial decomposition and zooplankton grazing. It has been shown that over 80 % of the phosphorus and 70 % of the nitrogen in the phytoplankton ingested by grazing zooplankton can be returned to the water as excreta (Butler et al. 1970). Phytoplankton exudates, whose carbon amounts to ca. 30 % of net production (Larsson & Hagström 1978), also contain variable amounts of N and P. During the summer period, most of the nitrogen (usually > 70 %) was in the form of dissolved or suspended organic coumpounds. DON is largely unidentified although amino acids and urea constitute a small component of the total DON (McCarthy 1980). It has been demonstrated that the balance of this nitrogenous material is not nutritionally suitable for oceanic phytoplankton (Thomas et. al. 1971). Our results also suggest that most of the nitrogen recycling in the euphotic layer during the growth period takes place between PON and DIN, while most of the DON is in a biologically inactive form causing long turn-over time for total N. Although most of the DOP in water consists of high molecular weight, refractile and enzyme-resistant material (Taft et al. 1970) not likely to serve as a source of phosphorus for microorganisms (Nalewajko & Lean 1980), the balance between DIP, POP and DOP suggests that total phosphorus recycled more completely than total nitrogen.

As shown by Bruun et al. (1981) the seasonal fluctuation of phytoplankton biomass significantly explained the variation of particulate matter in the euphotic layer. Phytoplankton biomass in the euphotic layer is a balance between growth, sedimentation, disintegration and decrease by grazing. During the vernal period, the growth of phytoplankton is predominantly regulated by inroganic nutrients available in the euphotic layer. The difference between the observed biomass values and the expected doubling rate values (Fig. 8) can mostly be explained by sedimentation (cf. Laakkonen et al. 1981). During the summer period, the growth rates were high despite the low concentrations of inorganic nutrients in the euphotic layer. At that time, the growth rate of phytoplankton was regulated by the nutrient recycling rate while the phytoplankton biomass was regulated by grazing.

Heterocystous blue-green algae are an exception: they are scarcely grazed by zooplankton and they can fix molecular nitrogen. Horstman (1975), however, reports that some rotifers are able to bite single cells from the trichome bundles of Aphanizomenon flos-aquae. The full role of phosphorus for N_2-fixing blue-green algal blooms is unknown but it is

assumed that the blooms can be connected to the upwelling of phosphorus rich water (Niemi, Å. 1979) and that blue-green algae are able to store surplus phosphorus in their cells (e.g. Fogg 1975). During the autumn, light and convection are the main factors regulating phytoplankton growth. The effect of deep water mixing was very clear in our study: phytoplankton biomass decreased suddenly after the stormy period in September and stayed low the rest of the year.

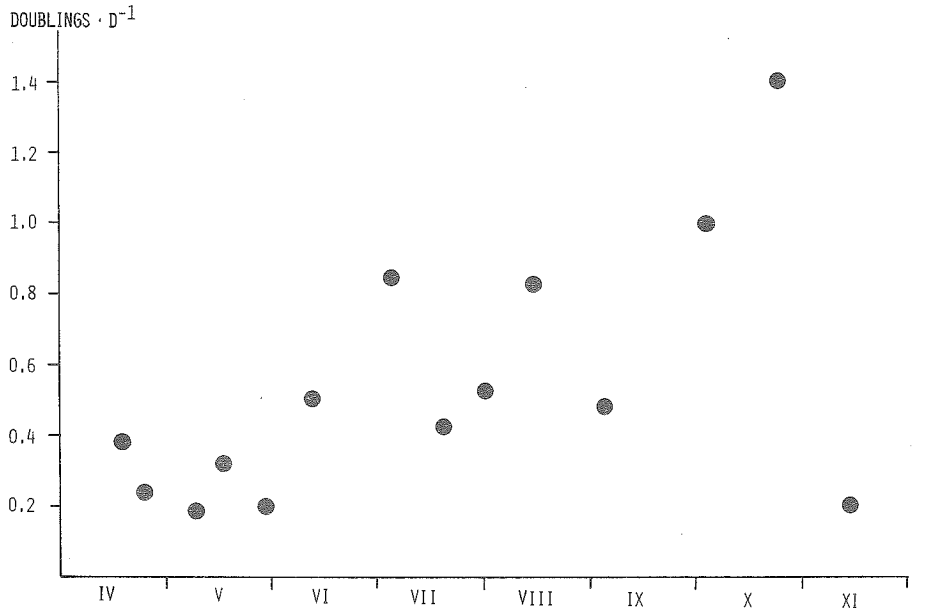

Fig. 8. Growth rate of phytoplankton (doublings d^{-1}) in the euphotic layer, 0-10 m, calculated from primary production *in situ* and phytoplankton biomass values.

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STUDIES ON THE DECOMPOSITION OF ORGANIC MATTER IN THE GULF OF FINLAND

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Abstract

To establish the carbon cycle in the Baltic Sea environment we need information on the bacterial decomposition of organic matter. For lack of appropriate methods, however, we still do not know enough about bacterial activity. The usefulness of a method based on bacterial glucose uptake for measuring the bacterial activity was tested in two open-sea areas in the Gulf of Finland. In addition to the activity measurements, bacterial numbers were determined by direct microscopic counting. The samples were collected from five depths in spring, midsummer and autumn during cruises of R.V. Aranda.

The bacterial activities and numbers in the Gulf of Finland are of the same order of magnitude as those in the Baltic Proper and in the unpolluted areas of the southern Baltic. No significant differences were noted between the two areas studied. A rather large proportion of organic material is presumably decomposed in the uppermost 20-m-thick water layer, where the bacterial activities and numbers are highest. Based on bacterial numbers from this study and data from the literature it can be calculated that about 22 % of the primary production of phytoplankton in the Gulf of Finland is channeled through bacteria.

1. INTRODUCTION

Studies on bacterial activity in natural waters are hampered by the lack of methods capable of producing unambiguous quantitative data. Determinations of the bacterial number and biomass are not enough to establish the efficiency of bacterial decomposition; instead, bacterial activity has to be measured. The activity of heterotrophic bacteria is generally measured by the method developed by Parsons and Strickland (1962) and Wright and Hobbie (1965, 1966), which is based on Michaelis-Menten enzyme kinetics, i.e. the multi-concentration method. The method allows us to determine the theoretical maximum velocity of substrate uptake (V_{max}), which is generally accepted as the measure of the size of the bacterial population on a substrate (Wright and Hobbie 1966), the sum K_t+S_n, which is the upper approximate of the natural substrate concentration (S_n stands for the

natural substrate concentration and K_t is a measure of the affinity of the uptake system for a substrate) and the turnover time (T_t) for a substrate. If the natural concentration of a substrate S_n is known, the actual uptake velocity of the substrate (v) at a given concentration can be calculated.

The kinetic method is rather easy and simple to apply and is also well-suited for use on a research vessel. Since the method requires that substrate be added in a number of different concentrations, the handling of large numbers of samples is somewhat tedious. In the single-concentration method developed by Williams and Askew (1968) radioactive substrate is added only once in a very low concentration; this allows us to determine no more than the turnover time of the substrate. The turnover time can be used as a relative measure of the activity of the heterotrophic bacteria, provided that the natural substrate concentration in the waters being studied is almost constant in time and space. If this is so, the shift in turnover time is due mainly to bacterial activity rather than to a change in substrate concentration. The data reported so far seem to indicate that the variation in the concentrations of the substrates used most often, glucose and amino acids, in natural waters is low compared with the variation in their turnover times (Andrews and Williams 1971, Grawford et al. 1974, Dawson and Gocke 1978). If the turnover time is accepted as a good enough measure for bacterial activity, we should stop to consider whether the parameters V_{max} and K_t+S_n produce so much more information that it is worth applying the kinetic method, which requires several additions. If it is enough to determine the turnover time, then only one addition per sample is needed and several samples can be treated with the amount of work required for handling one sample by the kinetic method.

In the present study the applicability of the activity determination based on the bacterial glucose uptake (both the multi-concentration and sing-concentration methods) was tested in the open sea on the research vessel Aranda. Also collected was preliminary data on the vertical variation in bacterial activities and numbers in the Gulf of Finland.

2. STUDY AREA

The sampling stations LL 7 ($59^{o}51N$ $24^{o}50E$) and LL 12 ($59^{o}29N$ $22^{o}54E$) are located in the open Gulf of Finland (Fig. 1).

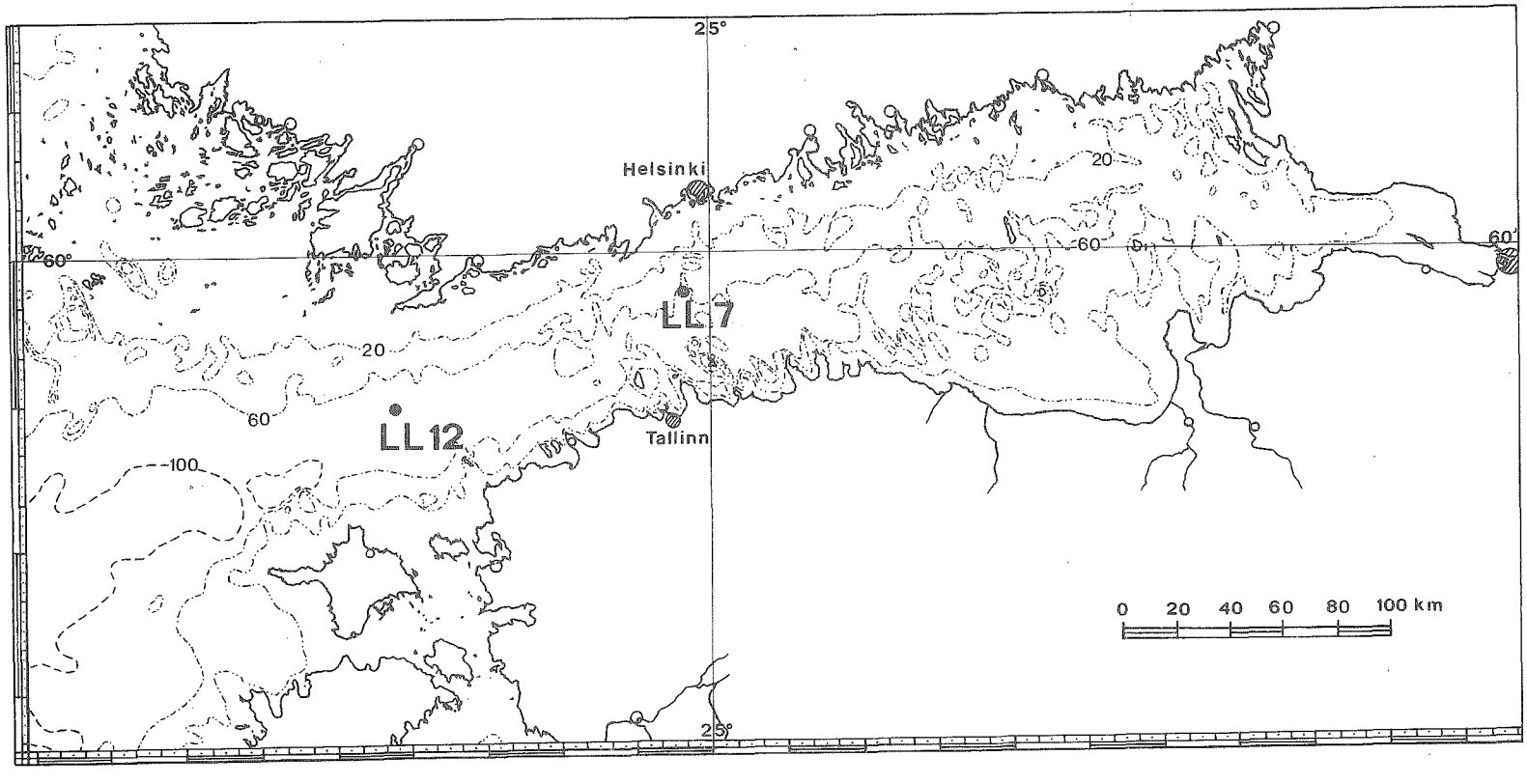

Fig. 1. Sampling stations in the Gulf of Finland.

The central part of the Gulf of Finland is 60 to 80 m deep, and the basin deepens towards south and west. The water body below the halocline (in general 40 to 60 m) is in connection with the Baltic Proper, there being no sill between it and the Gulf of Finland. Hence, the variation in the quality of the water in the Baltic is reflected in the water in the Gulf of Finland.

Most of the rivers that run into the Gulf of Finland are discharged into the eastern Gulf. The salinity in the eastern end of the Gulf is 4.5 ‰ and in the western end 6.5 to 7 ‰ Owing to the water body that extends from the Baltic Proper to the Gulf of Finland, the lowermost water layers in the Gulf of Finland show rather high salinities and concentrations of nutrients. The upwelling of deep water increases the nutrient concentrations in the surficial water, particularly in the eastern Gulf of Finland. The nutrient concentrations in the eastern Gulf are further increased by the abundant discharge of municipal waste waters (Perttilä et al. 1980).

3. METHODS

3.1 Sampling

At both stations the samples were taken from five depths by a Universal Series Sampler sterilized with alcohol. Attempts were made to collect the samples in accordance with the prevailing stratification of the water column, i.e. from the photic region of the mixed surface layer; from below the thermocline; from the so called winter water; from below the halocline and from as close to the bottom as possible.

Samples were first taken in early May at the time of the spring maximum of primary production when the water was not yet thermally stratified. Samples were next taken in late July when the thermal stratification was well developed. The third time samples were taken was in September; the stratification was then still distinct at LL 7, whereas at LL 12, where the samples were taken six days later owing to a storm, the thermal stratification was already vanishing.

3.2 Determination of bacterial activity

The activity of the heterotrophic bacteria was determined by measuring the activity from the glucose uptake of the bacteria. Kinetic

analysis (the multi-concentration method, Parsons and Strickland 1962, Wright and Hobbie 1965, 1966) based on Michaelis-Menten enzyme kinetics was conducted at three depths only (mixed surface layer, winter water and deep water). In addition to the glucose-carbon incorporated into the bacterial cells, the carbon respired was also determined at these depths. The samples collected from below the thermocline and halocline were assayed by the single-concentration method for glucose turnover time (Williams and Askew 1968).

The substrate used was D-(U-^{14}C) glucose (Radiochemical Centre, Amersham, England) with specific activity 291 mCi/mmol or 1.54 mCi/mg, radioactive concentration 200 mCi/dm^3, radiochemical purity 99 % and molecular weight 189.

To determine the kinetic parameters (V_{max}, T_t, K_t+S_n), radioactive glucose was added to the samples in five different concentrations giving glucose concentrations of 0.036, 0.70, 1.40, 2.80 and 3.50 µg glucose-C dm^{-3}.

At each addition three replicates and one blank were made. In the single-concentration method the glucose addition was 0.036 µg C dm^{-3}.

Formaldehyde was added to the blanks immediately after the addition of glucose; it was added to the actual samples after being incubated for three hours (in situ temperature, refrigerators).

The samples were filtered through a Millipore HAWP membrane with a pore size of 0.45 µm and a diameter of 25 mm. The ^{14}C-clucose on the filter not incorporated into the bacteria was washed with 25 ml water. Some of the washing water was used to rinse the sample vial.

It has been established that cellulose ester membrane filters like the Millipore filters retain particles that are smaller than their rated pore sizes (Sheldon and Sutcliffe 1969, Sheldon 1972, Salonen 1974, Hobbie et al. 1977, Cole and Likens 1979). Hence, it is likely that the majority of the bacteria less than 0.45 µm in size were retained on the Millipore filters employed (Williams 1970).

The radioactivity was measured by a 1215 Rackbeta liquid scintillation counter (Wallac Oy). For the measurement the filters were wetted with 200 µl distilled water and dissolved in 1 ml dioxane. After the filters had gone into solution 10 ml of xylene based PCS scintillation coctail were added into the vials. Standardization was performed using external-standard channels ratio method with carbon tetrachloride as quenching agent.

The percentage respiration value was determined by the method of Kuparinen and Uusi-Rauva (1980), which is a simplified modification of the Hobbie and Crawford (1969b) method.

The sample volume was 10 ml and the concentration of the added glucose in the sample was 3.50 µg C dm^{-3} (three replicate samples and one blank). The substrate was added in only one concentration, since the respiration percentage depends only slightly on the substrate concentration (Hobbie and Crawford 1969b, Barvenik and Malloy 1979, Kuparinen 1980). After incubating the samples for three hours 300 µl ethanolamine were added into a glass cup suspended from the rubber stop, (Fig. 2) to absorb the $^{14}CO_2$ produced by bacterial respiration. Then 200 µl 4M H_2SO_4 were added to the sample to terminate biological activity and to liberate $^{14}CO_2$ from the water. Sulphuric acid was added to the blanks immediately after the glucose had been added. To absorb $^{14}CO_2$, the vials were kept at room temperature for about 23 hours. Finally, the glass cup was transferred with its content into a liquid scintillation vial that contained 4 ml 94 % etanol and 10 ml PPO-POPOP solution (5.0 g PPO + 0.1 g POPOP in a litre of toluene). Radioactivity was measured as described above.

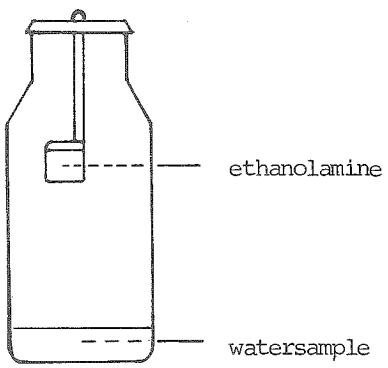

Fig. 2. Collecting the respired $^{14}CO_2$ into ethanolamine.

The numerical values of the kinetic parameters (V_{max}, K_t+S_n, T_t) were calculated merely from the glucose carbon incorporated into the cell. The values of V_{max} would increase and those of T_t decrease somewhat if the $^{14}CO_2$ removed by respiration were taken into account but would not (in theory) affect the value of the sum K_t+S_n (Hobbie and Crawford 1969a, 1969b).

3.3 Determination of bacterial number

The bacterial numbers were determined from five depths by direct microscopic counting of the bacteria after erythrosin dying (Sorokin

and Overbeck 1972, Rodina 1972). From 10 to 20 ml sample water fixed with formaldehyde were filtered through the membranes (Millipore GSWP, pore size 0.22 µm, diameter 25 mm) boiled in distilled water. The blank test was undertaken by filtering prefiltered sterile water. The bacterial cells were counted at 1600 magnification in combined phase-contrast and dark field illumination (Reichert Zetopan microscope). Ten to 30 randomly chosen microscope fields and generally at least 400 cells were counted for each sample. The counting was performed with the aid of an eyepiece provided with a 25-mesh ocular grid. Nine meshes were counted for each field of vision.

3.4 Physical and chemical determinations

The chemical analyses were performed at the chemistry laboratory of the Institute of Marine Research, Helsinki, in accordance with the standard procedures used at the Institute (Koroleff 1979). Temperature and salinity were determined with the aid of a CTD sonde.

4. RESULTS AND DISCUSSION

4.1 Physical and chemical conditions

During the first sampling in May the water was not yet thermally stratified, and the halocline was at a depth of about 50 to 60 m (Fig. 3). In July the thermocline was close to the surface (some 5 m) and extended to a depth of about 40 m. The halocline was then at a depth of 60 to 70 m. In September the thermocline was at a depth of 20 to 45 m at station LL 7, but no distinct halocline could be observed. At LL 12 the samples were taken after a storm that lasted for several days, and so the surficial water and winter water were partly mixed (cf. the other results of chemical and microbiological determinations). The thermocline had sunk to 45 to 60 m. Another weak thermocline was located at a depth of 20 to 30 m. The halocline was at 60 to 70 m.

The oxygen concentration was fairly high at both stations during the study period. In the deep water the oxygen saturation percentage was always above 30 %.

The nitrate, phosphate and silicate concentrations in the mixed surface layer (Figs. 4 to 6) were generally very low on account of

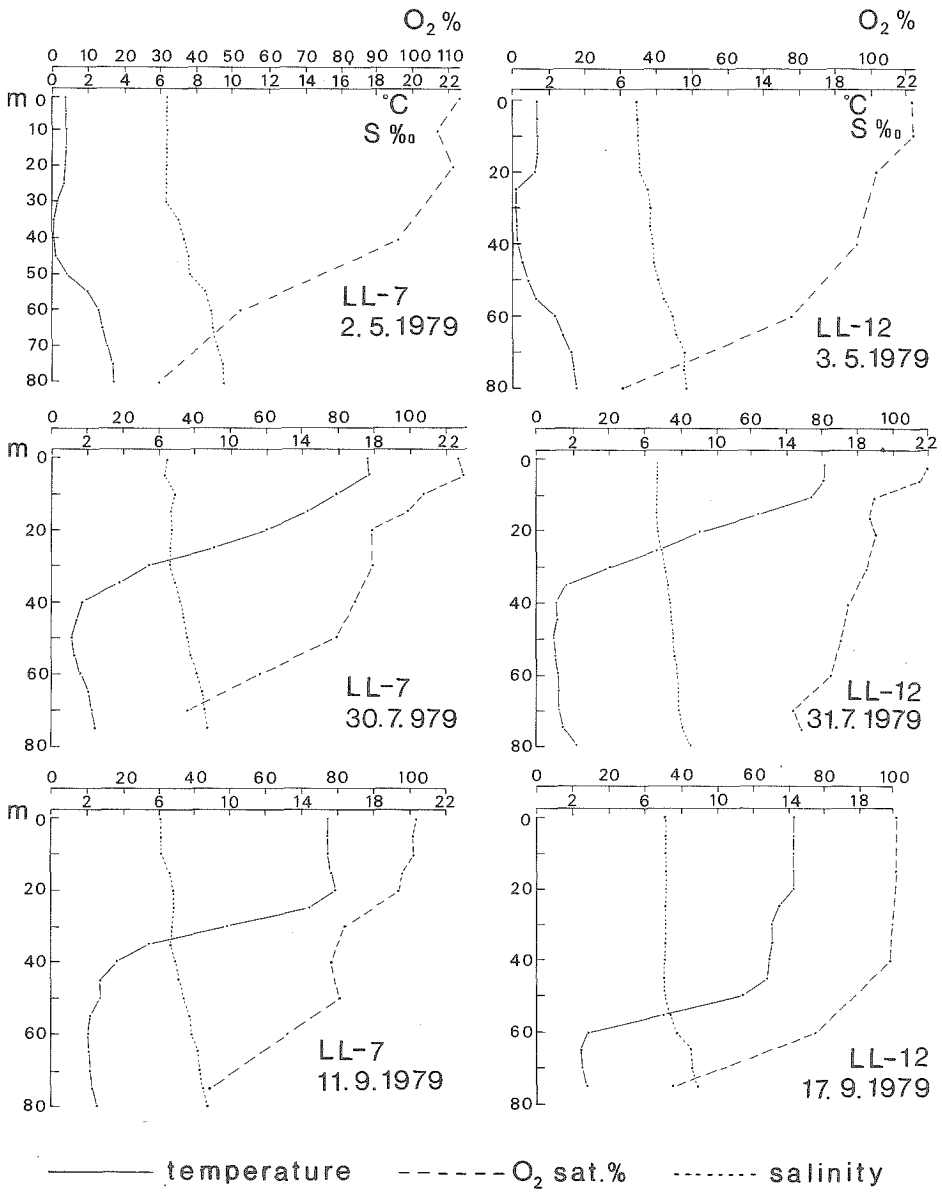

Fig. 3. Temperature, oxygen saturation percentage and salinity at stations LL 7 and LL 12.

