Diatom analyses of sediment from Himmerfjärden Estuary, Southern Archipelago of Stockholm

– has the water discharge from a constructed sewage treatment plant led to eutrophication?

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Abstract

A sediment core from Himmerfjärden estuary, south of Stockholm, was examined to detect records of eutrophication on the site since the opening of the sewage treatment plant Himmerfjärdsverket in 1974. The core was analysed with respect to the diatom record and lithology. Four macrofossil that were found in the sediment were dated using $^{14}$C-dating.

This study aims to detect changes in the environment of Himmerfjärden by using the diatom stratigraphy record. The results have been interpreted and discussed regarding natural environmental and climate change and/or anthropogenic impact, and detected changes will be associated with the history of the sampling site.

The results show that the lowermost zone started to deposit around 1300-1490 cal yr BP and the homogeneous sediment indicates that the area was not suffering from hypoxia at that time. There is a successive transition towards more distinct lamination further up in the core which show that the environment in Himmerfjärden have changed and become hypoxic. This may have to do with factors such as the opening of heavily trafficked Södertälje Canal, and also the increased nutrient input from Himmerfjärdsverket.

This study could be a part of the process of working towards a “good environmental status” in the Baltic Sea. However, continued and improved work is needed for further and more accurate interpretations.

Keywords: Baltic Sea, diatoms, eutrophication, coastal zone, Himmerfjärden
### Glossary

<table>
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<th>Definition</th>
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</thead>
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<tr>
<td><strong>Anoxia</strong></td>
<td>A total depletion in the level of oxygen, an extreme form of hypoxia</td>
</tr>
<tr>
<td><strong>Anthropogenic</strong></td>
<td>Of, relating to, or resulting from the influence of human beings on nature, e.g. anthropogenic pollutants.</td>
</tr>
<tr>
<td><strong>Baltic Proper</strong></td>
<td>Baltic Proper covers the part of the Baltic Sea, from the Åland Sea to the Danish sounds. Åland Sea, the Gulf of Finland and the Gulf of Riga is not included.</td>
</tr>
<tr>
<td><strong>Benthic</strong></td>
<td>The benthic zone is the ecological region at the lowest level of a body of water such as an ocean or a lake, including the sediment surface and some sub-surface layers.</td>
</tr>
<tr>
<td><strong>BP</strong></td>
<td>Before present. This is a time scale used mainly in geology ($^{14}$C-dating) and other scientific disciplines to specify when events in the past occurred. Standard practice is to use 1 January 1950, before nuclear weapons testing because it artificially altered the proportion of the carbon isotopes in the atmosphere. Making radiocarbon dating after that time likely to be unreliable.</td>
</tr>
<tr>
<td><strong>Diagenesis</strong></td>
<td>Diagenesis refers to the sum of all the processes that bring about changes (e.g. composition and texture) in a sediment or sedimentary rock subsequent to deposition in water. The processes may be physical, chemical, and/or biological in nature and may occur at any time subsequent to the arrival of a particle at the sediment - water interface.</td>
</tr>
<tr>
<td><strong>Hypoxia</strong></td>
<td>Low oxygen conditions (dissolved oxygen levels &lt;2mg/L).</td>
</tr>
<tr>
<td><strong>Raphe</strong></td>
<td>The median line or slit of the valve of certain diatoms.</td>
</tr>
<tr>
<td><strong>Recipient</strong></td>
<td>Receiver (water, sea, lake etc. that receives purified waste water).</td>
</tr>
<tr>
<td><strong>Sequestration</strong></td>
<td>The removal and storage of a substance, e.g. carbon or phosphorus, from the atmosphere in sinks (such as oceans, forests, soils) through physical or biological processes.</td>
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INTRODUCTION

