Anna-Stiina Heiskanen, Claus Lundsgaard, Marit Reigstadt, Kalle Olli and Sören Floderus

Sedimentation and recycling in aquatic ecosystems

- the impact of pelagic processes and planktonic food web structure

HELSINKI 1999
Preface

To celebrate the 10th anniversary of the Nordic Sediment Trap Association (NOSTRA) the presentations held at the 4th NOSTRA Symposium at the University of Tartu, Estonia, in January 1997, are collected into a joint proceedings appearing in the series "The Finnish Environment", under the theme: International cooperation. The series of symposia, first humbly called just "workshops", started in 1988, when the first meeting of the Nordic sediment trappers was held at the Tvärmine Zoological Station (University of Helsinki) in Finland. Already at that time, the idea was to create an informal platform for young Nordic scientists and graduate students working on the problems related to vertical flux in the aquatic environments. The second meeting was held in 1990 at the Kristineberg Marine Biological Station, in Sweden, and the third in 1994, at the Marine Biological Laboratory in Helsingør, Denmark.

The aquatic scientists using sediment traps in their research are in an intermediate position between the fields of planktology, sedimentology, hydrology, physical oceanography, and environmental sciences. Thus they are forced to communicate with scientists from different disciplines. Such necessity creates a natural platform for interdisciplinary meetings. The NOSTRA symposia have always aimed at and succeeded in gathering scientists from different scientific backgrounds, which has widened our understanding and knowledge of the functioning of the aquatic ecosystems.

Vertical flux (sedimentation) is a link between the pelagic and benthic regimes. The flow of organic material from the freely moving surface waters is governed by several interacting factors. Planktonic production is influenced by physical forcing, input of light and nutrients to the pelagic system. Furthermore, the channeling of the produced biomass is regulated by complex food web interactions and adaptive strategies of the planktonic organisms. The temporal fluctuations of the growth conditions in the pelagic ecosystem lead to emergence of transient blooms followed by massive "escapes" from the pelagic system, or increased turnover in the pelagic food web. These processes govern the input of organic material to the deep benthos, which is dependent on the production in the surface layers. However, the benthic realm, is in continuous interaction with the water column above, especially in shallow coastal areas or lakes. The vertical mixing and horizontal currents lead to resuspension of particulate material and transport of inorganic nutrients mineralized in the sediments to the water column, which both have a profound impact on sedimentation measurements.

The effects of eutrophication in limnic and coastal environments are manifested as increased production and sedimentation. Concurrently, the harmful substances and heavy metals are transported and accumulated along with the settling material in the aquatic environment. The interpretation of sediment trap results requires knowledge of all these processes. Thus, evidently, interdisciplinary meetings are essential and prerequisite for understanding the factors governing the flow of material and nutrient cycles in the aquatic environments.

The meetings of NOSTRA have never been restricted to Nordic scientists only. Understanding the (ultimately) limited expertise in the Nordic countries, as well as the requirements for greater internationalization in the present scientific
world, the invited lecturers have always included experienced "non-Nordic" scientists. Also participants from other countries have been welcome. Therefore, although the series of proceedings is called: "Nordic Sediment Trap Studies", the papers always include presentations from some non-Nordic regions as well. This helps us to widen our experience of various aquatic systems, which will ultimately increase the understanding of the similarities and differences in the rules and processes which govern the functioning of aquatic ecosystems.

During the last meeting in January 1997, we were happy to have a possibility to widen our "Nordic" perspective into the East and South, and to be acquainted with the colleagues, hospitality, and culture of Estonia. The first part of the 1990's has marked the opening of the Baltic countries and Russia, and thus an increased communication between scientists from the Nordic and Baltic countries as well as from Russia. Thus, we consider it appropriate and we are truly pleased to close the decennium and the circle of meetings which started in Finland in 1988, to the latest meeting in Tartu, Estonia, and to welcome the Baltic and Russian scientists to participate in the activities of NOStRA.

The symposium was supported financially by the Nordic Academy of Advanced Studies (NorFA), which we gratefully acknowledge. We also wish to thank all the participants and invited lecturers for their contributions, and for creating a nice symposium with a friendly atmosphere and vivid discussions.

Anna-Stiina Heiskanen
Claus Lundsgaard
Marit Reigstad
Sören Floderus
Kalle Olli
Contents

Introduction .................................................................................................................. 7
Claus Lunsgaard, Anna-Stiina Heiskanen, Marit Reigstad & Sören Floderus

Primary and export production:
Problems in quantifying and predicting vertical export ......................... 10
Paul Wassmann

Fate of a spring bloom in the Oslofjord ................................................................. 21
Svein Kristiansen, Tove Farbrot and Lars-Johan Naustvoll

Phytoplankton sedimentation dynamics and export production along
an in-shore off-shore gradient in the SW coast of Finland, Baltic Sea ...... 31
Petra Tallberg and Anna-Stiina Heiskanen

Dinoflagellate sedimentation followed by sediment traps
with daily collection periods: Should a preservative be used? ............... 38
Yehudit Viner, Tamara Zohary and Avital Gasith

The potential grazing of zooplankton and nektobenthic species on phyto-
plankton in an estuarine system: The Kuršiu Marios (Curonian) lagoon .. 44
Artūras Razinkovas and Zita R. Gasūnaite

Implications of particle-associated dissolved organic carbon
(DOC) for oceanic carbon cycling ................................................................. 51
Thomas Noji

West Spitsbergen Fjords (Svalbard, Norwegian Arctic):
Physical Setting and Sedimentation ............................................................... 58
Alexander Keck

Sedimentation in the open and enclosed water columns: The effect
of algal blooms, planktonic food web, and resuspension on the quality
of settling organic matter in the coastal northern Baltic Sea .................. 69
Anna-Stiina Heiskanen

Sediment – water interactions in the Vistula lagoon
– some preliminary results ............................................................................. 78
Elena E. Ezhova, Boris V. Chubarenko, Alexander I. Blazhchishin and Irina P. Chubarenko

Effects of the oxygen supply on the redox potential and the distribution
of sulphate in the lake sediment core. An experimental study ............... 84
Kaire Tõugu

Relationships between the composition of the fine particulate material
and heavy metals in the surface sediments of the Curonian Lagoon...... 90
Juozas Petkus, Arunas Galkus & Kestutis Jokas

Presentation of the Nordic Sediment Trap Association (NOSTRA) ....... 96
Introduction

Scientific background and objectives of the symposium

Claus Lunsgaard¹, Anna-Stiina Heiskanen², Marit Reigstad³ & Sören Flodén⁴

¹Marine Biological Laboratory, Strandpromenaden 5, DK-3000 Helsingør, Denmark
²Finnish Environment Institute, P.O.Box 140, FIN-00251 Helsinki, Finland
³Norwegian College of Fishery Science, University of Tromsø, N-9037 Tromsø, Norway
⁴GEUS, Environment & Climate, Thoravej 8, DK-2400 Copenhagen NV, Denmark

In the euphotic pelagic systems the retention and recycling of nutrients is influenced by the existence of dynamic and complex food webs. A driving force in the evolution has possibly been the competition for limiting elements. Despite of the present eutrophication of many freshwater and coastal systems nutrients are temporarily depleted. However, the pelagic systems are only partly closed systems since both nutrient input and export take place. The main export is due to sedimentation, although on the local scale the horizontal exchange due to advection may create large variations between areas.

On a short time scale the pelagic system may be far from a steady-state situation, but on an annual scale the material input and export may be in balance (Eppley & Peterson 1979). Therefore new production and sedimentation are equivalent with regard to the limiting element. Total sedimentation of the given element is thus determined by the nutrient supply to the pelagic system from external sources (e.g. Olesen & Lundsgaard 1995). However, the connection between sedimentation and the production based on recycling in the system is less obvious. Several factors may affect the residence time of the limiting elements and the number of recycling sequences in the water column before they are lost by sedimentation. The intensity of recycling has not only implications for the total productivity, but also for the elemental composition and the character of the sedimenting matter (Heiskanen et al. 1996).

On the long time scale, sedimentation and regeneration are two competing processes that determine the fate of particulate organic matter in the pelagic system (e.g. Wassmann 1990). Each of the living components of the pelagic food web contribute to both of these processes. Some groups of algae are known to sediment as intact cells (e.g. diatoms, Smetacek 1985), while for others the sedimentary losses are negligible due to their motility (Reynolds & Wiseman 1982). It is well known that copepods produce fast sinking faecal pellets, but also faecal particles from other organisms are observed in sediment traps (Fowler & Knauer 1986). Larvae of copepods discard their houses when unedible particles have aggregated on them, and these houses are a source of sedimenting marine snow (Silver & Gowing 1991). Bacteria are important for the decomposition and recycling of sinking detritus, but also other organisms promote degradation of detrital particles: For instance ciliates, copepods and fish may eat their own faecal material (coprophagy). Furthermore, the activity of these organisms may disintegrate faecal pellets and
aggregates thereby slowing down sedimentation velocity and increasing the susceptibility of organic matter to microbial degradation (e.g. Lampitt et al. 1990). On the other hand aggregation processes increase sedimentation velocities and thereby reduce the residence time of the material in the pelagic system (Allredge & Silver 1988).

These examples show that the structure of the pelagic food web is crucial for the fate of the organic matter. Various food web components accelerate sedimentation while others predominately promote retention (Peinert et al. 1989).

The Nordic countries have a long tradition for studies of pelagic processes, food web structure, trophic interactions as well as temporal and spatial variability in marine and freshwater plankton. Nordic investigations of seasonal sedimentation dynamics have provided the best and most complete data sets so far available from shallow areas (see the list of the Nordic publications on sedimentation, in the last chapter). The understanding of sedimentation dynamics could greatly benefit from an integration of the knowledge on pelagic processes and food web structures. This could lead to the identification of major mechanisms which influence the competition between recycling and sedimentation, and thereby regulate the overall productivity of the pelagic system and control the quality of sedimenting matter.

The workshop was arranged in order to evaluate, discuss and promote the present state of our knowledge regarding the relationship between pelagic recycling and sedimentation, with special emphasis on the ecological mechanisms and food web interactions which regulate this relationship. The arranged sessions included a wide range of topics, such as the effects of planktonic food web interactions and trophic structure on the sinking losses from the pelagic system, seasonality of the planktonic ecosystem and algal blooms, and the effect of algal strategies and behavior on sedimentation measurements. Furthermore, the workshop included talks on the impact of aggregation and resuspension on the quality of settling organic matter, and the effect of micro-scale particles and DOC for carbon flux in the marine environment, implications of the elemental composition of mesozooplankton and mysids for pelagic nutrient fluxes, and finally some presentations on the geo-ecological and -chemical aspects of the benthic-pelagic coupling.

References


Primary and export production: Problems in quantifying and predicting vertical export

Paul Wassmann
Norwegian College of Fishery Science, University of Tromsø, N-9037 Tromsø, Norway

Introduction

Several international research initiatives such as WOCE and J-GOFS have made attempts to comprehend the carbon cycle of the ocean. These programmes have used satellites for determination of ocean colour, from which, using complicated computations, phytoplankton stock, primary production and finally export production is calculated (e.g. Sathyendranath and Platt 1993), i.e. they are dominated by the concept that vertical flux is determined by bottom-up regulation. However, our present knowledge of the regulation of export production is limited and the question is how precise these estimates of export production are. In particular, there seems to be an impact of top-down regulation (e.g. Peinert et al. 1989, Wassmann et al. 1991, Andreassen et al. 1996). No universal algorithm exists which predicts export production as a function of total primary production on neither annual nor daily time scales. It is suggested that the only feasible way of approaching this challenge is by attempting to quantify pelagic-benthic coupling regionally and to characterize ecosystem functional types on a global scale.

Relation of primary and export production on a annual scale

In the following section total primary and export production will be abbreviated PT and PE, respectively. An overview on algorithms predicting export production on the base of total primary production in marine environments on an annual scale has been presented by Wassmann (1990, 1993) (Fig. 1). Some of the algorithms are based on comparisons of daily rates of PT and PE and are thus over-interpretations when data consecutively were extrapolated to an annual scale. Only data based on investigations of continuously integrated PE (close to the bottom of the euphotic zone) over time intervals of a year or the productive season and PT (at the same site, the same time interval and the same year) should accepted. These criteria were only met by two data sets from the boreal, coastal zone of the North Atlantic and sub alpine lakes (Fig. 2A). Obviously, significant variability with regard to the PE versus PT relationship was detected. Obviously, there is no universal algorithm. Does the variability of the algorithms reflect real difference in the PE vs. PT relationship in the various regions from which they were derived (e.g. Fig. 1)? Then different algorithms should be applied in different regions.

In case the algorithms depicted in Figure 1 are truly predicting annual PE on the base of PT, why are there significant differences? Results presented by Aksnes and Wassmann (1993) indicate that domination by copepods in the marine and
cladocerans in limnetic environments can give rise to very different scenarios of the primary versus export production relationship (Fig. 2A). Mesozooplankton species composition obviously influence the pelagic-benthic coupling. For example, copepods and cladocerans have different reproductive strategies (hence different grazing pressure) and cladocerans do not produce faecal pellets. In the case of subalpine lakes and boreal coastal areas we recognized that differences in the zooplankton community give rise to the observed variance. The question can be raised if the results presented in Figure 2A point at that various types of top-down regulation are the base for the observed variability? The few data which do exist from non boreal, North Atlantic environments suggest that coastal, boreal areas in the North Pacific Ocean with its high diversity and tropical bays experience more effective retention in the upper layers and less vertical export (Fig. 2A). This interpretation is in consistency with the notion that tropical environments are characterized by effective retention food chains. This may also be true for the North Pacific Ocean where at least the open ocean is characterized by extensive zooplankton grazing which prevents major accumulation of phytoplankton biomass (e.g. Frost 1987, Dagg 1993). PE as a function of PT in miscellaneous ecosystems with different production, recycling and export regimes could fall onto a suite of lines falling between maximum export (steep angle, straight line) and high retention (flat angle, curved line) efficiencies (Fig. 2B). In order to test this hypothesis annual investigations of plankton dynamics and vertical flux had to be carried out in different biogeographical zones with variable productivity rates and f-ratios.

Figure 2. (A) Export production as a function of total primary production from the North Atlantic, boreal coast (Wassmann, 1990; full line) and subalpine lakes (Aksnes and Wassmann, 1993; broken line) on an annual scale. The zooplankton of the former ecosystems is often dominated by copepods, the latter one by cladocerans (compare with Fig. 7). Also shown are two data points from Dabob Bay, a boreal, North Pacific fjord, and a tropical lagoon, Kaneohe Bay on Hawaii (open squares, 1 and 2, Hedges et al. 1988a, b and Taguchi 1982, respectively). Redrawn from Wassmann (1993). (B) Schematic diagram on the conceivable relationship between annual export production and total primary production in miscellaneous ecosystems with different production, recycling and export regimes. The functional lines of the various ecosystems could be spread in the shaded area. The relationships could fall onto a suite of lines contrasting between maximum export (steep angle, straight relationship) and high retention (flat angle, strong curvature) efficiencies.
Relation of primary and export production on a daily scale

The regulation of PE as a function of PT is not easily understood by more general evaluations such as the algorithms presented in Figure 1. The regulation of processes controlling sinking loss from marine pelagic systems have rather to be studied on a short-term and process-oriented basis. However, almost no studies do exist which would have the necessary detail in order to investigate the PE vs. PT relationship for longer periods of time on a daily basis. Such investigations seem to be necessary in order to prepare algorithms which have the necessary complexity and precision in order to answer the question how PT in the ocean can give rise to PE. In order to prepare this challenging task, I present below some theoretical evaluations of the concepts and scan through some already existing examples which could verify the theoretical evaluations.

Theoretical evaluations

Some basic relationships between daily PT and PE are presented in Figure 3. If aggregate formation, sinking rate and grazing are constant or exponential as compared to PT a linear or curvilinear relationship between daily estimates of PT and PE will be found (Fig. 3A). Depending on the efficiency of the retention food chain high and low cases would be recorded. Such a case is unlikely to exist. In Figure 3B it is assumed that aggregate formation, sinking rate and grazing are variable and that the relationship between PT and PE is not proportional, but greatly variable in time. This gives most probably rise to “loops” of variable size depending on the closeness of the coupling between PT and PE over time (Fig. 3B). While PT increases during spring and gives rise to an accumulation of biomass, PE will to begin with not increase, but after some time a high (critical) suspended concentration will be attained and aggregation as well as faecal pellet production will increase PE. While PT decreases at the cessation of the bloom, PE can still increase, produce a loop, the “export loop”, but will sooner or later fall back to a line, the “retention line” (Fig. 3). The angle and curvature of the retention line and the circumference, form and area of the export loops are measures for the retention efficiency in aquatic ecosystems.

Any disturbance or stochastic event in the pelagic ecosystem, may it be changes in light, turbulence, nutrients, advection of new algae etc., may give rise a deviations of the PT vs. PE relationship. Disturbances are probably reflected in looping behaviour followed by periods of zooming back on to a retention line or a retention point. The pelagic system “aims” at (a) a flattening of the loops, (b) to minimize the loop area and (c) a low angel of the retention line. The retention efficiency is thus reflected in the angle of the retention line, the size of the loop area and the time period involved to complete a loop of the PT vs. PE relationship. There may be different retention lines and loops throughout the year since the line and loops are a function of (a) the predominant phytoplankton types, the aggregation potential and the behaviour, composition and the dynamics of the zooplankton community, but also (b) the type, frequency and length of the episodic events in physical forcing.
Figure 3. Schematic presentation of the potential configuration of the relationship between daily total primary (PT) and export production (PE). (A) is based on the assumption that aggregate formation, sinking rate and grazing are constant fraction of PT or follow a power function. There may be low or high cases of export production. (B) indicates the most probably development of the PT vs. PE relationship. A “retention line” (stippled) may appear and “loops” (full line) of variable size depending on the closeness of the coupling between PT and PE over time may take place. See text for more details.

Examples from mathematical models

The lack of adequate data sets results in that data from a mathematical model on planktonic production and vertical flux from the southern Barents Sea, dominated by Atlantic water and the marginal ice zone (Wassmann and Slagstad 1993) were investigated. The vertical carbon flux in this model is a function of: (a) sinking diatoms, whose sinking rate is a function of nitrate concentration (an attempt to mimic aggregation), (b) Phaeocystis pouchetii colonies, (c) detritus from flagellates and (d) faecal pellets from meso-zooplankton grazing (Calanus finmarchicus or C. glacialis). Three measurements per week, i.e. about 70 data points per year, were selected for the years 1981–1983.

The seasonal variation in the PT vs. PE relationship from the Atlantic water, which experiences almost no stratification during spring and develops a weak density gradient later on, indicates clearly that this ecosystem develops slowly
along a retention line during spring and early summer until a rapid export loop takes off from this line (Fig. 4A). The loop last only for about 3 weeks after which the system falls back onto a second retention line which is similar to the first one. Although some interannual variability appears, the general impression is that these variations are confined to size and timing of the loop periods, i.e. when the phytoplankton bloom comes to an end and sinks.

The situation in the marginal ice zone is different. The stratification of the surface water is strong due to melting sea ice and ice-coverage varies greatly between years. Thus 1981 was a cold year where PT started first in the middle of May. 1982 was a medium-cold year where the ice cover was more variable. It allowed the penetration of radiation, letting the spring bloom to take place in May, but increased again in thickness thereafter before it disappeared completely in July. This is nicely reflected in Figure 4B which shows to loops of the PE vs. PT relationship, a larger one to begin with and a subsequent smaller one. The lack of significant ice coverage in 1983 gave rise to a scenario where the ecosystem developed more slowly with regard to PT and PE rates and tendencies for an retention line are found which is not discernible due to the large variability during the other years.

The differences between the two stations become obvious by comparing Figure 4A with B. As a consequence the PE rates are smaller and larger and the export loops cover smaller and larger areas, respectively. Stratification of surface water results in far less nutrient supply in the marginal ice zone compared to the Atlantic water stations. The dynamics of a marginal ice zone ecosystem with its more limited nutrient availability is reflected in the significant interannual variability in size, form and development of the export loops.

Grazing by meso-zooplankton can give rise to conspicuous changes in the PT vs. PE relationship (Fig. 5). When no grazing is involved, large amounts of phytoplankton-derived matter are exported to the aphotic zone, as reflected by a conspicuous export loop. Increased grazing decreases PE as well as the size of the loop. With very large amounts of over-wintering meso-zooplankton present in March and the consecutive growth and grazing, the export loop almost disappears and most of the PE and PT data points fall back onto the retention line. Obviously meso-zooplankton has the capacity to increase retention in the upper layers to an extent that major losses can be eliminated. Adequate abundance of meso-zooplankton results in that excursions of PE are “zoomed” back onto the retention line.

**Example from an experimental mesocosm study**

More adequate data sets of PT and PE for the purpose of daily investigations of pelagic-benthic coupling are available from mesocosm studies. Data from an experiment were the effect of dissolved silicate on PT and PE was tested (Wassmann et al. 1998) are shown in Figure 6. In the stratified water of the mesocosms and with abundant nutrient concentrations PT increased rapidly and decreased after a little more then a week. First after PT declined did PE increase. Both PT and in particular PE were greater in the NPS (Fig. 6B) as compared to the NP mesocosm (Fig. 6A). Two loops developed. In the NP mesocosms they were small and focused upon retention point with PT ca. 700 mg C m^{-2} d^{-1}, while in the NPS case the first export loop was larger and the second one in the same range as for the NP mesocosm. After intense excursions of the PT vs. PE relationship caused by the episodic supply of abundant nutrients, both mesocosms develop obviously towards one retention point. The disturbance of the equilibrium prior to the
Figure 4. The seasonal (March to September) PT vs. PE relationship at 72° 30’ N in the Atlantic water section (A) and the marginal ice zone at about 76° 15’ N (B) of the Barents Sea based on a model presented by Wassmann and Slagstad (1993). For details, see text. The time variations for the years 1981 (filled triangles), 1982 (open circles) and 1983 (filled squares) are depicted (a cold, intermediate and warm year, respectively). Remark that two retention lines appear in spring and autumn, respectively (A). No such lines were found for (B) due to the immense inter-annual variation.
Figure 5. The seasonal (March to September) PT vs. PE relationship at 72° 30’ N in the Atlantic water section of the Barents Sea as a function of variable over-wintering meso-zooplankton abundance in March, i.e., variable grazing. The arrows indicate how the export loop caused when grazing does not take place (filled triangles) is reduced by increased grazing (2,000 and 10,000 individuals of over-wintering CV stages of Calanus finmarchicus (open circles and filled squares, respectively). The figure is based on a model presented by Wassmann and Slogstad (1993). There is an obvious retention line during spring.