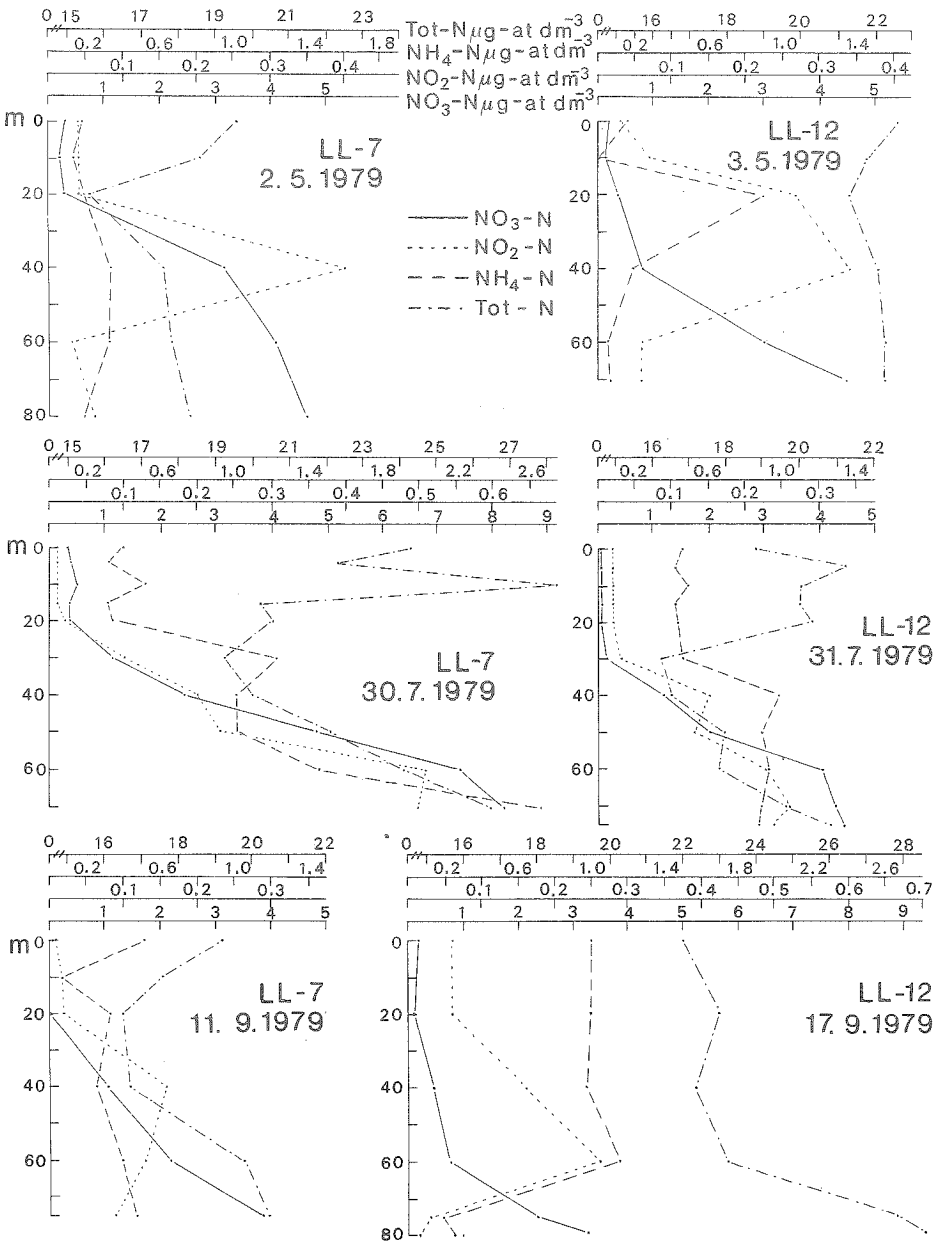

Fig. 4. Concentrations of nitrate nitrogen, nitrite nitrogen, ammonia and total nitrogen at stations LL 7 and LL 12.

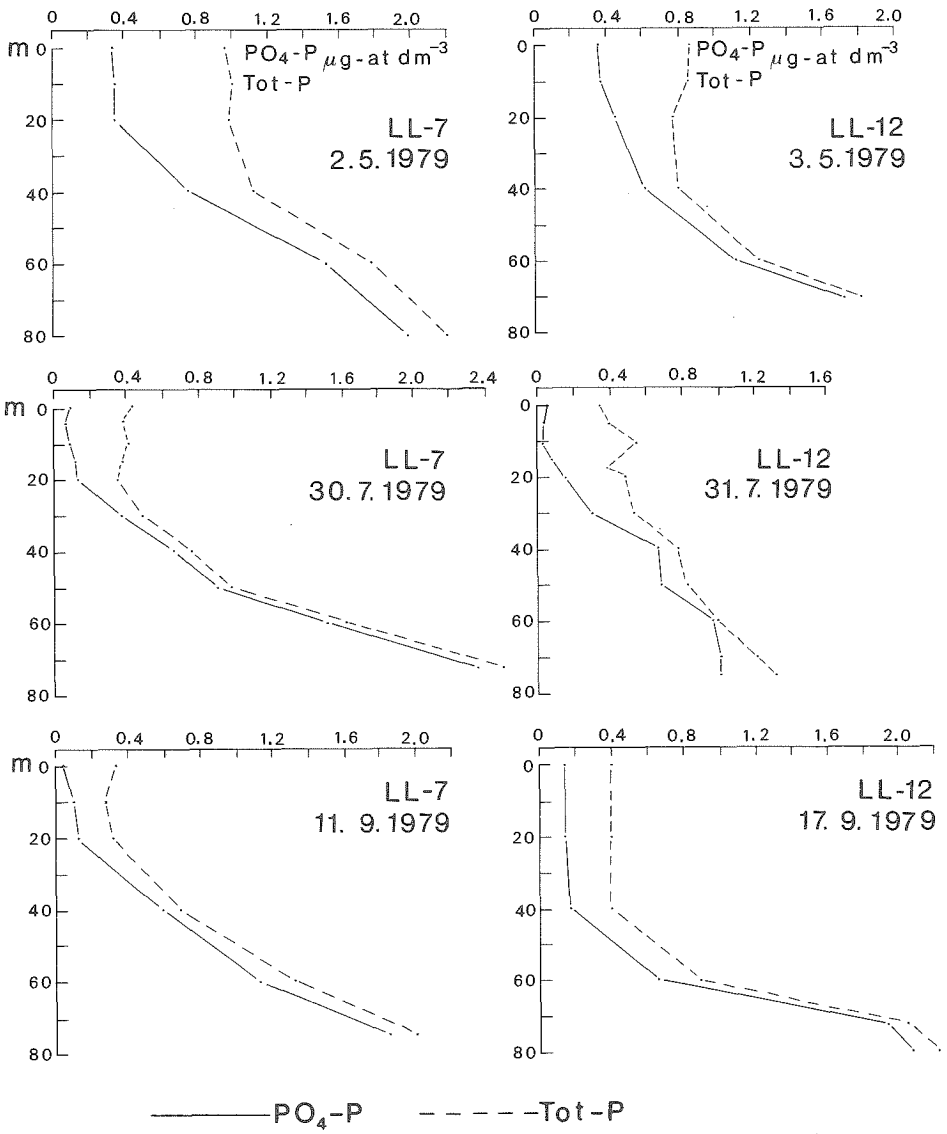

Fig. 5. Concentrations of phosphate phosphorus and total phosphorus at stations LL 7 and LL 12.

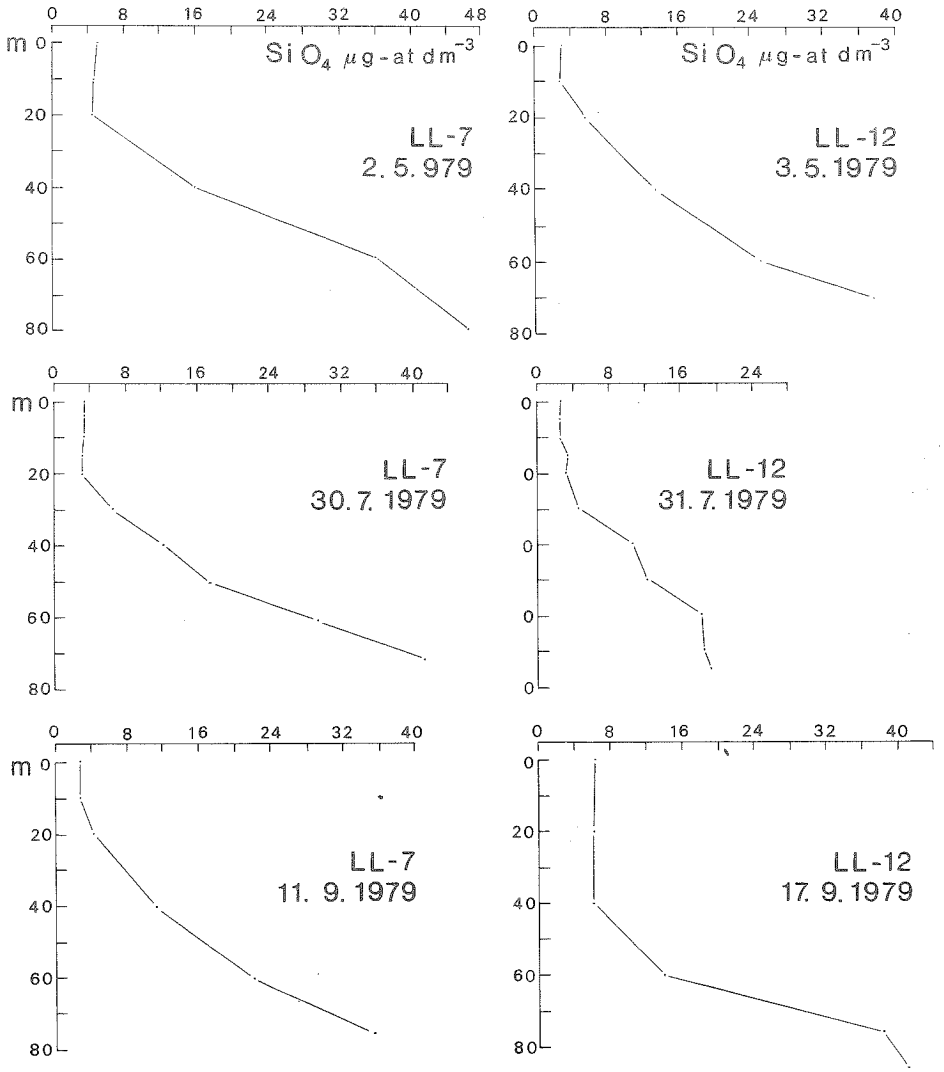

Fig. 6. Silicate concentrations at stations LL 7 and LL 12.

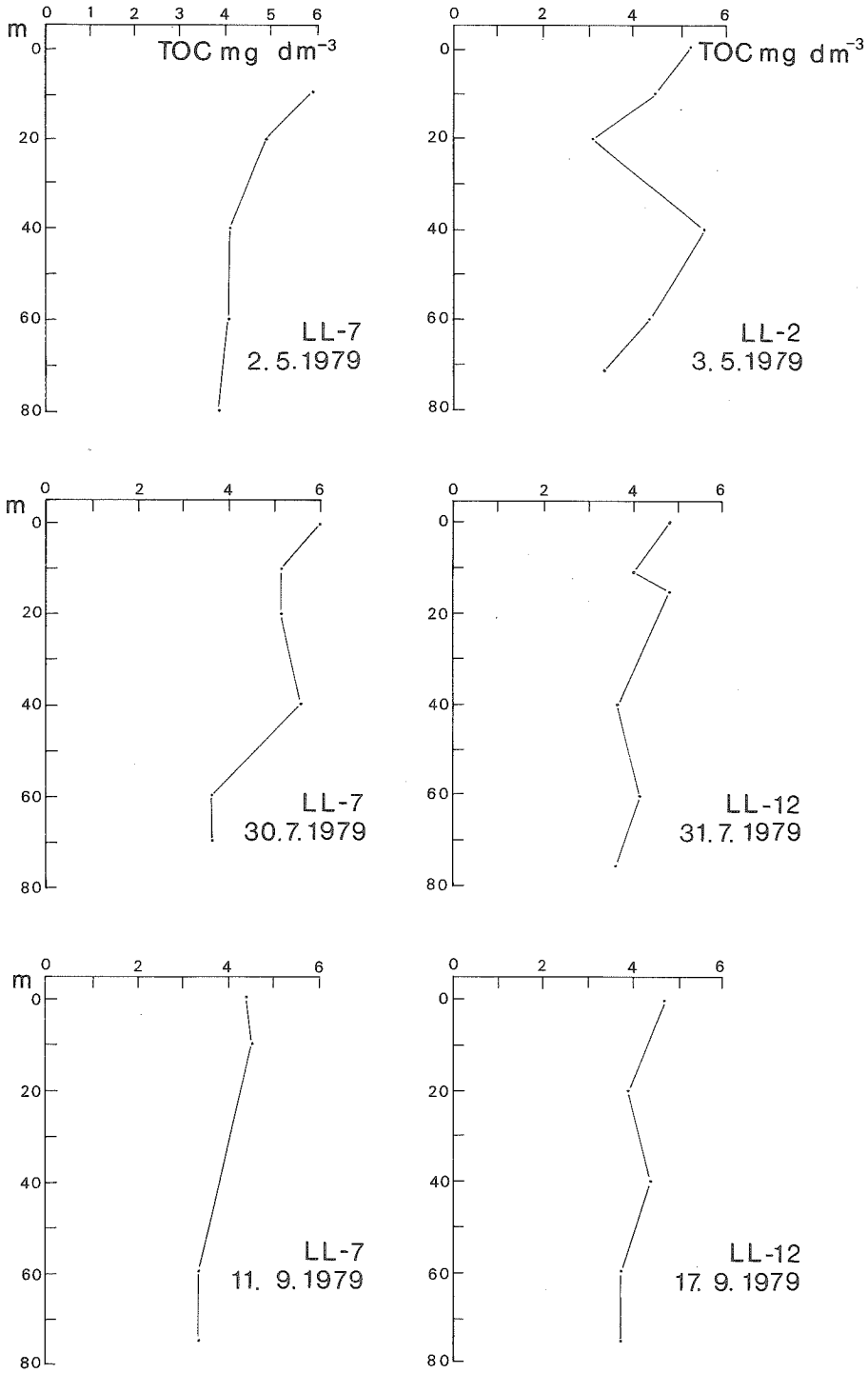

Fig. 7. Total concentrations of organic carbon at stations LL 7 and LL 12.

the primary production in this layer. The high total nitrogen concentrations in the uppermost 15 m thick water layer are due to phyto- and zooplankton.

The concentrations of most of the nitrogen, phosphorus and silicate compounds increased below the mixed surface layer. Particularly in July, the concentrations of nitrogen compounds (including nitrite and ammonia, whose concentrations at other times usually decrease in deep water) in winter water and deep water were fairly high at LL 7. The high nutrient concentrations in deep water are evidently due to the decomposition of organic matter and the mobilization of nutrients from the sediments.

The effect of the autumn storm on the thermal stratification at LL 12 is reflected very clearly also in the nutrient and silicate concentrations, which were approximately constant within the uppermost 40 m water layer.

The total concentration of organic carbon fluctuated between 3.1 and 6.0 mg dm^{-3} (Fig. 7). The concentrations were generally highest in the uppermost 10 to 20 m water layer. The concentration of total organic carbon did not exhibit marked variation in time or space.

4.2 Activity and number of heterotrophic bacteria

The correlation matrix of the physical, chemical and microbiological parameters is shown in Table 1.

In tables 2 and 3 threre are listed numerical values of the kinetic parameters and bacterial numbers reported by other authors. When comparing the data it is important to note from which depths and at which season the samples were taken.

4.2.1 Theoretical maximum velocity of glucose uptake

The theoretical maximum velocity of glucose uptake (V_{max}) varied between 0.003 and 0.084 µg C $dm^{-3}h^{-1}$ (Table 4, Fig. 8). The highest value was 28 times that of the lowest.

The V_{max} values were highest in the mixed surface layer (LL 12, 17th September, 1979 excluded). The average values for the mixed surface layer were somewhat higher in summer (0.04 to 0.08 µg C $dm^{-3}h^{-1}$) than in spring (0.02 µg C $dm^{-3}h^{-1}$) and autumn (0.01 to 0.03 µg C $dm^{-3}h^{-1}$). The V_{max} values for the winter water and deep water did not show any marked seasonal variation.

TABLE 1. The correlation matrix of the physical, chemical and microbiological parameters. The correlations at 5 % confidence level are denoted by x, at 1 % confidence level by xx and at 0,1 % confidence level by xxx.

Depth	Temperature	O_2	NO_3-N	NO_2-N	NH_4-N	Tot-N	PO_4-P	Tot-P	SiO_4	TOC	V_{max}	K_t+S_n	T_t	$\frac{1}{T_t}$	Bacterial number	
1,000	-0,633^{xx}	-0,658^{xx}	0,894^{xxx}	-0,276	-0,108	0,127	0,913^{xxx}	0,862^{xxx}	0,895^{xxx}	-0,696^{xx}	-0,633^{xx}	-0,001	0,644^{xx}	-0,636^{xx}	-0,201	Depth
	1,000	-0,047	-0,549^{x}	-0,483^{x}	0,425	0,111	-0,626^{xx}	-0,679^{xx}	-0,529^{x}	0,468	0,685^{xx}	0,063	-0,520^{x}	0,677^{xx}	0,539^{x}	Temperature
		1,000	-0,617^{xx}	0,356	0,042	-0,302	-0,722^{xx}	-0,631^{xx}	-0,793^{xxx}	0,482^{x}	0,191	-0,133	-0,435	0,219	-0,060	O_2
			1,000	0,274	-0,108	-0,031	0,866^{xxx}	0,852^{xxx}	0,867^{xxx}	-0,665^{xx}	-0,471	-0,089	0,441	-0,449	-0,083	NO_3-N
				1,000	0,122	-0,251	0,050	0,035	0,028	-0,107	-0,427	-0,183	0,192	-0,410	-0,315	NO_2-N
					1,000	-0,116	-0,300	-0,370	-0,277	-0,079	-0,016	-0,052	-0,116	0,028	0,237	NH_4-N
						1,000	0,196	0,182	0,202	0,256	0,204	0,148	0,149	0,147	0,365	Tot-N
							1,000	0,980^{xxx}	0,983^{xxx}	-0,656^{xx}	-0,521^{x}	0,057	0,691^{xx}	-0,541^{x}	-0,208	PO_4-P
								1,000	0,955^{xxx}	-0,606^{xx}	-0,482^{x}	0,033	0,620^{xx}	-0,493^{x}	-0,203	Tot-P
									1,000	-0,609^{xx}	-0,485^{x}	0,024	0,634^{xx}	-0,504^{x}	-0,204	SiO_4
										1,000	0,664^{xx}	0,102	-0,456	0,564^{x}	0,370	TOC
											1,000	0,027	-0,545^{x}	0,939^{xxx}	0,756^{xxx}	V_{max}
												1,000	0,520^{x}	-0,239	0,012	K_t+S_n
													1,000	-0,691^{xx}	-0,371	T_t
														1,000	0,722^{xx}	$\frac{1}{T_t}$
															1,000	Bacterial number

TABLE 2. Values of kinetic parameters for various marine areas.

a) The value that distinctly differs from the others (387 h) was omitted.
b) These values are based on the total glucose uptake (incorporated into cells and respired); the other values are based on the uptake of glucose incorporated into cells.

Place, season, depth	V_{max} (µg C $dm^{-1}h^{-1}$)	T_t (h)	K_t+S_n (µg C dm^{-1})	Reference
Bornholm Basin, April, 0–77 m	0,003–0,012	60–288	0,37–2,13	GOCKE (1977b)
Kiel Fjord, August, 2 m	1,86	2	3,97	
Kiel Fjord, 2–10 m				
the whole year	0,095–0,205	16–19	1,01–1,48	GOCKE (1977c)
April–September	0,157–0,364	6–7	0,93–2,06	
Kiel Bight, 2–18 m				
the whole year	0,025–0,034	78–107[a]	0,93–1,59	
April–September	0,036–0,052	23–31[a]	0,86–1,56	
Bornholm Basin, Danzig and Gotland Deeps, from the surface to the bottom	0,003–0,065			DAWSON ja GOCKE (1978)
Bothnian Bay off Kaskinen				
May–October, surface area polluted by municipal and industrial effluents	0,013–0,469	9–50	0,59–4,03	KUPARINEN (1980)
clean area	0,006–0,072	24–304	0,46–3,49	
Tropical Atlantic, 800 km off the coast	0,07		15	VACCARO ja JANNASCH (1966)
- " - , coast	0,02		60	
Tropical Pacific (eastern part)	0,0006–0,054		15–275	HAMILTON ja PRESLAN (1970)
Pacific Ocean (northwest), 0–1000 m	0,003–0,020	420–4300	8,36–14,55	TAKAHASHI ja ICHIMURA (1971)
Pacific Ocean (northwest), summer, 20–50 m	0,003–0,016[b]	2700–7600[b]	9–34[b]	SEKI et al. (1972)
Pacific Ocean, subarctic area, 20 m	0,009[b]	1300[b]	12[b]	
Pacific Ocean, Tokyo Bay, 0–24 m	0,9–7,2[b]	9–23[b]	20–62[b]	SEKI et al. (1975)
Gulf of Finland, open sea, May–September, 0–80 m	0,003–0,084	7–187	0,18–1,53	This study

TABLE 3. Values of bacterial numbers, bacterial biomasses and specific activity indices.