Human activities, such as land-use, is known to have impacts on the environment. Increased nutrient loadings from agriculture, industrial and urban sources have during the last century caused eutrophication of Baltic Sea waters (Zillén & Conley 2010). When nutrients, such as nitrogen and phosphorus, discharge into the water it can lead to eutrophication in the affected aquatic ecosystem. Large areas with formerly oxygenated bottoms in the deep basins of the Baltic Sea have turned anoxic during the last century (Larsson et al. 1985). Sewage outlets in the Baltic area have, on a local scale, severely affected the coastal marine environment. Eutrophication in sea water is a serious problem because it, inter alia (Bernes 2005):

- Increases primary production which leads to oxygen depletion in deep water bottoms and causes benthic organisms to die.
- Triggers algae blooms and thus enhance problems with toxic algae.
- Alters biodiversity. Eutrophication leads to change in the availability of sunlight and certain nutrients to an aquatic ecosystem. This can cause shift in the species composition so that the more tolerant species survive and new competitive species invade and out-compete original inhabitants.

Marine eutrophication was for a long time considered as a problem only in the inner coastal zone. But in the end of the 1960s one became more aware that the oxygen depletion in the deep waters of open Baltic Sea got worse during the post war period (Elmgren & Larsson 1997). In the 1980s it became clear that oxygen depletion was not only caused by climate change, but from the eutrophic effects due to heavily increased nutrient input.

Water exchange between the Baltic Sea and the world oceans occurs through Öresund and Store Bælt and is mostly driven by sea-level difference, caused by the air-pressure, between Kattegat in the south and the southwestern Baltic Sea. The water residence time in the Baltic Sea is about 30 years long (HELCOM 2010), and as the water exchange is limited most of the nutrients that are discharged in to the system remains there (Bernes 2005). This makes the Baltic Sea susceptible to anthropogenic emissions of nutrients and contaminants.

Himmerfjärden, located in the Stockholm archipelago about 60 kilometres south of Stockholm, came to be one of the main areas to study environmental impacts due to anthropogenic nutrient input (Elmgren & Larsson 1997). Himmerfjärden’s drainage basin is part of Sweden’s northern Baltic Sea river basin district (Franzén et al. 2011). A sewage treatment plant was constructed in the area in 1974 which uses Himmerfjärden as recipient of the purified waste water.

The ongoing research project UPPBASER (Understanding Past and Present Baltic Sea Ecosystem Response) running at Södertörn University between 2014-2016 aims to study how changes in land use and climate along the coast of the Baltic Sea have affected its environment the last 2000 years. One area included in UPPBASER is the Himmerfjärden area. Since the start of the sewage treatment plant, Himmerfjärdsverket, the site has been exposed to several environmental experiments. Further reason making Himmerfjärden of high interest to study is because it may also have been
affected by the heavy trafficked Södertälje Canal, which through a lock in Södertälje connects Lake Mälaren to the western part of the bay.

One way to detect environmental change, such as eutrophication, through time is to analyse the species composition of diatoms found in sediment records. These organisms are very sensitive to changes in the environment such as salinity, pH and nutrient and sunlight availability. Diatoms are therefore excellent indicators to assess environmental change in the past.

The aim of this study is to examine environmental change in the Himmerfjärden estuary by using diatom analysis on a dated sediment core. Expected outcome of the study is to find answer to research questions as:

- In what way has the opening of the sewage treatment plant Himmerjärdsverket affected the environmental status of Himmerfjärden?
- Has the opening of Södertälje Canal affected the environmental status of Himmerfjärden and how is it recorded?

The results will be interpreted and discussed regarding natural environmental and climate change and/or anthropogenic impact, and detected changes will be associated with the history of the sampling site.