Figure 6. The PT vs. PE relationship from a 27 day long mesocosm experiment where N (nitrate) and P (phosphate) and N, P and DSI (dissolved silicate) were added to the mixed upper layers of the sea enclosure (NP mesocosm and NPS mesocosm, respectively). PT was measured every second day, PE continuously over two days periods. Data from Wassmann et al. (1998).
start of the experiment gave rise to a stimulation of the export food web (e.g., growth of diatoms and aggregation), until the retention food web fought back and introduced a new “status quo”.

**Systematic patterns in the relationship between primary vs. export production: Is prediction and ecosystem classification conceivable?**

One-pulse and multi-pulse systems can be distinguished. One major “disturbance” (light, stratification, nutrients, advection; upwelling) gives rise to 1–2 retention lines and one loop. The size and form of the loop is dependent on the type of phytoplankton present, the types of grazers and grazing efficiency (Fig. 7A). Several “disturbances” may give rise to several retention lines and several loops. Again, the size of the loops is dependent on the type of phytoplankton present, the grazer types, the grazing efficiency as well as the time between the disturbances (Fig. 7B). Zooplankton grazing will have a significant effect on the PT vs. PE relation-

---

**Figure 7.** Schematic presentation of central elements of the PT vs. PE relationship. The time variation of one (A) and multi-pulse systems (B). The influence of zooplankton grazing pressure on the PT vs. PE relationship (C). The influence of rapid and slow increases of PT on PE (D).
ship. Grazing will lower the angle of the retention line and lower the excursion of the export loop (Fig. 7C). Also the rapidity of the time evolution will play a role for the functional relationship between PT and PE (Fig. 7D). When PE increases rapidly, a flat line will appear at the beginning with a loop at low PT rates while a more slowly development of both PT and PE will gives rise to a more pronounced loop and smoother development over time.

The schematic features exemplified in Figure 4 could probably be depicted and quantified in the ocean, should adequate data be available. They contain the potential to be expressed mathematically and, thus, be used as tools for quantifying the export of organic carbon from the surface ocean in order to build up a more sound base for global carbon models. For different biogeographic scenarios in the word ocean classifications as those illustrated in Figure 2A could be developed. However, achieving such a goal would represent a great endeavour as detailed investigations of principle rates and basic components of retention and export food chains had to be conducted on a daily basis over lengthy periods of time and for principle regions of the world ocean. From a global point of view, our prospects of an strongly improved, quantitative understanding of export and retention food chain and their principle rates, constants and mechanisms are not encouraging. However, focused, systemecological investigations of contrasting ecosystems and scenarios which include the necessary detail with regard to components and time resolution may pave the road to significant improvements of our understanding of the dynamics of the export and retention food chains. If these investigations are carried out in a systematic manner and incorporated into detailed mathematical models, extrapolations over larger biogeographic zones and contrasting ecological scenarios may lead to more valid generalizations.

References


Fate of a spring bloom in the Oslofjord

Svein Kristiansen, Tove Farbrot and Lars-Johan Naustvoll

Department of Biology, University of Oslo, P.O. Box 1069 Blindern, N-0316 Oslo, Norway

Introduction

Autotrophic production and heterotrophic consumption are uncoupled during spring blooms in temperate waters. This uncoupling results in dense phytoplankton populations which may deplete most of the nutrients in the euphotic zone (Bienfang and Ziemann 1992). The spring bloom is a characteristic feature of plankton communities also in Norwegian fjords (Matthews and Heimdal 1980), and more than half of the extensive biomass accumulated during the bloom may sediment out of the euphotic zone (Wassmann 1991). Diatoms usually dominate the spring bloom, but the haptophyte Phaeocystis sp. may be important in fjords in Norway (Hasle and Smayda 1960, Lannergren and Skjoldal 1976, Hegseth et al. 1995). Traditionally, nutrients (nitrate or silicic acid) are thought to limit the spring bloom. However, the spring bloom may also decline in nutrient-rich water, and coagulation of cells into rapidly sinking aggregates has lately been suggested as an important factor in terminating the spring bloom in such waters (Kiørboe et al. 1994, Tiselius and Kuylenstierna 1996). Coagulation theory may also be used to predict maximum cell densities of single diatom species during blooms (Jackson 1990, Kiørboe et al. 1994).

We studied the spring bloom in the Oslofjord and asked the following questions: Did nutrients limit phytoplankton growth during the spring bloom? What was the fate of the spring bloom?

Methods

Large quantities of ice in the Oslofjord prevented sampling from a ship during winter 1996. Samples were therefore collected at 1 m depth from a pier in Drøbak Sound, a narrow neck of the Oslofjord, southern Norway. Nine samples were collected from 27 February – 26 March 1996 using a non-toxic water sampling bottle.

Concentration of chlorophyll a (Chl a) was measured in acetone extracts using a Turner Designs fluorometer calibrated with Sigma Chl a. Phosphate, silicic acid and ammonium concentrations were measured using conventional methods (Solórzano 1969, Strickland and Parsons 1972). Nitrate and nitrite concentrations were measured with a ChemLab autoanalyzer using methods adopted from Strickland and Parsons (1972). Samples for particulate carbon and nitrogen were collected onto GF/F glass fiber filters and analyzed using a Carlo Erba elemental analyzer. Samples for particulate silica were filtered onto 0.6 μm polycarbonate filters and analyzed according to Paasche (1980). Quantitative phytoplankton samples were
preserved with neutralized formaldehyde and counted in an inverted microscope (40M Wild) using 2-ml chambers. More than 150 cells were counted of the dominating species. Average cell dimensions were used to calculate phytoplankton carbon from cell volume by the equations given in Strathmann (1967).

Uptake rates of carbon, ammonium, nitrate and silicic acid were measured using the isotopes $^{14}$C (Strickland and Parsons 1972), $^{15}$N (Kristiansen and Paasche 1989) and $^{30}$Si (Tréguer et al. 1991). The isotopes were added to separate polycarbonate incubation bottles. The bottles were incubated for 5 hours (10h−15h local time) at in situ temperature (between −1 and 0 °C) and exposed to 50 % of surface irradiance. The incubations were terminated by filtering the samples onto GF/F glass fiber filters ($^{15}$N) or onto 0.6 μm polycarbonate filters ($^{14}$C and $^{30}$Si). The funnels and filters were rinsed with 5−10 ml 0.6 μm filtered seawater (0.6 μm polycarbonate filters), and the filters were dried at 60 °C. Activities or concentrations of the isotopes were 220 kBq $^{14}$C and 0.7 kBq $^{30}$Si added to 250 ml samples, and 0.05 μmol ammonium and 0.05 μmol nitrate and 0.5 μmol nitrate (all 99 atom−% $^{15}$N) added to 1,000 ml samples. Ambient nitrate concentrations on 22 and 26 March were 0.2 mmol m$^{-3}$. The corresponding nitrate uptake rates are from the low $^{15}$N (0.05 μmol) addition bottles, the other nitrate uptake rates (ambient nitrate concentrations > 5 mmol m$^{-3}$) are from the high $^{15}$N (0.5 μmol) addition bottles. Samples for determining added $^{14}$C and $^{30}$Si were subsampled from each bottle.

Coagulation theory (Jackson 1990, Kierboe et al. 1994) was used to calculate critical cell densities (net algal growth balanced by coagulation and grazing) of the dominating species using the equation given in Tiselius and Kuylenstierna (1996):

$$C_r = 0.384\mu (\alpha \gamma d)^{-1}$$

where $C_r$ is the critical cell density (cells cm$^{-3}$), $\mu$ is the algal net growth rate (s$^{-1}$), $\alpha$ is the stickiness coefficient (= 0.15), $\gamma$ is the fluid shear rate (s$^{-2}$) calculated from daily average wind speed and $d$ is the equivalent spherical diameter (ESD in cm). Net algal growth rates (d$^{-1}$) were calculated from cell density measurements $(\ln N_t - \ln N_0) t^{-1}$ where $N_0$ and $N_t$ are cell densities at the beginning and end of a period of time t days, or by regression of the natural logarithm of cell density vs time. Growth rates from daily in vivo fluorescence measurements (Turner Designs Fluorometer) of exponentially growing cultures of Thalassiosira nordenskioldii Cleve and Detonula confervacea (Cleve) Gran (3 °C and a 12:12 h light-dark cycle) isolated during the bloom were used as maximum possible net growth rate.

**Results**

All samples were collected in water more or less filled with broken ice (Table 1). Surface salinity (1 m depth) varied between 25.7 and 28.4 psu, the lowest salinities were measured early and late during the 4 weeks sampling period. Variable breeze prevailed in the fjord during the spring bloom with daily average wind speed < 5.1 m s$^{-1}$ (Fig. 1). Our sampling started during early phase of the spring bloom with 4.9 mg Chl a m$^{-3}$ (Table 2). Concentrations of nitrate, phosphate and silicic acid gradually decreased during the bloom, and nitrate and silicic acid concentrations were close to detection limit at the end of the bloom (< 0.2 and 0.05 mmol m$^{-3}$ respectively). One sample was collected after the bloom collapsed (26 March). Nitrate and silicic acid concentrations increased slightly in this last sample, while phosphate concentration decreased further. Concentration of Chl a was 23 mg m$^{-3}$ for almost 3 weeks (5−22 March), and the bloom peaked on 19 March.
Table 1. Local ice conditions (in quarters), salinity (psu) and daily surface irradiance (PAR in mol m$^{-2}$).

<table>
<thead>
<tr>
<th>Date</th>
<th>Ice conditions</th>
<th>Salinity (psu)</th>
<th>PAR (mol m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>27 Feb</td>
<td>3/4</td>
<td>—</td>
<td>12.2</td>
</tr>
<tr>
<td>29 Feb</td>
<td>3/4</td>
<td>25.78</td>
<td>17.2</td>
</tr>
<tr>
<td>5 Mar</td>
<td>1/2</td>
<td>26.12</td>
<td>19.4</td>
</tr>
<tr>
<td>8 Mar</td>
<td>1/2</td>
<td>27.89</td>
<td>12.2</td>
</tr>
<tr>
<td>12 Mar</td>
<td>1/2</td>
<td>28.25</td>
<td>18.4</td>
</tr>
<tr>
<td>15 Mar</td>
<td>3/4</td>
<td>27.80</td>
<td>19.2</td>
</tr>
<tr>
<td>19 Mar</td>
<td>3/4</td>
<td>28.40</td>
<td>16.8</td>
</tr>
<tr>
<td>22 Mar</td>
<td>1/4</td>
<td>28.23</td>
<td>27.7</td>
</tr>
<tr>
<td>26 Mar</td>
<td>No ice</td>
<td>25.71</td>
<td>29.6</td>
</tr>
</tbody>
</table>

Table 2. Nutrients (mmol m$^{-3}$) and chlorophyll a (mg m$^{-3}$) concentrations.

<table>
<thead>
<tr>
<th>Date</th>
<th>Nitrate (mmol m$^{-3}$)</th>
<th>Phosphate (mmol m$^{-3}$)</th>
<th>Silicic acid (mmol m$^{-3}$)</th>
<th>Chlorophyll a (mg m$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>27 Feb</td>
<td>8.1</td>
<td>0.43</td>
<td>7.63</td>
<td>4.9</td>
</tr>
<tr>
<td>29 Feb</td>
<td>5.4</td>
<td>0.23</td>
<td>6.31</td>
<td>12.2</td>
</tr>
<tr>
<td>5 Mar</td>
<td>3.8</td>
<td>0.11</td>
<td>4.56</td>
<td>22.7</td>
</tr>
<tr>
<td>8 Mar</td>
<td>5.7</td>
<td>0.22</td>
<td>3.61</td>
<td>27.3</td>
</tr>
<tr>
<td>12 Mar</td>
<td>6.0</td>
<td>0.20</td>
<td>3.52</td>
<td>27.2</td>
</tr>
<tr>
<td>15 Mar</td>
<td>6.7</td>
<td>0.18</td>
<td>2.62</td>
<td>32.3</td>
</tr>
<tr>
<td>19 Mar</td>
<td>5.5</td>
<td>0.15</td>
<td>0.45</td>
<td>37.5</td>
</tr>
<tr>
<td>22 Mar</td>
<td>&lt;0.2</td>
<td>0.13</td>
<td>0.05</td>
<td>23.9</td>
</tr>
<tr>
<td>26 Mar</td>
<td>0.2</td>
<td>0.06</td>
<td>0.35</td>
<td>4.1</td>
</tr>
</tbody>
</table>

Figure 1. Average daily wind speed (m s$^{-1}$). Sampling dates are indicated by arrows. Data from Department of Agricultural Engineering, Ås.
(38 mg Chl a m$^{-3}$). Nutrients and Chl a concentrations expressed as % of maximum values clearly show that the surface water first became silicic acid depleted (19 March, Fig. 2). Three days later the surface water also was nitrate depleted, and the bloom collapsed.

Diatoms dominated the plankton community (Fig. 3). A total of 25 diatoms and 16 autotrophic flagellates (dinoflagellates, euglenophytes and prymnesiophytes) were identified. The most abundant species were *Thalassiosira nordenskioeldii* Cleve and *Chaetoceros socialis* Lauder which had similar maximum cell densities (1.4 x 10$^6$ and 1.2 x 10$^6$ cells m$^{-3}$ respectively). Converted to phytoplankton C-biomass (C$_{phyt}$), diatoms accounted for 94–99 % of C$_{phyt}$ and *T. nordenskioeldii* alone accounted for 66–74 % until 22 March (Fig. 4). Only a few heterotrophs were observed in our samples (dinoflagellates, ciliates, tintinnids and copepods). Heterotrophic cell abundance (not sampled explicitly) did increase slightly before and after the bloom collapsed.

During the most intense part of the bloom with 23–38 mg Chl a m$^{-3}$ (5–19 March) the particulate ratios were stable, indicating a community in balance (Table 3). The C$_{phyt}$:C ratio (phytoplankton C : particulate C) varied through the bloom. It was 1.0–1.3 during the most intense part of the bloom (5–19 March), and thereafter it decreased to 0.5–0.6. Consequently detrital C varied with time. It increased when the bloom collapsed, and it was not possible to correct the ratios above for detrital C.

The absolute uptake rates of nitrate-ammonium (AN), C and Si gradually increased during the first part of the bloom (Fig. 5). The rates decreased abruptly after 15 March, before maxima in Chl a and total cell density were reached (Figs. 2, 3). Chl a-specific C uptake rate (assimilation number) was high (7–9 gC (g Chl a)$^{-1}$ h$^{-1}$) until 15 march, and then it decreased to 2.4 gC (g Chl a)$^{-1}$ h$^{-1}$ in the last sample (26 March, Table 4). The f-ratio (nitrate uptake divided by summed nitrate-ammonium uptake rates) was high (0.88) until 19 March and then decreased to 0.48 on 22 March. Nitrate and silicic acid concentrations increased slightly from 22 to 26 March, and were followed by weak increases in the f-ratio and in AN and Si uptake rates.

Cell densities of the 6 most abundant species declined at different dates (Fig. 3). Cell densities of *T. nordenskioeldii* declined after 15 March while *C. socialis*, *D. confervacea* and *C. diadema* declined after 19 March and *C. debilis* declined after 19 March. Cell density of *Chaeoceros* sp. was more variable and only declined 3% during the same period. *T. nordenskioeldii* and *Detonula confervacea* declined 20% per day while *C. debilis* Cleve, *C. diadema* (Ehrenberg) Gran and *C. socialis* declined 10–15 % per day. Maximum observed cell density of *T. nordenskioeldii* (1.35 x 10$^9$ m$^{-3}$) was close to the calculated critical cell density using coagulation theory (1.0 x 10$^9$ m$^{-3}$, Table 5). Cell densities and average wind speed the last 2 days were used in calculation of the critical cell density. Net growth rate of *T. nordenskioeldii* was 0.16 d$^{-1}$ which is lower than expected maximum growth rate. Growth rate in exponentially growing cultures of this diatom was close to 0.7 d$^{-1}$. Assuming the same high net growth rate (0.7 d$^{-1}$) in the fjord samples gives a critical cell density of 4.7 x 10$^9$ m$^{-3}$. Maximum cell densities of the other 5 dominating diatoms were <5% of the calculated critical cell densities. A fixed stickiness coefficient (α = 0.15; Tiselius and Kuylenstierna 1996) was used in the calculations above. The α is variable, and may be estimated for individual species by assuming C$^*$ = maximum observed cell density (in the equation given above). Estimated α for *T. nordenskioeldii* was 0.10 while α for the other species was in the range 4–10. The dominating diatoms all form chains which will decrease the critical cell density. Average chain length of *T. nordenskioeldii* was 261 μm and 15 cells chain$^{-1}$ which converts into a critical cell density of 0.5 10$^9$ cells m$^{-3}$ or 50 % of critical cell density assuming no chains (Table 5).
Figure 2. Concentrations of nitrate, silicic acid, phosphate and chlorophyll a (Chl a) as % of maximum values during the spring bloom (February 27 to March 26).

Figure 3. Cell densities of 6 dominating species. Only species with densities 50 cells ml⁻¹ in one or more of the samples are included (C. diad = Chaetoceros diadema (Ehrenberg) Gran, C. deb = C. debilis Cleve, C. soc = C. socialis Lauder, Chaet = Chaetoceros sp., D. conf = Detonula confervacea (Cleve) Gran and T. nord = Thalassiosira nordenskioldii Cleve).
Table 3. Ratios between chlorophyll $a$ and particulate C (Chl $a$C in g mol$^{-1}$), ratio between phytoplankton C and particulate C ($C_{phyto}$C) and ratios between particulate N, C and Si (N:C, N:Si and Si:C all atomic ratios).

<table>
<thead>
<tr>
<th>Date</th>
<th>Chl $a$C (g mol$^{-1}$)</th>
<th>$C_{phyto}$C</th>
<th>N:C</th>
<th>N:Si</th>
<th>Si:C</th>
</tr>
</thead>
<tbody>
<tr>
<td>27 Feb</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>29 Feb</td>
<td>0.46</td>
<td>0.7</td>
<td>0.11</td>
<td>0.88</td>
<td>0.12</td>
</tr>
<tr>
<td>5 Mar</td>
<td>0.62</td>
<td>1.0</td>
<td>0.12</td>
<td>0.71</td>
<td>0.16</td>
</tr>
<tr>
<td>8 Mar</td>
<td>0.70</td>
<td>1.3</td>
<td>0.11</td>
<td>0.56</td>
<td>0.20</td>
</tr>
<tr>
<td>12 Mar</td>
<td>0.60</td>
<td>1.2</td>
<td>0.11</td>
<td>0.59</td>
<td>0.19</td>
</tr>
<tr>
<td>15 Mar</td>
<td>0.62</td>
<td>1.2</td>
<td>0.12</td>
<td>0.63</td>
<td>0.19</td>
</tr>
<tr>
<td>19 Mar</td>
<td>0.63</td>
<td>1.0</td>
<td>0.12</td>
<td>0.73</td>
<td>0.17</td>
</tr>
<tr>
<td>22 Mar</td>
<td>0.44</td>
<td>0.6</td>
<td>0.09</td>
<td>0.52</td>
<td>0.17</td>
</tr>
<tr>
<td>26 Mar</td>
<td>0.17</td>
<td>0.5</td>
<td>0.08</td>
<td>0.44</td>
<td>0.19</td>
</tr>
</tbody>
</table>

Table 4. Chlorophyll $a$ (Chl $a$)-specific C uptake rate (g C (g Chl $a$)$^{-1}$ h$^{-1}$) and f-ratio (nitrate uptake rate (nitrate+ ammonium uptake rate)$^{-1}$).

<table>
<thead>
<tr>
<th>Date</th>
<th>Chl $a$-specific rate</th>
<th>f-ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>27 Feb</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>29 Feb</td>
<td>7.1</td>
<td>0.88</td>
</tr>
<tr>
<td>5 Mar</td>
<td>8.6</td>
<td>0.94</td>
</tr>
<tr>
<td>8 Mar</td>
<td>7.2</td>
<td>0.89</td>
</tr>
<tr>
<td>12 Mar</td>
<td>6.9</td>
<td>0.92</td>
</tr>
<tr>
<td>15 Mar</td>
<td>6.7</td>
<td>0.96</td>
</tr>
<tr>
<td>19 Mar</td>
<td>3.6</td>
<td>0.95</td>
</tr>
<tr>
<td>22 Mar</td>
<td>4.4</td>
<td>0.48</td>
</tr>
<tr>
<td>26 Mar</td>
<td>2.4</td>
<td>0.67</td>
</tr>
</tbody>
</table>

Table 5. Equivalent spherical diameter (ESD in $\mu$m), daily average shear rate ($s^{-1}$) the last 2 days before maximum cell density of the given species, net growth rate ($d^{-1}$), calculated critical cell density ($C_c$) and maximum cell density ($C_{max}$) recorded (both in $10^4$ m$^{-2}$). The species are Chaetoceros diadema C. debilis, C. socialis, Detonula confervacea, Thalassiosira nordenskioeldii and Chaetoceros sp.