Place, season, depth	Bacterial number (10^6 cells cm^{-3})	Biomass (mg C m^{-3})	Spec. act. index (10^{-12} µg C $cell^{-1}h^{-1}$)	Reference
Gotland Deep, July				
0-230 m	4-9,5			SEPPÄNEN ja VOIPIO (1971)
Gulf of Finland (Ajax), years 1973-74				
0-70 m	0,8-1,7			VÄÄTÄNEN (1976)
North Sea, summer, 1 m	8,3			
Kiel Fjord, summer, 1 m	6,5			GOCKE (1976)
Plussee, summer, 1 m	6,6			
River Elbe, summer, 1 m	5,3			
Bornholm Basin, May, 0-93 m	0,3-0,9	0,9-3,0	2-38	GOCKE (1977a)
Danzig Deep, " 0-106 m	0,2-1,8	1,1-6,9	14-37	DAWSON ja GOCKE (1978)
Gotland Deep " 0-246 m	0,3-0,5	1,1-2,2	9-29	
Gulf of Maine, August, 1-40 m	0,6-8,3		1-105	WRIGHT (1978)
Gulf of Finland, open sea, May-September				
0-80 m	0,05-1,0	0,2-5	9-152	This study

Table 4. The theoretical maximum velocities of glucose uptake (V_{max}, $\mu g\ C\ dm^{-3}h^{-1}$), the sums of the transport constant and the natural glucose concentration (K_t+S_n, $\mu g\ C\ dm^{-3}$), and the turnover times (T_t, h) by multi-concentration (a) and single-concentration (b) methods at stations LL 7 and LL 12 in May to September 1979. The means with 95 % confidence levels. r^2 = coefficient of correlation, n = number of points in the regression line. x) unrealiable data.

Date of sampling and depth (m)	V_{max}	K_t+S_n	T_t^a	T_t^b	r^2	n
LL 7 2.5.1979						
10	0,018±0,001	0,50±0,16	28±9	35±8	0,986	15
20				23±2		
40	0,010±0,001	0,81±0,24	82±24	72±17	0,973	14
60				63±2		
80	0,006±0,0003	0,39±0,13	70±23	58±13	0,990	15
30.7.1979						
0	0,084±0,008	0,59±0,21	7±2	8±2	0,974	15
10				9±2		
20	0,019±0,003	1,53±0,37	80±15	86±29	0,948	14
40				62±46		
60 x)	0,007±0,003	0,48±1,27	70±183	94±68	0,680	11
11.9.1979						
0	0,033±0,008	0,36±0,54	11±16	20±3	0,850	15
20				12±2		
40	0,005±0,0005	0,35±0,23	76±48	92±50	0,970	14
60				69±73		
75	0,005±0,001	0,95±0,31	187±55	146±39	0,954	15
LL 12 3.5.1979						
10	0,019±0,002	0,40±0,21	21±11	25±3	0,973	15
20				20±1		
40	0,003±0,0002	0,31±0,13	100±43	74±30	0,989	15
60				102±40		
71	0,004±0,0003	0,26±0,18	69±46	74±8	0,982	15
31.7.1979						
0	0,039±0,006	0,49±0,32	13±8	14±15	0,943	15
15				13±3		
40	0,007±0,001	0,71±0,47	109±68	117±89	0,916	13
60				93±180		
75	0,006±0,001	0,18±0,32	28±51	31±19	0,939	15
17.9.1979						
0	0,012±0,002	0,46±0,33	38±27	45±29	0,947	14
20				52±71		
40	0,012±0,003	0,46±0,57	37±45	25±11	0,839	15
60				93±49		
75	0,006±0,002	1,04±0,82	165±117	140±81	0,750	15

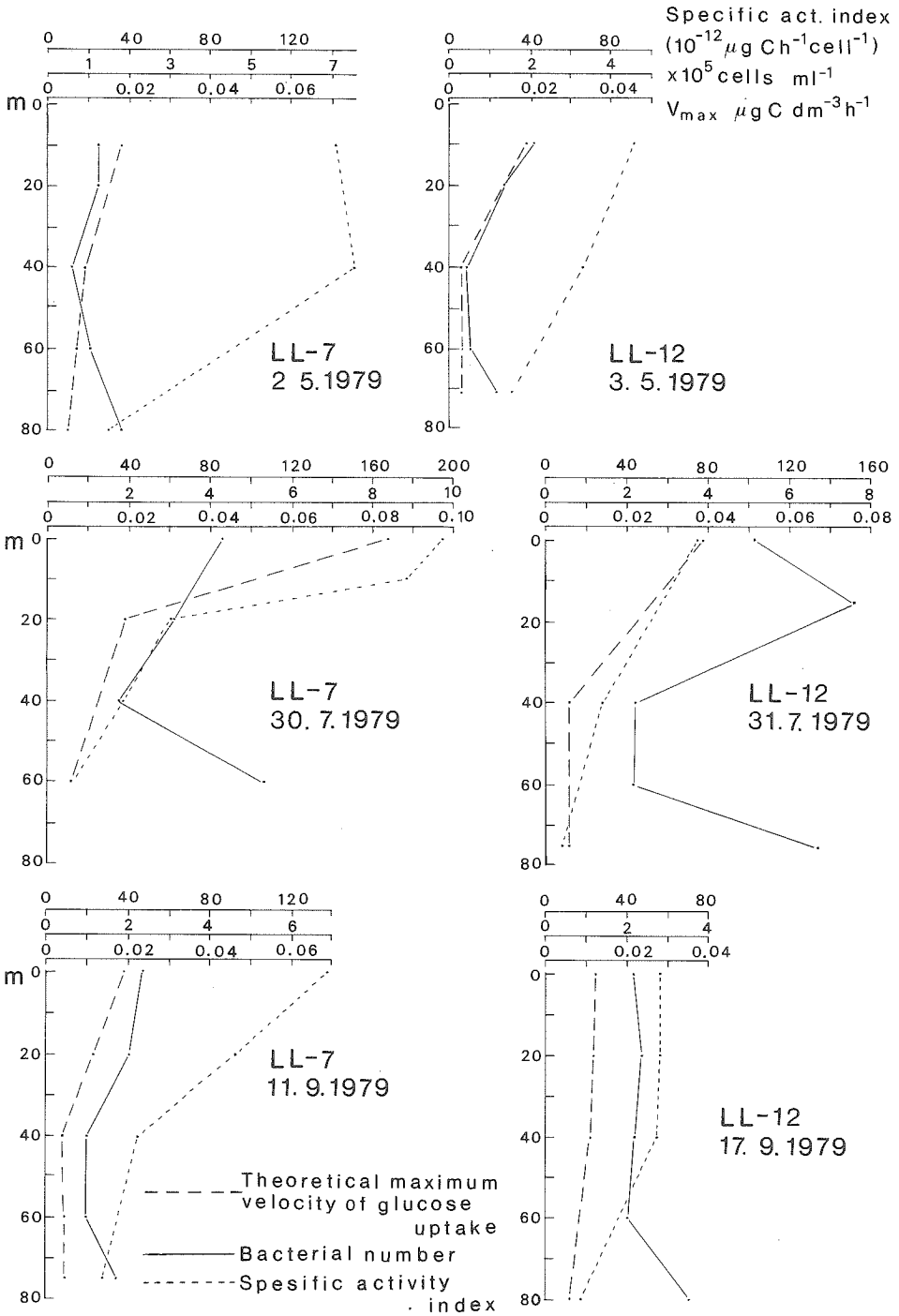

Fig. 8. Theoretical maximum velocities of glucose uptake, bacterial numbers and specific activity indices at stations LL 7 and LL 12.

The V_{max} values for the Gulf of Finland are of the same order of magnitude as those for the Bornholm Basin, the Danzig Deep and Gotland Deep (Dawson and Gocke 1978), the Kiel Bight (Gocke 1977c) and tropical areas of the Atlantic (Vaccaro and Jannasch 1966) and Pacific (Hamilton and Preslan 1970). In contrast, the V_{max} values were higher in the Kiel Fjord (Gocke 1977c), which is polluted by municipal and industrial effluents. In the Bothnian Sea off Kaskinen, which is polluted by effluents from the wood-processing industry, the V_{max} values reported at the outermost station (Kuparinen, 1980) agree well with those measured for the Gulf of Finland in this study.

Kinetic parameters are also used as the basis for trophic classification (Spencer 1978a). In most cases V_{max} increases and T_t decreases from oligotrophic towards eutrophic waters (Hobbie and Crawford 1969a, Albright and Wentworth 1973, Seppänen and Ojanen 1973, Overbeck 1977, Gocke 1977c, Spencer 1978a, 1978b). Spencer (1978a) has defined $V_{max} = 0.01$ µg C $dm^{-1}h^{-1}$ as the upper limit for oligotrophy. Thus, on the basis of the V_{max} values in the photic zone, the Gulf of Finland is mesotrophic. According to the primary production classification suggested by Wetzel (1975), the trophic state of the Gulf of Finland is between oligotrophy and mesotrophy.

4.2.2 Sum K_t+S_n

The sum K_t+S_n did not vary much during the study period: the difference between the lowest (0.18 µg C dm^{-3}) and highest (1.53 µg C dm^{-3}) values was about nine-fold (Table 4, Fig. 9). The average for the whole data is 0.57 µg C dm^{-3}.

The differences between the K_t+S_n values of samples taken simultaneously from different observation sites and samples taken from a given site at different times were generally less than double (expressed as averages of the K_t+S_n valus for different depths at each station). The differences between the depths were also small (four-fold at the most).

In May and July the K_t+S_n values were highest in the winter water (excluding LL 12 on 3rd May, 1979, when the 10-m value was slightly higher than the 40-m one) and decreased towards the surface and the bottom. In September the surficial waters and winter water did not show any difference, whereas the K_t+S_n values of the deep water were about 2.5 times higher than those of the surface water.

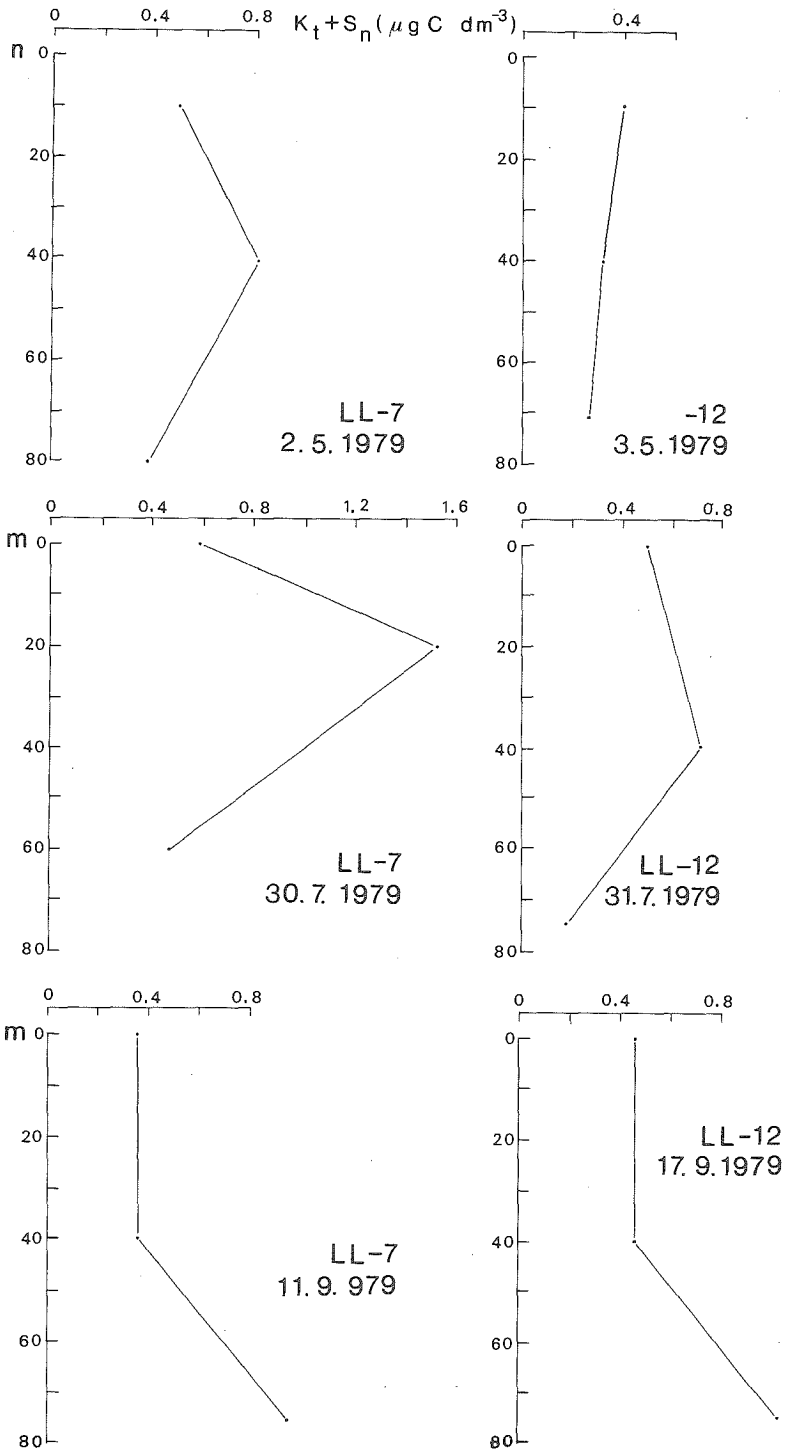

Fig. 9. K_t+S_n values at stations LL 7 and LL 12.

The K_t+S_n values were lower in the Gulf of Finland than, e.g. in the Bornholm Basin (Gocke 1977b), Kiel Bight and Fjord (Gocke 1977c) or in the Bothnian Sea off Kaskinen (Kuparinen, 1980). The K_t+S_n values reported from the oceans are much higher than any of those measured from the Baltic (Hamilton and Preslan 1970, see table 2).

4.2.3 Turnover time of glucose

The turnover times of glucose (T_t) were determined by the single-concentration method (five depths) and the multi-concentration method (three depths, five additions) (Table 4, Fig. 10). As demonstrated by the t-test ($t = 0.909$, $n = 17$), the turnover times obtained by these two methods do not show any significant statistical difference.

The turnover times fluctuated between 7 and 187 hours, being shortest (about 10 to 40h) in the uppermost 20 m thick water layer and usually increasing in the winter water (generally 60 to 120h). In May and July the turnover times decreased towards the bottom (30 to 90h), tu in September they increased markedly in deep water (140 to 190h). The trends were similar at both stations.

The average turnover times of the water column in May and July were 50 to 60 h; they were somewhat longer in September (c. 70 to 90 h).

The turnover times recorded from the topmost 20 m of water in the Gulf of Finland (averaging 23 h) correspond well to the turnover times measured in the Kiel Bight (averaging 27 h in the uppermost 18 m during April to September, Gocke 1977c). Off Kaskinen (at the outermost station 24 to 304 h, average 149 h, Kuparinen 1980) and in the Bornholm Basin (60 to 288 h, Gocke 1977b) the average turnover times were longer than in the Gulf of Finland. Turnover times up to thousands of hours long have been measured in the open Pacific (Takahashi and Ichimura 1971, Seki et al. 1972); in contrast, the turnover times in the polluted areas in the Pacific were merely a few hours (Seki et al. 1975).

Contrary to expectations, the results obtained in the present study by the single-concentration and multi-concentration methods did not differ significantly from each other. Williams (1973) has demonstrated on a theoretical basis that the kinetic method gives values for T_t and K_t+S_n that are too high, and that the single-concentration method results in turnover times that are more correct than those obtained by the multi-concentration method. Williams'

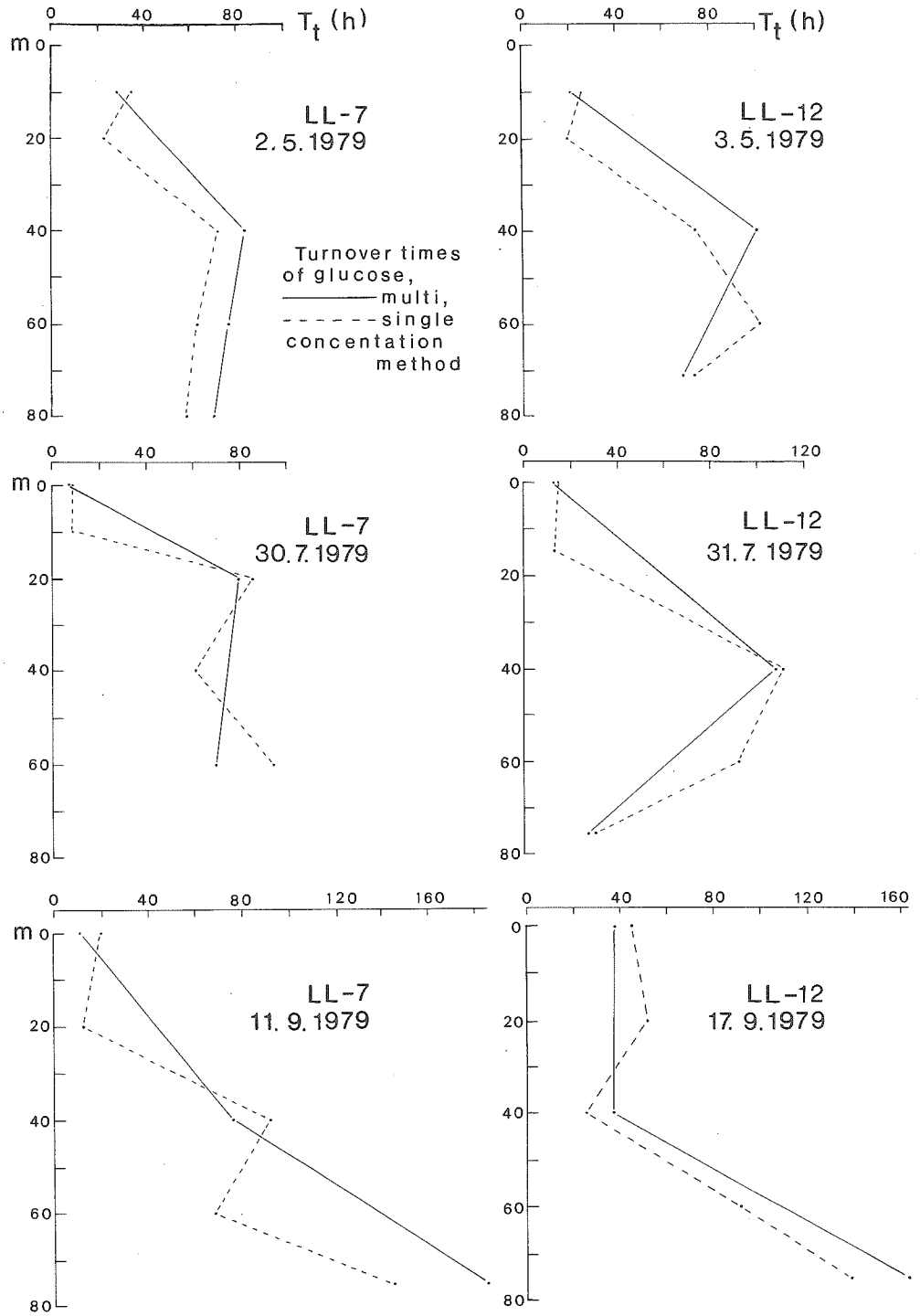

Fig. 10. Turnover times of glucose measured by single-concentration and multi-concentration methods at stations LL 7 and LL 12.

concept (1973) is supported by experimental data from the Baltic Sea by Gocke (1977b). In his studies Gocke (1977b) demonstrates that the turnover times obtained by these two methods differ more from each other in oligotrophic waters than they do in eutrophic waters. According to him, the single-concentration method should be used particularly in oligotrophic waters.

When applying the single-concentration method, it is important to know how much glucose can be added without affecting the turnover time. Wright (1974) has estimated that if the added substrate concentration is less than 20 % of the natural substrate concentration, the single-concentration method gives turnover times that are correct within an accuracy of 10 %.

The glucose addition (0.036 µg C dm^{-3}) used in the present study when the single-concentration method was applied was less than 3 % of the lowest concentration (1.36 µg C dm^{-3}, Meyer-Reil et al. 1979) measured in the southern Baltic. If the K_t+S_n values are considered as the upper approximate value of the concentration of glucose that the bacteria can take up (the chemical glucose determination may also include the glucose that the bacteria cannot use), then the glucose concentration in the Gulf of Finland was about 0.3 µg C dm^{-3} (based on the approximation $K_t=S_n$ presented by Gocke, 1977c), i.e. the concentration of glucose added in the sample was a mere 12 %.

In kinetic analysis of the bacterial glucose uptake, the amount of glucose added may affect the values of all the kinetic parameters (Williams 1973). In the present study the glucose additions were smaller than those used in many other studies. The concentration range used by Gocke in most of his studies is very close to that in the present work. Hence, the large differences in the numerical values of the kinetic parameters between the Baltic Sea and the oceans may be attributed not only to true differences between biotopes but also to differences in methods.

4.2.4 Percentage respiration value

The percentage respiration values varied between 8 % and 31 %; values less than 15 % or more than 25 % were rare (Table 5). The average of the whole data was 19.5 %.

The respiration percentages in samples taken simultaneously did not differ much from each other (excluding the samples collected in September). As a rule the mixed surface layer exhibited the highest

TABLE 5. Respiration percentages (%) at stations LL 7 and LL 12 in May to September 1979.

Date of sampling and depth (m)		Respiration percentage	Mean
LL 7	2.5.1979		
	10	25	
	40	16	24
	80	31	
	30.7.1979		
	0	20	
	20	20	20
	60	-	
	11.9.1979		
	0	15	
	40	8	12
	75	14	
LL 12	3.5.1979		
	10	27	
	40	22	24
	71	23	
	31.7.1979		
	0	24	
	40	12	18
	75	17	
	17.9.1979		
	0	21	
	40	21	19
	75	16	

respiration percentage and the winter water the lowest. The highest percentages were measured in spring.

Most of the reported respiration percentages are around 30 % (Hobbie and Crawford 1969a, 1969b, Williams 1970, Gocke 1975, 1976). Lower percentages have, however, been measured, e.g. 6 % in the Plussee (Overbeck 1975) and 13 % in the estuary of the Pamlico river (Crawford et al. 1974). The respiration percentages reported by Dawson and Gocke (1978) from the basins of the Baltic Proper (average 18 %) correspond closely to the data from the Gulf of Finland. The differences between the biotopes are obviously significant (Gocke 1976).

The percentage respiration values generally varied only slightly

with depth. The studies by Dawson and Gocke (1978) also show no marked vertical variation.

Since the percentage respiration values remained relatively constant at all depths, there would not be any significant change in the vertical distribution of the bacterial activity at different times and depths, even if the respiration had been taken into account. Since the mixed surface layer tends to show the highest and the winter water the lowest respiration percentages, the V_{max} values of the mixed surface layer and deep water would increase and their T_t values decrease somewhat more than those of the winter water.

The studies by Gocke (1976) demonstrated that the respiration percentages were higher in summer than in winter. Gocke (1976) postulates that this is due to the variation in temperature. Winter data are lacking from the Gulf of Finland, but by comparing with each other the data for May, July and September we note that the respiration percentages are highest in May even though the water temperature is then still the same as in winter. The relation between the temperature and percentage respiration value is probably indirect, the latter being predominantly controlled by other factors, such as the production of organic matter and the physiology of the bacterial cells (Hobbie and Crawford 1969b).

4.2.5 Bacterial number

As a rule the bacterial numbers were of the order of 10^5 cells cm^{-3} (0.5 to 9.8 x 10^5 cells cm^{-3}, Table 6, Fig. 8).

The bacterial numbers were generally highest in the mixed surface layer (0 to 20 m) and lowest in the winter water (20 to 60 m), increasing again towards the bottom. The largest differences in bacterial numbers between different depths were observed in July; although measurable, the vertical differences were not that clear in May and September.

If we assume 0.06 μm^3 as the average bacterial cell colume (Zimmermann 1977, Hagström et al. 1979), 1.1 g cm^{-3} as the cell density (Doetsch and Cook 1973, ref. Ferguson and Rublee 1976), 0.23 as the ratio of dry weight to wet weight (Roberts et al. 1957, ref. Ferguson and Rublee 1976) and 0.344 as the ratio of bacterial carbon to dry weight (Ferguson and Rublee 1976), we obtain values between 0.2 and 5 mg C m^{-3} for the bacterial biomass. The average bacterial biomass per unit surface area is 108 mg C m^{-2} (calculated from the means of

TABLE 6. The bacterial numbers (cells cm^{-3}) and specific activity indices (10^{-12} µg C h^{-1} $cell^{-1}$) at stations LL 7 and LL 12 in May to September 1979.

Date and depth (m)	Bacterial number	Specific activity index
LL 7 2.5.1979		
10	126 000	143
20	126 000	
40	64 000	152
60	107 000	
80	185 000	30
30.7.1979		
0	981 000	86
10	890 000	
20	307 000	63
40	178 000	
60	536 000	13
11.9.1979		
0	236 000	139
20	202 000	
40	103 000	45
60	100 000	
75	175 000	29
LL 12 3.5.1979		
10	209 000	92
20	136 000	
40	47 000	66
60	51 000	
71	120 000	32
31.7.1979		
0	516 000	76
15	762 000	
40	228 000	29
60	220 000	
75	681 000	9
17.9.1979		
0	217 000	57
20	239 000	
40	223 000	55
60	200 000	
75	358 000	18

the total data by dividing the water column into layers of 0-20 m, 21-60 m and 61-80 m).

Studies undertaken in the Gulf of Finland off Tvärminne during

May-November in 1980 suggest that the average volume of the brackish water bacteria is smaller than the above, i.e. only about 0.03 μm^3 (Virtanen, A. unpublished data).

The bacterial numbers off Tvärminne (see Table 3, Väätänen 1976) are somewhat higher than those at LL 7 and LL 12. The higher bacterial numbers in coastal waters may be due to the occasional upwelling of deep water rich in nutrients. In contrast, the bacterial numbers in the deep basins of the Baltic are generally very close to those in the open Gulf of Finland (Gocke 1977a, Dawson and Gocke 1978). Higher bacterial numbers have been reported from the Gotland Deep (Seppänen and Voipio 1971). In the polluted marine areas the bacterial numbers are often tenfold compared to those in the unpolluted areas (Gocke 1976).

If we assume that aquatic bacteria have about 120 generations a year, that is, a generation time of about three days (Hoppe 1976), we can estimate that the bacterial production in the Gulf of Finland was c. 13 g C $m^{-2}a^{-1}$, that is, 36 mg C $m^{-2}d^{-1}$. Bacterial production in the Kiel Bight has been measured to be 9 g C $m^{-2}a^{-1}$, that of the Kiel Fjord 57 g C$m^{-2}a^{-1}$ (Meyer-Reil 1977) and that in the sea off Stockholm (70 km from Stockholm) 15 g C $m^{-2}a^{-1}$ (Hagström et al. 1979).

In the present study it was measured that 80 % of the glucose carbon remains in the cell. According to Payne (1970), about 60 % of the carbon assimilated by bacteria turn into bacterial biomass. It is possible that the portion of glucose that remains in the cell is higher than in carbon compounds on an average. If we assume that the growth efficiency is about 60 % (Payne 1970), then the amount of carbon that is channeled through the bacteria (the carbon incorporated into cells and that respired) was 22 g C$m^{-2}a^{-1}$ in the Gulf of Finland. The primary production of phytoplankton in the Gulf of Finland is some 100 g C $m^{-2}a^{-1}$ (Lassig et al. 1978), which implies that the amount of carbon channeled through the bacteria is 22 % of the primary production. In the sea off Stockholm, about 25 % of the amount of carbon fixed by phytoplankton was channeled through bacteria (Hagström et al. 1979). In the Kiel Bight the amount of carbon channeled throught bacteria was 9 % of the primary production. In the more polluted Kiel Fjord the corresponding figure was 60 % (primary production 158 g C $m^{-2}a^{-1}$, Bodungen 1975, ref. Probst 1977).

4.2.6 Specific activity index

The specific activity index, which can be calculated from the V_{max} values and the bacterial numbers (the ratio of V_{max} to the bacterial number, unit 10^{-12} µg C h^{-1} $cell^{-1}$), is a measure of the ability of the bacterial population to take up the substrate in question (Wright 1978).

The indices of specific activity fluctuated between 9 and 152 x 10^{-12} µg C h^{-1} $cell^{-1}$ (Table 6, Fig. 8). On an average the values of the indices were highest in spring and lowest in autumn and decreased invariably towards the bottom.

The bacteria in the Gulf of Finland appear to be very well adapted to utilizing the glucose that exists in water in low concentrations (and possibly other similar substrates), because the specific activity indices were rather high (averaging 63 x 10^{-12} µg C h^{-1} $cell^{-1}$). For instance in the deeps of the Baltic Sea the specific activity index was on an average only 21 x 10^{-12} µg C h^{-1} $cell^{-1}$ (Dawson and Gocke 1978) and in the Gulf of Maine 25 x 10^{-12} µg C h^{-1} $cell^{-1}$ (Wright 1978). Also the fairly low K_t+S_n values of glucose suggest that brackish water bacteria are well adapted to utilizing glucose that occurs in very low concentrations.

The exceptionally high numerical values of the specific activity indices recorded in May could be attributed to the sudden increase in bacterial activity due to the onset of primary production. Wright (1978) has noted that the addition of glucose into water does not increase the bacterial number much at first, whereas the specific activity indices do increase. Odum (1971, p. 11) has also stated that the amount of bacteria does not increase proportionally to the increase in labile organic matter. The activity of the bacteria, however, does increase, and turnover times of substrates become shorter. The growth rates of the bacteria have been noted to be very high particularly in spring when the number of bacterial cells is still low but primary production has already begun (Meyer-Reil 1977, Hagström et al. 1979)

4.2.7 Vertical variations in bacterial activity

Most of the organic material produced in the photic zone is decomposed in the uppermost 20 m thick water layer. This is indicated by the fact that the V_{max} values are at their highest and the turnover times at their lowest in this layer.

We should remember, however, that the glucose method only allows us to measure the activity of the bacteria that utilize glucose. It is possible that in the winter water and deep water there is a bacterial population specialized in decomposing compounds that are not easily decomposable, and whose activity cannot be estimated reliably by the glucose uptake method.

If we consider merely the bacterial numbers, we see that they are lowest in the winter water increasing again below the halocline. The bacterial activity does not, however, necessarily correlate with the total bacterial number, some of the bacteria possibly being metabolically inactive for lack of suitable substrates (Jannasch 1969, 1970, Wright 1978), too low a temperature (Hoppe 1976), unsuitable salinity (Rheinheimer 1968), etc. Thus, e.g. in the Kiel Bight in summer, about one half of the bacteria were metabolically active and in winter only one fifth (Hoppe 1976).

The vertical distribution of the bacterial numbers at LL 7 and LL 12 was similar to the distributions off Tvärminne (Väätänen 1976) and in the deeps of the Baltic Proper (Gocke 1977a). Väätänen (1976) and Gocke (1977a) suggest that the higher bacterial numbers in the deep water compared to that in the winter water is caused by the deep water currents that admix bacteria from the sediments to the water.

The increase in bacterial numbers in and below the halocline may also be due to the fact that the sinking of the particles (both bacterial cells and detritus) slows down in the discontinuity layer of salinity where the density of the water increases. This hypothesis is in agreement with studies by Jerlow (1955) and Kullenberg (1969), who have demonstrated that the number of particles is lowest in the winter water but increases towards the bottom.

The V_{max}, which apparently indicates bacterial activity and the intensity of decomposition rather than the actual bacterial number, does not increase towards the bottom. T_t, on the other hand, may either increase (in September at both stations and in July at LL 7) or decrease (in May at both stations and in July at LL 12) towards the bottom. Since the turnover time of a substrate depends on both the velocity of substrate uptake and the substrate concentration it is not possible, without determining the natural glucose concentration, to establish whether the changes in the turnover times are due to changes in glucose concentration or in the actual velocity of glucose uptake, i.e. bacterial activity (see introduction).

The vertical distribution of the V_{max} values in the surface layer (0 to 60 m) in the Bornholm Basin and the Danzig Deep (Gocke 1977a) was similar to that in the Gulf of Finland. In the Bornholm Basin and Danzig Deep the V_{max} values increased below the halocline, whereas in the Gulf of Finland the V_{max} values of the winter water did not differ much from those of the deep water. The fact that in the deep basins of the Baltic Proper both the bacterial numbers and the glucose uptake rate increased but in the Gulf of Finland the increase in bacterial numbers did not result in an increase in V_{max} is obviously due to the difference between the bacterial populations in the deep water and in the basin water. The basin water is not encountered at LL 7 or LL 12.

In the Gulf of Finland the bacterial glucose uptake rate in deep water is lower than in winter water, which is also reflected in the decrease in the specific activity index (ratio of V_{max} to cell number) towards the bottom. Hence the theoretical maximum velocity of glucose uptake (V_{max}) cannot always be taken as a measure of the size of the bacterial population. The very significant correlation ($r = 0.756$, $n = 17$) shown in Table 1 between the bacterial number and V_{max} is due to the fact that in the mixed surface layer and winter water these parameters were closely related to each other (12 out of 17 data pairs derive from these water layers), although this relation was lacking in the underlying water.

In May and July the K_t+S_n values were at their highest at a depth of 20 to 40 m, decreasing often towards the surface and bottom. In September, however, the sum exhibited the highest values in deep water. The trends were similar at both stations. A similar change is revealed by the glucose turnover times. The increase in turnover times may be attributed to the increase in the value of parameter K_t+S_n. This increase results either from the increase in the glucose concentration or the decrease in the ability of the bacteria to take up glucose (i.e. the increase in K_t) in deep water. Due to both of these reasons the turnover time increases provided that there is no corresponding increase in the bacterial number.

Decisive conclusions on seasonal, horizontal and vertical variations in bacterial activity cannot be drawn on the basis of three replicate samplings, two stations and three to five sampling depths. The samples taken from a given station at different times often derive from completely different water bodies (Väätänen 1976), and the daily variation in the chemical and biological parameters may be large even in the same water body (Meyer-Reil et al. 1979). The present data,

however, suggest that stations LL 7 and LL 12 do not differ significantly in the rate of microbiological decomposition of organic matter. The results may apply to the open sea of the Gulf of Finland in general.

4.2.8 Factors affecting bacterial activity

As a rule microbial activity is controlled by numerous factors that act simultaneously; direct relations between microbial activities and individual parameters can seldom be shown (Bölter et al. 1977).

Hence, the correlations between various parameters established in the present study may be indirect. To mention one instance: the correlations between the temperature and microbiological parameters do not necessarily mean that an increase in temperature results in an increase in microbial activity, for where the temperature is high (mixed surfice layer) there is in general also more labile organic material. The effect of depth on the correlation between V_{max} and temperature and on that between T_t and temperature was studied by means of partial correlation coefficients; it appears that other factors related to depth influence bacterial activity at least as much as does temperature. Similarly the significant correlations between glucose turnover times and the concentrations of phosphorus and silicate do not imply that the long turnover times were due to the high nutrient concentrations. The increase in turnover times with depth is more likely due to the decrease in the concentration of labile organic material or the decrease in temperature depthwards, or both. The increase in the concentrations of phosphorus and silicate results from the accumulation of nutrients in deep water (there is a very significant correlation between the concentrations of phosphorus and silicate and depth).

The activity of deep water bacteria is probably controlled more by the amounts of easily decomposable organic material than by temperature, for the bacteria that live in persistently cold waters are well adapted to low temperatures (Hoppe 1976, Hodson 1977).

The temperature in the Baltic Sea in the water below the thermocline is fairly low for most of the year. The winter water does not warm up until the autumn when the thermal stratification vanishes, and the deep water remains cold the year round. These waters may have their own bacterial population that is well adapted to the cold water (Väätänen 1976).

4.2.9 Bacterial glucose uptake as a measure of bacterial activity

Glucose uptake probably measures only the decomposition of labile organic material. Nonetheless, it is interesting to note that there is a significant or fairly significant correlation between the total concentration of organic carbon (TOC) and the parameters describing the bacterial activity (V_{max} and $\frac{1}{T_t}$, table 1).

The dissolved organic material in natural waters includes many different compounds and hence, the whole of the carbon reserve cannot be labelled radioactively; instead, only certain labelled compounds are applicable. Before the uptake of glucose or any other compound or group of compounds can be used as a relative measure of bacterial activity, it is important to establish whether, with the aid of the glucose uptake, we are measuring a constant proportion of total bacterial activity, or whether this proportion varies in accordance with the environmental conditions.

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A COMPARISON OF METHODS FOR ESTIMATING PHYTOPLANKTON DAILY PRIMARY PRODUCTION AND PRODUCTION CAPACITY OFF TVÄRMINNE, SOUTH COAST OF FINLAND, IN 1979

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Abstract

Phytoplankton daily primary production and primary production capacity were measured in the sea zone of the Tvärminne archipelago, south coast of Finland, in 1979. The daily production results showed that the values given by a 2-h incubator method are about twice as high as those measured by a 24-h in situ method. The production capacity rate obtained by two different incubation methods were almost the same, even though different light intensities, incubation times and temperatures were used.

1. INTRODUCTION

In Finland, incubator measurements of phytoplankton primary production have been widely used to estimate phytoplankton production capacity for monitoring purposes. Incubator measurements are also used to supplement *in situ* measurements, which are time-consuming and often difficult to carry out.

The incubator method used most often in Finland is based on exposure to constant light and constant temperature (Lassig & Niemi 1972, Finnish Standards Association 1977). The incubator method used in the monitoring programme organized by the Helsinki Commission (Interim Baltic Marine Environment Protection Commission 1980) is based on constant light, but *in situ* temperature. The measurements made in this way can be used to calculate daily primary production with the aid of the light adaptation curve of the phytoplankton population (Gargas 1975, Gargas & Hare 1976).

The method recommended for measurements of daily primary production in Finland is a 24-h *in situ* incubation (Lassig & Niemi 1972, Finnish Standards Association 1977).

The present study compares the daily production values obtained by an incubator and an *in situ* method and the production capacity values obtained by two different incubator methods.

2. MATERIAL AND METHODS

The water samples were taken in the sea zone of the Tvärminne archipelago during the ice-free period in 1979. A further description of the sampling site is given by Laakkonen et al. (1981).

The production capacity was estimated by two methods:

In the method described by Lassig & Niemi (1972), here called PC_4, the capacity was measured following a 4-h incubation in constant light (Philips TL 20/33, energy 13 J $cm^{-2}h^{-1}$) and temperature (18 °C). The sample depths were 0, 2, 4, 6, 8, 10 and 15 m. Dark fixation was measured on samples from the same depths. Glass bottles of 125 cm^3 were used.

In the method described by Gargas (1975), here called PC_2, the capacity was measured following a 2-h incubation in constant light (Philips TL 20/33, energy 33 J $cm^{-2}h^{-1}$) and *in situ* temperature (mean of 0-15 m). The samples were taken from 0, 1, 2, 3, 5, 10 and 15 m. Dark fixation was measured on samples from 0, 5 and 15 m. Glass bottles of 25 cm^3 were used.

Daily production was also measured by two methods:

In the method described by Lassig & Niemi (1972), here called DP_{24} the samples were incubated *in situ* for 24 h. The sample depths were 0, 1, 2, 3, 4, 5, 6, 8, 10, 12.5 and 15 m. Dark fixation was measured at every second depth. Glass bottles of 125 cm^3 were used.

In the method described by Gargas (1975), here called DP_2, daily production was obtained by transforming the 2-h capacity values to correspond to the *in situ* values. The light adaptation curve of the phytoplankton, the actual daily irradiation and the tramsmission of green light in the water were taken into consideration when transforming the values. The light adaptation curve of the phytoplankton was obtained from measurements with integrated samples (0-15 m) incubated at light intensities of 1-175 % of the PC_2 incubator light. Neutral filters of 99, 90, 70, 50, 30 and 10 % were used. The light intensity of about 175 % was obtained by mirrors.

The *in situ* experiments were started between 11.00 and 12.00 hours and the incubator experiments about 1 h later. Before incubation, 500 mm^3 of radiocarbon solution (activity 5.06 $\mu Ci/cm^3$) was added to the 125-cm^{-3} samples and 100 mm^3 (activity 19.5 $\mu Ci/cm^3$) of radiocarbon solution was added to the 25-cm^{-3} samples. After the incubation the samples were filtered immediately on membrane filters (pore size 0,45 μm). The activity of the filters was measured with a GM-tube counter.

Daily irradiation above the sea-level was recorded with a Kipp & Zonen solarimeter connected to an Aandreaa data-logger.

The transmission of green light was measured with a luxmeter equipped with a Gossen light-accepting element with a green filter.

3. RESULTS

The values for the daily irradiation are presented in Fig. 1 and those for the transmission of green light in the water in Fig. 2.

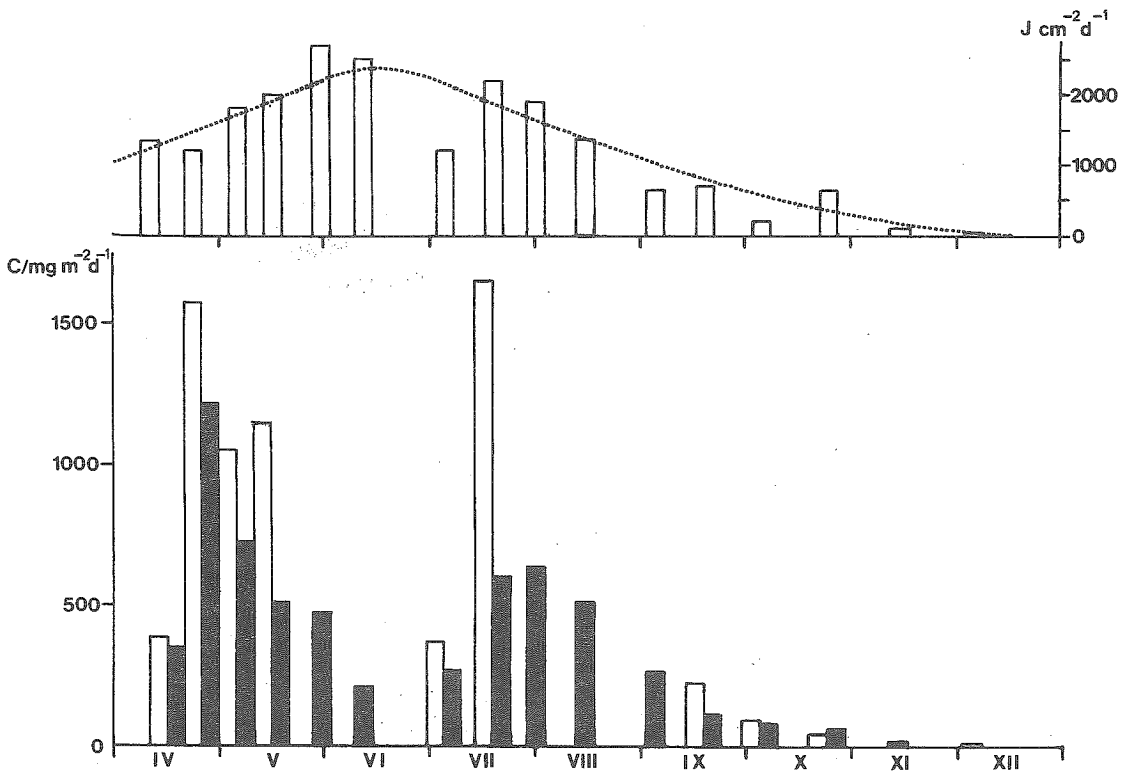

Fig. 1. Above: Daily irradiation at Tvärminne (columns) and the mean curve of irradiation for southern Finland during 1958-67 (dotted line, Rossi 1976).