<table>
<thead>
<tr>
<th>Species</th>
<th>ESD ($\mu$m)</th>
<th>Shear rate ($s^{-1}$)</th>
<th>Growth rate ($d^{-1}$)</th>
<th>$C_c$</th>
<th>$C_{max}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>T. nord</td>
<td>27.9</td>
<td>0.24</td>
<td>0.16 (0.74)$^{1}$</td>
<td>1.0(4.7)$^{1}$</td>
<td>1.35</td>
</tr>
<tr>
<td>D. conf</td>
<td>12.1</td>
<td>0.08</td>
<td>0.14 (0.79)$^{1}$</td>
<td>31(176)$^{1}$</td>
<td>0.55</td>
</tr>
<tr>
<td>C. debilis</td>
<td>13.7</td>
<td>0.09</td>
<td>0.2</td>
<td>28.0</td>
<td>0.60</td>
</tr>
<tr>
<td>C. diadema</td>
<td>22.5</td>
<td>0.08</td>
<td>0.18</td>
<td>6.4</td>
<td>0.27</td>
</tr>
<tr>
<td>C. socialis</td>
<td>8.2</td>
<td>0.08</td>
<td>0.13</td>
<td>93.2</td>
<td>1.22</td>
</tr>
<tr>
<td>Chaet</td>
<td>15.9</td>
<td>0.07</td>
<td>0.1</td>
<td>5.5</td>
<td>0.23</td>
</tr>
</tbody>
</table>

Culture growth rates
Figure 4. Dominating diatoms as percentage (%) of total phytoplankton carbon biomass. (E. braa = Eutreptiella braarudii Throndsen, other species as in Fig. 3.)

Figure 5. Uptake rate of carbon (C, mmol m⁻³ h⁻¹) and uptake rates of silicic acid (Si) and ammonium + nitrate (AN) (both in μmol m⁻³ h⁻¹).

No depth profiles were sampled during our investigation. A well mixed upper layer (5–6 m deep) is usually found during the spring bloom in the fjord (personal observation). By assuming a 5 m homogeneous upper layer, maximum sedimentation rates (no other loss terms) can be calculated from the measured concentrations of particulate carbon (PC). Maximum rates were 92 mg C m⁻² d⁻¹ during the period 19–22 March and 470 mg C m⁻² d⁻¹ during the period 21–26 March.
Discussion

The diatom *T. nordenskiöeldii* dominated most of the spring bloom. Cell density of *T. nordenskiöeldii* decreased in the last week of the bloom, and a mixture of 6 diatoms (*T. nordenskiöeldii*, *D. confervacea* and *Chaetoceros* spp.) dominated the phytoplankton community during the last week. These 6 species are all common during the spring bloom in the fjord, and *T. nordenskiöeldii* often dominates during early spring bloom (Hasle and Smayda 1960, Lange *et al*. 1992). The nutrient concentrations decreased during the bloom, and concentrations of nitrate and silicic acid were close to detection limit when the bloom collapsed. Nutrients usually become exhausted during the spring bloom in the Oslofjord, and nitrate or silicic acid may limit the growth (Kristiansen 1987, Paasche and Erga 1988). However, low nutrient concentrations do not necessarily imply low phytoplankton growth rates (Goldman and Glibert 1983, Harris 1986). Paasche and Erga (1988) used different criteria to identify potential nitrogen or phosphorus limitation of phytoplankton growth in the fjord, and they concluded that the spring bloom was limited by nitrogen. Nutrient deficiency is difficult to elucidate in natural plankton communities, and it tends to be most pronounced during culmination of blooms (Saksenhaug and Olsen 1986, Paasche and Erga 1988). The uptake rates (C, AN & Si) all decreased after 15 March which clearly show reduced diatom growth rates. Also the Chl a-specific C uptake rate showed reduced diatom growth rate after 15 March. The different particulate ratios (except Si:C) changed after 19 March, probably because of the changing uptake rates. The concept of new production (Dugdale and Goering 1967) must be used with great caution because of the anthropogenic supply of nutrients to the fjord. Our measured nutrient concentrations did not show any signs of severe eutrophication, and the f-ratio indicated a shift from a totally autotrophic dominated system using nitrate as N-source for growth (f-ratio > 0.9) to a more regenerative system using equal amounts of nitrate and ammonium as N-sources (f-ratio = 0.5–0.7). The spring bloom consequently collapsed because of nutrient deficiency. It is, however, difficult to identify N or Si as the limiting nutrient for phytoplankton growth during the bloom.

Cell density of *T. nordenskiöeldii* started decreasing from 15 March, before the other diatoms decreased. It is unlikely that changing water masses or grazing caused this difference between species. However, *T. nordenskiöeldii* was the only species with maximum cell density close to the calculated critical cell density, and coagulation theory (Jackson 1990) may explain the early decline in cell density of this species. Coagulation theory has been used successfully to explain decline of spring blooms in Scandinavian waters (Kjørboe *et al*. 1994, Tiselius and Kuylenstierna 1996). The uptake rates presented here clearly show that the spring bloom in the Oslofjord was limited by nutrients (N or Si). The decline of single species may, however, be explained by coagulation theory.

Only a few grazers were found in our samples, and most of the spring bloom probably sedimented out of the eupotic zone. Mass sedimentation occurred after 19 March, and cell densities of the dominating species decreased 10–20% day⁻¹. Maximum calculated sedimentation rate (470 mg C m⁻² d⁻¹) is similar to measured sedimentation rates during spring bloom in Norwegian fjords and in the Kattegat (Skjoldal and Wassmann 1986, Wassmann 1991, Olesen 1993).
Conclusions

The spring bloom in the Oslofjord in 1996 was dominated by diatoms, and especially by *Thalassiosira nordenskiöldii*. The uptake rates of C, N and Si clearly showed that the bloom collapsed because of nutrient deficiency. Most of the accumulated biomass probably sedimented out of the euphotic zone. Cell density of *T. nordenskiöldii* decreased before the spring bloom collapsed. It is postulated that *T. nordenskiöldii* reached a critical concentration and sedimented out according to coagulation theory. In other words: The spring bloom declined because of nutrient exhaustion but the species composition was controlled by floc formation and sedimentation.

Acknowledgments

Prof. S. Myklestad (University of Trondheim) kindly analyzed the CN-samples. Meteorological measurements were obtained from Department of Agricultural Engineering, Ås. This work was funded by the Research Council of Norway.

References


Phytoplankton sedimentation dynamics and export production along an in-shore off-shore gradient in the SW coast of Finland, Baltic Sea

Petra Tallberg¹ and Anna-Stiina Heiskanen²

¹Department of Limnology and Environmental Protection, P.O. Box 27, FIN-00014 University of Helsinki, Finland
²Finnish Environment Institute, P.O. Box 140, FIN-00251 Helsinki, Finland

Introduction

The quality of settled material and the composition of sinking phytoplankton provide information about the functioning of the pelagic ecosystem as well as the processes governing the export and retention of organic matter in the pelagic system (Peinert et al. 1987, Wassmann 1990, Passow and Peinert 1993). In the estuaries, the sinking material derive from terrestrial, littoral and freshwater (river) sources (allochthonous material) as well as from material produced in the planktonic system (autochthonous material). The downward flux of organic material is an important source of food for the benthos, especially in the shallow coastal areas (e.g. Smetacek, 1984, 1986). The semienclosed Pojo Bay is an estuarine system which is separated from the open Gulf of Finland by shallow sills and several separate basins in the morphologically variable archipelago in SW coast of Finland. There is a salinity gradient from 0–2 (practical salinity scale) in the Pojo Bay up to 7–8 in the open sea area (Niemi 1973, 1975).

The aim of this study was to determine the importance of phytoplankton carbon (PPC) for the total export flux of carbon at three sampling stations, Pojo Bay, Storfjärden and Storgadden (representing a semienclosed fjord-like bay, archipelago region and open sea areas, respectively) in the western Gulf of Finland (Fig. 1) during a seasonal cycle (from March to November) in 1992. In particular, we wanted to assess the major organic loading source responsible for the oxygen deficit in the deep of the Pojo Bay.

Material and methods

The downward flux of phytoplankton was measured with sediment traps below the productive layer along a salinity gradient at three stations in a coastal area in the Gulf of Finland (Fig. 1). The hydrography and nutrient dynamics of the study area has been described in more detail by Niemi (1975), Haapala (1994) and Stipa (1996). The sediment traps were retrieved and sampled particulate organic carbon (POC) and phytoplankton and water samples were taken weekly between March 10 and May 26, and thereafter every other week until the end of November.
1992. Water samples were analyzed for chlorophyll a (CHL), NO$_3$, NO$_2$, NH$_4$, PO$_4$, SiO$_2$ as described in Tallberg and Heiskanen (1998). Primary production was measured with the $^{14}$C technique during same time as the water samples were taken (Tuomi et al. 1998). Concentrated formaldehyde was used as a preservative in the traps (final concentration ca. 1.9%). The total volume of the sediment trap sample was measured and the subsamples for phytoplankton counts and POC filtrations were taken from homogeneous suspension. (see Heiskanen and Tallberg 1998, for detailed description). Samples for POC were filtered on precombusted Whatman GF/F glassfiber filters, the swimmers were picked from filters under a stereo microscope using forceps, and carbon contents of the filters was measured using CHN-analyzer (Leco, Sweden). Subsamples for phytoplankton counts were preserved with Lugol’s solution and the cell numbers were enumerated by an inverted microscope (Utermöhl 1958). The biovolumes and carbon contents of phytoplankton were determined as in Edler (1979).

**Results and discussion**

During the spring bloom, the vertical export of phytoplankton and other particulate material was dominated by diatoms as typical in many temperate coastal ecosystems (Fig. 2). While phytoplankton species mainly from fresh water origin (*Aulacoseira ambiguia* Simonsen, *Melosira varians* Agardh, *Rhizosolenia minima* Levander) dominated the settling flux in the Pojo Bay (Fig. 2), the phytoplankton deposition was dominated by marine diatom species, *Skeletonema costatum* main-
Figure 2. Sedimentation rates of the major phytoplankton species (mg C m\(^{-2}\) d\(^{-1}\)) at the three stations during the seasonal cycle in 1992 (from early April to the end of November). Note the different scales.
ly, at Storgadden and *Chaetoceros wighamii* Brightwell and *C. holsaticus* Schütte at Storfjärden (Fig. 2).

The dinoflagellate *Peridiniella catenata* and the euglenoid *Eutreptiella* spp., which were present in a large numbers in the trap material at Storgadden (Fig. 2), are both motile swimmers which migrate through the water column, and cannot thus be regarded as a part of the (passive) vertical flux (Heiskanen 1995). Filaments of the chain-forming cyanobacteria, *Aphanizomenon flos-aquae* were abundant in all traps during summer (Fig. 2). This indicated that downward flux of cyanobacteria can be relatively high occasionally, although the chains possess gas-vacuoles and can regulate their position in the water column when growth conditions are good and ample nutrient supply is provided (Heiskanen and Olli 1996).

The settled phytoplankton carbon in the Pojo Bay derived mostly from allochthonous sources, as the discrepancy between the measured primary production and the total settled POC and PPC was high (PPC accounted for more than 100% of the concurrent primary production in May, Tallberg and Heiskanen 1998). This conclusion is supported by the composition of the settling phytoplankton, which comprised mainly of freshwater diatoms, and by the fact that the deposition peaks coincided fairly well with the runoff peaks from the Svartå river (Tallberg and Heiskanen 1998). The absence of any proper spring maxima and generally the low primary production (Fig. 3) were probably due to high turbidity suppressing algal primary production in the Pojo Bay (Tuomi et al. 1998). The low C% and high C:N ratio of the settled material denoted for dominance of allochthonous sources in the Pojo Bay. Also material resuspended from shallow regions and littoral zones and transported to the sampling site may have increased sedimentation rates at this area (Heiskanen and Tallberg 1998).

The fraction of exported phytoplankton carbon in relation to primary production at Storfjärden and Storgadden sampling stations was much lower than in the Pojo Bay (Fig. 3). At the outer stations, PPC flux probably represented better the flux of autochthonous material from the photic zone better, thus giving a more reliable estimate of the export flux at the study area.

The primary sedimentation of POC (calculated using the 2-source mixing model of Gasith, as presented in Heiskanen and Tallberg 1998) resulted in considerably lower export flux, especially in the Pojo Bay, where potential resuspension (and lateral transport of allochthonous particulate material with low organic carbon content from the littoral zone and river sources) was estimated to provide more and 90% of the total settling flux. At the other stations, resuspension was estimated to increase the settling flux on average by 60 to 70% during the whole seasonal cycle, being lowest in spring and increasing towards autumn (Heiskanen and Tallberg 1998). The estimated primary sedimentation was between 30 and 48% of the total primary production measured during the seasonal cycle in 1992 (Table 1). This fraction was used to approximate the annual e-ratio in the

**Table 1.** Total export flux of organic carbon (primary sedimentation; S; g C m⁻²) and primary production (PP; g C m⁻²) during the whole seasonal cycle from March to the end of November at the three coastal stations in 1992. The fraction (%) of export flux of total primary production was assumed to represent the e-ratio. Data from Heiskanen & Tallberg (1998).

<table>
<thead>
<tr>
<th>Station</th>
<th>S</th>
<th>PP</th>
<th>e-ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pojo Bay</td>
<td>9</td>
<td>31</td>
<td>30</td>
</tr>
<tr>
<td>Storfjärden</td>
<td>34</td>
<td>71</td>
<td>48</td>
</tr>
<tr>
<td>Storgadden</td>
<td>38</td>
<td>107</td>
<td>36</td>
</tr>
</tbody>
</table>
Figure 3. Primary production, sedimentation of particulate organic carbon (POC) and the flux of phytoplankton carbon (PPC) (mg C m$^{-2}$ d$^{-1}$) at the three stations during the seasonal cycle in 1992 (from early April to the end of November). The runoff from Svartå river (open squares) is shown in the Pojo Bay picture. Note the different scales.
study area, which was relatively well in accordance with the e-ratio (and export production) calculated using the algorithm by Wassmann (1990), especially at the Storgadden and Pojo Bay stations (Heiskanen and Tallberg 1998).

Conclusions

The settled phytoplankton consisted mostly of fresh water diatoms in the innermost station of the Pojo Bay. At this station, the flux of phytoplankton carbon exceeded the concurrent primary production considerably. This denoted that most of the settling material (>90%) derived from allochthonous and/or resuspended sources in the Pojo Bay.

The fraction of total primary sedimentation vs. total primary production (i.e. e-ratio) during the 8 month study period was highest in Storfjärden, and lowest in the Pojo Bay, suggesting that downward flux of autochthonous, primary material was more predominant in the archipelago (Storfjärden) and in the open sea area (Storgadden).

Acknowledgments

We thank the staff of Tvärminne Zoological Station (University of Helsinki) for generous help and support during this study, and K. Suominen for the primary production data. This study was financed by the Walter and Andréde Nottbeck’s Foundation (P.T.) and the Academy of Finland (A-S.H.).

References


Dinoflagellate sedimentation followed by sediment traps with daily collection periods: Should a preservative be used?

Yehudit Viner1, Tamar Zohary1 and Avital Gasith2

1 Israel Oceanographic and Limnological Research, Y. Alon Kinneret Limnological Laboratory, P.O. Box 345, Tiberias, 14102 Israel
2 Institute of Nature Conservation, Tel Aviv University, Ramat Aviv, 69978 Israel

Introduction

An approach to study the rates of algal sedimentation and decomposition is to position sediment traps with and without preservatives at different depths in the water column for short-term collection periods. In the traps containing preservatives all settled cells and cell parts are presumably preserved in their original state. Material caught in the poisoned traps should therefore provide an estimate of the vertical flux of cells from the trophogenic layer into the layer where the trap is located. In the traps without preservatives, some of the trapped material is lost during the collection period due to microbial decomposition. The difference in the catch between traps with and without a preservative should therefore provide information on decomposition rates within the traps. Thus comparison of poisoned and non-poisoned traps placed at increasing depths should provide information on decomposition rates in the water column.

The question of our study was that how the sedimentation losses of a vertically migrating armored dinoflagellate population (Eppley et al. 1968) could be measured by means of sediment traps. Many armored dinoflagellates shed their thecae (the enveloping shells) during cell division and form cysts (resting stages) when growth conditions become adverse. In order to assess the sedimentation losses of the population in a lake it is necessary to estimate the sedimentation rates of all the different forms and components, i.e. live cells, dead cells, cysts, empty thecae and naked protoplasm (cells without thecae). One of the problems in using poisoned traps is “contamination” due to vertically migrating organisms (“swimmers”), like the dinoflagellates. Due to migration, descending cells can be trapped in the poisoned traps and thus lead to an overestimation of the sinking flux (Lee et al. 1988, 1992, Hedges et al. 1993, Wakeham et al. 1993, Heiskanen 1995). Non-preserved traps have some disadvantages, too, like the losses due to bacterial decomposition and grazing during deployment, which will reduce the amount of organic material accumulating in the trap, especially over long collection periods (Lee et al. 1987, Karl and Knauer 1989).

In a study of the population dynamics of dinoflagellates in Lake Kinneret (Israel), we deployed traps with and without formaldehyde for short (24 h) collection periods in an attempt to overcome some of the problems inherent with the use of sediment traps. The objective of this paper is to present our findings regarding sedimentation losses of dinoflagellates (Peridinium gatunense and Peridiniosis spp.) and to assess the applicability of the short-term sediment trap measurements for this purpose.
Study area

Lake Kinneret is a warm monomictic freshwater lake, extending over 170 km² in the northern Israel at an elevation of 210 m below the mean sea level, with a mean depth of 24 m, and a maximum depth of 43 m. The lake is stratified from May to December, during which the epilimnion becomes gradually depleted of nutrients, while the hypolimnion turns anaerobic, with increasing concentrations of sulfides and ammonia. Between January and June each year, a heavy bloom (up to 250 g wet wt m⁻²) of dinoflagellates occurs. The major bloom-forming species (usually >90% of total phytoplankton biomass) is a large dinoflagellate (50–60 μm diameter), Peridinium gatunense Nygaard. It is accompanied by several smaller (ca. 20 μm diameter) dinoflagellates: Peridiniopsis elpatiewskyi, Ps. cunningtonii, Ps. borgei, Ps. penardiforme and Ps. polonicum, which usually reach their maximum abundance in early summer when the P. gatunense bloom is already declining (Pollinger and Hickel 1991).

Methods

Sedimentation rates of Peridinium gatunense and Peridiniopsis spp. were measured by sediment traps with and without a preservative (formaldehyde), exposed for 24 hours. The measurement was repeated with 2 to 3 weeks intervals throughout the annual cycle of 1994 (P. gatunense), and both 1994 and 1995 (Peridiniopsis spp., only). Two arrays of positively buoyant traps, each consisting of 4 cylinders (aspect ratio: 1:11) with replaceable 300 ml screw-cap jars in the bottom of the cylinders, were deployed at 35 (hypolimnion) and 15 m (epilimnion) depth in the deepest part of Lake Kinneret (Fig. 1). A dialysis bag containing 10 ml of concentrated formaldehyde and a small weight was placed inside two of the jars in each trap. After 24 h exposure the traps were retrieved, and the contents of the jars were collected. One replicate of each treatment was preserved with formaldehyde (2%) for the cell counts. Live cells, dead cells, cysts, thecae and naked protoplasts of all dinoflagellates in 1 ml subsamples were counted using the Utermöhl (1958) inverted microscope technique. The other replicate was used for dry weight and organic carbon measurements, the results of which will be reported elsewhere.

In order to convert the cell counts from cells ml⁻¹ to sedimentation rates expressed in g wet wt m⁻² d⁻¹, we multiplied the cell numbers by the cell biovolume computed from linear dimensions and the geometrical shape, assuming that cells have the same density as water. The results were also corrected for the surface area of the trap cylinders.

Results and discussion

The appearance of the live cells of Peridinium gatunense in the sediment traps followed the bloom development in the water column. The bloom began in January, peaked in April and declined in May-June. Sediment traps collected thecae, which were shed during cell division, throughout the entire bloom season, while dead cells and protoplasts appeared only in May–June, after the decline of the bloom began (Fig. 2). Sedimentation rates of Peridiniopsis spp. live cells were highest one month after the peak of P. gatunense cells, following the later appearance of the
water column maximum of *Peridiniopsis*. The sedimentation rates of *Peridiniopsis* spp. components (except thecae) were generally an order of magnitude lower than the sedimentation rates of *P. gatunense* components (Fig. 2). This was due to the smaller size and lower water column abundance of *Peridiniopsis* spp. Cysts of both *P. gatunense* and *Peridiniopsis* spp. were extremely rare, and are therefore their flux is not shown in Figure 2.

The number of live cells of both *Peridinium gatunense* and *Peridiniopsis* spp. trapped in the formaldehyde-containing (F+) traps was generally 5 to 10 times higher than in the traps without formaldehyde (F-) (Fig. 2). Formaldehyde addition did not seem to make a difference to the number of settled dead cells or thecae of *P. gatunense*, although this had some effect on the trap catches of *Peridiniopsis* thecae, dead cells and protoplasts. This led us to conclude that the large difference in live cell catches between the F+ and F- traps was not due to decomposition in the non-poisoned traps, as there was no reason to expect live cells to decompose faster than dead cells. The effect of grazing was also ruled out, since we did not find potentially efficient grazers inside the traps. The difference was most likely an artifact of the methodology, caused by the diel vertical migration of these dinoflagellates (Berman and Rodhe 1971, Pollingher and Berman 1975). Cells swimming downwards were trapped in the F+ traps, but they could swim into and out of the F- traps. Similar conclusions regarding sedimentation of another dinoflagellate, *Peridiniella catenata*, in the Baltic Sea were made by Heiskanen (1995).
Figure 2. Sedimentation rates of live cells, thecae, dead cells and proplasts of the dinoflagellates *Peridinium gatunense* and *Peridiniopsis* spp., measured by sediment traps with (F+) and without formaldehyde (F-) and moored at 15 m depth in Lake Kinneret, Israel, during the seasonal cycle in 1994 and 1995 (*Peridiniopsis* spp. only) (D=December, J=January, F=February, etc.).