Below: Daily primary production obtained by the 2-h incubation method (DP_2, white columns) and the 24-h *in situ* method (DP_{24}, black columns).

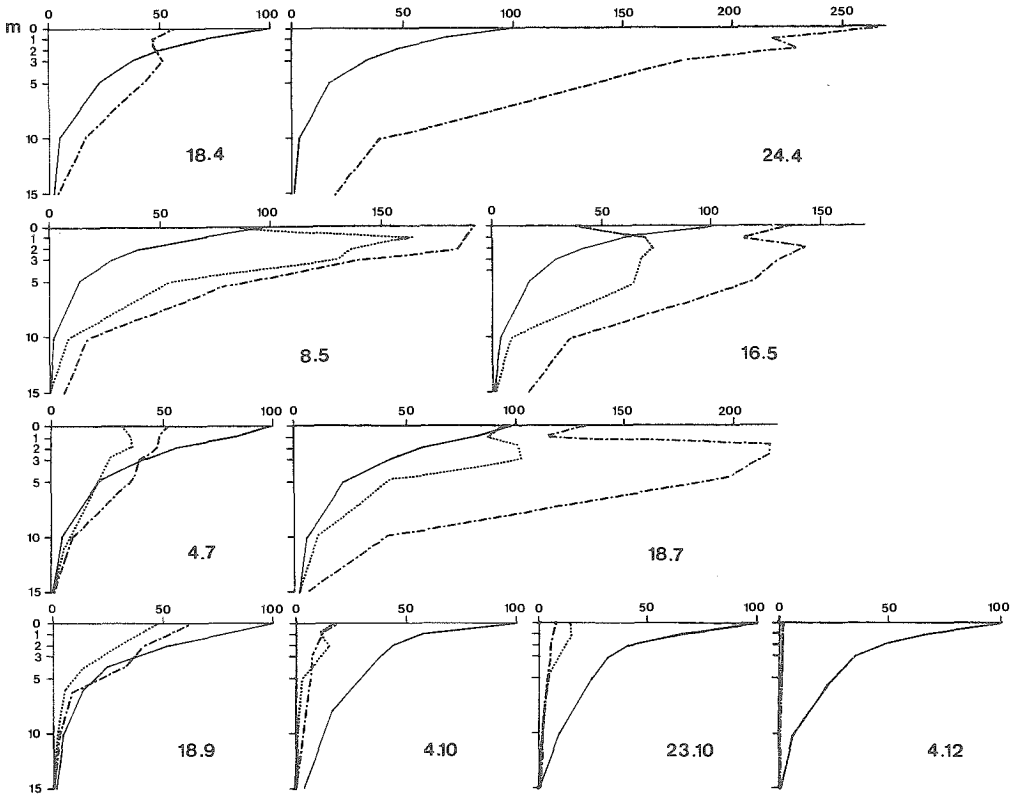

Fig. 2. Vertical transmission of green light as percentage of the light intensity just below the surface (continuous line) and the distribution of daily primary production (C/mg $m^{-3}d^{-1}$) measured by the *in situ* method (DP_{24}, dotted line) and the incubator method (DP_2, broken line).

The light adaptation curve of the phytoplankton was almost the same throughout the study period: maximum production was usually measured at 100 % or 175 % of the incubator light intensity. Only on December 4th was clear inhibition observed at the 175 % light intensity (Fig. 3).

The seasonal variation of daily production was similar for both methods. On average, the daily production values based on the 2-h incubation (DP_2) were twice as high as the corresponding DP_{24} values. The ratio of the DP_2 to the DP_{24} values varied between 0.7 to 2.1. The highest ratios were found at the end of the vernal bloom and during the blue-green algal bloom.

At both times the proportion of detritus in seston was high (Leppänen & Tamelander 1981). During the bloom of blue-green algae zooplankton was also abundant (Forsskåhl & Sundberg 1981). The regression formula for the daily production values (C/mg $m^{-2}d^{-1}$) is $DP_{24} = DP_2 \times 0.4 + 75$ ($r = 0.918^{xx}$, $n = 7$).

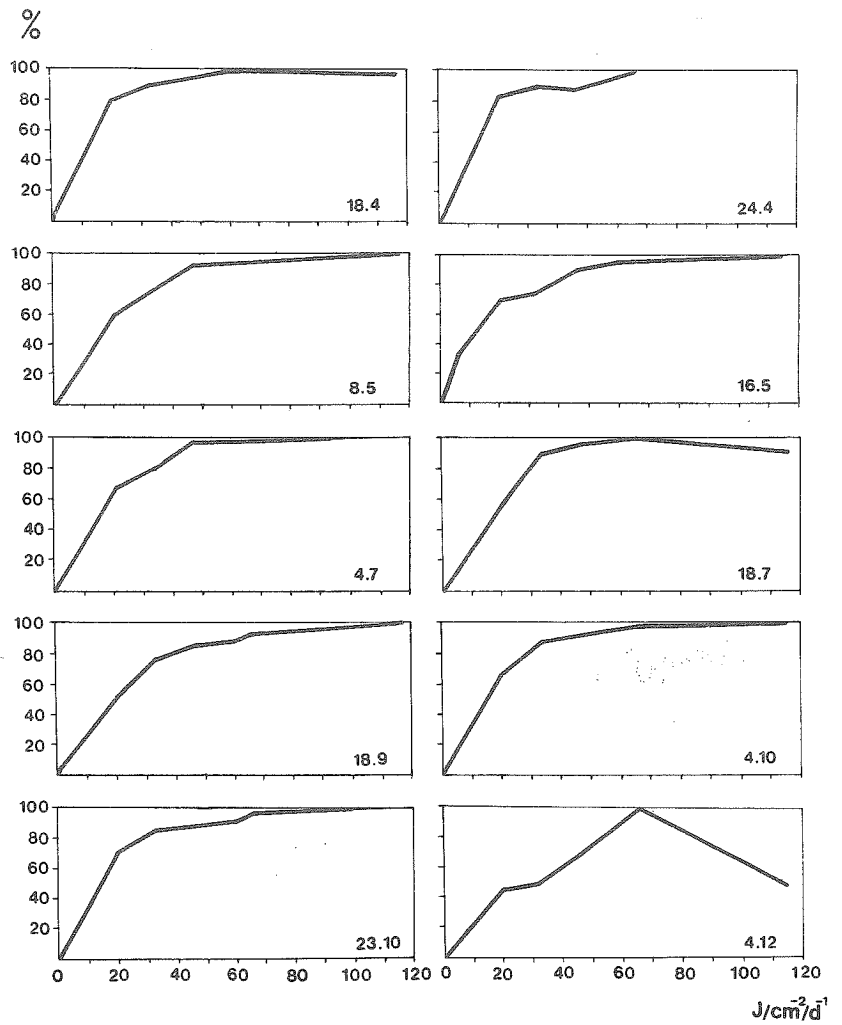

Fig. 3. The light-adaptation curves of the phytoplankton on the sampling dates.

The vertical distribution of the daily production values was similar for the two methods although there were some differencies, especially near the surface and at the 1 % light level (Fig. 2). The lower limit of DP_{24} correlated well with the 1 % level but the corresponding compensation depth for DP_2 was clearly deeper. The regression formula for the production values (C/mg $m^{-3}d^{-1}$) for each sampling depth is $DP_{24} = DP_2 \times 0.5 + 10$ ($r = 0.888^{xxx}$, n = 48).

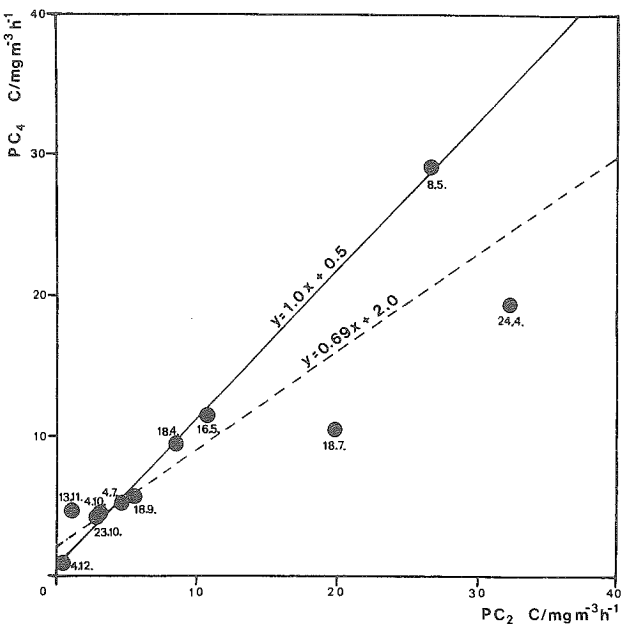

Fig. 4. The relation between the primary production capacity results (C/mg $m^{-3}h^{-1}$, mean of 0-15 m) obtained with the 2-h (PC_2) and the 4-h (PC_4) incubations. Broken line: the correlation equation for the whole material. Continuous line: the correlation equation when the widely differing values for 24.4 and 18.7 are excluded.

The seasonal variation of the production capacity values (C/mg $m^{-3}h^{-1}$) followed the daily production (Fig. 1 and Fig. 4). The linear regression formula for the capacity values obtained by the two methods is $PC = 0.7 \times PC_4 + 2.0$ ($r = 0.896^{xxx}$, n = 11). On two sampling occasions during the plankton peaks (24 April and 18 July), the PC_2 values were

significantly higher than the corresponding PC_4 values (Fig. 4). If these values are excluded, the regression formula is $PC_2 = 1.0 \times PC_4 + 0.5$ ($r = 0.997^{xxx}$, $n = 9$).

4. DISCUSSION

It is a common observation that in the ^{14}C method the apparent production rate decreases with increasing incubation time (Vollenweider & Nauwerk 1961, Buckingham et al. 1975, Gieskes et al. 1979). During short periods such as 2 and 4 h, however, the assimilation rate is nearly constant (Savidge 1978, Shifrin 1980).

With the combinations of light energy, exposure time and temperature used in the present study the production capacity rate obtained by the two methods was almost equal.

The effect of a long incubation time was seen clearly when the daily production values were compared. Daily primary production measured with *in situ* incubation (DP_{24}) approximates net production (e.g. Steemann Nielsen 1977), whereas the transformed daily production (DP_2) is near gross production (Gargas 1975). During long incubation periods there is a greater depression of production caused by excreta, decomposing organic material, changes in concentrations of CO_2 and nutrients, and by grazing and sedimentation of algae in the experimental bottles (Fogg 1958, Steemann Nielsen & Hansen 1959, McAllister et al. 1964, Nalewajko 1966, Gieskes et al. 1979). This depression became pronounced when the phytoplankton biomass and the ratio of seston to phytoplankton were high. This explains the clear differences between the values obtained with DP_2 and DP_{24} and between those given by PC_2 and PC_4 during the vernal phytoplankton maximum in April-May, and during the zooplankton maximum in July.

Our results show that the two incubator methods (PC_4 and PC_2) give almost the same production capacity rates. The values of the two daily production methods (DP_{24} and DP_2) show good correlation and are fully comparable, although higher values were obtained by the DP_2 method. For example the 24-h *in situ* measurements gave the annual production as 78 g m^{-2} whereas according to the transformed 2-h values it was 144 g m^{-2}. It is obvious that at least during plankton peaks short incubation times give more reliable values for actual production than long ones.

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EFFECT OF FORMALIN FIXATION ON PARTICULATE PRIMARY PRODUCTION VALUES WHEN USING ^{14}C METHOD

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Abstract

The effect of formalin fixation on particulate primary production in natural brackish-water samples collected from the surface water of the open sea area off Tvärminne, at the entrance of the Gulf of Finland, was studied. The formalin fixation decreased the production values significantly but did not stop the whole biological activity in the samples. Our results indicate that fixation with formalin causes bigger error in particulate production values than a few hours storage in total darkness at room temperature.

1. INTRODUCTION

Concentrated formalin is recommended for stopping the metabolism of algae in primary production samples after incubation when filtration cannot be carried out immediately (e.g. Strickland & Parsons 1972, Lassig & Niemi 1972, Gargas 1975). However, the formalin fixation has been reported to decrease production values varyingly. Hällfors & Niemi (1974) observed, when formalin fixation was used, ca. 15 % decrease of the production values measured during a bloom of *Chrysochromulina* flagellate in the Gulf of Finland. Ilmavirta (1974) reported an average decrease of 21 % for samples form the lake Pääjärvi and Ilmavirta & Jones (1979) reported varying decreases depending on the algal composition of the samples. Lehmusluoto & Niemi (1977) found an average decrease of 10 % in production values of samples from the Gulf of Finland. Steemann Nielsen (1975, 1977) also reported disastrous effects of formalin fixation. The aim of this study is to check the effect of formalin fixation and storage on particulate primary production during various growth periods.

2. MATERIAL AND METHODS

Experiments were made using brackish-water phytoplankton samples collected from the surface water at station Tvärminne (c.f. Lassig et al. 1978), an undisturbed, open sea area at the entrance to the Gulf of Finland

(Niemi 1973). The samples were taken on May 25, August 24 and November 14, 1978. The incubation was carried out in 1 dm^3 sterile laboratory glass bottles. 5 cm^3 of ^{14}C solution (activity 5 $\mu Ci\ cm^{-3}$) was added to each 1 dm^3 sample. The samples were incubated 4 h at 15 ^oC temperature and at illumination of 13 J $cm^{-2}h^{-1}$ (Philips TL/33 fluorescent tubes). After incubation the 1 dm^3 samples were mixed thoroughly together. 100 cm^3 of the mixed sample was measured into 125 cm^3 sterile glass bottles. 0.5 cm^3 of concentrated formalin solution was added to half of the samples. The samples were then filtered as follows: immediately, 0.5 h, 1 h, 2 h and 4 h after the incubation. The samples were stored in total darkness at room temperature. Each group composed of three parallel samples, (four parallel samples in May). The radioactivity of the samples were measured with the GM-counter.

3. RESULTS AND DISCUSSION

The results are presented in Table 1.

Table 1. Effect of formalin fixation on primary production measurements. The results are given as percentages of values obtained with samples filtered immediately after incubation. CV % = coefficient of variation for parallel samples.

date	hours stored before filtration	unfixed	CV %	fixed	CV %	diff. % between fixed and unfixed samples
25.5.	0	100	5	77	8	23
	0.5	92	8	73	2	21
	1	89	12	71	7	21
	2	100	8	79	8	21
	4	99	6	72	5	27
24.8.	0	100	1	91	2	9
	0.5	99	3	87	2	12
	1	97	2	85	3	12
	2	96	2	86	3	10
	4	93	2	82	3	12
14.11.	0	100	2	91	5	9
	0.5	85	1	79	3	7
	1	83	2	79	1	5
	2	83	3	79	2	5
	4	80	4	80	5	0

The deviation between parallel samples was small: 2-12 % in May, 1-3 % in August and 1-5 % in November. The difference between fixed and unfixed groups was insignificant.

Storage before filtration had a significant effect on the production values (Table 2) and the decrease was of same magnitude for both unfixed and fixed samples.

Table 2. The significance of the effect of fixation and storage on the production values. F = F-ratio of the analyse of variances, df = degrees of freedom, p = probability level for F-ratio.

	25.5.			24.8.			14. 11.		
	F	df	p	F	df	p	F	df	p
fixation	127.081	1/37	0.001	175.112	1/20	0.001	25.422	1/20	0.001
storage	3.423	4/37	0.018	11.140	4/20	0.001	39.920	4/20	0.001
both	0.482	4/37	0.749	0.663	4/20	0.645	2.595	4/20	0.068

Fixation with formalin decreased production values significantly (Table 2). The effect was immediate and did not exclude the effect of storage. In May fixation decreased the values ca. 23 %, in August ca. 11 % and in November ca. 5 %. It seems that the effect of fixation is proportional to the algal biomass (the correlation between algal biomass in the sample water and decrease percentage is 0.999^{+++} (Forsskåhl 1980)). The results are not conclusive due to small n-value (n = 3).

The formalin dose used did not stop the biological activity so that respiration decreased production values equally in fixed and unfixed samples. In addition decreased production values of fixed samples varied, possibly due to formalin-induced cell damage and changes in the permeability of algal cell walls. It seems that the decrease depends on phytoplankton species composition and biomass in samples. Therefore it is not advisable to use the mean decrease percentage of 10 % proposed by Lehmusluoto & Niemi (1977).

Our results indicate that fixation with formalin causes a bigger error in particulate production values than a few hours storage in total darkness at room temperature.

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SIMPUKOIDEN RASKASMETALLIPITOISUUKSISTA SUOMEN RANNIKKOVESISSÄ

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Abstract

Concentrations of zinc, copper and manganese in soft parts of bivalves Mytilus edulis L. and Macoma baltica (L.) and concentrations of zinc, copper, manganese, iron, nickel and lead in the shells of these mussels have been investigated. Mussels were collected at 12 stations in shallow waters of the coast of Finland. Dependence of concentrations of metals in mussels on the salinity, length of shells and depth of stations have been examined.

Изучены концетрации цинка, меди и марганца в мягких тканях моллюсков Mytilus edulis L. и Macoma baltica (L.) а также концетрации цинка, меди, марганца, железа, никеля и свинца в раковинах этих моллюсков. Материал собран на 12 станциях в прибережных водах Финляндии. Рассматривалась зависимость концентраций металлов в моллюсках от солености, длины раковины и от глубины станции.

1. Johdanto

Raskasmetalleilla on tärkeä merkitys elävässä luonnossa mm. entsyymien rakenneosina. Viime aikoina ihmisen toiminnan tuloksena ovat raskasmetallien pitoisuudet kohonneet luonnossa niin paljon, että ne saattavat vaikuttaa haitallisesti eläviin organismeihin. Meren raskasmetallilikaantuminen aiheuttaa biokemiallisia, morfologisia, fysiologisia ja geneettisiä muutoksia vesieliöissä (ICES 1978a). Itämeren maiden yhteistyönä seurataan haitallisten aineiden kulkeutumista mm. vesieliöihin.

Joillakin vesieliöillä on kyky peruselintoimintojen kärsimättä kerätä ja sietää suuria määriä ympäristömyrkkyjä, mm. raskasmetalleja. Tällaisia eliöitä ovat simpukat.

Tässä tutkimuksessa tarkastellaan Suomenlahden ja Pohjanlahden simpukoiden raskasmetallipitoisuuksia sekä mahdollisuutta käyttää sinisimpukkaa *(Mytilus edulis* L.*)* ja itämerensimpukkaa *(Macoma baltica (*L.*)* indikaattorieliöinä raskasmetallien biologisessa seurantatarkkailussa Suomen rannikolla. Sen lisäksi selvitetään kirjallisuustietojen perusteella yhteyttä ravinnonottotavan ja raskasmetallikerääntymisen välillä.

Näytteet kyseessä olevaan työhön kerättiin rannikkovesistä. Raskasmetallianalyysit suoritettiin Merentutkimuslaitoksella Helsingissä ja Moskovan yliopistossa. Työ on osa Moskovan yliopiston biologisen tiedekunnan yleisen ekologian ja hydrobiologian oppituolissa 14.5.1980 hyväksytystä diplomityöstä.

2. Raskasmetallien esiintyminen Itämeressä

2.1 Raskasmetallien lähteet ja kulkeutumistiet

Itämeren valuma-alueella, johon kuuluvat Puolan, Ruotsin ja Suomen valtioiden alueet, osa luoteista Neuvostoliittoa, osa Tanskaa, Saksan Demokraattista Tasavaltaa ja Saksan Liittotasavaltaa, asuu noin 70 miljoonaa ihmistä. Tältä alueelta teollisuus- ja talousjätteet kulkeutuvat suureksi osaksi Itämereen.

Itämeren alueella suoritetaan vuodesta 1972 lähtien Kansainvälisen merentutkimusneuvoston (ICES) ja Merentutkimuksen tieteellisen komitean (SCOR) asettaman yhteisen työryhmän koordinoimana jatkuvaa ympäristömyrkkyseurantaa, joka vuodesta 1979 alkaen on Helsingin sopimuksen mukaista seurantaa.

Näiden tutkimusten perusteella on arvioitu, että Itämeren maiden alueelta kulkeutuu vuosittain 30-40 t elohopeaa Itämereen. Pääosa tästä tulee teollisuuden kuormittamien jokien mukana. Ilman kautta on arvioitu tulevan 10-15 %. Kadmiumia kulkeutuu noin 200 t vuodessa. Ilman kautta tulee noin 45 %, jokien mukana 55 %. Lyijyn kokonaiskuormitus on noin 5400 t. Ilman kautta siitä kulkeutuu 75 %, jokien mukana 25 %. Lyijykuormituksen pääosa tulee liikenteestä, autojen pakokaasuista (Häsänen 1978).

Suomessa on meriympäristötoimikunnan nimeämä työryhmä arvioinut Itämeren suojelusopimuksen tarkoittamien vaarallisten aineiden joutumista Itämereen. Tämän arvion mukaan Suomen alueelta vuonna 1972 kulkeutui Itämereen jokien kautta 290 t sinkkiä, 0.2 t elohopeaa ja muutamia kymmeniä tonneja kromia, nikkeliä ja kuparia. Ilman kautta Itämereen kulkeutui arviolta 30 t sinkkiä ja nikkeliä sekä muutamia tonneja lyijyä (Bremer et al. 1974).

2.2 Merivesi

Meriveden metallipitoisuudet vaihtelevat vuodenajan, syvyyden ja näytteenottopaikan suhteen. Kremlingin (1978) mukaan Bornholmin altaassa olivat huhtikuussa 1975 mangaanin kokonaispitoisuudet pintavedessä keskimäärin 1.4 $\mu g/dm^3$, josta 70 % oli liuenneena. Pohjan lähellä mangaanin kokonaispitoisuus oli 18.4 $\mu g/dm^3$ (72 m). Kiintoaineeseen sitoutuneen mangaanin määrä kohosi 75 %:iin 65 m:ssä, laskien jälleen 28 %:iin välittömästi pohjan läheisyydessä.

Samalla asemalla mitatut sinkkipitoisuudet olivat 3.8-7.0 $\mu g/dm^3$, kadmiumpitoisuudet 0.12-0.14 $\mu g/dm^3$ ja kuparipitoisuudet 1.2-1.5 $\mu g/dm^3$. Ainoastaan noin 1.7 % sinkistä, 3.3 % kadmiumista ja 9.8% kuparista oli sitoutuneena kiintoaineeseen. Pintavedessä kiintoaineeseen sitoutuneen kuparin, sinkin ja kadmiumin määrä oli hieman suurempi kuin syvännevedessä, mikä johtui ilmeisesti piileväleväkukinnasta.

2.3 Sedimentit

Metallipitoisuudet pohjasedimenteissä ovat yleensä huomattavasti korkeammat kuin merivedessä. Merentutkimuslaitoksen tutkimusten mukaan (Niemistö & Tervo 1978) metallipitoisuudet sedimenteissä olivat Itämeren pohjoisosissa ulkomerialueilla seuraavat: sinkki 46-477 $\mu g/g$, kadmium 0.050-5.640 $\mu g/g$, kupari 7-64 $\mu g/g$ ja mangaani 150-18500 $\mu g/g$ kuiva-ainetta.

Suomen rannikon edustalla tavatut sinkki- ja kuparipitoisuudet olivat samaa luokkaa, paitsi kuparipitoisuus, joka oli Helsingin ja Porin edustalla 200 µg/g kuiva-ainetta (Interim commission for the marine environment of the Baltic Sea area 1975).

2.4 Eliöstö

Itämeren perustasotutkimusten yhteydessä määriteltiin raskasmetallipitoisuudet ravintoketjun eri tasoilla mm. eräissä kaloissa ja selkärangattomissa Suomen rannikkovesissä ja Pohjois-Itämeren avomerialueilla. Raskasmetallipitoisuuksien keskiarvot on esitetty taulukossa 1.

TAULUKKO 1. Raskasmetallipitoisuuksien keskiarvot Suomenlahden ja Pohjanlahden kaloissa ja selkärangattomissa µg/g tuorepainosta (Voipio et al., 1977).

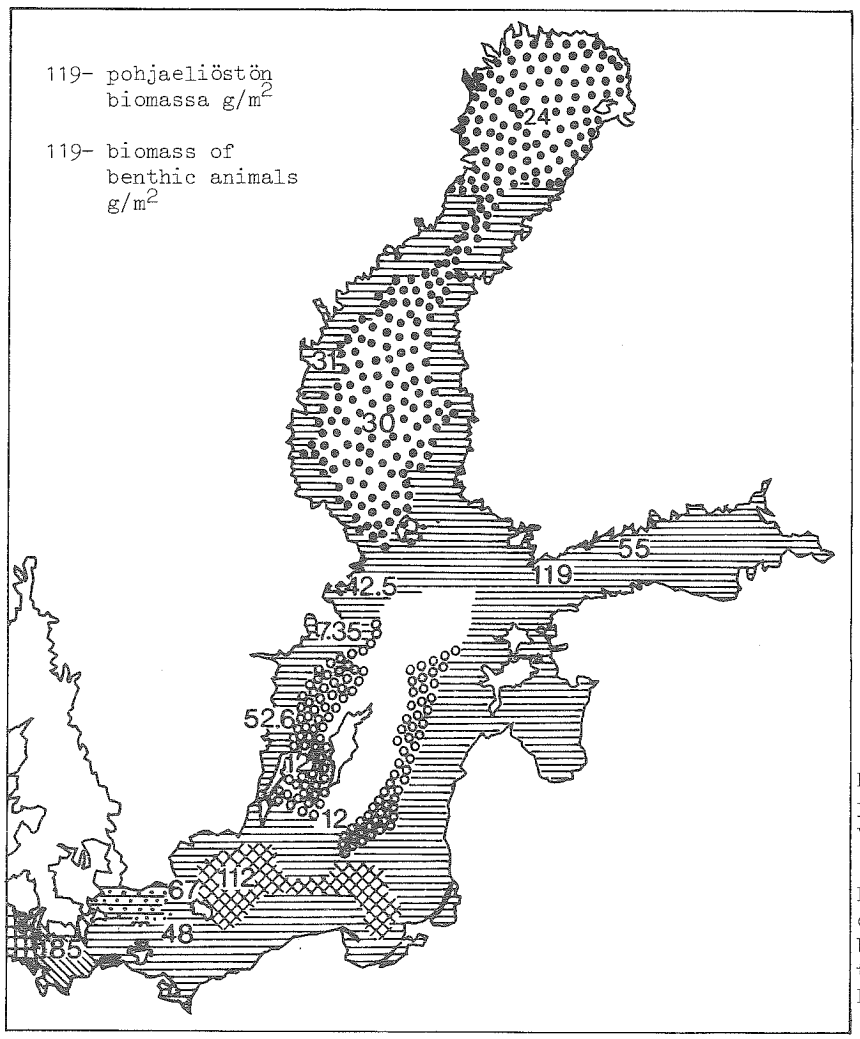
TABLE 1. Mean values of heavy metals for some fish and invertebrate species in the Gulf of Finland and the Gulf of Bothnia (µg/g, wet weight) according to Voipio et al., 1977.

	Zn	Cu	Pb	Cd	Hg
Clupea harengus	6.4	0.39	0.10	0.023	0.02
Clupea sprattus	10.2	0.31	0.05	0.020	0.04
Cadus morhua	3.4	0.14	0.14	0.011	0.07
Platichthys flesus	5.2	0.26	0.08	0.013	0.04
Macoma baltica	85	9.0	0.90	0.25	0.69
Mesidotea entomon	21.9	3.9	0.54	0.42	0.06

3. Itämerensimpukan ja sinisimpukan fysiologis-ekologiset erityispiirteet

3.1 Simpukoiden elinolosuhteet Itämeressä

Itämeren pohjoisosassa elää vain kolme merisimpukkalajia, sinisimpukka - *Mytilus edulis* L., itämerensimpukka - *Macoma baltica* (L.) ja hietasimpukka - *Mya arenaria L.*, ja yksi murtovesisimpukka - *Cerastoderma glaucum (Poiret)*. Itämerensimpukka esiintyy valtalajina laajoilla alueilla Itämerta (kuva 1). Happitilanteesta riippuen lajien levinneisyys vaihtelee erityisesti syvimmillä alueilla vuodesta



Kuva 1. Itämeren pohjaeliöstön valtalajit (Zenkevitch 1956).

Fig. 1. Species dominating in benthic communities in the Baltic Sea (Zenkevitch 1956).

Pontoporeia affinis - *Mesidotea*

Macoma baltica

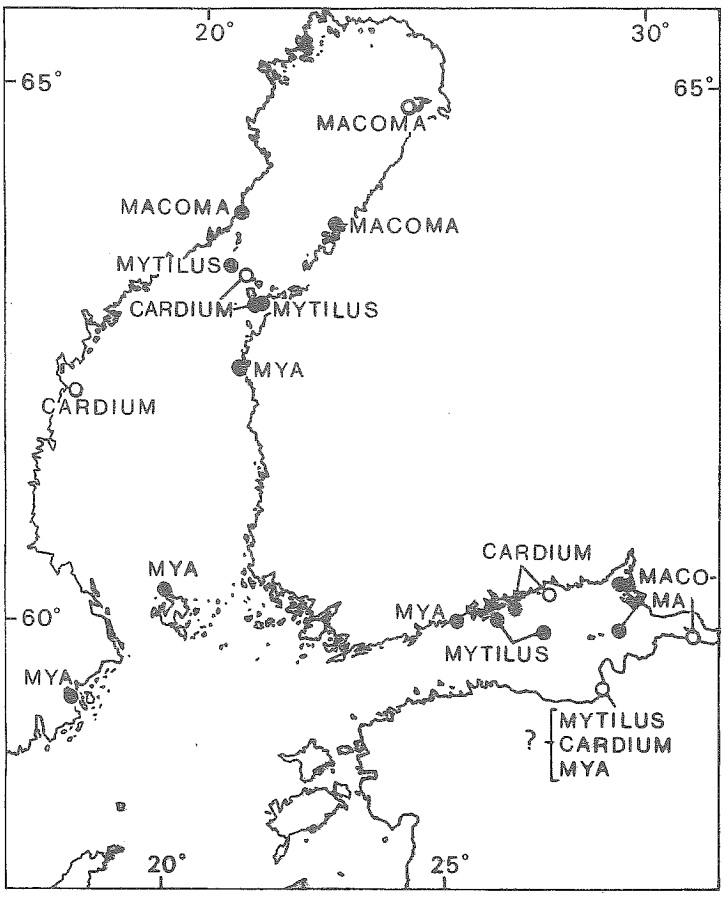
Polychaeta - *Crustacea* - *Scoloplos* - *Pontoporeia femorata* - *Mesidotea*

Macoma calcarea

Astarte borealis

Syndosmya alba

Cyprina islandica



Kuva 2. Itämeren pohjoisosissa tavattavien simpukoiden sisimmät löytöpaikat. Tyhjät renkaat kuorilöytöjä (Lassig 1965).

Fig. 2. The innermost finds of the *lamellibranchs Mytilus edulis*, *Macoma baltica*, *Cerastoderma claucum (Poiret)* and *Mya arenaria* in the northern Baltic area. Empty circles refer to finds comprising shells only (Lassig 1965).

toiseen (Andersin et al. 1978).

Itämerensimpukan laaja levinneisyys selittyy sopeutumisella mitä erilaisimpiin elinympäristöihin sekä ravinnosta kilpailevien ja simpukoita syövien pohjaeläinten vähäisyydellä suurimmassa osassa Itämerta (Järvekülg 1979). Itämerensimpukka työntyy myös syvimmälle Suomen- ja Pohjanlahteen (kuva 2). Alhaisimmat veden suolapitoisuudet, joissa itämerensimpukkaa on tavattu, ovat 2-3 °/oo. Sinisimpukka esiintyy vielä suolapitoisuudessa 4.0-4.5 °/oo (Lassig 1965).

Itämeressä eräät kalat ja sukeltavat linnut käyttävät ravintonaan simpukoita. Esimerkiksi sinisimpukoita syövän haahkan levinneisyysalue käy hyvin yhteen sinisimpukan levinneisyysalueen kanssa. Itämerensimpukka on kampelan, siian, särjen ja lahnan perusravintoa ja sinisimpukka siian, särjen ja säynävän perusravintoa (Järvekülg 1979).

Kuten tunnettua, monilla merilajeilla, jotka asustavat Itämeressä, on laaja syvyyslevinneisyys. Itämerensimpukkaa, joka valtamerissä elää matalassa vedessä, on Itämeressä tavattu 200 m:n syvyydessä ja sinisimpukkaa, joka myös on litoraalilaji, 70 m:n syvyydessä (Lassig 1965). Mutta Itämeressäkin näiden simpukoiden esiintymistiheydet ovat suurimmillaan matalassa vedessä.

3.2 Simpukoiden ravinnonotto

Sinisimpukka suodattaa ravintonsa vedestä. Drzucimskin (1961) mukaan tämän lajin ravinto koostuu pääosiltaan pii- ja viherlevistä, ensinmainituista erityisesti keväällä ja jälkimmäisistä kesällä. Ravinnon laadusta riippuen lipidien suurin pitoisuus simpukoiden kudoksissa tavataan piilevien massaesiintymisen aikana ja hiilihydraattien suurin pitoisuus viherlevien massaesiintymisen aikana. Sorokinin (1977) mukaan sinisimpukka käyttää kasviplanktonin lisäksi ravintonaan myös bakteeriplanktonia ja liuenneita orgaanisia aineita.

Levinneisyysalueensa eri osissa itämerensimpukkaa tavataan kaivautuneena monentyyppisten pohjien pintakerrokseen, aina puhtaasta hiekasta liejupohjaan saakka. Mutta simpukan lukumäärä on aina alhaisempi hiekkapohjalla ja kasvaa orgaanisen aineksen lisääntyessä. Tämä on nähtävästi yhteydessä siihen, että orgaanisen aineksen osuuden lisääntyessä kasvaa myös pohja-aineksen ravintoarvo ja itämerensimpukan ravinto-olosuhteet paranevat. Simpukan esiintyminen ei näinollen riipu pohjan mekaanisesta rakenteesta, vaan ravinnon saannista eri pohjatyypeillä (Semenova 1974).

Itämerensimpukka kerää ravintonsa pohjan pintakerroksesta tai

suodattaa suoraan vedestä. Se haalii ravintonsa kurottautuvan sifon avulla ja imee ravintohiukkaset veden mukana.

Itämerensimpukka muuttaa elintoiminnoillaan pohjakerrostumien mekaanista ja kemiallista rakennetta. Vienanmerellä Moskovan yliopiston biologisen aseman lähistöllä on 100 m x 70 m alueella epätasaisen tiheä itämerensimpukkapopulaatio, keskimäärin 2380 yksilöä neliömetrillä ja tiheimmillään 4820 yksilöä neliömetrillä. Populaation arvioitiin vuorokaudessa käsittelevän pohja-ainesta 0.2 t ja puolessa vuodessa 38.2 t. Tästä määrästä simpukat sulattivat ravinnokseen 0.78 t. Ravinto sisälsi 0.53 t orgaanisia yhdisteitä, joista edelleen valkuaisaineet muodostivat 0.25 t ja hiilihydraatit 0.14 t (Bubnova 1973).

4. Simpukoiden käyttö raskasmetallien seurannassa

Kirjallisuusaineisto simpukoiden kyvystä kerätä suuria raskasmetallipitoisuuksia on laaja (Brooks & Rumsby 1965, Segar & al. 1971). Goldberg (1975) ehdotti, että sinisimpukkaa alettaisiin käyttää hyväksi maailmanlaajuisessa meriympäristön seurannassa. Mutta tuloksia voidaan verrata ainoastaan siinä tapauksessa, että simpukoiden metallipitoisuuksien suhde ympäristön metallipitoisuuksiin ei riipu elinolosuhteista. Ympäristötekijöiden vaikutuksen minimoimiseksi ja tulosten vertailukelpoisuuden parantamiseksi on Phillips (1976) luetellut tekijöitä, jotka tulee ottaa huomioon.

Itämeren seurantaohjelmassa vuonna 1974 ehdotettiin käytettävän muiden eliöiden ohella sinisimpukkaa kivikkorannoilla ja itämerensimpukkaa syvemmissä vesissä myrkyllisten aineiden seurantaan (ICES 1974). Vuonna 1977 Itämeren tutkijoiden asiantuntijakokouksessa ehdotettiin itämerensimpukkaa käytettävän elohopean, kadmiumin, sinkin, lyijyn ja kuparin seurantatarkkailuun viiden vuoden aikana. Yksityiskohtainen keräysmenetelmän kuvaus on annettu Itämeren seurantatutkimusten ohjekirjassa (ICES 1978b).

5. Tutkimusaineisto

5.1 Tutkimusmenetelmät

Simpukoiden keruu suoritettiin 28.6.-16.7.1978. Itämerensimpukat kerättiin pohjamudasta 1 m:n syvyisessä vedessä muovilapiolla. Sinisimpukat kerättiin 1-2 m:n syvyydestä sukeltamalla simpukkayhdyskuntien

olinpaikoille. Sinisimpukat olivat kiinnittyneet laiturirakennelmiin, kiviin ja rakkoleviin. Seilin ja Tvärminnen alueilla näytteet kerättiin haralla 5-14 m:n syvyydestä (asemat 9, 10 ja 11, kuva 4 ja taulukko 2).

Samanaikaisesti simpukkanäytteiden kanssa otettiin suolapitoisuusnäytteet (200 ml) ja merivesinäytteet (1000 ml) raskasmetallipitoisuuksia varten. Syvyydeltä 1-2 m vesinäytteet kerättiin suoraan polyetyleenipulloihin ja syvyydeltä 5-14 m Ruttnerin noutimella. Metallimäärityksiä varten olevat näytteet kestävöitiin lisäämällä niihin 10 ml 0.1 N NaOH.

Ennen preparointia simpukoiden kuoret puhdistettiin päällyskasvustosta ja sen jälkeen pestiin puhtaalla merivedellä. Simpukat preparoitiin vuorokauden kuluessa näytteenotosta. Preparoinnin yhteydessä kaikki pehmeät osat huolellisesti irroitettiin kuoresta. Preparointivälineinä käytettiin valkoisia muoviveitsiä ja teräspinsettejä, joiden kärkiosat eristettiin valkoisella teflonteipillä. Näytteet kuivattiin petrimaljoissa kuivauskaapissa 105 asteen lämpötilassa vuorokauden ajan ja säilytettiin eksikaattorissa analysointiin saakka. Mahdollisuuksien mukaan ennen kuivausta punnittiin pehmeiden osien tuorepaino. Ennen analysointia määriteltiin kuivapaino.

Analyysiä varten pehmeät osat valmistettiin biologisten aineiden liuottamismenetelmällä paineessa (ICES 1978b). Näytteet (kuivapaino 0.2-1.9) liuotettiin lasipulloissa lisäämällä 10 ml 65 % typpihappoa ja kuumentamalla näytteitä 120 asteen lämpötilassa 1.5 atm paineessa 30 minuutin ajan. Analyysiä varten näytteet laimennettiin lisäämällä 40 ml tislattua vettä.

Kuoret valmistettiin analyysiä varten kuivapolttomenetelmällä. Noin 1.5 g kuivattuja kuoria homogenoitiin ja poltettiin tuhkaksi 460 asteessa vuorokauden aikana. Tuhka liuotettiin lisäämällä 5 ml kuumennettua suolahappoa (1:1). Saatu liuos suodatettiin paperifiltterin läpi (Filtrak 90), ja laimennettiin 50 ml saakka 0.5 N suolahapolla.

Biologisten näytteiden ohella valmistettiin muutamia nollakokeita saman metodiikan mukaan.

Simpukoiden pehmeistä osista sinkki ja kupari määriteltiin Merentutkimuslaitoksessa atomiabsorbtiospektrofotometrillä (Perkin Elmer 303, HGA 72 ja deuterium-taustakorjaajalla). Mangaani määriteltiin samoista näyteliuoksista Moskovan yliopiston biologisella laitoksella atomiabsorbtiospektrofotometrillä (Carl-Zeiss AAS-1). Kuorien metallipitoisuudet määriteltiin Moskovan yliopiston biologian laitoksella.

Kaikki metallipitoisuudet määritettiin liekillä, paitsi kudosten kuparipitoisuudet grafiittiuunilla. Meriveden suolaisuus ja metallipitoisuudet määriteltiin Merentutkimuslaitoksessa.

Saatujen metallipitoisuusarvojen riippuvuutta suolapitoisuudesta, kuoren pituudesta jne. määriteltiin lineaarisen regressioanalyysin avulla. Analyysi suoritettiin Moskovan yliopistossa ES-1022 tietokoneella "Stepwise multiple regression" ohjelman avulla.

5.2 Tutkimustulokset

5.2.1 Metallipitoisuudet merivedessä

Tulokset metallipitoisuuksista merivedessä on esitetty taulukoissa 2 ja 3. Ruttnerin noutimella otettujen vesinäytteiden metallipitoisuudet olivat huomattavasti normaalia suurempia, joka ilmeisesti johtui näytteiden kontaminoitumisesta noutimen sisäpinnoilta. Muut metallipitoisuusarvot vastasivat kirjallisuudessa tavattuja arvoja.

5.2.2 Metallipitoisuudet sinisimpukan pehmeissä osissa ja kuorissa

Kirjallisuustietoja Itämeren pohjoisosien simpukoiden pehmeiden osien raskasmetallipitoisuuksista on esitetty kuvassa 3. Tämän työn tulokset on esitetty kuvissa 4 ja 5 sekä taulukoissa 2-6.

Sinisimpukan pehmeiden osien sinkkipitoisuudet olivat 127-443 µg/g, kaikkien asemien keskiarvon ollessa 178 µg/g kuiva-ainetta. Kaikkein suurimmat sinkkipitoisuudet olivat näytteissä, jotka kerättiin Tvärminnen luota (asema 11). Tältä alueelta on myös aikaisemmin löydetty kohonneita sinkkipitoisuuksia silakassa ja kilohailissa (ICES 1977).

Sinisimpukan pehmeiden osien kuparipitoisuudet olivat 7.6 - 27.3 µg/g keskiarvon ollessa 16.3 µg/g. Mangaanipitoisuudet olivat 17-103 µg/g, keskiarvo 56 µg/g. Saadut mangaanipitoisuudet olivat jonkin verran korkeampia aikaisempiin tutkimuksiin verrattuna, paitsi asemalla 12 (Porkkala), jossa mangaanipitoisuus oli sama kuin Phillipsin (1978) havaitsema.

Regressioanalyysissä huomioitiin ainoastaan ne regressiosuorat, joiden multtippelikorrelaatiokertoimet (r) olivat merkitseviä 95 % tasolla. Regressioanalyysi sinisimpukan pehmeiden osien metallipitoisuuksien riippuvuudesta kuorenpituudesta (L), suolapitoisuudesta (S) ja aseman syvyydestä (H) osoitti, että kuparipitoisuuksia kuvaa

regressioyhtälö:

$$(Cu) = 29.7 - 0.5\ L \qquad (r = 0.61)$$

Tämä tarkoittaa, että sinisimpukka, jonka kuoren pituus on 20 mm sisältää kuparia keskimäärin 20 µg/g kuiva-ainetta. Kuoren pituuden ollessa 40 mm kuparipitoisuus on keskimäärin vain 10 µg/g. Sen lisäksi kuparipitoisuuksien negatiivinen korrelaatio suolapitoisuuksien kanssa on merkitsevä (taulukko 5). Aseman syvyydellä ei ollut merkitystä.

Mangaanipitoisuuksia kuvaa regressioyhtälö:

$$(Mn) = 6.2 + 2.0\ L \qquad (r = 0.50)$$

Tämä tarkoittaa, että sinisimpukan kuoren pituuden ollessa 20 mm, sen pehmeät osat sisältävät keskimäärin 46 µg/g mangaania. Kuoren pituuden ollessa 40 mm mangaanipitoisuus kohoaa kaksinkertaiseksi ollen keskimäärin 86 µg/g. Sinkkipitoisuudet sinisimpukan pehmeissä osissa eivät korreloineet tutkittujen parametrien kanssa.

Tulokset sinisimpukan kuorien metallipitoisuuksista on esitetty kuvassa 5 ja taulukossa 3. Mangaanipitoisuudet kuorissa olivat 48 - 569 µg/g keskiarvon ollessa 194 µg/g kuiva-ainetta. Suurimmat arvot havaittiin asemilla 10 Seilin luona ja 11 Tvärminnen luona. Kuorien rautapitoisuudet olivat 31-842 µg/g keskiarvon ollessa 154 µg/g. Suurimmat arvot havaittiin asemilla 9 Saaristomerellä ja 11 Tvärminnen luona. Muiden metallien pitoisuudet kuorissa vaihtelivat seuraavasti: kupari 1-11 µg/g, lyijy 9-38 µg/g, nikkeli 11-34 µg/g ja sinkki 3-14 µg/g.