In order to present the differences in catches between F+ and F- traps we calculated the ratio F+/F- for each category and species, when the number of individuals counted exceeded 50 for both treatments. A ratio of 1 means that the F+ and F- catches are equal. As the ratio increases, so does the difference between F+ and F- catches. The mean difference in the catches of *Peridinium gatunense* live cells between F+ and F- traps was 10-fold for the upper traps and 4-fold for the lower traps (Fig. 3). These differences were attributed to diel vertical migration behavior. In the case of live cells, the standard deviation of the F+/F- ratio was large (Fig. 3) because there was a great variability in cell abundance throughout the annual cycle, from one cell ml⁻¹ at the beginning and end, to thousands of cells ml⁻¹ at the peak of the bloom.

The differences in catches of thecae between F+ and F- traps for both dinoflagellate genera were small, as shown by F+/F- ratios close to 1 both in the upper and lower traps (Fig. 3). This implies that over 24 hours, losses of thecae from the non-poisoned traps (due to grazing and decomposition) were minor.
Figure 3. The mean ratio between the trap catches measured with (F+) and without formaldehyde (F-) for fluxes of the live cells and thecae of *Peridinium gatunense* and the thecae of *Peridiniopsis* spp. (including only the cases when at least 50 cells or thecae were counted in both treatments). The vertical bars denote for the standard deviation of the mean. Upper traps (up) were placed at 15 m (epilimnion), lower traps (low) were placed at 35 m depth (hypolimnion).

Conclusions

Sedimentation losses of vertically migrating dinoflagellates measured by sediment traps containing preservatives resulted in severe overestimation of the vertical flux of live cells. In Lake Kinneret, the vertical flux of *Peridinium gatunense* was 5 to 10 times higher in the preserved trap cylinders. The use of short (24 h) trap exposure times did not eliminate this effect. We recommend that traps without a preservative and deployed for a short time interval (24 h) should be used for measuring the vertical flux for live dinoflagellates and other vertically migrating organisms such as zooplankton and cyanobacteria. Moreover, one should know the diel migration pattern of these organisms, in order to ensure that the traps are installed and removed at a time of day when the organisms have migrated away from the trap. Some of the problems associated with sediment traps, like decomposition during deployment, are reduced if short collection periods are used. Furthermore, we recommend that replicate traps with formaldehyde should be used to measure the vertical flux of dead components of dinoflagellates.
Acknowledgments

This project was carried out as part of Y. Viner’s M.Sc thesis. We thank U. Pollingher for supervision of the dinoflagellate counts, and Meir Hatab, Nir Koren, Jack Graham, Alon Mindel and Boaz Arraham for assistance with the field work. Funding was provided by the Israel Ministry of Science, Joint Israel-Germany Program BMBF grant 01310.

References


The potential grazing of zooplankton and nektobenthic species on phytoplankton in an estuarine system: The Kuršių Marios (Curonian) lagoon

Artūras Razinkovas and Zita R. Gasiūnaitė

Center for System Analysis, Klaipėda University, Manto 84, LT 5808, Klaipėda, Lithuania

Introduction

Zooplankton grazing is considered to be one of the main processes, responsible both for quantitative (density, biomass, production) and qualitative (community structure and successional shifts in the dominant species) changes in the phytoplankton community (Sterner 1989, Kivi et al. 1993, Riegman et al. 1993 Sarnelle 1993, Edgar and Green 1994). Cladocerans are the most effective grazers among the crustaceans and tend to eliminate small edible algae from plankton, giving opportunity for large, grazing resistant species, especially filamentous cyanobacteria, to increase their numbers (Lynch and Shapiro 1981, Kasprzak and Lathrop 1997).

Generally, nektobenthic mysids are omnivorous (Bozhko 1969, Siegfried and Kopache 1980, Matievska 1984) eating all kind of organic material in their environment (Mauchline 1980). There are, however, ontogenetic as well as seasonal differences between the diets of certain species (Kost and Knight 1975). The mysid species investigated in this study (Paranympha lacustris, Neomysis integer and Limnomyys benedeni) are considered to be omnivorous, but having detritus as the main component of their diet (Dedyu 1965, Vorobjova 1980, Achorrov 1982, Jensen and Heerkloos 1983, Vladimirov and Toderash 1983). A recent investigation of the mysid diet in the Curonian lagoon, based on gut analysis of mysids (Jankauskiene, pers. comm.), revealed that phytoplankton is a relatively important food source comprising up to 60% of the total gut contents of mysids.

The objective of this study was to evaluate the role of mesozooplankton and nektobenthic mysids as grazers of phytoplankton biomass and to estimate their potential impact on the seasonal succession and development of phytoplankton in the ecosystem of the Kuršių Marios lagoon.

Description of the study area

The Kuršių Marios lagoon is connected to the south-eastern Baltic Sea through the narrow Klaipėda strait (Fig. 1). The area of the lagoon is 1,584 km² and its mean depth is 3.8 m; maximum depth is 5.8 m in the southern region and 10-12 m in the artificially deepened Klaipėda Strait harbour area. The southern and central parts of the lagoon contain freshwater due to discharge from the Nemunas
River and other smaller rivers, while the salinity in the northern part varies from 0 to 8 (Practical Salinity Scale), depending on the wind which influence the inflow brackish water from the Baltic Sea. The predominant flow is from the south to the north discharging annually approximately 22 km$^3$ fresh water into the Baltic Sea. Intrusions of brackish water are most frequent from August to October, when 70% of the total annual inflow from the Baltic Sea occurs (Pustelnikovas 1994, Stankevičius 1996).

**Materials and methods**

Quantitative mesozooplankton samples were taken at the station in the northern part of the lagoon (Fig. 1), approximately every third or fourth day from March to November 1995. Pooled duplicate vertical hauls were taken with a 150 m mesh plankton net (13 cm diameter) from 4 m depth. Samples were fixed with 4% formalin. Mesozooplankton individuals were counted and measured (total length excluding spines) in a Bogorov tray using a binocular scope. The average length of crustaceans was determined for each sample. Lengths were converted to wet weight using length-weight relationships from Salazkin et al. (1984) and Jorgensen et al. (1991). Rotifers were not quantitatively measured. Temperature and salinity were also measured. When salinity was above 1, samples were not included in the analysis, since they contained mostly brackish water species brought in by the inflow from the Baltic Sea.
Quantitative samples of nektobenthic mysids were obtained by trawling an epibenthic sled over an area of 30 m². Triplicate samples were trawled weekly from 3 depths (0.3, 0.6, 1.5 m) at 2 stations from April to November in 1986–1988 (N=270). Samples were washed on a 0.5 mm sieve and preserved with a mixture of alcohol, formalin and sucrose.

We used previously published data to obtain an estimate of the seasonal primary production (determined using O₂ method; Krylova 1980) in the study area. Daily ingestion of zooplankton was calculated using a body-weight relationship (R=0.00476 W⁰.₈; Sushchenya 1975). Ingestion estimate of the nektobenthic mysids Neomysis integer, Paramysis lacustris and Limnomyis benedeni, was based on the measured biomass, and calculated using the energetic requirements determined experimentally (Jansen and Heerkloss, 1983) and during the field investigations (Vladimirov and Toderash 1983). Daily ingestion was calculated using temperature correction according to Salazkin et al. (1984). Assimilation efficiency was assumed to be 60% (Sushchenya 1975, Jorgensen et al. 1995). Linear interpolation was used to produce daily biomass and concentration values for the whole annual cycle. All calculations were performed using ModelMaker modelling software.

**Results and discussion**

The seasonal pattern of nutrient dynamics and phytoplankton biomass development in the Kuršių Marių lagoon, as presented in Figure 2, is based on published observations of Krylova (1980, 1985) andStankevičius (1996). The seasonal cycle is similar to other coastal environments in the Baltic Sea, which are influenced both by fresh water and brackish water inflow (e.g. Stegmann and Penfert 1984). Inorganic nitrogen and phosphorus reach the highest concentrations during the spring flood, when nutrient rich waters from Nemunas River spread to the whole lagoon. Phosphorus concentrations decline in late spring, and increase slightly during summer, while nitrogen concentrations decrease strongly in July-August (Fig. 2). The annual development of the phytoplankton biomass is characterised by two biomass peaks: in spring and in summer, respectively. The first peak is dominated by diatoms, while the summer peak consists mostly of the chain-forming cyanobacteria, Aphanizomenon cf. flos-aquae (Uzel 1959, Krylova 1985, Oleina and Kavolyte 1994).

Seasonal succession of freshwater zooplankton is characterised by a sequence of three dominant species: Cyclops sp. in spring, Daphnia longispina in midsummer and Chydrorus sphaericus in late summer (Fig. 3). The shift from the dominance of Cyclops sp. to that of D. longispina and the concurrent considerable increase in zooplankton density (from 0.1x10⁶ up to 6x10⁶ ind. m⁻²) and biomass (0.4–18 g m⁻²) is probably due to the temperature change at this time. Bloom of filamentous cyanobacteria (Aphanizomenon flos-aquae) may have an impact on the shift from D. longispina dominance to that of C. sphaericus (Gasiunaitė and Oleina 1998). The general successional sequence of mesozooplankton is slightly modified in the different parts of the lagoon. There are also interannual differences.

The population dynamics of mysids is characterised by two annual density peaks (varying between 0.5 and 60 ind. m⁻²) corresponding to the two generations of the dominating species Paramysis lacustris and Neomysis integer (Razinkovas 1990).

Our calculations suggest that mesozooplankton may have a higher grazing potential than larger and less abundant mysids. The estimated ingestion of mesozooplankton and mysids is highest after the primary production peaks (Fig. 4).
Figure 2. Seasonal cycle of inorganic nutrient concentrations and total phytoplankton biomass in the Kuršiu Marių lagoon (after Krylova 1980, 1985 and Stankevičius 1996).

Figure 3. The relative abundance (%, density) of the major mesozooplankton species in the Kuršiu Marių lagoon during the seasonal cycle in 1995.
The co-occurrence of the peaks of mesozooplankton and nektobenthic mysid indicates that these groups may have a similar trophic position in the food web of the Kuršiu Marios. Mysis, however, are more detritovorous than mesozooplankton (Siegfried and Kopache 1980, Vorobjova 1980, Achrrorov 1982, Matievska 1984) and are therefore more important as consumers of detritus originating from phytoplankton.

As a conclusion, it can be summarized that during the first primary production peak in spring, phytoplankton is not controlled by grazing since the biomass of the potential nektobenthic and mesozooplanktonic grazers is low, but rather by other environmental factors, such as nutrient limitation. Later the increasing grazing pressure on small edible algae is accompanied by the increase of large chain-forming, and presumably non-edible, cyanobacteria. By the end of the summer, the formation of cyanobacterial biomass is controlled mostly by physical factors (temperature, light and wind mixing). However, during the two major phytoplankton bloom peaks, mesozooplankton and mysids do not seem to be able to control phytoplankton biomass. Thus, most of the produced algal biomass is either channeled to bacterial decomposition in the water column or exported to the benthic food chain through sedimentation. However, the grazers are likely to be important for the structural changes in the phytoplankton species composition during the seasonal succession.

References:


Implications of particle-associated dissolved organic carbon (DOC) for oceanic carbon cycling

Thomas Noji
Institute of Marine Research, P.O. Box 1870, N-5024 Bergen, Norway

Introduction

The downward transport of organic carbon in the ocean is dependent upon the primary production of organic material, the size and density of the material, whether it is particulate or dissolved, the degree to which it is consumed and recycled in the upper ocean, and downward transport of the organic material by convection. Each of these factors is in turn controlled by a subset of biological and physical variables. The suite of recognized variables potentially regulating carbon sedimentation is growing. Whereas in the past scientists were chiefly concerned with phytoplankton biomass and herbivore grazing, more recent investigations (Noji and Rey 1996a) have attempted to close the gaps in organic carbon budgets by re-evaluating the accuracy of sediment-trap data and by considering the importance of less tangible carbon pools such as respiration by vertically migrating zooplankton as well as dissolved organic (DOC).

Increasing evidence leads us to deduce that DOC in the ocean is an important component of the biological carbon pump (Volk and Hoffert 1985, Longhurst and Harrison 1989, Siegenthaler and Sarmiento 1993). This is indicated by discrepancies between new production estimates for phytoplankton and sediment-trap findings (Michaels et al. 1994a) as well as seasonal surges in subsurface concentrations of DOC (Michaels et al. 1994b). In both cases the accumulation of DOC during the spring phytoplankton bloom and subsequent vertical mixing in fall and winter are the main processes suggested to explain the field data.

Usually the sedimentation of particulate organic carbon (POC) in sediment traps is wrongly equated with that of total organic carbon. DOC in the traps is disregarded, because sedimentation is primarily mediated by particles, and it has been considered extremely difficult or impossible to separate allochthous DOC — leached from living zooplankters termed swimmers (Lee et al. 1988) — from DOC in or on the sinking particles. Furthermore, not only do sedimenting particles, e.g. marine snow aggregates (Alldredge and Gotschalk 1988, Lampitt et al. 1993) and fecal pellets (Schrader 1971, Honjo and Roman 1978), possess an interstice (Noji et al. 1991, Stolzenbach 1993) containing dissolved organic material including carbon, but organic molecules, e.g. cell membrane remnants, DNA and cell exudates (Malinsky-Rushansky and Legrand 1996), may adhere to these particles (Waite et al. 1995). In a sediment trap, such substances may be released into solution by simple diffusion. Further particulate material may be dissolved by exo-enzymatic (Smith et al. 1992, Bochdansky et al. 1995) lysis and in unpoisoned samples by bacterial activity (Khripounoff and Crassous 1994, Bodungen et al. 1995) and thereby contribute to the DOC content in trap samples. Few investigators
have addressed this dissolved component, although there are notable exceptions (e.g. Knauer et al. 1990, Hansell and Newton 1994, Körtzinger et al. 1994). This is surprising, since indications exist that the DOC fraction in aggregates (Herndl and Peduzzi 1988) and copepod fecal pellets (Jumars et al. 1989, Urban-Rich, submitted) may be as large as that for POC. Ignoring this particle-associated DOC (pDOC) underestimates downward carbon flux via particles.

The first results on estimates of pDOC were recently presented (Noji et al., submitted), and the importance of pDOC for carbon cycling in the central Greenland Sea in relation to the sedimentation of POC, convection and DOC as well as the respiration of zooplankton stocks was recently elucidated (Noji et al. 1996b, accepted). These findings as well as some comments on other implications of pDOC for pelagic recycling are summarized here.

**Biomass of sinking particles, zooplankton swimmers and DOC from sediment traps**

During investigations of ESOP (European Subpolar Ocean Programme – Marine Sciences and Technology Program 2 of the Commission of the European Communities), a mooring consisting of three sediment traps was deployed in the Central Greenland Basin (75°N, 0°) from August 1993 to June 1995. Depths of the traps were 200, 775 and 1,735 m for the first year and 300, 900 and 2,000 m for the second. Each sediment trap (Aquatec Meerestechnik, Kiel, Germany) collected up to 20 samples per year at pre-defined intervals ranging from about 1 to 4 weeks each. Before deployment sampling cups were filled with filtered (0.2µm) sea water collected from 1000 m at the site of deployment and enriched with 3% NaCl. Mercurochlore was added to each cup (2 ml saturated solution per 100 ml sea water).

After recovery, samples were left undisturbed for two weeks, after which subsamples of supernatant were collected for analysis of DOC (Børsheim and Myklestad, in press). This method of separating particles for DOC was preferred to filtration, because the latter often introduces contamination. Zooplanktonic swimmers were removed using a 180 µm sieve, after which remaining swimmers were removed by tweezer under a dissecting microscope; dry weight of swimmers (SWM) in each sample was measured. Samples were then filtered in duplicate for analysis of total particulate material (TPM), particulate organic carbon and nitrogen (POC, PON), chlorophyll a and phaeopigments (the sum of the last two is termed the chlorophyll equivalent – CEQ).

**Chemometric approach**

The data used for latent variable (LV) analyses were in units of weight per trap sample, i.e. not flux rates. Summarily, the suite of variables for each sample was: DOC (mg), SWM (mg), TPM (mg), POC (mg), PON (mg), CEQ (µg), POC/PON, POC/CEQ, and TPM/POC.

After initial statistical testing, it was concluded that in order to predict DOC content in each sample, the best approach was to apply a comprehensive model based on all samples after the systematic removal of outliers. By doing so, the resulting LV regression (n=95) was:

\[
\text{DOC} = 2.9 + 0.1756 \text{SWM} + 0.0134 \text{TPM} + 0.0131 \text{CEQ} + 0.0040 \text{PON} + 0.0035 \text{POC} + 0.0001 \text{POC/PON} - 0.0076 \text{POC/CEQ} - 0.0043 \text{TPM/POC}.
\]
These results indicate that swimmers and total particulate material are the two most influential factors for predicting the DOC content in traps samples.

The model results compared very well with the measured values of DOC in the supernatant of trap samples (Fig. 1). Derivations of this equation can be used to predict the DOC content of samples as associated only with particulate matter entering the traps:

\[ \text{pDOC}_{\text{min}} = \text{DOC} - 0.1756 \text{SWM} - 2.9 = 0.0134 \text{TPM} + 0.0131 \text{CEQ} + 0.0040 \text{PON} + 0.0035 \text{POC} + 0.0001 \text{POC/PON} - 0.0076 \text{POC/CEQ} - 0.0043 \text{TPM/POC}, \]

\[ \text{pDOC}_{\text{max}} = \text{DOC} - 0.1756 \text{SWM} = \text{pDOC}_{\text{min}} + 2.9. \]

Figure 1. DOC content of trap samples (n=106) in six depths, each comprising between 10 and 20 samples collected for different time intervals between August 1993 and May 1995, ranged from almost 600 to <20 mg. The LV model based on all data (DOC = 6.1 + 0.1628 SWM + 0.0242 TPM + 0.0095 CEQ + 0.0040 POC + 0.0001 POC/PON - 0.0031 POC/CEQ - 0.0028 TPM/POC; solid gray line) predicts DOC contents surprisingly similar to the measured values in most cases. After the removal of 11 outliers, the refined LV model (solid black line) predicts DOC with slight improvement. Statistical outliers, excluded from the calculations used to develop the refined model but included in this graph, encompass the most significant deviations (*) between measured and predicted DOC, notably some measured and predicted data for outliers were quite similar (+).
Revised rates of vertical carbon flux

Estimates for the vertical flux of pDOC for two years of deployment at 6 discrete depths (Fig. 2) in the central Greenland Sea were on average about equal to those for POC. The pDOC\textsubscript{max} - POC flux ratios in shallow (180/300 m), midwater (700/900) and deep-sea (1735/2100) depths averaged 0.50, 1.02 and 1.71, respectively, and ranged from 0.24 to 8.8. Since most DOC in aggregates exists as long chain polymers with low solubilities, the large pDOC:POC ratios in some samples indicate that a considerable amount of DOC is generated by particles and released in the collecting cup of the trap.

Loss of DOC from particles is a potential error in trap measurements and should be considered when this methodology is used. Neglecting pDOC in sediment-trap estimates of carbon flux may be a partial cause for discrepancies between CO\textsubscript{2} drawdown in the ocean surface vs. biomass accumulation and export estimated by sediment traps. We note that the vertical flux of nitrogen and phosphorus in particles may be similarly underestimated by sediment-traps.

![Vertical Flux of Carbon in Particles](image)

Figure 2. Sedimentation rates of pDOC for the same samples as shown in Fig. 1 were calculated from the refined LV model by subtracting the DOC attributable to zooplankton swimmers. pDOC\textsubscript{min} and pDOC\textsubscript{max} represent the range of uncertainty, which is dependent upon the LV model constant of 2.9 mg DOC per sample. Statistical outliers corresponding to large differences between measured and predicted DOC (labelled with * in Fig. 1) are not included. A clear parallel between the vertical flux of particulate and dissolved organic carbon is demonstrated. The ratio of pDOC\textsubscript{max}:POC averaged 1.08±1.42 for the set of flux rates (n=100), with a tendency for higher ratios when the flux rate for POC is low.

The biological carbon pump in the Greenland Sea

With regard to the cycling of organic carbon in the Greenland Sea, a large portion of the organic carbon resulting from new production, estimated to be about 57 g C m\textsuperscript{-2} a\textsuperscript{-1}, was not recovered as particle flux at 200 m, a depth well below the biologically productive upper mixed layer. The rate of particle sedimentation out of the upper mixed layer can be presumed to be several times larger than the rate recorded at 200 m, and accordingly considerable recycling presumably occurred in the upper 200 m of the ecosystem. Reports in the literature certainly support this assumption, as depth-dependent reductions in the amount of sinking POC,
i.e. differences between sedimentation rates at discrete depths, are usually large. For example, POC sedimentation rates went from about 400 mg m\(^{-2}\) d\(^{-1}\) at 50 m to only 20 mg m\(^{-2}\) d\(^{-1}\) at 250 m during a study in August 1988 in the Norwegian Sea (e.g. Bathmann et al. 1991), indicating a reduction in particle flux of a scale of magnitude over a distance of 200 m. On the other hand, the downward mixing of DOC near the surface in summer, an accumulation of which was estimated to be over 24 g m\(^{-2}\) during one year of our investigation (Børshjem 1996), is a process of strong potential importance for the downward flux of carbon (Michaels et al. 1994b, Carlson and Ducklow 1995), although recent data by Børshjem (unpublished) indicate that most of this summer surface DOC may be respired by bacteria. The combined effects of these processes presumably result in the substantial deficit of newly produced organic material in the investigation reported here.

An additional important consideration for biologically mediated carbon flux is the seasonal migration of herbivorous copepods to deep water, where these stocks overwinter for most of the year. Hirche (1997) can now show that from the initiation to the end of diapause in the deep Greenland Sea overwintering stocks of the dominant copepods, Calanus hyperboreus and C. finnarchicus, exhibited a decrease in specific biomass due to respiration as well as a decrease in abundance due to mortality. Equivalent to approximately 3.5 g C m\(^{-2}\), most of which was attributable to respiration, this was a significant downward transport of carbon via zooplankton. There was no evidence for the diel migration of the dominant copepods, a finding supported by other observations in arctic waters (Hansen et al. 1990), which would also have resulted in substantial downward carbon transport (Dam et al. 1995).

The chief uncertainties of a simple budget for the flux of organic carbon (Table 1) are the magnitudes of: (1) the recycling of sedimenting material in the upper 200 m and (2) the downward flux of DOC. Since no substantial deep convection can be expected in late summer, we assume that the downward transport of DOC was confined to depths above 200 m. Therefore, the annual flux of organic carbon to water below 200 m is mostly a result of particle sedimentation and zooplankton respiration/mortality, the cumulative estimate for which is about 5.5 g. Over half of this transport is attributable to overwintering zooplankton.

Table 1. Production and removal of biogenic carbon from the upper mixed layer (g C m\(^{-2}\) m\(^{-2}\)). DOC data from Børshjelm & Myklestad (in press). Data on overwinterer respiration from Hirche (1997).

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Annual new production</strong></td>
<td>57</td>
</tr>
<tr>
<td><strong>Annual removal</strong></td>
<td></td>
</tr>
<tr>
<td>Particle-bound carbon export at 200 m</td>
<td></td>
</tr>
<tr>
<td>POC</td>
<td>1.48</td>
</tr>
<tr>
<td>pDOC</td>
<td>0.45</td>
</tr>
<tr>
<td>Carbonate-C</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Downward transport of DOC</td>
<td>24–48</td>
</tr>
<tr>
<td>Overwinterer respiration</td>
<td>3.5</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>30–54</td>
</tr>
</tbody>
</table>

**Acknowledgements**

This work was supported by the Commission of the European Union under contracts MAS2–CT93–0057 and MAS3–CT95–0015 of the Marine Sciences and Technology program as well as by the Norwegian Research Council under project num-
ber 101317/410. Thanks to several anonymous referees for this and related manuscripts, as well as Alice Aldredge, for helpful comments. I thank the NOSTRA steering committee for the opportunity to present these results at the 4th NOSTRA workshop held in Tartu, Estonia.

References


West Spitsbergen Fjords  
(Svalbard, Norwegian Arctic):  
Physical Setting and  
Sedimentation

Alexander Keck

Institute of Oceanology, Polish Academy of Sciences, 81-712 Sopot, Poland  
Present mailing address: P.O. Box 33, N-9001 Tromsø, Norway

Introduction

Studies of vertical particulate flux in Arctic coastal environments are scarce. Investigations have been carried out, e.g., at shallow sites off Baffin Island (Atkinson and Wacasey 1987, Hsiao 1987), in Hudson Bay (Tremblay et al. 1989), the Beaufort Sea (Carey 1987), the northern Bering Sea (Fukuchi et al. 1993) and the northeast coast of Greenland (Weslawski et al. 1997). There are also reports from deep shelf and oceanic environments (Hargrave et al. 1989, 1994; Andreassen et al. 1996, Bauerfeind et al. 1997), and only one of these publications is from the Svalbard area as yet. All of these investigations have in common a study site near to an Arctic coastline, however, the local properties of the sites, as e.g., bathymetry, persistence of ice cover, and hydrodynamics are often greatly diverse from one place to another. Most studies of this kind provide evidence or at least indications that the dynamics of suspended biomass and settling fluxes are to a large extent triggered or controlled by physical forces as e.g., light regime, meteorological conditions, turbulence, advection and fluvial runoff (e.g., Eilertsen et al. 1989, Kierboe 1993, Falkenhaug et al. 1995, Keck and Wassmann 1996). However, the causal dependencies between biological and physical events are not always demonstrated by simultaneous observations. Often the lack of thorough documentation of physical events together with biological observations may therefore imply more uncertainties as beneficial for the understanding of how these processes are coupled with each other. This makes comparisons between diverse published results or their application in favour of an advance in our understanding sometimes more difficult than desirable.

Comprehensive information on vertical fluxes in Svalbard fjords was not available so far, apart from a few indications on the size of sedimentation given by Weslawski et al. (1993, 1995). The present article intends to give a short overview of the physical conditions of importance for water column ecology and sedimentation in Spitsbergen fjords, and present some characteristic results on hydrography and vertical particle fluxes from the west and northwest coast of this island in summer 1993 and 1994.
Figure 1. Maps of study sites.
a) Svalbard with fjord locations 1993;
Physical environment

The archipelago of Svalbard (Fig. 1A) exhibits near arctic desert conditions with low annual precipitation (140–600 mm; DNMI (1994)). However, despite its location at high latitudes (within 76–81°N), Svalbard also experiences mild climatic influences, predominantly along its western boundaries. This is due to the relatively warm and saline North Atlantic current which meets cold and less saline water from the Arctic Ocean along frontal zones in the Barents and Greenland Seas, and a branch of which follows as West Spitsbergen Current the west and in part also north coast of Spitsbergen before entering the Arctic Ocean. The majority of fjords on Spitsbergen (the archipelago’s main island) are glacier-dominated, i.e., generally influenced by retreating tidewater glaciers and hinterland glaciers (Svyitski et al. 1987). Freshwater discharge, as a highly seasonal phenomenon in this area, is only significant during the short summer period, but then it introduces large volumes into the fjords predominantly due to glacier ice-melt (Fig. 2). It has been shown that glacial ablation and calving/rafting from tidewater glaciers on Spitsbergen represent the largest source of freshwater input (ca. 70%) compared to other sources like precipitation and snow/ice melt (Weslawski et al. 1995). The meltwaters are highly turbid, and the glacial discharge is the main source of suspended sediments introduced to these embayments. Suspended particle concentrations at the glacier front may range from 500 to over 1000 mg/l (Elverhøi et al. 1980, Görlich et al. 1987), and cause heavy (predominantly inorganic) sedimentation. Erosion and resuspension (e.g., by advection) and sediment focusing (Hilton 1985) are different processes leading to exponential increases in sedimentation rates toward the seabed, and are common for coastal zones in general. As mentioned above, one of the consequences of the meltwater discharge is turbidity entailing decreased light availability for photosynthesis (Eilertsen et al. 1989) and various biogeochemical interactions between seawater, clay, silt and organic particles leading to enhanced settling via flocculation and agglomeration processes (Svyitski 1980, 1995; Eisma 1993). The enhanced sedimentation may result in increased stress for benthic organisms and even cause burial of bottom communities near to the source of sediment discharge (Görlich et al. 1987).

The freshwater input produces a distinct surface layer of brackish water, the outflow of which generates an estuarine counter current. The result is a rather persistent haline stratification throughout summer. An eventual thermal stratification – quite unlike its significance for boreal and warmer latitudes – will never gain the same importance in Arctic coastal zones. The stratification is gradually broken down, first by autumnal surface cooling (vertical convection) and wind-induced vertical mixing, later by the input of salt at the surface during sea ice formation (brine rejection) continuing and reinforcing the process of vertical convection. Tidal energy and density displacements in deeper water may contribute to vertical mixing. Brines may also be added laterally, i.e., flowing down from shallow depths following a salinity gradient (gravity flows) (Lewis and Perkin 1982).

Vertical mixing is known to displace phytoplankton cells to deeper, aphotic layers and thereby limit light availability for them. However, light availability will also be increasingly limited with the onset of winter darkness. During the lucid periods of the year, the amount of solar irradiation and the characteristic daylength periodicity found in the Arctic affect the seasonal progression of plankton abundance, the organisms’ interactions with each other, and their coupling to the bottom communities in providing a food source through sedimentation (pelagic-benthic coupling).
Figure 2. Conceptual scheme of the physical setting for pelago-benthic coupling in glacial fjords in summer.

Figure 2 summarizes all the external factors which may affect pelagic productivity in glacier-fed Arctic fjords and, thus, also settling fluxes with their inherent multiple functionality for these ecosystems (i.e., as a benthic food source, for nutrient recycling and potential carbon sequestration (see Keck and Wassmann 1996, and references therein).

**Materials and Methods**

The data for this investigation were collected in the course of July and August, 1993 and 1994, during joint summer cruises with R/V "Jan Mayen" (Univ. of Tromsø). The study sites were three selected fjord locations and a fjord-shelf transect (Kongsfjord) in the west and northwest area of Spitsbergen (Fig. 1). Hydrographical profiles and water samples were taken using a combined CTDF-profiler (Neil-Brown)/rosette sampler (General Oceanics) and a mini-STD probe (SD 200, Sensordata, Bergen). Qualitative phytoplankton samples were obtained with a conventional net (mesh size 20 mm) and preserved in 1% buffered formaldehyde. Sediment trap arrays with 4-6 traps each were moored at water depths of 95-330 m. The lowermost traps were placed 1 or 2 m above the sea floor. All traps consisted of gimbaled perspex cylinders with aspect ratios over 6:1 and opening diameters of 9.3 (Elementa, Sweden) or 7.4 cm (KC-maskiner, Denmark). No preservation solution was employed during the deployments which were either extremely or moderately short-termed (1993 study: 6–8 hrs; 1994 study: 13–51 hrs). For further details on mooring, sampling and filtration procedures see Keck and Wassmann (1996). The results presented here are based on analyses of dry weight (TPM, total particulate matter), organic matter and carbon (POM, POC), chlorophyll a/phaeopigments and microscopical identification/enumeration of intercepted and suspended particulate matter. The methods are described in Keck and Wassmann (1996) except for the microscopical work following Utermöhl (1958) (courtesy J. Wiktor, Inst. of Oceanol. PAS, Sopot).
Results and Discussion

Hydrography

The results shown here are from short-term studies in summer, but may not be considered as representative for the whole season. However, they can be regarded as typical for a period of near-maximum meltwater runoff in mid-summer (cf. Weslawski et al. 1995). Seasonal shorefast sea ice usually has disappeared by June, with the marginal pack-ice zone having retreated beyond the northern shelf of Spitsbergen. The water column in all of the fjords studied in 1993 was well stratified at the end of July (Fig. 3). The density profile was clearly controlled by salinity, and meltwater discharge was obviously the most decisive factor hereby. The lowest surface salinities (practical salinity scale, PSS78) were found at Isfjorden station (28.7) and in the inner Magdalenefjorden (30.6). The distance to glacial runoff apparently determines the salinity of the brackish layer at the respective locations, however, surface current patterns may cause a deflection of the glacial plumes which may have been the case for the Raudfjorden station (33.0).

Figure 3. Hydrographical profiles at four different fjord stations, T: in situ temperature (°C); S: salinity (Practical Salinity Scale); SgTh: density (sigma theta; kg m⁻³); Chl in-situ-fluorescence (mg Chl a m⁻³)
The Isfjorden station has no tidewater glacier in its vicinity, but a combined rive-
rine (meltwater) discharge from the southern coastline of this fjord was appar-
tently important enough to have reduced surface salinity to that extent. The tempera-
ture profiles suggest that also a considerable warming of the surface (6→8°C) 
from intensive solar radiation (daylength 24 hrs) has taken place. As indicated by 
in situ-fluorescence profiles, a weak phytoplankton bloom was encountered at 
each station, commonly with a fluorescence maximum between 10 and 20 m. The 
degree of vertical mixing differs between the stations. Stratification was consist-
tently strongest in the upper 20–25 m at all stations except the Raudfjorden site. 
Compared to the other stations, the latter seemed to be more governed by a stra-
tified sublayer of relatively warm shelf water (>2°C) reaching down to 100 m 
depth, approximately corresponding to the sill depth in the mouth area of the 
fjord. A marked discontinuity separates this layer from the profoundly cold 
(-1.7°C) and dense (S: 34.7) basin water. The Magdalenefjord which displays a 
sublayer of similar T and S characteristics as the Raudfjord, also has such a deep 
basin, yet in its inner part. The sill depth here is 48 m, and the bottom water 
exhibits most extreme values (T: -1.9°C (near freezing point); S: 34.9). The steep 
gradients in temperature and salinity in the two basins were found to be accom-
panied by sharp decreases in dissolved oxygen in the range of 0.8–1.8 ml/l along 
a 60 m-interval (20 m-values: 7.7–7.9 ml/l), whereas the O₂ concentrations in the 
water column of the outer Magdalenefjord keep within the 20 m-values. All these 
gradients indicate the impeded water exchange between the deep basins and the 
water above the respective sill depths. The only mechanism possible for the evolu-
tion of these dense and cold bottom waters exists during winter when brines are 
rejected from newly forming sea ice and descending to deeper strata of matching 
density (Lewis and Perkin 1982).

**Vertical particulate fluxes**

Profiles of settling fluxes of total particulate matter (TPM) and diverse organic 
fractions are depicted for the Kongsfjord area (Fig. 4) and for the already men-
tioned fjords (Fig. 5). Figure 4A shows the strong effect of the glacial meltwater and 
sediment discharge from the Kongsbreen glacier at the head of the Kongsfjord 
(see Fig. 1B, station IV). It is obvious that most of the suspended sediments are 
deposited in the inner fjord area, and already at station III this effect is considere-
ably reduced. Following a steeply exponential decrease in sedimentation rates, the 
two shelf sites exhibit similar profiles when compared to the outer fjord (st. III).

The organic carbon fraction of the sedimented matter (POC; Fig. 4B) also 
shows decreases along the transect inner fjord (IV) – outer shelf (I), but rather a 
linear one. The signal of an apparently subglacial sediment discharge near 50 m is 
better resolved for this variable (POC) along the section than for the total mass of 
solids intercepted. It demonstrates the potential importance of glacial sediment 
input as an allochthonous POC source, not only for the outer fjord but also for the 
shelf and possibly even the adjacent deep sea region. Both figures (4A,B) show 
increases in sedimentation rates by approaching the sea floor. This is a common 
observation in many temperate or subpolar coastal zones.

The depth profiles of the POC/PON ratios (Fig. 4C) reveal several charac-
teristics: (1) Except for a few values in the surface layer approximating the Redfield 
ratio (7:1), the higher ratios indicate that the organic matter is substantially de-
graded; (2) the ratios increase generally with depth on all stations indicating both 
vertical remineralisation processes and dilution with bottom-resuspended mate-
rial; and (3) the strikingly different nature of the organic matter discharged by the 
glacier (st. IV). These sediments (C/N range 18–21) display ratios much higher
Figure 4. Vertical profiles of settling flux along a fjord-shelf section, Kongsfjord. Total particulate matter (TPM); particulate organic carbon (POC); particulate organic carbon to nitrogen (POC/PON) ratio. Lowest traps 2 m above seabed (I-V: sampling stations; see Fig. 1).

Figure 5. Vertical profiles of settling flux at four different fjord stations. Total particulate matter (TPM); fraction of the particulate organic matter of the total particulate matter (POM/TPM); chlorophyll a; d) phaeopigments. I: Isfjord; R: Raudfjord; Mi: Inner Magdalenefjord; Mo: Outer Magdalenefjord. Lowest traps 1 and 2 m above seabed.
than the values of the resuspended matter at all the other sites. Thus it illustrates both the different provenance of the material and its aged condition owing to advanced remineralization and diagenetic processes.

TPM sedimentation profiles in the other fjords (studied in 1993) are chiefly similar considering the upper part of the water column (Fig. 5A), but the extent of secondary sedimentation due to resuspension differs between the stations. While the Isfjord station is located in a relatively wide and open area, the outer Magdalenefjord and Raudfjord locations may be more exposed to sediment focusing (Hargrave and Kamp-Nielsen 1977, Hilton 1985) via the surrounding slopes. The profile from the inner station in Magdalenefjord – comparable to st. IV in Kongsfjord – demonstrates the effect of the glacial runoff, with an apparent major discharge near 50 m depth.

The normalized contents of the sedimented organic matter (POM; Fig. 5B) appear more or less inversely related to TPM sedimentation. The figure shows the decrease of POM as a result of the depth-related increase in sedimentation and the increased dilution of organic particles by inorganic ones. The organic fractions of the inner Magdalenefjord profile take a uniform shape. This signifies the obviously homogeneous origin of the total particulate matter, viz., as predominantly being derived from the glacial discharge.

The sedimentation profiles of chloroplast pigments (Figs. 5C, D) exhibit shapes and proportions more or less similar to the corresponding TPM fluxes, whereas the inner Magdalenefjord profile – as an exception – shows a homogeneity resembling that of its POM/TPM fractions. Phaeopigment fluxes surpass those of chlorophyll a (chl a) by a factor most frequently between 2 and 3. This indicates increased herbivory (Downs and Lorenzen 1985) and suggests the presence of a well-developed pelagic food web as commonly reported from boreal coastal regions in summer. The strong depth-dependent increase in chl a sedimentation at the outer Magdalenefjord station is particularly noteworthy as it not only reflects resuspension (similar to the TPM profiles), but also may indicate the local importance of the above-mentioned sediment focusing engendering additional supplies of organic matter for secondary sedimentation. As revealed by several futile attempts of sediment coring at this location, the bottom evidently was not made up of soft sediments. This again points to higher current velocities which could have created locally increased suspended matter loads and in turn increased sedimentation rates.

Suspended chl a biomass was found to be highest in the upper 20 m of the water column (see also in-situ fluoresc., Fig. 3), with max. concentrations at the stations ranging between 0.8 and 2.3 mg m⁻³ (for this interval). Table 1 gives the integrated chl a biomasses for this depth interval at each station, as well as the daily losses by sedimentation (Taguchi and Hargrave 1978) at 20 m, and the residence times for the integrated biomasses (in case no other loss terms would occur). The numbers suggest that losses are relatively small at each station, and the (theoretical) residence times correspondingly large. Similar loss rates were reported from the Barents Sea (Wassmann 1990). By contrast, bloom-type mass sedimentations (frequently encountered during spring) would give rise to loss rates an order of magnitude higher (Wassmann 1994).
Table 1. Integrated chlorophyll a (chl) biomass (between 0 and 20 m), and the daily loss rate (% day⁻¹) of suspended chl at 20 m depth, and the residence time of chl in West Spitsbergen fjords, in early August 1993.

<table>
<thead>
<tr>
<th>Location</th>
<th>Suspended chl (mg m⁻³)</th>
<th>Loss rate of chl (% day⁻¹)</th>
<th>Residence time (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isfjorden</td>
<td>14.7</td>
<td>4.56</td>
<td>21.9</td>
</tr>
<tr>
<td>Magdalenefjorden (inner)</td>
<td>12.0</td>
<td>5.42</td>
<td>18.5</td>
</tr>
<tr>
<td>Magdalenefjorden (outer)</td>
<td>9.9</td>
<td>3.53</td>
<td>28.3</td>
</tr>
<tr>
<td>Raudfjorden</td>
<td>35.6</td>
<td>3.46</td>
<td>28.9</td>
</tr>
</tbody>
</table>

Preliminary analyses of the phytoplankton in the surface waters of the fjords (net plankton >20 µm) revealed the predominance of dinophyceans (mainly Ceratium arcticum and Dinophysis rotundata). High numbers of small faecal pellets were also found. The sediment traps suspended at 20 and 50 m displayed autotrophic flagellates and cryptophyceans (Cryptomonas sp., Leucocryptos sp.) as the prevailing organisms. However, faecal pellets represented the quantitatively most important detrital mass in the traps. Findings on relatively high zooplankton (mainly calanoid copepods) abundances (in prep.) and the above preliminary results indicate that the water column during the study period was in a state of regenerative mode of production (steady state type of pelagic community sensu Šmetacek 1984) being typical for the summer season.

Conclusions

Sedimentation in arctic fjords reveals similar rates in comparison to temperate coastal environments, however, discharge from tidewater glaciers creates locally more extreme conditions. Else, the most characteristic findings of the investigations reported here are:

- a well-stratified water column due to meltwater runoff;
- relatively low chlorophyll biomasses with dinophyceans, cryptophytes and other autotrophic flagellates as the prevailing phytoplankton;
- a high production of faecal pellets and thus phaeopigments by zooplankton;
- relatively low losses of chlorophyll a biomass from the euphotic zone.

These results are indicative of a summer situation characterized by a well-developed food web in the upper pelagial and being based on grazing and remineralization chains enabling minimal coupling with the benthic communities.

Acknowledgments

The findings presented here are selected aspects of comprehensive studies (in prep.) supported by grants from the Norwegian Polar Institute (NP 31/93, NP 19/94), the Roald Amundsen Centre for Arctic Research (1994) and the Norw. Research Council (NFR/KAS scholarship to A. Tatur, Inst. of Ecology, Polish Acad. Sci.). Microscopical analyses were kindly provided by J. Wiktor (Inst. of Oceanology, Polish Acad. Sci.), and A. Tatur was an appreciated partner during the 1994 study. Thanks are also due to cruise leaders, masters and crew of R/V "Jan Mayen" for successful field operations.
References


Sedimentation in the open and enclosed water columns: The effect of algal blooms, planktonic food web, and resuspension on the quality of settling organic matter in the coastal northern Baltic Sea

Anna-Stiina Heiskanen

Finnish Environment Institute, P.O.Box 140, FIN-00251 Helsinki, Finland

Introduction

Sedimentation of particulate material is one of the major loss processes of the biomass produced in eutrophic pelagic system (e.g. Wassmann 1990). Heterotrophic plankton organisms (such as copepods, calanoids, and some protozoa) may retard or accelerate sinking loss from the pelagic system depending on the behavior, food selection and life cycle of the dominant organisms (see Wassmann, 1998a, in this issue, for a review). The food web structure (e.g. Peinert et al. 1989, Wassmann 1998b) and evolutionary adaptations of the planktonic organisms (i.e. Smetacek 1985, Olli 1997, Heiskanen 1998) have a major impact on the channeling of the organic material and nutrients either to the retention food chain (efficient regeneration of nutrients) or to the export food chain (loss of nutrients from the pelagic system through vertical flux, i.e. sedimentation). Thus the channeling of nutrients in aquatic ecosystems is largely governed by the life cycles and evolutionary adaptations of the key species (Verity and Smetacek 1996).