Regressioanalyysi suoritettiin sinisimpukan kuorien pitoisuuksien riippuvuudesta kuorenpituudesta (L), iästä (T), suolapitoisuudesta (S) ja aseman syvyydestä (H). Regressiosuorat määräytyivät ainoastaan raudalle ja mangaanille:

$$(Mn) = -67.1 + 82.2\ T \qquad (r = 0.54)$$
$$(Fe) = -551.7 + 107.5\ T + 13.6\ L \qquad (r = 0.71)$$

Nämä yhtälöt osoittavat, että vanhempien kuorten rauta- ja mangaanipitoisuudet ovat keskimäärin suurempia kuin nuorten ja rautapitoisuuden kasvu kuorissa riippuu myös kuoren pituudesta, joka kasvaa simpukan vanhetessa. Kuoren pituuden korrelaatio suolapitoisuuden kanssa oli merkittävä (Taulukko 5).

TAULUKKO 2. Tiedot näytteenottopaikoista ja metallipitoisuuksista sinisimpukan pehmeissä osissa ja vedessä.

TABLE 2. Data of the stations and concentrations of metals in soft tissue of mussel *Mytilus edulis* L. and in water.

Asema Station	Päiväys 1978 Date	Sijainti Location	Syvyys Depth	S/ °/oo	Simpukoita näytteessä Number of mussels	Kuoren pituus (mm) Length of shells (mm)	k.a. g d.w.	k.a. % d.w.	Cu µg/g	Vesi Cu µg/dm^3 Water	Zn µg/g	Vesi Zn µg/dm^3 Water	Mn µg/g
2	1.7	62°56'21°11'	2	4.89	30	18-22	0.9911	-	27.3	0.88	143	2.0	59
					20	23-27	1.3229	-	18.1		140		69
4	1.7	62°26'21°10'	1	5.98	25	23-27	1.4206	-	20.8	0.88	136	2.1	54
					8	28-34	0.4582	-	16.4		202		91
5	3.7	62°09'21°19'	1	5.95	30	24-26	1.6575	-	13.0	0.76	149	1.2	65
					20	28-31	1.5662	-	15.3		184		62
6	4.7	61°57'21°22'	1	5.94	30	24-28	1.9294	-	15.5	0.80	132	1.7	73
7	7.7	61°26'21°28'	2	6.04	20	20-25	0.6968	-	20.1	0.79	161	1.5	17
8	8.7	61°03'21°20'	1	6.12	25	23-26	1.1845	-	20.1	0.64	158	1.5	24
9	11.7	60°08'22°10'	12	6.73	25	24-26	1.5730	7.8	16.3	(24)	151	(185)	60
					15	29-31	1.2500	6.6	15.6		142		-
					15	29-31	1.3743	6.8	21.8		136		58
					10	34-36	1.0621	4.5	10.1		164		-
					10	34-36	1.1985	5.0	7.6		140		-
					10	34-36	1.0790	5.8	10.9		140		-
					10	34-36	1.2340	6.0	18.2		184		62
					10	34-36	1.2862	5.9	14.4		161		63
					10	39-42	1.1954	-	15.9		146		77
10	11.7	60°14'22°10'	10	6.69	25	24-26	1.3412	6.4	15.5	(6.6)	136	(26)	76
					10	34-36	0.9881	4.7	8.6		129		103
11	13.7	59°51'23°15'	5	5.93	10	34-36	1.2541	5.1	12.8	(3.3)	443	(23)	63
12	16.7	59°58'24°25'	1	5.99	25	23-28	1.8658	-	12.7	0.60	127	1.5	31

( ) - Ruttnerin noutajalla otetut vesinäytteet

( ) - samples of water, taken by a Ruttner sampler

TAULUKKO 3. Metallipitoisuudet sinisimpukan kuorissa (µg/g k.a.). Tiedot näytteenottoasemista taulukossa 2.

TABLE 3. Concentrations of metals in shells of mussel *Mytilus edulis* L. (µg/g d.w.). Data of the stations in the table 2.

Asema Station	Kuoren keskipituus Mean length shells mm	Ikä (v.) Age year	Metallipitoisuudet kuorissa Contents of metals in shells					
			Pb	Cu	Mn	Ni	Fe	Zn
2	20	2	19	6	120	18	35	5
	20	3	18	4	122	20	31	4
	25	3	19	1	90	32	65	4
	25	4	18	4	77	30	85	3
4	25	3	17	5	271	24	52	14
	25	4	12	5	229	24	57	5
	31	3	13	7	119	27	41	6
	31	4	15	5	193	29	71	9
5	25	3	27	10	125	29	113	4
	25	4	14	9	156	25	40	6
	29	3	20	1	63	28	33	4
	29	4	10	3	138	22	56	4
6	26	2	19	1	143	22	52	3
	26	3	19	1	204	21	84	7
7	23	2	16	3	169	22	98	4
	23	3	19	6	146	29	115	9
8	24	2	9	3	64	23	52	5
	24	3	17	2	48	29	43	6
9	25	3	17	5	136	25	118	4
	25	4	16	8	159	20	123	4
	30	3	18	8	153	28	246	5
	30	4	14	6	158	30	169	4
	35	3	17	2	83	11	365	7
	35	4	38	10	163	21	424	13
	40	4	15	1	300	34	668	4
	40	5	15	6	260	34	714	6
	45	4	16	10	226	23	350	6
	45	5	16	10	226	23	462	6
10	25	2	18	5	201	26	62	4
	25	3	19	1	229	18	92	6
	30	3	24	4	520	22	147	6
	30	4	18	7	869	24	172	7
	35	4	14	8	410	25	180	5
	35	5	12	2	562	21	191	6
11	25	3	23	4	278	20	388	5
	25	4	16	2	285	24	351	8
	30	4	23	4	516	21	712	9
	30	5	18	4	461	28	835	10
	35	5	11	6	202	23	480	8
	35	6	11	1	522	21	842	9
12	26	2	14	11	104	25	72	4
	26	3	23	6	133	31	85	6
	26	4	15	4	88	17	62	4

TAULUKKO 4. Tiedot näytteenottopaikoista ja metallipitoisuuksista itämerensimpukan pehmeissä osissa ja vedessä.
TABLE 4. Data of the stations and concentrations of metals in soft tissue of mussel *Macoma baltica* (L.) and in water.

Asema Station	Päiväys 1978 Date	Sijainti Location	Syvyys Depth	S/ °/oo	Simpukoita näytteessä Number of mussels	Kuoren pituus (mm) Length of shells (mm)	k.a. g d.w.	k.a. % d.w.	Cu µg/g	Vesi Cu µg/dm^3 Water	Zn µg/g	Vesi Zn µg/dm^3 Water	Mn µg/g
1	28.6	63°02'21°21'	1	4.89	50	9–11	0.4821	18.1	71	0.88	814	2.0	101
					15	11–14	0.2029	14.1	168		1158		–
3	1.7	62°49'21°11'	1	4.66	35	12–15	0.9516	–	121	0.57	896	1.2	91
7	7.7	61°26'21°28'	1	6.03	41	13–16	1.3167	–	235	0.66	1295	0.9	103
9	11.7	60°08'22°10'	24	6.73	34	16–18	2.4416	19.5	84	–	673	–	67
10	11.7	60°14'21°59'	10	6.70	35	17–19	1.4674	10.8	68	(6.6)	1271	(26)	236

( ) - Ruttnerin noutajalla otetut vesinäytteet

( ) - samples of water, taken by a Ruttner sampler

TAULUKKO 5. Sinisimpukan pehmeiden osien (a) ja kuorien (b) metallipitoisuuksien korrelaatiomatriisi aseman syvyyden (H), suolapitoisuuden (S), kuorenpituuden (L) ja simpukoiden iän (T) suhteen. Alleviivatut kertoimet ovat merkitseviä 95 % tasolla. Havaintojen lukumäärät (a)-22, (b)-43.

TABLE 5. Correlation coefficients of concentrations of metals in soft parts (a) and in shells (b) of the mussel *Mytilus edulis* L. according to the depth of stations (H), salinity (S), length of shells (L) and age of mussels (T). Underlined coefficients are significant at 95 % level. Number of observations (a)-22, (b)-43.

(a)

H	S	L	Cu	Mn	Zn	
1.00	0.75	0.56	-0.32	0.35	-0.06	H
	1.00	0.54	-0.53	0.16	-0.09	S
		1.00	-0.61	0.50	0.34	L
			1.00	-0.41	-0.19	Cu
				1.00	0.03	Mn
					1.00	Zn

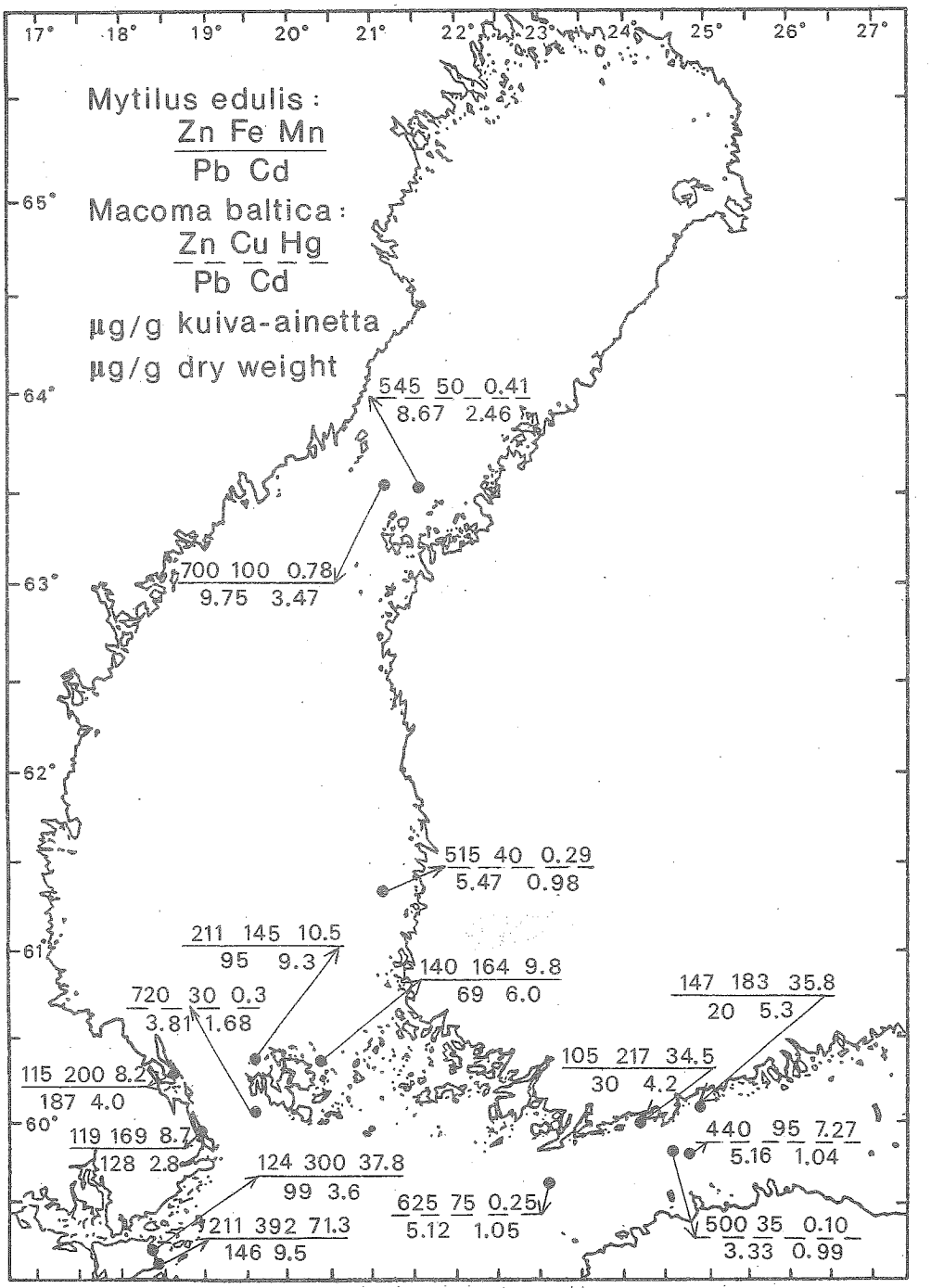
(b)

H	S	L	T	Pb	Cu	Mn	Ni	Fe	Zn	
1.00	0.78	0.61	0.33	0.12	0.22	0.38	0.03	0.43	0.03	H
	1.00	0.56	0.21	0.01	0.26	0.32	-0.05	0.25	0.11	S
		1.00	0.62	-0.10	0.24	0.39	0.13	0.62	0.20	L
			1.00	0.22	0.07	0.54	0.12	0.66	0.33	T
				1.00	0.19	-0.02	-0.02	0.05	0.28	Pb
					1.00	-0.08	0.16	-0.03	0.10	Cu
						1.00	-0.01	0.57	0.36	Mn
							1.00	0.09	-0.11	Ni
								1.00	0.40	Fe
									1.00	Zn

TAULUKKO 6. Metallipitoisuudet itämerensimpukan kuorissa (µg/g k.a.). Tiedot näytteenottoasemista taulukossa 4.

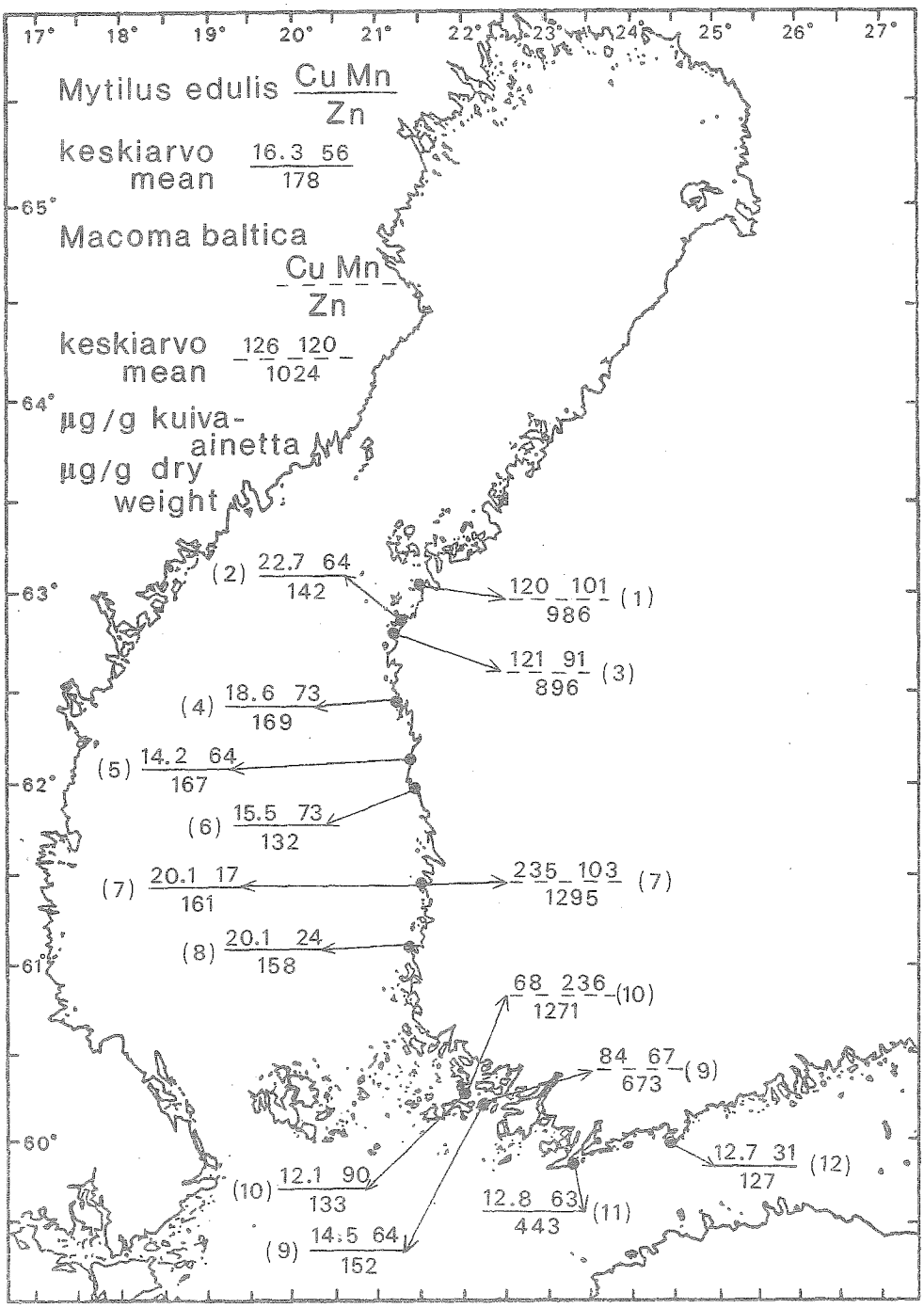
TABLE 6. Concentrations of metals in shells of mussel *Macoma baltica* (L), (µg/g d.w.). Data of the stations in the table 4.

Asema Station	Kuoren keskipituus (mm) Mean length of shells (mm)	Metallipitoisuudet kuorissa Concentrations of metals in shells					
		Pb	Cu	Mn	Ni	Fe	Zn
1	10	15	7	75	27	255	8
1	13	16	10	59	31	611	10
3	14	22	14	23	26	281	13
7	15	28	19	41	27	531	18
9	17	18	22	47	27	508	8
10	18	29	27	74	28	855	7



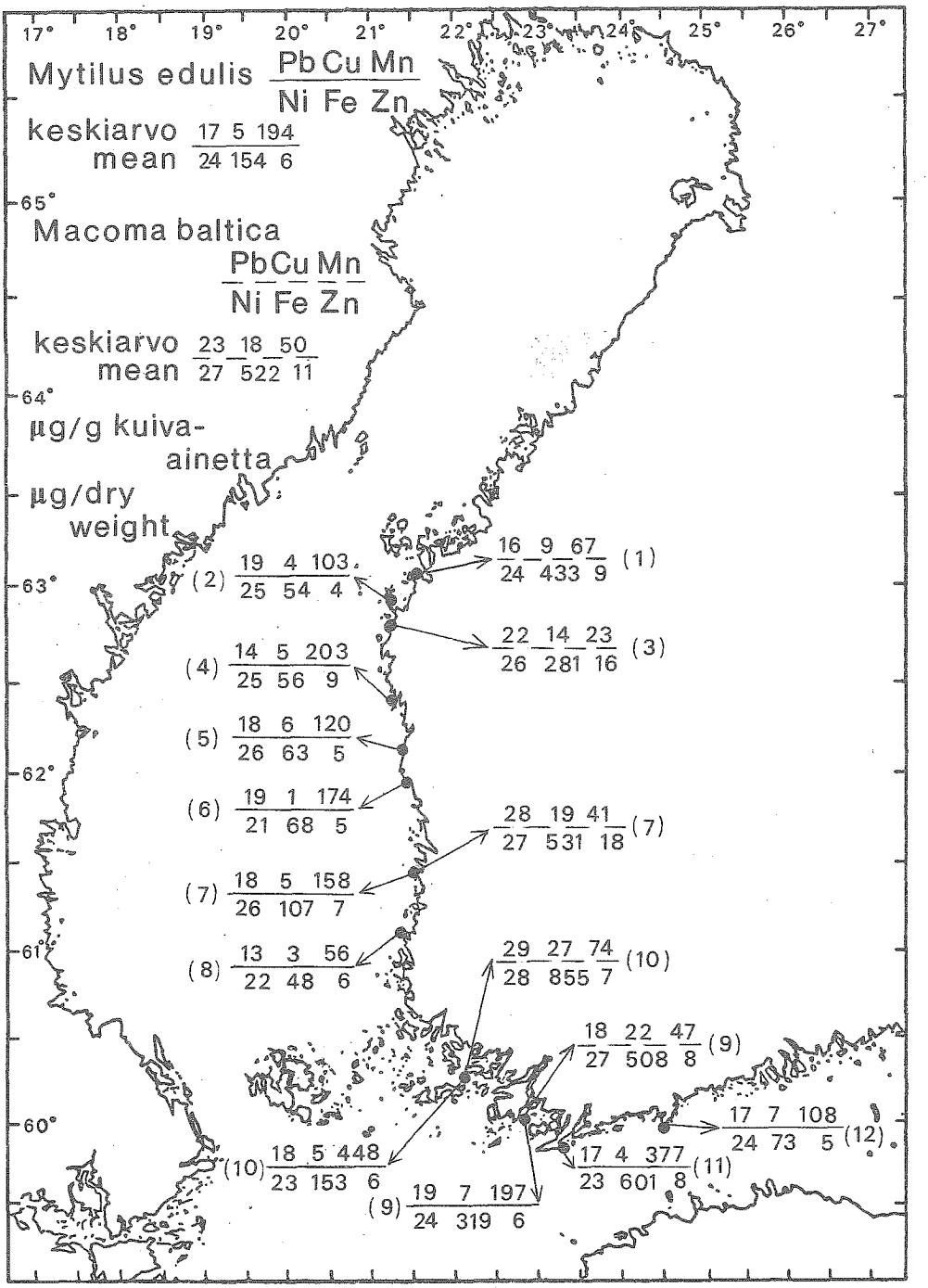
Kuva 3. Simpukoiden pehmeiden osien metallipitoisuudet pohjoisella Itämerellä kirjallisuustietojen mukaan (ICES 1977, Phillips 1977, 1978).

Fig. 3. Concentrations of heavy metals in soft tissue of mussels in the northern parts of the Baltic Sea (ICES 1977, Phillips 1977, 1978).



Kuva 4. Simpukoiden pehmeiden osien metallipitoisuudet Suomen rannikolla kesä-heinäkuussa vuonna 1978.

Fig. 4. Concentrations of metals in soft tissue of mussels by the coast of Finland in June-July 1978.



Kuva 5. Simpukoiden kuorien metallipitoisuudet Suomen rannikolla kesä-heinäkuussa vuonna 1978.