In the coastal waters of the Baltic Sea, a large part of the settling material periodically derives from biogenic processes, consisting of planktonic organisms and their remains (Fig. 1). In the proximity of the coastline, some settling material can also be transported from terrestrial and littoral systems. Furthermore, occasionally, resuspended material from the littoral zone and from the sediments contribute considerably to the total sedimentation (Blomqvist and Larsson 1994, Heiskanen and Leppänen 1995, Heiskanen and Tallberg 1998). Settling material is the major supply of organic matter to the deep benthos (Smetacek 1984). In this paper, I will mainly discuss the effect of seasonal succession of algal blooms, planktonic food web structure and resuspension on the seasonal fluctuations of the quality and quantity of settling organic material both in the open sea area at the entrance of the Gulf of Finland, and in the experimental mesocosms.
Material and Methods

Sedimentation of particulate material was measured during three seasonal cycles at the entrance of the Gulf of Finland, northern Baltic Sea, by simple cylindrical sediment traps (Fig. 2A). Using combined sediment trap and water column sampling, it was estimated how much of the seasonal primary production is channeled into sedimentation and which are the major factors governing the magnitude of the export flux (Heiskanen and Leppänen 1995, Heiskanen et al. 1998, Heiskanen and Tallberg 1998).

The impact of external nutrient additions on the sinking losses from the regenerating planktonic system during summer was investigated by enclosing natural planktonic community in the experimental enclosures during two mesocosms experiments. The experiments were conducted in the archipelago region in the large plastic enclosures which were fastened on floating ladders (Fig. 2B). These mesocosms were manipulated by daily or weekly nutrient additions. The combined impact of bottom-up and top-down control on the pelagic system was investigated by adding fish fry to some of the enclosures with and without nutrient additions (see Heiskanen et al. 1996, Olli et al. 1996, for the experimental design and sampling).

Results and Discussion

Seasonality and sedimentation of the pelagic ecosystem in the coastal northern Baltic Sea

The major new production periods in the northern Baltic Sea are the vernal bloom and the blooms of cyanobacteria during late summer (Fig. 3). Most of the vernal bloom biomass consists of chain-forming diatoms and dinoflagellates (Niemi 1973). After melting of the ice cover the vernal bloom begins at the end of April. After decline of nitrate, in early May, many diatom species start to form resting stages
which settle rapidly from the pelagic system (Heiskanen 1998). The daily loss rates of diatoms varied between 30–60% of suspended population, indicating that sinking is the major loss process of diatoms (Heiskanen and Kononen 1994, Heiskanen 1998). Sinking rates can be high; 5–10 m d⁻¹, or even 70 m d⁻¹ as observed in the Baltic Proper, which implies that aggregation is prerequisite that such sinking velocities could be possible (Passow 1991). The organic contents of settling material starts to increase concurrently with the elevated sinking flux of diatoms (Heiskanen and Leppänen 1995, Heiskanen et al. 1998).

The abundance of dinoflagellates is generally highest soon after the peak of diatoms has passed (Kononen and Niemi 1984, 1986). The most dominant dinoflagellate species are the chain-forming *Peridiniella catenata* and *Scrippsiella hangoei*, the latter of which forms resting after sexual reproduction at the end of the vernal bloom cysts (Heiskanen 1993, Larsen et al. 1995). After a strong dinoflagellate bloom, *S. hangoei* cysts can form a considerable fraction of settling organic material (Heiskanen 1993), although the sinking loss rates of vegetative dinoflagellate cells are generally low (Heiskanen 1995). Despite the dominance of dinoflagellates in the water column, diatoms contribute most to the settled phytoplankton biomass (Fig. 4), denoting that the major part of the vernal dinoflagellate biomass disintegrate in the water column and form slowly settling organic detritus (Heiskanen 1998). Many of the vernal bloom species share the common survival strategy in which the rapid bloom formation is followed by seeding of the resting stages having high sinking rates (e.g. Smelacek 1985). Accordingly, the vernal blooms species are the major vehicle of the export flux during the seasonal cycle in the northern Baltic Sea.
Figure 3. A. Contribution of major taxonomic groups to total phytoplankton biomass (mg C m\(^{-2}\)) in the surface layer (0 to 15 m) and B. their fraction (%) of the total phytoplankton biomass during spring and summer in 1988 at the entrance of the Gulf of Finland, Baltic Sea (data from Heiskanen 1995, Uitto et al. 1997).

Figure 4. A. Contribution of the different phytoplankton groups to the total particulate organic carbon (POC) in the surface layer (between 0 and 15 m) B. and to the total sedimentation of POC (corrected for migration contamination) at 15 m depth during spring and summer in 1988 at the entrance of the Gulf of Finland, Baltic Sea (from Heiskanen 1998).
The biomass of zooplankton is low during spring (Viitasalo 1992). Although the number of adult copepods starts to increase at the end of the vernal bloom, most of the phytoplankton biomass has already settled by then (Lignell et al. 1993, Heiskanen 1995). Despite the interannual differences in the development of the later life-stages of copepods (Viitasalo et al. 1994), they cannot control the vernal bloom biomass, thus leaving sedimentation to be the major loss process for the vernal bloom.

The major part of the annual primary production is produced during spring (Fig. 5). The export of particulate nitrogen is generally equal with the magnitude of the initial nitrogen pool of the water column (Heiskanen 1998). As 30–60% of the vernal primary production is exported by sedimentation (Lignell et al. 1993, Heiskanen and Leppänen 1995, Heiskanen et al. 1998), the importance of vernal bloom for the benthic ecosystem is crucial. Moreover, the settling biomass has also an impact on the oxygen conditions of the sediments thus having consequences for the internal loading of nutrients (e.g. Jørgensen 1996). Generally, the availability of nitrogen is limiting the magnitude of the vernal bloom (Kivi et al. 1993, Tamminen 1995), while there is always a small surplus of phosphorus left in the water column after the termination of the vernal bloom.

During summer, the small pico- and nanoplanktonic organisms dominate the plankton community (Kuosa 1990). Zooplankton is able to consume most of the algal production and sinking losses are low (Uitto et al. 1997). Nutrients are recirculated in the "microbial loop" and major part of the nitrogen supply to the autotrophs is provided by heterotrophic mineralization (Tamminen and Irmisch 1996).

During summer, the concentrations of inorganic nutrients are low in the surface layer (e.g. Heiskanen and Kononen 1994). At times, the upwelling of nutrient rich deep water supplies nutrients to the surface waters (Haapala 1994), enabling growth of the chain-forming diazotrophic cyanobacteria otherwise in the nitrogen poor pelagic environment (Kononen et al. 1996). Cyanobacterial blooms are a natural part of the seasonal cycle in the Baltic Sea (Kononen 1992). Some of the bloom forming species (e.g. *Nodularia spumigena*) are potentially toxic (Sivonen et al. 1989). Nevertheless, on the seasonal basis, it seems that the importance of cyanobacterial blooms in the pelagic nutrient cycles is less crucial in comparison to the vernal phytoplankton blooms (Heiskanen 1998).
Algal production and biomass increase slightly during summers, when an intense cyanobacterial bloom with massive surface accumulations have been observed. However, the total biomass levels (per surface or volume unit) are generally lower than during the preceding vernal bloom (Kononen 1992, Heiskanen and Kononen 1994, Tuomi et al. 1998). Temporally integrated primary production during summer 1992, when extensive blooms of *Nodularia spumigena* occurred (Kahru et al. 1994), was less than 40% of the total annual primary production, and less than 30% of this production settled (Heiskanen and Tallberg 1998; Fig. 5). Moreover, the sinking loss rates from the cyanobacterial bloom biomass are generally low (<2% d^{-1} of the suspended biomass; Heiskanen and Kononen 1994), provided that sufficient external nutrient supply is available and enabling successful buoyancy control of cyanobacteria (Heiskanen and Olli 1996). Since zooplankton do not seem to consume cyanobacteria either, the most probable fate of these blooms is dissolution and decomposition in the water column (Sellner et al. 1994).

**Sedimentation dynamics in the enclosed (mesocosms) and open water columns**

During the mesocosms experiment in 1993 (Olli et al. 1996), nutrient enrichments induced a series of blooms dominated by an euglenoid flagellate (Fig. 6). The bloom biomass was rapidly harvested by mesozooplankton, which could effectively control the biomass accumulation. Sedimentary losses were low (<2% d^{-1}), although slightly elevated at the enclosures which were enriched by nutrients (Fig. 6).

![Graph of sedimentation dynamics](image)

*Figure. 6. Upper panels: Concentration of chlorophyll a at two size fractions in the control unit and the mean concentration in the units with nutrient enrichments (arrows indicate days when N and P were added). Lower panels: Sedimentation of particulate organic carbon (columns; bars denote SD of the mean between 3 replicate nutrient enriched enclosures) and daily loss rates (lines with dots) during the mesocosms experiment in 1993 (data partly from Olli et al. 1996).*
During the late summer mesocosms experiment in 1988 (Heiskanen et al. 1996), it was found out that there was differences in the retention and loss phosphorus and nitrogen. Nitrogen was lost by greater extent by sedimentation, while phosphorus accumulated into the detrital pool of the pelagic system. It was also conceivable that the nitrogen limitation in the manipulated enclosures was enhanced by more effective assimilation of N by the heterotrophic organisms (Heiskanen et al. 1996). Sedimentation of N (and C) were more efficient than that of P also in the open pelagic system during the spring bloom (Heiskanen et al. 1998). It seems likely that the common properties of new production systems (i.e. high sedimentation rates of large phytoplankton cells) seem to promote nitrogen limitation due to the more effective sedimentary loss of nitrogen in comparison to that of phosphorus (Heiskanen 1998).

Resuspension is elevated during summer, while the overall contribution of resuspension to the total sedimentation is relatively difficult to estimate (e.g. Blomqvist and Larsson 1994, Heiskanen et al. 1998). Sediment traps moored in the open water column collected material enriched with P due to resuspension of sediment particles with high concentration of mineral or adsorbed P (Heiskanen et al. 1998). However, the N:P ratios of settled material fluctuated considerably, which indicated that the dominant source of settling material varied depending on the hydrodynamics during each collection periods (Heiskanen and Tallberg 1998). During calm periods primary sedimentation and high N:P ratios were typical, while if upwellings occurred settled material had low N:P (and C:P) ratios (Heiskanen et al. 1998). The N:P loss ratio of primary settling material is thus possible to obtain from the enclosed mesocosms, while the field measurements of N and P settlement are distorted with fluctuating impact of resuspension.

References


Sediment - water interactions in the Vistula lagoon - some preliminary results

Elena E. Ezhova, Boris V. Chubarenko, Alexander I. Blazhchishin and Irina P. Chubarenko.

P.P. Shirshov Institute of Oceanology, Atlantic Branch, Pr.Mira 1, 236000 Kaliningrad, Russia

Introduction

The Vistula lagoon is a coastal enclosed shallow basin situated in the south-east of the Gdansk Bay, Baltic Sea. The average depth of the lagoon is 2.7 m and salinity varies between 1.4 and 6.0 (average 3.8, Practical Salinity Scale). Input of fresh water from 21 rivers comprise 17% of the total annual inflow to the lagoon (Anon. 1985).

The anthropogenic impact is strong in the Vistula lagoon area. There is a lot of economic activities (fisheries, shipping, recreation, agriculture). High concentrations of pollutants, such as pesticides, chlorine-hydrocarbons, and arsenic (Blazhchishin 1995) and a significant input of nutrients are characteristic to the basin. Studies of the water-sediment interactions are important for the effective waste-water management as well as for understanding the functioning of the shallow lagoon ecosystem, and its impact on the coastal Baltic Sea. During summer 1995, we studied the quality and distribution of the bottom sediments, resuspension in relation to the local wind-wave conditions, currents, and the spatial-temporal distribution of nutrients and chlorophyll a.

Materials and methods

Current measurements were carried out at 10 sites in the Russian part of the Vistula lagoon using BPV-2 current meters (measurement range between 2.5 and 148 cm s⁻¹ and direction range from 0 to 360 degrees). The average of current flow and direction during 200 s is stored by 30 min intervals. Current meters were positioned 70–80 cm above the bottom on metallic tripods, which had the side length about 2.8 meters. The tripods cause little current resistance and have a negligible influence on current measurements. The influence of wave motion was also minimized.

Several wind-wave simulation methods were compared, until the method by Shore (1984) was chosen for the analysis of resuspension processes in Vistula lagoon. This method includes both deep-water and shallow-water approach. The calculations were carried out for two wind speeds (5 and 10 m s⁻¹) for each direction (SW, E, NE, W). The calculated results were in good agreement with the field measurement (Anon. 1985).

In order to define the zones of resuspension, the wave penetration depth was calculated for different areas of the Vistula lagoon. Following Sly (1978) and Floderus (1988) wave penetration depth is the depth where the orbital wave mo-
tion is equal to one quarter of the wave length and it is able to resuspend fine bottom material. The wave penetration depth was determined for 9 wind speed intervals (0–3, 3–7, 7–11, 11–15, 15–19, 19–22, 22–26, 26–31, above 31 m s⁻¹), for 8 wind directions (N, NE, E, SE, S, SW, W, NW), and for one month in every season (i.e. April, July, September, January), and for one year as a whole. Wind statistics are based on the historical data (1961–1975) from the Vistula lagoon. In the calculation of the resuspension frequency and extent in the different bottom areas of the Vistula lagoon, the wind probability during one year was used (Anon. 1985). Although this criterion cannot be used to make a quantitative estimation of the material resuspended from the bottom, it can be used to estimate the spatial coverage of bottom areas susceptible to the wave motion effects in the Vistula lagoon.

The classification of bottom sediments was based on the granulometric analysis of samples, sonar and echo sounder data. Two maps for upper layer of sediments (0–5 cm) were drawn at scale 1: 50,000.

Resuspension rate was measured by three sediment traps which were mounted on tripods and equipped with 5 plastic cylinders each. The cylinder length was 300 mm, diameter 55 mm (height:diameter-ratio=5:5). The cylinders were placed 20, 40, 60, 100 and 150 cm above the bottom. The material was collected for 8 to 14 days between May and June 1995.

Spatial distribution and the seasonal development of inorganic nitrogen (IN), phosphorus (IP) and chlorophyll a concentrations as well as primary production rate were modeled using the model MIKE 21 EU (developed by DHI/ WQI; a joint Danish-Russian-Polish project studying the Vistula lagoon). The model was calibrated against 1994–1995 monitoring data and rather good correspondence between measured and calculated values was attained (Kwiatkowski et al. 1996).

Results

The results of the current measurements, wind data, river discharge and sea level variations were used to calibrate the MIKE21 HD numerical model of Danish Hydraulic Institute. The model was used to describe the current flow pattern in the Vistula lagoon.

The steady current structures for spring drain and for different kinds of wind were calculated. Six regions of water circulation and paths of currents jets were pointed in the Russian part of the Vistula lagoon.

The resuspension of bottom sediments is most frequent near the shoreline (Fig. 1A). The deepest areas (marked by 1 on Fig. 1A) as well as the areas in wave shadow (marked by 2 on Fig. 1A) are less frequently resuspended. However, the greatest extent of resuspension occurred in the deepest area (marked by 3 on Fig. 1B) in the central part of lagoon because of more longer wave fetch.

The distribution of the quality of the bottom sediments in the Russian part of the Vistula lagoon is shown in Fig. 2. Silty mud or clayey silt are the most widespread sediments in the lagoon. There was a large area of cockle-shell grounds (shells of bivalvan Dreissena polymorpha and gastropods Vulpata sp. and Bithynia sp.) in the Russian part of the lagoon. They were either on the sediment surface or covered by aleuritic silt layer (thickness up to 5 cm).

After resuspension events, sedimentation rate (as measured by sediment traps) varied between 100 10⁻³ – 110 10⁻³ kg m⁻³ h⁻¹, while otherwise it was between 2.7 10⁻³ – 4.1 10⁻³ kg m⁻² h⁻¹. The area of intensive resuspension covered 40 to 100 % of lagoon (Chubarenko 1994). Resuspension was most intense when westerly winds were stronger than 5 m s⁻¹, which was the case for the most part of the year.
Figure 1. Resuspension frequency (a) and resuspension extent (b) for one year in the Vistula lagoon.

Fig. 2. The map of bottom sediments in the Russian part of Vistula lagoon.

Figure 2. The map of bottom sediments in the Russian part of Vistula lagoon.
**Nutrients distribution and development of phytoplankton**

The modelling results indicated that nutrient concentrations increased from the Polish parts of the lagoon to the Polish-Russian border (near the Paslenka river mouth). Concentrations are moderate at the central-east part, relatively high close to the entrance, and highest usually in the north-east region which is influenced by the Pregel river and the city of Kaliningrad.

The nutrient concentrations show a distinct seasonal variation with high levels in winter and in the beginning of spring (IN: 1,900 µg N l⁻¹; IP: 45 µg P l⁻¹), sharp decrease in the middle of April (IN: 10–20 µg l⁻¹, IP: 10–17 µg l⁻¹), and an annual minimum during summer. The average autumn concentrations of IN were slightly above the relatively constant summer values. Concentration of IP start to increase in May–June up to the annual maximum in August (180–225 µg l⁻¹). The significant difference in nutrients concentrations between spring and summer is connected with the nutrient uptake by phytoplankton during the spring bloom. Experimental studies indicate that phytoplankton growth is potentially limited by nitrogen during whole summer, and by phosphorus during a very short period after the end of the spring bloom (Senin 1996).

The modeled primary production rates of phytoplankton were highest in April, decreased drastically in May, and increased again in summer. The modelling results indicated that the biomass pattern followed primary production rates. The chlorophyll a concentrations were lowest in winter (1.6–14 µg l⁻¹), increased up to 44–63 µg l⁻¹ during the spring bloom, and declined significantly during the first half of summer, and increased again up to (40–50 µg l⁻¹) in July-September. The difference between various regions of the Vistula lagoon was related to the temporal development of the spring bloom which first appeared in the inner, western part of the Vistula lagoon, and reached the north-easterly part some days later. In summer the highest phytoplankton biomass developed in the north-eastern part, close to the mouth of Pregel river and the outlet of the Kaliningrad sewage treatment plant, apparently due to high nutrient load in this area.

**Discussion**

The estimated nutrient loading to the Vistula lagoon was ca. 16,900 tonnes of total nitrogen (TN) year⁻¹ and 2,545 tonnes of total phosphorus (TP) year⁻¹ during 1994 and 1995 (Ezhoava and Chubarenko 1996). Taking into account that approximately 22% of nitrogen loading and 35% of phosphorus loading is exported by the water exchange through the Baltic Strait (Kwiatkowski et al. 1996), the remaining loading is 10,786 tons of TN and 1,288 tons of TP per year. Also resuspension adds to the high level of total nutrients in the lagoon. The upper layer of bottom sediments is constantly stirred up due to intensive wind-wave mixing and shoaling, redistributing labile inorganic nutrients to the water column. Thus, despite the high nutrient concentration maintained in the Vistula lagoon, blooms of cyanobacteria have not been observed.

On the contrary, cyanobacterial blooms and anoxia in the bottom sediments, leading to massive death of aquatic organisms, occur almost every summer in the Curonian lagoon. Both lagoons are very similar with regards of climate, bathymetry, sediment quality, nutrient concentrations, wind regime and other physical forcing factors, while the salinity in the Curonian lagoon is very low (close to fresh water). Total nutrient loading is two times higher in the Curonian lagoon, but when related to the water volume, values are comparable: 3,952 tonnes TN and 72 tonnes TP km⁻³ year⁻¹ to the Curonian and 2,926 tonnes TN and 808 tonnes
TP km$^3$ year$^{-1}$, to the Vistula lagoon (HELCOM 1993). Although nitrogen is limiting phytoplankton growth in the Vistula lagoon during summer, chlorophyll $a$ concentrations are generally above 100 $\mu$g l$^{-1}$, while values up to 420 $\mu$g l$^{-1}$ have been reported in the Curonian lagoon (Anon. 1996).

The planktonic fauna and flora and the dominating species are rather similar in both lagoons. Some differences have also been observed: The size of algal cells, for example, is significantly smaller in the Vistula than in the Curonian lagoon. Moreover, the cell volume of the same species can differ up to 10 times between the lagoons (Krylova 1985). These size differences may have further consequences on algal nutrient assimilation as well as for the availability of algal cells for the planktonic grazers in these systems.

These general points are corresponding well with some observed phenomena:

- in the Vistula lagoon the zooplankton grazers feed mainly on phytoplankton while in the Curonian lagoon more than 50% of their food consists of detritus (Krylova and Naumenko 1992).
- in the Vistula lagoon the produced phytoplankton biomass has been estimated to be totally consumed by zooplankton while in the Curonian lagoon there is an excess production (Krylova 1985);
- in the Vistula lagoon the fish species are benthic-feeders almost during all of their life cycle, feeding on zooplankton only as younger life stages (Aristova 1975);
- growth rate, photosynthetic activity, and community reproduction rate are two times higher, and the organic matter turnover is two times lower in the Vistula lagoon than in the Curonian lagoon (Krylova 1985).

We assume that primary producers are less effectively controlled by zooplankton in the Curonian lagoon than in the Vistula lagoon, presumably due to the low nutritional value of algae and an additional control of zooplankton by top-predators. In the Vistula lagoon, the transfer of organic matter and energy through pelagic and benthic food web is more efficient than in the Curonian lagoon. This may be a reason for more stable functioning of the Vistula ecosystem, although external nutrient loading has increased lately.

**Conclusion**

The further investigations of the lagoon ecology should be based on an integrative approach combining physical, chemical or biological features of the system. Studies concerning the functioning of the benthic and planktonic food webs and their impact on nutrient recycling will, most probably, promote the understanding of the trends in the development of the lagoon ecosystem.

**Acknowledgments**

A large part of the work summarized in this paper has been made during the Danish-Russian-Polish project “Vistula lagoon” in 1994–1996, supported by the Danish Ministry of Environment. We are grateful to our Polish colleague J. Kwiatkowski for fruitful collaboration, and to all staff, who has been participating expeditions, for providing excellent field data. We thank Dr. A.-S. Heiskanen and
members of the NOSTRA steering committee for kind assistance with the manuscript. Participation at the 4th NOSTRA workshop was supported by grant of Nordic Academy for Advanced Study.

References


Effects of the oxygen supply on the redox potential and the distribution of sulphate in the lake sediment core. An experimental study.

Kaire Tõugu

Institute of Ecology, Kevade 2, Tallinn EE0001, Estonia.

Introduction

The most important reactions in a water body occur at or near “geochemical boundaries”, where various physical, chemical and biological factors act together. Among all geochemical boundaries the sediment-water interface has the greatest impact on the cycling of chemical elements in lakes. Gradients in physical and chemical properties, and biota abundance are greatest across this interface (Santschi 1988). Different approaches have been developed for studying water-sediment interface, for example the analysis of pore-water concentrations in the sediment profiles. According to Brinkman et al. (1982), the most important requirements of a pore water sampler are:

1. minimal disturbance of the sediment-water interface and sediment structure,
2. prevention of oxidation of anoxic pore water,
3. little or no changes in temperature or pressure,
4. sufficient sample volume,
5. minimal water flow (streaming) through the sediments,
6. high depth resolution, since gradients, especially those close to the interface or to the redox boundary, can be rather steep.

One of the most important and interesting elements in limnology is sulphur. In the dependence of environmental conditions sulphur can occur in the form of different compounds. Sulphate is the common form of inorganic sulphur in oxygen rich water. During the oxidation of organic matter, energetically the most favourable oxidant is consumed first. After the utilization of oxygen and nitrates, sulphate reduction should start (Froelich et al. 1979). It means that the concentration of sulphate in water decreases and various sulphur containing compounds, which composition depends on the conditions in lake, for instance, sulphides of trace elements or organic compounds containing reduced sulphur can accumulate in sediments. Vertical distribution of sulphate reduction has been modeled for freshwater sediments. It has been shown that sulphate reduction becomes limited due to insufficient sulphate supply when sulphate concentration in pore water decreases below 30 mM (Lovley and Klug 1986). The probability of the occur-
rence of redox reactions can be characterized by redox potentials (Eh). Sulphate is reduced at the Eh values between +115 mV and -450 mV. However, for initiating the process, Eh must decrease below -95 mV (Mitchell et al. 1984).

In natural water several redox reactions take place at the same time and the observed redox potential is usually a mixed potential (Langmuir 1971; Lindberg and Runnels 1984; Stumm and Morgan 1981). It means that the observed potential values cannot be related to a particular dominant reaction in solution. Usually the values of redox potentials are controlled by reactions of organic matter.

Redox potential measurements have been used as an indication of oxygen penetration into the lake sediments. There is no direct relationship between redox potential and oxygen concentration. However, when water is in equilibrium with atmospheric oxygen the value of redox potential is positive and fairly high (Wetzel 1983). When oxygen concentration approaches zero the redox potential decreases. There is no measurable oxygen when redox potential value is below 100 mV (Hargrave 1972). This does not imply that oxygen controls redox potential, but rather that strongly reducing substances responsible for lowering redox potential do not exist in the presence of oxygen.

**Methods**

The experiments were performed with cores taken from Lake Harku. Lake Harku is a shallow (max. depth 2.5m) lake with an area of 1.64 km², situated at the western border of Tallinn. It is a hypereutrophic lake with long water residence time. Water in the lake is well mixed during summer season and oxygen is present in the entire water column. Even in winter the oxygen content is remarkable. The pH of water is 9.0–9.2 in winter, and 7.2 in summer (Mäemets 1977).

In cooperation with "Englo" Ltd we have constructed a special device for the study of the distribution of sulphate and Eh values in the water column and in the sediments. The experimental device consisted of a transparent tube with holes in the wall for insertion of electrodes and taking samples from water, sediments or pore water (Fig.1). The tube with closed holes was equipped with extension rods and used as a piston corer in routine sediment sampling. Immediately after sampling both ends of the tube were closed vacuum tightly and the tube (about 1/3 water and 2/3 sediment) was carefully transported to the laboratory in vertical position and left in lab at 20ºC in the dark.

In order to study the influence of seasonal changes (chemical, microbiological etc.), the sediment cores for laboratory experiments were taken in April and June.

In the laboratory, the Pt electrodes for Eh measurements were placed into selected holes. The sediment column was moved by piston, if necessary. Calomel-electrode (in 3M KCl solution) served as the reference. The samples of water above the sediment and pore water were taken with a syringe through selected holes. Filters were placed between injector and syringe in order to avoid the contamination of samples by sediment particles. Aliquots were withdrawn slowly in order to minimize the mixing of water in the tube. The concentration of sulphate in the samples was determined by ion chromatography IVK-II (SDO, Estonia). The minimum detectable quantity was 0.2 mg l⁻¹. The standard deviation was 1.5%.

For the study of the impact of oxygen on sulphate transmission, water in the tube was saturated with air – during 3 hours after 5 days of sampling in the April experiment and during 3 days after 2 weeks of sampling in the June experiment. After saturation the tube was again closed hermetically.
Figure 1. Device for the study of processes in lake water and sediment.

Results and discussion

The Eh values in the water and sediment and their temporal changes are presented in Table 1. Immediately after the sampling the Eh values in the core taken in April were slightly negative. The Eh values in the tightly closed system became continuously more negative. During the aeration on the 6-th day of the April experiment, the Eh values in the bulk water phase increased rapidly up to +283 mV. The Eh value in the sediment near the surface (0.1 cm) increased by 25 mV, whereas it remained unchanged in deeper layers of sediment. After aeration, when the tube was closed hermetically, changes in the Eh values were more remarkable in bulk water and immediately below the sediment surface. The Eh value in water decreased by 300 mV during 3 days. In the upper 0.1 cm layer of sediment the Eh increased by 260 mV during 2 days and then dropped 350 mV during the following 3 days.

In June the effect of aeration was less pronounced and reflected mainly in an increase in the Eh value above water-sediment interface. In the sediments below 1.5 cm the Eh values continued to decrease as before the aeration. The most significant difference in comparison with the Eh curves from April, was the absence of a positive shift in the Eh values in the upper layers of sediments after aeration.

These results tend to indicate that the oxidation processes in the sediment in summer are comparable faster and take place in the same time scale with the oxygen transportation to the sediment.
Table 1. Temporal changes in Eh values (V) in water (+) and sediments (-).

a) April experiment (starting on April 7).

<table>
<thead>
<tr>
<th>depth, cm</th>
<th>April 7</th>
<th>April 11</th>
<th>April 12*</th>
<th>April 14</th>
<th>April 15</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>0.079</td>
<td>-0.120</td>
<td>0.283</td>
<td>0.048</td>
<td>-0.023</td>
</tr>
<tr>
<td>-0.1</td>
<td>-0.068</td>
<td>-0.129</td>
<td>-0.153</td>
<td>0.111</td>
<td>0.074</td>
</tr>
<tr>
<td>-1</td>
<td>-0.067</td>
<td>-0.204</td>
<td>-0.201</td>
<td>-0.225</td>
<td>-0.223</td>
</tr>
<tr>
<td>-2</td>
<td>-0.133</td>
<td>-0.160</td>
<td>-0.190</td>
<td>-0.199</td>
<td></td>
</tr>
<tr>
<td>-3</td>
<td>-0.088</td>
<td>-0.160</td>
<td>-0.049</td>
<td>-0.041</td>
<td></td>
</tr>
<tr>
<td>-4</td>
<td>-0.074</td>
<td>-0.083</td>
<td>-0.103</td>
<td>-0.216</td>
<td>-0.234</td>
</tr>
<tr>
<td>-6</td>
<td>-0.128</td>
<td>-0.134</td>
<td>-0.166</td>
<td>-0.156</td>
<td></td>
</tr>
<tr>
<td>-16</td>
<td>-0.001</td>
<td>-0.026</td>
<td>-0.070</td>
<td>-0.076</td>
<td></td>
</tr>
<tr>
<td>-28</td>
<td>0.002</td>
<td>-0.048</td>
<td>-0.046</td>
<td>-0.144</td>
<td></td>
</tr>
</tbody>
</table>

b) June experiment (starting on June 15).

<table>
<thead>
<tr>
<th>depth, cm</th>
<th>June 16</th>
<th>June 22</th>
<th>June 30*</th>
<th>July 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>0.233</td>
<td>0.174</td>
<td>0.307</td>
<td>0.278</td>
</tr>
<tr>
<td>-1.5</td>
<td>0.027</td>
<td>-0.003</td>
<td>-0.044</td>
<td>-0.047</td>
</tr>
<tr>
<td>-8</td>
<td>0.015</td>
<td>-0.008</td>
<td>-0.086</td>
<td>-0.094</td>
</tr>
<tr>
<td>-10</td>
<td>-0.051</td>
<td>-0.116</td>
<td>-0.199</td>
<td>-0.201</td>
</tr>
<tr>
<td>-14</td>
<td>-0.037</td>
<td>-0.132</td>
<td>-0.248</td>
<td>-0.248</td>
</tr>
</tbody>
</table>

* — Eh values after the aeration of water

The data on the sulphate contents (Table 2) show that in anoxic conditions sulphate might be partly reduced and/or bound to the sediment. In the beginning of the experiment the sulphate-ion concentration in all depths of water as well as in pore water in April was less than in June. The increase in sulphate concentration in April experiment may be caused by desorption of sulphate-ion and/or hydrolysis of sulphate esters. It should be noted that oxidation of reduced sulphur compounds can occur also in anaerobic sediments (Dormblaser et al. 1994, Urban et al. 1994).

In June the sulphate concentration in the sediment column was higher than in the experiment in April. The higher temperature and mixing of soft upper part of sediment may increase the diffusion of sulphate-ion and oxygen into the sediment. At the same time the consumption of oxygen was also more intensive. The decrease in the sulphate concentration was observed after 24 hours after beginning of the laboratory experiment (Table 2).

In the April experiment a remarkable increase in sulphate concentration in pore water up to the depth of 14 cm below water-sediment interface occurred after 2 days of aeration. This could suggest that large amounts of sulphur were in a reduced form, and oxygen diffusion into the sediment was sufficient for sulphur oxidation. After the oxygen was consumed (on the sixth day) sulphate was again reduced. It should be noted that only minimal changes were observed in the first 3 cm below the interface. Unlike in April, aeration increased the sulphate concentration in June to the depth of only 1 cm below the interface; no significant change was observed deeper in the sediment. This may suggest that in spite of similar conditions in the laboratory, occurrence of different forms of sulphur in sediment depend on the season when the core was taken.
The data in Table 2 show that the sulphate concentration in the bulk water phase was substantially decreased after 6 weeks air-tight incubation. Under these conditions reduction processes dominated and the sulphur was accumulated in the sediment.

Table 2. Temporal changes in SO₄²⁻ concentration (mg L⁻¹) in water (+) and sediment (-)

a) April experiment (starting on April 7)

<table>
<thead>
<tr>
<th>depth, cm</th>
<th>April 8.</th>
<th>April 12.</th>
<th>April 14.*</th>
<th>April 20.</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.5</td>
<td>65.8</td>
<td>65.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>32.0</td>
<td>60.4</td>
<td>68.6</td>
<td>68.6</td>
</tr>
<tr>
<td>-0.5</td>
<td>34.2</td>
<td>60.5</td>
<td>61.3</td>
<td></td>
</tr>
<tr>
<td>-1.5</td>
<td>25.6</td>
<td>33.8</td>
<td>32.4</td>
<td></td>
</tr>
<tr>
<td>-2.5</td>
<td>16.6</td>
<td>24.3</td>
<td>24.7</td>
<td></td>
</tr>
<tr>
<td>-4.5</td>
<td>11.8</td>
<td>15.1</td>
<td>22.1</td>
<td>1.3</td>
</tr>
<tr>
<td>-5.5</td>
<td></td>
<td>19.7</td>
<td>9.4</td>
<td></td>
</tr>
<tr>
<td>-8.5</td>
<td>11.2</td>
<td>17.2</td>
<td>31.0</td>
<td></td>
</tr>
<tr>
<td>-14.5</td>
<td>7.0</td>
<td>7.5</td>
<td>12.6</td>
<td>10.0</td>
</tr>
</tbody>
</table>

b) June experiment (starting on June 15)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>50.9</td>
<td>43.5</td>
<td>44.6</td>
<td>48.6</td>
<td>50.3</td>
<td>39.8</td>
</tr>
<tr>
<td>3</td>
<td>47.0</td>
<td>48.2</td>
<td>45.8</td>
<td>46.4</td>
<td>49.3</td>
<td>38.8</td>
</tr>
<tr>
<td>1</td>
<td>47.9</td>
<td>41.6</td>
<td>39.5</td>
<td>33.3</td>
<td>47.9</td>
<td>39.0</td>
</tr>
<tr>
<td>-1</td>
<td>41.3</td>
<td>18.1</td>
<td>10.6</td>
<td>14.4</td>
<td>38.1</td>
<td>6.5</td>
</tr>
<tr>
<td>-2</td>
<td>36.0</td>
<td></td>
<td>9.3</td>
<td>1.0</td>
<td>3.1</td>
<td>1.9</td>
</tr>
<tr>
<td>-3</td>
<td>19.4</td>
<td></td>
<td>1.3</td>
<td>1.0</td>
<td>1.1</td>
<td>1.8</td>
</tr>
<tr>
<td>-11</td>
<td>4.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* — after the aeration of water

**Conclusion**

Our preliminary study show that the proposed experimental method and device are applicable for the study of the circulation of elements in lake water and sediment. Different conditions (oxygen, acidification, temperature, etc.) could be modeled.

The experiments affirm that in anoxic conditions sulphate is reduced, however, only a small fraction of the produced sulphides becomes bound to the sediments as metal sulphides or organic sulphur compounds. Considerable part of the sulphide can be rapidly reoxidized in oxic conditions.

The cores taken in various seasons demonstrated different behaviour under similar conditions.
Acknowledgments

I thank prof. J.-M. Punning for valuable discussions. This research was supported by the Estonian Science Foundation (Grant No. 1593).

References


Relationships between the composition of the fine particulate material and heavy metals in the surface sediments of the Curonian Lagoon

Juozas Petkus, Arunas Galkus & Kestutis Joksas

Institute of Geography, Akademijos 2, LT-2600 Vilnius, Lithuania

Introduction

The Curonian lagoon (Kuršių, marios) is a freshwater basin in the western part of Lithuania which is separated from the Baltic Sea by a long (over 100 km) and narrow (1–5 km) sand spit, the Curonian Spit (Kursiu nerija). The southern part of the lagoon is a part of the Kaliningrad district (Russia). The Klaipeda Strait is the only link between the Baltic Sea and the Curonian Lagoon. It is situated in the northern part of the lagoon, with large sea-port of Klaipeda on its eastern bank. The eastern shore of the lagoon is divided in two parts by the Nemunas river delta. The Nemunas river is responsible for over 90% of the total runoff, carrying the major part of the dissolved matter and suspended sediments to the Curonian lagoon. The Curonian lagoon is a large accumulation basin in which a substantial part of sediments and pollutants settle down. Due to shallow depth (maximum depth is 5m; only the Klaipeda port is artificially deepened) the sedimentation dynamics are rather complicated. During strong storms the whole water column is mixed and the upper layer of sediments are resuspended. The Curonian lagoon is also an important region of industrial freshwater fishing and recreation. For this reason it is important to predict the prospects of its contamination.

Suspended particulate material may sorb a major part of dissolved elements, including pollutants, and the subsequent deposition of particulate material clears the water column. Still, the pollutants accumulated in the bottom sediments may become the source of secondary pollution as a result of resuspension.

The investigation presented here aim at the assessment of the distribution of the fine particulate material in the sediments and their relative content of reactive compounds, such as organic matter. Furthermore, the chemical analysis of Cu, Zn, Ni, Pb, Cr, Co and Cd was carried out, and their spatial distribution analyzed.

Material and methods

Samples of bottom sediments from the Curonian lagoon were collected using a sampling dredge. A sub-sample representing layer of 0 to 3 cm of the surface sediments was taken from the middle of the sample (avoiding contact with the dredge surface) with a plastic spoon and put into a plastic vessel for transportation to the laboratory of the Division of Marine Geochemistry at the Institute of
Geography in Vilnius. Here the samples were dried at 30°C, sieved and the fraction smaller than 0.05 mm was analyzed microscopically. When it was impossible to sieve a sample (having formed aggregates when drying) it was dispersed in distilled water by means of ultrasonic disperser and the suspended particles were filtered through cellulose membrane filters (pore size 0.45 μm; Mytyschy, Russia).

Three preparations were made from each sample, and their composition was averaged. In order to make the identification of organic particles easier, a part of the preparation was exposed to 3% eritrosine (C₉H₄O₄J₅Na₂ * H₂O) solution in 5% carabolic water. For identification of ferriferous particles the same part of preparation was exposed to 4% yellow blood salt (K₃Fe(CN)₆ * 3H₂O) solution in 5% hydrochloric acid which dyed the ferriferous particles into blue. The preparations were clarified using “Canadian balsam” and later they were examined visually using polarization microscope (consult the authors for more detailed description of the method). Cu, Zn, Ni, Pb, Cr, Cd and Co were analyzed from 28 surface sediment samples using an atomic absorption analyzer (Saturn, Russia), after fully mineralizing 0.3g of dry sediment powder in a mixture of HCl, H₂SO₄, HClO₄ and HF.

The coefficient of sedimentation activity (Kₐ) was calculated according to Galkus (1996). The granulometric data obtained in the studied region (excluding extreme values) was used to obtain a curve describing the percentage of fine particulate matter (<0.05 mm) as a function of the median diameter (D₅₀) of the sample. Kₐ was calculated as a difference between the measured fraction of fine matter in the sample and the one estimated by the regression. Positive Kₐ values indicate that the surface sediments were mostly characterized by fine particulate material (<0.05 mm), while negative values indicate the predominance of more coarse material. In the areas where Kₐ<0, most of the fine particulate material is either resuspended and transported elsewhere, or there occurs a heavy deposition of more coarse material. Sorption coefficient (Kₐ) reflects the saturation of fine particulate matter with biogenic material and clay which have the highest sorption capacity. The value of Kₐ range from 0 to 100 %. The coefficient of heavy metal pollution (Kₐₚ) was calculated by summing up the sediment concentrations of Cu, Zn, Ni, Pb, and Cr (μg/g) and by dividing the obtained value by 100. Furthermore, the distribution of combined Co and Cd concentrations (Co+Cd μg g⁻¹) is presented.

Results and Discussion

Based on the spatial distribution of the calculated sedimentation activity coefficients (Kₐ), three different sedimentation areas could distinguished in the Curonian lagoon (Fig. 1). In the southern region, the Kₐ could not be calculated since the fraction of the fine particulate material (<0.05 mm) in the sediments was maximal, indicating that this was the area of most active fine material deposition. Only in the southern- and easternmost part of this region small areas where Kₐ varied between + 0.1 and 0.5, could be distinguished, indicating a slight deficiency of fine particulate material in the surface sediments. This could be accounted for rivers flowing into these parts of the Curonian lagoon. The high Kₐ – value (+ 16.9), near the mouth of the Nemunas river where the flow-velocity abruptly decrease, indicate favourable conditions for fine material sedimentation in this area.

In the middle region, where the water flow is directed towards north, sedimentation activity coefficients are negative (from -0.1 to -0.9). Only in two sites, not far from the shore, they are positive (in front of Drevnera settlement +3.2 and between the Juodkrante and Preila settlements +0.5). Generally, the deficiency of
Figure 1. Spatial distribution of the values of the sedimentation activity coefficient ($K_s$) in the surface sediments of the Curonian lagoon (describing the areas of active sedimentation or transport of the fine material). 1: Sampling sites; 2: Maximum accumulation of fine materials ($K_s$ could not be calculated; see text); 3: High accumulation of fine materials ($K_s > 0$); 4: Transport and erosion areas (sediments mostly characterized by coarse material; $K_s < 0$).

Figure 2. Spatial distribution of the sediment sorption coefficients ($K_s$; %) in the surface sediments of the Curonian lagoon (describing the areas most susceptible for sediment sorption of heavy metals and other pollutants). 1: Sampling sites; 2: $K_s$ isoline (%)
the fine particulate material in the sediments of the middle region is probably
due to the unfavorable settling conditions created by the flow of Nemunas river
and other smaller rivers draining into the Baltic Sea. In the northern part of the
Curonian lagoon, the sedimentation activity coefficients are positive (+0.1→5.2),
probably as a result of coagulation and flocculation of suspended matter in the
mixing zone of freshwater and brackish Baltic Sea water in the Klaipeda strait.