Fig. 5. Concentrations of metals in shells of mussels by the coast of Finland in June- July 1978.

5.2.3 Metallipitoisuudet itämerensimpukan pehmeissä osissa ja kuorissa

Tulokset metallipitoisuuksista itämerensimpukan pehmeissä osissa ja kuorissa on esitetty kuvissa 4 ja 5 sekä taulukoissa 4 ja 6.

Itämerensimpukan pehmeiden osien sinkkipitoisuudet olivat 673 - 1295 µg/g keskiarvon ollessa 1024 µg/g kuiva-ainetta. Nämä tulokset ovat korkeammat kuin aikaisemmissa tutkimuksissa löydetyt. Poikkeuksen muodosti asema 9, joka oli tutkimuksen syvin asema (24 m). Aseman simpukoiden sinkkipitoisuudet vastasivat pitoisuuksia, joita on määritetty aiemmin syvempien merialueiden itämerensimpukoista (ICES 1977).

Itämerensimpukoiden pehmeiden osien kuparipitoisuudet olivat 68-235 µg/g keskiarvon ollessa 126 µg/g. Suurin kuparipitoisuus tavattiin asemalla 7 Porin lähistöllä. Vastaavia arvoja löysi myös Häkkilä (1977) Porin edustan itämerensimpukoissa (suurin kuparipitoisuus 280 µg/g). Mangaanipitoisuudet olivat 67-237 µg/g keskiarvon ollessa 120 µg/g.

Itämerensimpukan kuorien metallipitoisuudet on esitetty taulukossa 6. Rautapitoisuudet olivat 255-855 µg/g keskiarvon ollessa 522 µg/g. Muut metallipitoisuudet olivat pienemmät, mangaania keskimäärin 50 µg/g, kuparia 18 µg/g ja sinkkiä 11 µg/g. Lyijy- ja nikkelipitoisuudet olivat samaa suuruusluokkaa, lyijyä keskimäärin 23 µg/g ja nikkeliä 27 µg/g.

Regressioanalyysin tuloksia tulee tarkastella suuntaa antavina pienen havaintomateriaalin vuoksi. Tällöin tarkasteltiin itämerensimpukan pehmeiden osien metallipitoisuuksien riippuvuutta kuoren pituudesta (L), veden suolapitoisuudesta (S) ja syvyydestä (H).

Itämerensimpukan pehmeiden osien metallipitoisuuksia kuvaavat regressioyhtälöt:

$$(Zn) = 2213 - 741\ S + 217\ L \qquad (r = 0.88)$$

$$(Mn) = 392 - 161\ S + 48\ L \qquad (r = 0.89)$$

Näiden yhtälöiden mukaan sinkki- ja mangaanipitoisuudet simpukan pehmeissä osissa ovat keskimäärin suurempia alhaisissa suolapitoisuuksissa ja kohoavat kuoren pituuden kasvaessa.

Itämerensimpukan kuorien metallipitoisuuksien riippuvuudelle kuoren pituudesta, veden suolapitoisuudesta ja syvyydestä, sekä pehmeiden osien metallipitoisuuksista määräytyi seuraavat regressioyhtälöt:

$$(Pb) = -12.1 - 0.5\,H + 2.5\,L \qquad (r = 0.91)$$
$$(Cu) = -20.4 + 2.5\,L \qquad (r = 0.97)$$

Yhtälöiden mukaan lyijypitoisuudet kuorissa keskimäärin pienenevät syvyyden kasvaessa ja lyijy- ja kuparipitoisuudet suurenevat kuoren pituuden kasvaessa.

Sinkin, mangaanin ja kuparin pitoisuudet itämerensimpukan kuorissa eivät korreloineet vastaavien metallipitoisuuksien kanssa simpukoiden pehmeissä osissa (korrelaatiomatriisia ei ole esitetty tässä yhteydessä suuren kokonsa ja merkitsevien kertoimien vähäisyyden takia).

5.2.4 Metallien kerääntymiskertoimet sinisimpukalle

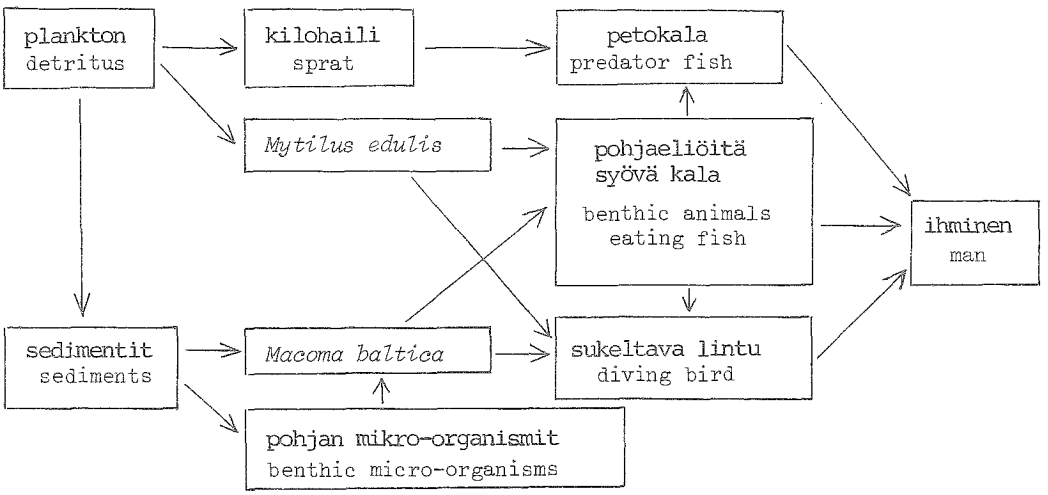
Kuparin ja sinkin kerääntymiskertoimet sinisimpukalle laskettiin keskiarvopitoisuuksien suhteena simpukan pehmeissä osissa ja merivedessä. Sinisimpukan pehmeiden osien kuparipitoisuuksien keskiarvo oli 16.3 µg/g ja sinkkipitoisuuksien keskiarvo oli 178 µg/g kuiva-ainetta. Meriveden kuparipitoisuuksien keskiarvo oli 0.76 ug/dm^3 ja sinkkipitoisuuksien keskiarvo oli 1.6 µg/dm^3. Ruttnerin noutimella otettuja vesinäytteitä ei laskuissa huomioitu.

Kerääntymiskertoimet olivat 2.1×10^4 kuparille ja 1.1×10^5 sinkille. Nämä arvot ovat lähellä arvoja, jotka on saatu Mustassa meressä elävälle *Mytilus galloprovincialis* sinisimpukalle: $0.1\text{-}1.0 \times 10^4$ kuparille ja $0.7\text{-}7.0 \times 10^4$ sinkille (Burdin et al. 1979).

6. Tulosten tarkastelu

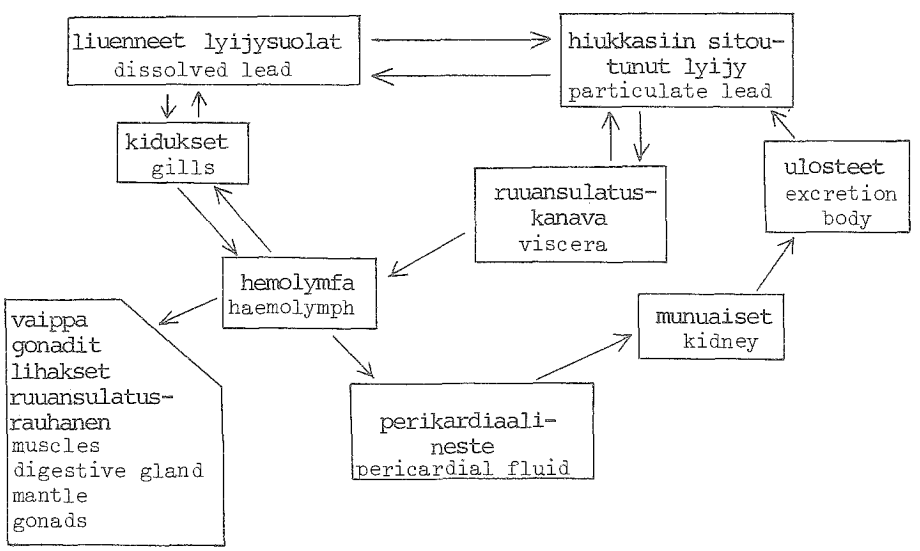
Raskasmetallit kulkeutuvat vedestä ravintoverkkoa pitkin aina ihmiseen saakka (kuva 6). Oheisesta kuvasta käy ilmi, että simpukoiden sijainti ravintoverkossa on tärkeä ajateltaessa niiden käyttöä raskasmetalliseurannassa, sillä ne ovat ihmisen ravintonaan käyttämien kalalajien ravintoeläimiä.

Raskasmetallien kerääntymismekanismit simpukoissa ovat olleet viimeaikaisten tutkimusten kohteena. Schulz-Baldes (1978) on esittänyt lyijyn kerääntymismekanismin selityksen (kuva 7). Hänen mukaansa lyijy kulkeutuu sinisimpukkaan yhtä paljon kidusten kuin ruuansulatuskanavan kautta.



Kuva 6. Itämeren ekosysteemin ravintoverkko (Bagge & Salo 1967, yksinkertaistettu).

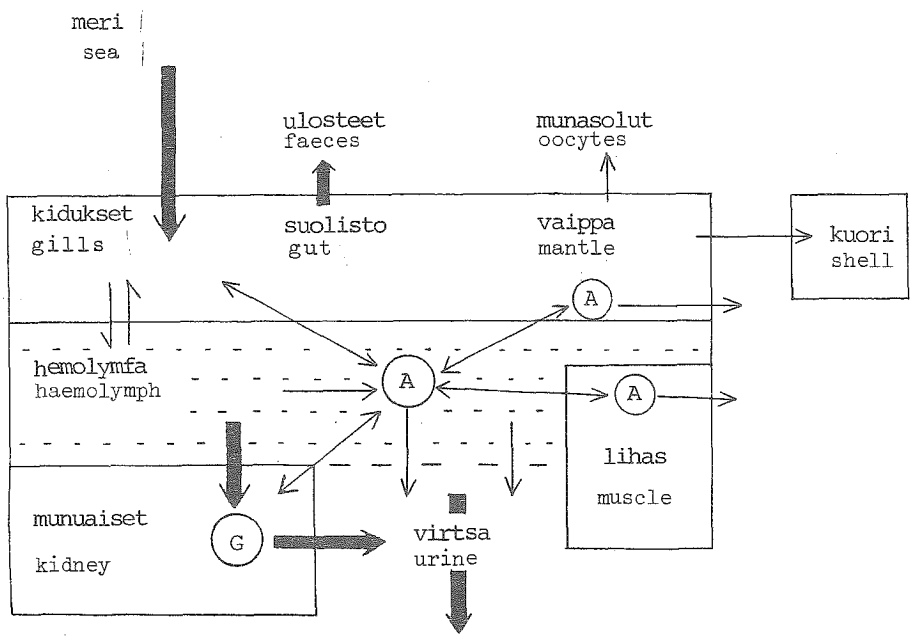
Fig. 6. Marine food-web of the Baltic Sea, simplified from Bagge & Salo (1967).



Kuva 7. Liuenneen ja kiintoaineeseen sitoutuneen lyijyn kulkeutuminen, kierto ja poistuminen sinisimpukalla (Schulz-Baldes 1978).

Fig. 7. Model for uptake, circulation and loss of dissolved and particulate lead by the common mussel *Mytilus edulis* L. (Schulz-Baldes 1978).

George ja Pirie (1980) ovat tutkineet sinkin metaboliaa sinisimpukassa. Biokemiallisissa ja histologisissa tutkimuksissaan he ovat päätyneet seuraavanlaiseen selitykseen sinkin kerääntymisestä sinisimpukassa (kuva 8). Sinkki kulkeutuu kidusten, suoliston ja vähemmässä määrin vaipan kautta hemolymfaan. Ainoastaan 0.5 - 1.0 % pehmeiden osien sinkistä on hemolymfassa (vaikkakin hemolymfan osuus pehmeiden osien kokonaistilavuudesta on 50 %). Sinkkipitoisuus tässä kudoksia huuhtelevassa nesteessä on vain vähän korkeampi kuin ympäröivässä merivedessä, koska sinkki erittyy nopeasti munuaisiin. Hemolymfan sinkistä noin 40 % sijaitsee soluissa (amebosyyteissä) ja jäljellejäävästä osasta 98 % on sitoutunut johonkin suurimolekyyliseen yhdisteeseen (mol. p. 70000 D), mikä selittää sinkin nopean erittymisen munuaisiin.



Kuva 8. Sinkin kulkeutuminen sinisimpukassa. A - amebosyytit, G - munuaissolujen granulit. Tarkemmin tekstissä.(George & Pirie 1980).

Fig. 8. A model for dynamics of zinc in the mussel *Mytilus edulis*. A - amoebocyte, G - granules in kidney cells. (Redrawn from George & Pirie 1980).

Vaikka munuaiset olivat vain 3 % pehmeiden osien painosta, ne sisälsivät kolmanneksen saastumattomilta alueilta kerättyjen sinisimpukoiden pehmeiden osien sinkistä (George & Pirie 1980). Saman tutkimuksen mukaan myös muiden metallien (Cd, Cu, Fe, Pb) pitoisuudet olivat suurimmat nimenomaan munuaisissa. Metallit eivät kuitenkaan jakautuneet samalla tavalla eri elimiin. Kupari oli kaikkein tasaisimmin jakautunut ja munuaiset sisälsivät ainoastaan 15 % pehmeiden osien kokonaiskuparista. Suolisto ja munuaiset sisälsivät kadmiumia, rautaa ja sinkkiä suurin piirtein yhtä paljon (20-40 %), mutta suurin osa lyijystä (yli 70 %) oli kerääntynyt munuaisiin.

Sinkki varastoituu munuaisissa solunsisäisiin granuloihin, jotka käsittävät noin 20 % solujen tilavuudesta. Sinkki erittyy sinisimpukasta etupäässä munuaissolujen granulojen eksosytoosin avulla virtsaan ja sitä kautta ulos. Sinkin kulkeutuminen suolistosta ja kiduksista hemolymfan kautta munuaisiin kestää muutamia vuorokausia, mutta sinkin erittyminen munuaisista virtsaan on huomattavasti hitaampi prosessi ja kestää useita kymmeniä vuorokausia (George & Pirie 1980). Paitsi munuaisten toiminnan tuloksena sinisimpukasta poistuu sinkkiä myös ulosteiden, sukusolujen ja amebosyyttien mukana ja jonkin verran varastoituu kuoreen.

Tämän tutkimuksen mukaan itämerensimpukan pehmeissä osissa oli huomattavasti suurempia metallipitoisuuksia kuin sinisimpukassa. Itämerensimpukassa kuparipitoisuus oli keskimäärin 8 kertaa, sinkkipitoisuus 6 kertaa ja mangaanipitoisuus 2 kertaa suurempi kuin sinisimpukan pehmeissä osissa. Itämerensimpukassa oli kuivapainon osuus märkäpainosta melkein 3 kertaa suurempi kuin sinisimpukassa. Itämerensimpukan metallipitoisuuksia lisää mahdollisesti myös muihin kudoksiin kuin munuaisiin varastoituneet metallit eikä se pysty yhtä tehokkaasti kuin sinisimpukka erittämään elintoiminnoille haitallisia metalleja munuaisten kautta ulos.

Ravinnonottotavalla saattaa olla merkitystä raskasmetallien kertymiselle, koska itämerensimpukka kerää ravintonsa pohjan pinnalta ja sinisimpukka suoraan merivedestä. Tällöin metallit kulkeutuvat itämerensimpukkaan ehkä enemmän ravintohiukkasiin sitoutuneina ruuansulatuskanavan kautta kuin liuenneina kidusten kautta.

Simpukoiden kuoriin eivät kaikki metallit varastoidu samalla tavalla. Sinisimpukan kuorissa olivat kuparipitoisuudet pienemmät ja sinkkipitoisuudet huomattavasti pienemmät kuin pehmeissä osissa. Sen sijaan mangaanipitoisuudet olivat keskimäärin 3.5 kertaa suuremmat

kuorissa kuin pehmeissä osissa. Tämä osoittaa mangaanin metabolian sinisimpukassa täysin eroavan sinkin metaboliasta. Mangaani varastoituu tehokkaasti sinisimpukan kuoreen päinvastoin kuin sinkki. Mangaanipitoisuudet olivat sinisimpukan kuorissa keskimäärin 4 kertaa suuremmat kuin itämerensimpukan kuorissa.

Itämerensimpukan sinkki-, kupari- ja mangaanipitoisuudet olivat suuremmat pehmeissä osissa kuin kuorissa. Itämerensimpukka pystyi tehokkaammin kuin sinisimpukka varastoimaan kuoriinsa metalleja mangaania lukuun ottamatta. Itämerensimpukan kuorien kupari- ja rautapitoisuudet olivat keskimäärin 3.5 kertaa ja sinkkipitoisuudet 2 kertaa suuremmat kuin sinisimpukan kuorien vastaavat pitoisuudet. Sen sijaan lyijy- ja nikkelipitoisuudet olivat keskiarvojen mukaan vain vähän suuremmat itämerensimpukan kuorissa.

Regressioanalyysi osoitti sinisimpukan pehmeiden osien kuparipitoisuuksien pienenevän ja mangaanipitoisuuksien suurenevan kuoren pituuden kasvaessa. Tämä johtuu mahdollisesti siitä, että näiden metallien kerääntymistä säätelevien elinten suhteellinen osuus muuttuu simpukan kasvaessa. Esimerkiksi kidusten suhteellinen pinta-ala pienenee sinisimpukan pehmeiden osien kuivapainon kasvaessa (Vahl 1973). Sinisimpukan pehmeiden osien kuparipitoisuuksilla oli myös negatiivinen korrelaatio meriveden suolapitoisuuden kanssa.

Rauta- ja mangaanipitoisuudet sinisimpukan kuorissa kohosivat kuoren pituuden kasvaessa ja simpukoiden vanhetessa. Ehkä kuori on pääasiallinen poistumatie näille metalleille sinisimpukan pehmeistä osista, koska kuorissa havaittiin keskimäärin suurempia mangaanipitoisuuksia kuin pehmeissä osissa. Tässä tutkimuksessa ei määritelty simpukoiden pehmeiden osien rautapitoisuuksia, mutta molempien simpukoiden kuorissa havaittiin suuria rautapitoisuuksia.

Vertailtaessa eri alueiden simpukoiden metallipitoisuuksia suurimmat rauta- ja mangaanipitoisuudet sinisimpukoiden pienimmän kokoluokan kuorissa havaittiin asemalla 11 Tvärminnen luona. Tällä asemalla oli myös suurin sinkkipitoisuus sinisimpukan pehmeissä osissa. Asemalla 10 Seilin luona oli suuria mangaanipitoisuuksia sinisimpukan kuorissa.

Kohonneita kuparipitoisuuksia sinisimpukan pehmeissä osissa havaittiin asemilla 7 Porin lähistöllä ja 8 Rauman lähistöllä. Tätä havaintoa tukee myös se, että asemalla 7 todettiin itämerensimpukan pehmeissä osissa tämän tutkimuksen suurimmat kuparipitoisuudet. Asemalla 2 todettiin niin ikään suuria kuparipitoisuuksia sinisimpukan

pehmeissä osissa, mutta regressioanalyysin mukaan ne johtuivat nähtävästi simpukoiden pienestä koosta ja alhaisesta suolapitoisuudesta.

Käytettäessä sinisimpukkaa ja itämerensimpukkaa yhtä aikaa raskasmetallien seurannassa, ne täydentävät toinen toistaan. Tämänkin tutkimuksen tulokset vahvistavat käsitystä, että sinisimpukka kerää metalleja lähinnä vedestä ja planktonista ja itämerensimpukka sedimenteistä.

7. Yhteenveto

1. Itämerensimpukan pehmeiden osien metallipitoisuudet olivat suuremmat kuin sinisimpukan. Itämerensimpukan pehmeissä osissa olivat kuparipitoisuudet keskimäärin 8 kertaa, sinkkipitoisuudet 6 kertaa ja mangaanipitoisuudet 2 kertaa suuremmat kuin sinisimpukan pehmeissä osissa.

2. Simpukoiden kuoriin eivät kaikki metallit varastoidu samalla tavalla. Itämerensimpukan kuorissa sinkki-, mangaani- ja kuparipitoisuudet sekä sinisimpukan kuorissa sinkki- ja kuparipitoisuudet olivat pienemmät kuin pehmeissä osissa. Sen sijaan sinisimpukan kuorissa mangaanipitoisuudet olivat keskimäärin 3.5 kertaa suuremmat kuin pehmeissä osissa.

3. Itämerensimpukan kuorissa oli kupari- ja rautapitoisuudet noin 3.5 kertaa ja sinkkipitoisuudet noin 2 kertaa suuremmat kuin sinisimpukan kuorissa. Mangaanipitoisuudet sinisimpukan kuorissa olivat noin 4 kertaa suuremmat kuin itämerensimpukan kuorissa.

4. Sinisimpukan pehmeiden osien kuparipitoisuus keskimäärin pieneni ja mangaanipitoisuus suureni kuoren pituuden kasvaessa sekä kuorien rauta- ja mangaanipitoisuudet suurenivat kuorenpituuden ja iän kasvaessa.

5. Asemalla 7 Porin lähistöllä havaittiin sinisimpukan ja itämerensimpukan pehmeissä osissa sekä asemalla 8 Rauman lähistöllä sinisimpukan pehmeissä osissa kohonneita kuparipitoisuuksia.

6. Asemalla 11 Tvärminnen luona havaittiin kohonneita rauta- ja mangaanipitoisuuksia sinisimpukan kuorissa, ja kohonneita sinkkipitoisuuksia sinisimpukan pehmeissä osissa. Asemalla 10 Seilin luona havaittiin kohonneita mangaanipitoisuuksia sinisimpukan kuorissa.

Lopuksi haluan kiittää Merentutkimuslaitoksen ylijohtajaa prof. Aarno Voipiota ja yleisen meritieteen osaston johtajaa FT Paavo Tulkkia mahdollisuudesta toteuttaa tämä tutkielma sekä Moskovan yliopiston biologian laitoksen dosenttia K.S. Burdinia työn ohjauksesta.

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