The spatial distribution of the sorption coefficient values (Kc) is more compli-
cicated (Fig. 2). The maximum values are recorded in the southern (up to 90) and
western (up to 86) part of the Curonian lagoon, while values exceeding 81 are
also recorded in the northern part (i.e., the zone bordering on the western shore).
At one site, in front of the Nemunas delta, a high Kc-value (79) is also measured.
In the central part of lagoon and along the eastern shore the sorption coefficient
values are on average 30 (minimum 16). The lowest value of Kc (3.6) was recorded
close to the shore, in front of Dreverna, and the highest (90) value in the middle of
the southern part of the lagoon.

Based on the qualitative evaluation of the favourable and unfavorable accumu-
lation areas of the fine particulate material, and their sorption coefficients, the
zones which are most receptive for pollutants were identified (Fig. 3). According
to this qualitative compilation, the sediments which potentially retain most of the
pollutants stretch along the western shore of the lagoon to the middle of the sou-
thern part where they join a corresponding zone in the southernmost part of the
lagoon. We also distinguished such retention areas in front of the Nemunas delta
and in the northernmost part of the lagoon, in the Klaipeda strait.

Figure 3. Qualitative classification of the surface sediments potentially receptive for heavy
metals and other pollutants in the Curonian lagoon. 1: non-recep-
tive; 2: slightly receptive; 3: moderately receptive; 4: recep-
tive; 5: highly receptive.
Figure 4. Spatial distribution of the heavy metal pollution coefficient ($K_{hm}$; μg/(100^4 g)) in the surface sediments of the Curonian lagoon (showing the values of summed concentrations of Cu, Zn, Ni, Pb, and Cr (μg g⁻¹) divided by 100). 1: sampling sites; ($K_{hm}$ values for each site are indicated); 2: isoline, where $K_{hm} = 1$.

Figure 5. Spatial distribution of the combined Co and Cd concentrations ((Co+Cd μg g⁻¹) in the surface sediments of the Curonian lagoon. 1: sampling sites (Co+Cd concentrations (μg g⁻¹) at each site are indicated); 2. isoline with concentrations of Co+Cd (μg g⁻¹).
The highest concentrations of heavy metals in the surface sediments were recorded in the Klaipeda strait (Cu: 54.4; Zn: 121.9 μg g⁻¹), in the southern part of the lagoon (Ni: 30; Cd: 4.1; Pb: 52.2; Cr: 107.2 μg g⁻¹), and in the front of the town, Nida (Co: 10.5 μg g⁻¹). These values were considerably higher than the minimum concentrations recorded near the towns of Preila (Cu: 0.1; Cd: 0.4; Co: 0.1 μg g⁻¹), Juodkrante (Ni: 0.1; Pb: 6.7 μg g⁻¹), and Dreverna (Zn: 12.4 μg g⁻¹). The lowest concentration of Cr (6.4 μg g⁻¹) was recorded close to the eastern shore in the southern part of the lagoon.

The spatial distribution of the total heavy metal concentration reveals that the zones, where values of heavy metal pollution coefficient (K₉₉) exceed 1 (i.e. the areas with the highest total heavy metal concentrations in the sediments), are located in the Klaipeda strait and border the western shore of the lagoon including almost all of the southern part and the Nemunas delta (Fig. 4). The concentrations of combined Co and Cd follow the distribution pattern of K₉₉ (Fig. 5). The increased concentration of Co and Cd in front of the town Dreverna indicated this area to be receptive for heavy metal pollution, on the contrary to the central lagoon where unfavorable conditions for sedimentation prevail.

**Conclusions**

Since the fine particulate matter, and especially the biogenic and clay components of this material, absorb most of the chemical elements and pollutants, the increased concentrations of pollutants does not necessarily reflect increased pollution, but rather the natural background of the elements. As a result of favourable hydrodynamic conditions, fine material accumulates mostly in the southern part of the Curonian lagoon, where also heavy metals are strongly retained.

The flow from the Nemunas river is generally directed to the north, which creates a unfavorable region for settling of the fine particulate matter. For this reason, chemical microelements do not accumulate in these regions, with the exception of some small bays close to the shore.

In the Klaipeda strait, which is the mixing zone of the brackish Baltic Sea water and freshwater, sedimentation of fine particulate material probably increased due to the coagulation and flocculation. Concurrently, also the concentrations of heavy metals are high in the bottom sediments of the Klaipeda strait.

**Reference**

Presentation of the Nordic Sediment Trap Association (NOSTRA)

NOSTRA is a scientific organization promoting and supporting coordination of sediment trap studies in the Nordic countries. NOSTRA organizes research symposia and workshops for Nordic scientist and research students in the field of sedimentation and invites non-Nordic specialists to these meetings. NOSTRA is headed by a committee which consists of 4 members, representing Denmark, Finland, Norway and Sweden. The participants from each country elect their representative during the Nordic research conferences on sediment trap studies. These representatives serve as the steering committee until the next conference, and they elect among themselves a chairperson who heads the committee.

The main object of the committee is to organize future research conferences and workshops on sediment trap studies, to apply for financial support and to edit, print and distribute proceedings of the meetings. The committee also informs members about scientific issues of joint interest through a newsletter and represents the interest of NOSTRA in the Nordic countries and also abroad, should the need arise. A steering committee of NOSTRA was elected during the workshop at the Marine Biological Laboratory, Helsingør, 1993. The committee consisted of the following persons: Sören Floderus (Sweden), Claus Lundsgaard (Denmark), Anna-Stiina Heiskanen (Finland) and Marit Reigstad (Norway). The committee was headed by Sören Floderus.

During the symposium in 1997, in Tartu, Estonia, a new NOSTRA committee was formed. The present committee consists of the following persons: Anna-Stiina Heiskanen (Finland), Paul Wassmann (Norway), Sören Floderus (Sweden), and Claus Lundsgaard (Denmark). The Baltic and Russian contact persons are Kalle Olli (Estonia), Arturas Razinkovas (Lithuania) and Elena Ezhova (Russia).
List of presentations and participants

Presentations

SESSION 1: Impact of pelagic processes and food web structure on recycling and export.


Svein Kristiansen (with T. Farbrot and L.J. Naustvoll): Fate of the spring bloom in the Oslofjord, Norway.

Petra Tallberg (with A-S Heiskanen and K. Suominen): In-shore and off-shore variation in the settling phytoplankton in the coastal Gulf of Finland.


Arturas Razinkovas and Zita Gasinaita: Effects of zooplankton and nektonic species on sedimentation in estuarine ecosystem: Kurshiu marios (Curonian) lagoon ecosystem.

Claus Lundsgaard: Production of sedimenting matter in different compartments of the marine pelagic food web.

Peeter Nõges: General features of the nutrient budget of Lake Võrtsjärv

Tiina Nõges and Veljo Kissand: Food web structure in shallow eutrophic Lake Võrtsjärv (Estonia)

Tom Noji (invited): Implications of particle-associated DOC for oceanic carbon cycling.

Mikal Heldal: Micro-scale particles in the surface waters: sizes and total numbers.

Alexander Keck: Sedimentation in the Svalbard area
SESSION 2. Elemental composition of food web components – implications for recycling and sedimentation.

Anna-Stiina Heiskanen: Sedimentation in open and enclosed water columns: the effect of planktonic food web structure and resuspension on the quality of settling organic matter in the Baltic Sea

Sabine Jähmlich: Aggregates in the benthic boundary layer of the Mecklenburg Bight (western Baltic Sea); factors controlling their formation.

Elena Gorokhova (with Sture Hanson and Jakob Walve): Elemental composition and fractionation of carbon and nitrogen by the mysid shrimp Mysis mixta (Crustacea, Mysidae) and its zooplankton prey.


Søren Floderus: Geo-ecological constraints on food-web modelling.
Ivar Murdmaa: Nutrient fluxes from endoupwelling into the upper ocean.
Egidijus Trimonis: Sediment fluxes in the Klaipeda Strait.

Mirja Leivuori and Henry Vallius: Studies on heavy metal and nutrient sedimentation in the Baltic Sea.

Henry Vallius and Mirja Leivuori: Studies on heavy metal and nutrient sedimentation in the Baltic Sea.

Juozas Petkus: Spatial and temporal variability in composition of sedimentary matter.

Kaire Tõugu and Agu Karindi: Experimental study of the dependence of the distribution of sulfates in the lake sediment core on the oxygen supply.

POSTER SESSION

Yehudit Winer: The role of sedimentation processes in the dynamics of the bloom forming dinoflagellate Peridinium gatunense in Lake Kinneret, Israel.

Participants

DENMARK

Claus Lundsgaard
Marine Biological Laboratory
Strandpromaden 5
DK-3000 Helsingør, DENMARK
phone: +45 49211633—319
fax: +45 49261165
e-mail: Claus.Lundsgaard@inet.uni-c.dk

Michael Olesen
Marine Biological Laboratory
Strandpromaden 5
DK-3000 Helsingør, DENMARK
phone: +45 49211633—319
fax: +45 49261165
e-mail: mblMio@inet.uni-c.dk

ESTONIA

Agu Karindi
Institute of Ecology
Kevade 2, Tallinn, 0001, ESTONIA
phone: +372 245 0732
fax: +372 245 3748
e-mail: agu@eco.edu.ee

Veljo Kisan
Institute of Zoology and Hydrobiology
Tartu University
EE2400 Tartu, ESTONIA
or Võrtsjärv Limnological Station
Institute of Zoology and Botany
Estonian Academy of Sciences
EE2454 Rannu, Tartu County, ESTONIA
phone: +372 7 454543
fax: +372 7 383013
e-mail: kisand@ut.ee

Peeter Nõges
Võrtsjärv Limnological Station
Institute of Zoology and Botany
Estonian Academy of Sciences
EE2454 Rannu, Tartu County, ESTONIA
phone: +372 7 454543
fax: +372 7 383013
e-mail: Tiina@lim.tartu.ee

Tiina Nõges
Võrtsjärv Limnological Station
Institute of Zoology and Botany
Estonian Academy of Sciences
EE2454 Rannu, Tartu County, ESTONIA
phone: +372 7 454543
fax: +372 7 383013
e-mail: Tiina@lim.tartu.ee

Kalle Olli
Institute of Botany and Ecology
Tartu University, Lai st. 40
EE-2400 Tartu, ESTONIA
phone: +372 7 441325 or +372 7 431370
fax: +372 7 441272
e-mail: olli@ut.ee

Mart Saarso
MSOffshore Ltd
Box 3453
EE0001 Tallinn, ESTONIA
phone: +372 2 433 452
fax: +372 2 453 587
e-mail: thesis@online.ee

Kaire Tõugu
Institute of Ecology
Kevade 2, Tallinn, 0001, ESTONIA
phone: +372 245 0732
fax: +372 245 3748
e-mail: kaire@eco.edu.ee

FINLAND

Anna-Stiina Heiskanen
Finnish Environment Institute
P.O.Box 140
FIN-00251 Helsinki, FINLAND
phone: +358 9 40300320
fax: +358 9 40300390
e-mail: Anna-Stiina.Heiskanen@vyh.fi

Mirja Leivuori
Finnish Institute of Marine Research
P.O.Box 33
00931 Helsinki, FINLAND
phone: +358 9 613941
fax: +358 9 61394494
e-mail: Leivuori@fimr.fi

Petra Tallberg
Department of Limnology
and Environmental Protection
Section of Limnology
P.O.Box 27 (Viikki, E-Building)
00014 Helsinki University, FINLAND
phone: +358 9 708 5472
fax: +358 9 708 5257
e-mail: petra.tallberg@helsinki.fi

Henry Vallius
Geological Survey of Finland
Geochemistry Department
P.O.Box 96
FIN-02150 ESPOO, FINLAND
phone: +358 2055011
fax: +358 2055012
e-mail: Henry.Vallius@gsf.fi

GERMANY
Sabine Jähmlich
Geomar Forschungszentrum
Wischofstr. 1–3
D-24148 Kiel, GERMANY
phone +49 431 600 2684
fax +49 431 600 2928
e-mail: sjaehmil@geomar.de

ISRAEL
Yehudit Winer
Israel Oceanographic & Limnological Research Ltd.
The Yigal Allon Kinneret
Limnological Laboratory
P.O.Box 345
Tiberias 14102, ISRAEL
phone: +972 06 721444
fax: +972 06 724627
e-mail: tamarz@inter.net.il

LITHUANIA
Zita Gasiunaité
Centre for System Analysis
Klaipėda University, Manto 84
Klaipėda, LT-5808, LITHUANIA
phone: +370 6 212936
fax: +370 6 212940
e-mail: zita@samc.ku.lt

Juozas Petkus
Marine Geochemistry Department
Institute of Geography, Akademijos 2
LT-2600, Vilnius, LITHUANIA
fax: +370 2 729245
phone: +370 2 729291

Arturas Razinkovas
Centre for System Analysis
Klaipėda University, Manto 84
Klaipėda, LT 5813, LITHUANIA
phone: +370 6 212936
fax: +370 6 212940
e-mail: art@samc.ku.lt

Egidijus Trimonis
Institute of Geography, Academijos 2
LT-2600 Vilnius, LITHUANIA

NORWAY
Mikael Heldal
Institutet for Mikrobiologi
Universitetet i Bergen
Jahnabakken 5
5020 Bergen, NORWAY
phone: +47 55582662
fax: +47 55589671
e-mail: Mikael.Heldal@im.uib.no

Alexander Keck
The University Courses on Svalbard
Dept. of Arctic Biology
P.O.Box 156/157
N-9170 Longyearbyen, NORWAY
Present affiliation:
Institute of Oceanology
Polish Academy of Sciences
81–712 Sopot, Poland
Mailing address:
P.O.Box 33,
N-9001 Tromsø, Norway
e-mail: keck@online.no

Svein Kristiansen
Department of Biology
University of Oslo
P.O.Box 1069 Blindern
N-0316 Oslo, NORWAY
phone: +47 22854529
fax: +47 22854438
e-mail: svein.kristiansen@bio.uio.no

Thomas Noji
Institute of Marine Research
P.O.Box 1870
N-5024 Bergen, NORWAY
phone: +47 5523 8500 or
+47 5523 8464 (direct)
fax: +47 55238584
e-mail: thomas.noji@imr.no

Marit Reigstad
Norwegian College of Fishery Science
University of Tromsø
N-9037 Tromsø, NORWAY
phone: +47 77644525
fax: +47 77646020
e-mail: maritr@nfh.uit.no

Paul Wassmann
Norwegian College of Fishery Science
University of Tromsø
N-9037 Tromsø, NORWAY
SWEDEN

Søren Floderus
Taangvagen 15
SE-310 42 Haverdal, SWEDEN
Present address:
GEUS, Environment & Climate
Thoravej 8
DK-2400 Copenhagen NV, Denmark
phone: +45-38 14 23 61
fax: +45-38 14 20 50
e-mail: sf@geus.dk

Elena Gorokhova
Dept. Of Systems Ecology
Stockholm University
S-106 91 Stockholm, SWEDEN
phone: +46 8 16 42 56
fax: +46 8 15 84 17
e-mail: elenag@system.ecology.su.se

Jakob Wålve
Department of Systems Ecology
Stockholm University
106 91 Stockholm, SWEDEN
phone: +46 8 16 42 22
fax: +46 8 15 84 17
e-mail: jakobw@system.ecology.su.se

RUSSIA

Elena E. Eshova
P.P. Shirshov Institute of Oceanology
Atlantic Branch Pr. Mira 1
236000 Kaliningrad, RUSSIA
phone: +7 0112-45 15 74
fax: +7 0112-27 29 45
e-mail: lena@ioran.koenig.su

Ivar Murnmaa
Laboratory of Physico-Geological Research
P. P. Shirshov Institute of Oceanology
Russian Academy of Science
Moscow, RUSSIA
fax: +7 095 1245983
e-mail:

The purpose of this list is to collect papers written by Nordic scientists, and presenting studies where sediment traps have been used as devices for measuring vertical flux (both limnic and marine environments). Also Ph.D. thesis dealing with sediment trap studies are listed. Papers are listed in 1) chronological (year of publication) and 2) alphabetical (first author) order. The list is by no means complete, so if you find your papers missing, please send the publications (or references) to Anna-Stiina Heiskanen (Finnish Environment Institute, P.O. Box 140, FIN-00251 Helsinki, Finland, email: anna-stiina.heiskanen@vyh.fi) in order to be included in the forthcoming list compilation.


**Title of publication**
Sedimentation and recycling in aquatic ecosystems
- the impact of pelagic process and planktonic food web structure

**Abstract**
The proceedings of the Symposium “Sedimentation and recycling in aquatic ecosystems – the impact of pelagic processes and planktonic food web structure” organized by the Nordic Sediment Trap Association (NOSTRA) at the University of Tartu, Estonia, in January 1997, is including summaries of a number of talks and posters presented. The aim of the symposium was to summarize and discuss the present understanding of the relationship between pelagic recycling and sedimentation, with a special emphasis on the ecological mechanisms and food web interactions which regulate this relationship. The presentations covered a wide range of topics from the microbial dynamics of the planktonic food web to the sedimentological features of the shallow coastal embayments. The proceedings shows the wide scope of the aquatic scientists interested in the pelagic-benthic coupling and highlights some recent sediment trap results from several aquatic environments ranging from the glacial fjords in the high arctic (Spitsbergen) to the algal blooms in a subtropical lake (Lake Kinneret, Israel).

**Keywords**
sedimentation, vertical flux, recycling, plankton, food webs, eutrophication, aquatic communities

**Publication series and number**
The Finnish Environment 263

**Theme of publication**
International cooperation

**Project name and number, if any**

**Financier/commissioner**
Nordic Academy of Advanced Studies (NorFa)

**Project organization**

<table>
<thead>
<tr>
<th>ISSN</th>
<th>ISBN</th>
</tr>
</thead>
<tbody>
<tr>
<td>1238-7312</td>
<td>952-11-0385-X</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>No. of pages</th>
<th>Language</th>
</tr>
</thead>
<tbody>
<tr>
<td>112</td>
<td>english</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Restrictions</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Public</td>
<td>87 FIM</td>
</tr>
</tbody>
</table>

**For sale at/distributor**
Edita Ltd. Customer service tel +358 9 566 0266 telefax +358 9 566 0380

**Financier of publication**
Finnish Environment Institute

**Printing place and year**
Edita Ltd, Helsinki 1998
**Sedimentation and recycling in aquatic ecosystems – the impact of pelagic processes and planktonic food web structure**

Asiasanat

- sedimentaatio, hiukkasaineen vajoaminen, ravinteet, kierrätys, plankton, ravinnotketjut, rehevöityminen, hiukkasaineen keräälysilinterit, vesiekosysteemit

Julkaisusarjan nimi ja numero

| Suomen Ympäristö | 263 |

Julkaisun teema

| Kansainvälinen yhteistyö |

Projektihankkeen nimi ja projektinumero

| Nordisk Forskarakademi (NorFa) |

Projectiryhmään kuuluvat organisaatiot

| ISSN | 1238-7312 | ISBN | 952-11-0385-X |
| Sivuja | 112 | Kieli | english |
| Luottamuksellisuus | Public | Hinta | 87 FIM |

Julkaisun myynti/jakaja

| Oy Edita Ab asiakaspalvelu, puh. (09) 566 0266 fax (09) 566 0380 |

Julkaisun kustantaja

| Suomen ympäristökeskus |

Painopaikka ja -aika

<p>| Oy Edita Ab, Helsinki 1998 |</p>
<table>
<thead>
<tr>
<th><strong>Utgivare</strong></th>
<th>Finlands miljöcentral</th>
<th><strong>Datum</strong></th>
<th>Januari 1999</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Författare</strong></td>
<td>Anna-Stiina Heiskanen, Claus Lundsgaard, Marit Reigstad, Kalle Olli (edit.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Publikationens titel</strong></td>
<td>Sedimentation and recycling in aquatic ecosystems – the impact of pelagic process and planktonic food web structure</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Publikationens delar/andra publikationer inom samma projekt</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Sammantag</strong></td>
<td>Den Nordiska föreningen för sedimentfällor (NOSTRA) organiserade ett symposium “Sedimentering och cirkulering av näringsämnen i akvatiska ekosystem – betydelsen av pelagiska processer och den planktiska näringsskedjan” vid Dorpat universitet, Estland, i januari 1997. Flere av presentationerna och posters är nu samlade i denna sammanställning. Symposiets syfte var att sammanfatta den nuvarande kunskapen om förhållandet mellan sedimentering och näringscirkulering. I synnerhet var det meningen att diskutera hur strukturen hos den planktiska näringsskedjan och växelverkan mellan organismer och andra ekologiska mekanismer påverkar detta förhållande. Presentationerna omfattar ett brett urval av olika ämnen som varierade från den mikrobiella dynamiken hos det planktiska näringssnätet till de sedimetologiska processerna i kustnära områden. Denna sammanställning av föredragen visar hur omfattande intresse de forskare som undersöker kopplingen mellan pelagiala och bentiska system kan ha. Sammanställningen presenterar resultat från ett brett spektrum av olika akvatiska miljöer, från glaciala fjorder på Spetsbergen till en subtropisk insjö i Israel.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Nyckelord</strong></td>
<td>sedimentering, cirkulering, plankon, näringsnät, eutrofiering, sedimentfällor, akvatiska ekosystem</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Publikationsserie och nummer</strong></td>
<td>Miljön i Finland 263</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Publikationens tema</strong></td>
<td>Internationellt samarbete</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Projektets namn och nummer</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Finanslér/uppdragsgivare</strong></td>
<td>Nordisk Forskarakademi (NorFa)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Organisationer i projektgruppen</strong></td>
<td>ISSN 1238-7312, ISBN 952-11-0385-X</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sidantal 112, Språk engelska</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Offentlighet Offenlig, Pris 87 FIM</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Beställningar/distribution</strong></td>
<td>Oy Edita Ab Kundservice tel. (09) 566 0266 telefax (09) 566 0380</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Förläggare</strong></td>
<td>Finlands miljöcentral</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Trycken/tryckningsort och -år</strong></td>
<td>Oy Edita Ab, Helsingfors 1998</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>