**BACKGROUND**

**Eutrophication**

In nature, eutrophication occurs when there are too much fertilizing nutrients, e.g. nitrogen and phosphorus, released in water and soil. The definition of eutrophication, according to Nixon (1995) is: “Eutrophication is defined as an increase in the rate of supply of organic matter in an ecosystem.” In an aquatic ecosystem the added nutrients make phytoplankton flourish at the surface and when they die they sink to the bottom and are decomposed by bacteria. Even benthic phytoplankton are influenced by nutrient availability. The population of microbial decomposers grows and consumes oxygen, which leads to oxygen depletion. This suffocates or drives away bottom-dwelling marine life and creates a hypoxic zone (Withgott & Brennan 2011). Hypoxia is defined as <2mg/L dissolved oxygen in water which defines the level when reduced concentrations of dissolved oxygen becomes harmful to aquatic organisms. Hypoxia alters biochemical cycles and causes large ecosystem disturbances, e.g. low nitrogen/phosphorus (N/P) ratios when high internal load of phosphorus is released from the sediment (Zillén & Conley 2010). High N-availability increases the spring blooms of phytoplankton which leads to enhanced oxygen consumption in the bottom waters. In low oxygen bottom waters (low redox-sensitive) phosphorus is released from the sediments, leading to increased concentrations of phosphate in the water column (Zillén & Conley 2010). This results in positive feedback loop between P-availability, cyanobacteria blooms during summers and increased hypoxia, and thereby amplifies eutrophication (Conley et al. 2002).

As discussed in the introduction, the ecosystem of the Baltic Sea is sensitive to changes, mainly
from both N and P inputs. Eutrophication and associated hypoxia have one of the largest impacts on the health of the Baltic Sea (HELCOM 2007). The hypoxic area in the Baltic Sea is currently covering averaging 41,000 km² annually and has grown to be a severe environmental problem for the sea and its dependents (Zillén et al. 2008). Recent hypoxia is thought to be caused by anthropogenic factors, e.g., population density and changes in land use, when enhanced eutrophication due to emissions of nutrients ends up in the sea (Zillén et al. 2008). Local nutrient input is mostly originated from agriculture, municipal wastewaters, riverine input and aquaculture (Bonsdorff et al. 1997).

Biodiversity and the functioning of estuaries can be affected by increased nutrient and sediment loads. There is almost always a decrease in aquatic biodiversity when eutrophication increases, which leads to a major impact on the specific composition of algal communities (Weckström et al. 2007). Increased nutrient levels have led to altered N/P ratios, increased sedimentation rates and also increased input of organic matter to the benthic system. This causes inter alia increased pelagic and benthic primary production, increased turbidity and reduced transparency in the aquatic system and reduced oxygen reserves even above the halocline (Bonsdorff et al. 1997).

Most marine areas have faunas of great importance in the interface between sediment and water. Deposit feeders are organisms that live at the soft bottoms and live on organic matter in the sediment layers (Bernes 2005). These organisms remix seabed material when looking for food, or simply just eat the sediment. This effect is called bioturbation (Jonsson 2003). Laminated sediments are common in the coastal zones in the Baltic Sea and indicative of a hypoxic period, where no benthic macro organisms have existed to perform bioturbation (Jonsson 2003). The colors of the lamination indicates seasonal fluctuations in amount and/or type of sediment deposited. Differences in sedimentation rate and the composition of sedimenting material are the most significant factors that leads to annually laminated sediments, together with alternations in diagenetic processes (Jonsson et al. 1990). In fact, the area in the Baltic Proper covered with laminated sediments is estimated to have increased about four times since 1960s (Jonsson et al. 1990).

The Baltic Sea

The Baltic Sea is a semi-enclosed brackish water basin with a salinity gradient of around 10‰ by the thresholds in the south down to around 1‰ in the north (Bernes 2005). It is a young and shallow inland sea with a short and dramatic geological history, approximately 16,000 years with alternations between limnic and brackish water conditions (Andrén et al. 2011). It is one of the world’s largest brackish water bodies and also one of the busiest maritime areas in the world. The sea surface area is about 400,000 km² and is surrounded by a drainage area four times as large as the surface area (WWF 2013). About half of the Baltic Sea is, in present climate, ice covered in winter (HELCOM 2007a). The dominant oceanographic feature in the Baltic Proper is the permanent salinity stratification, where the deep saline water is separated from the surface brackish water by a halocline. This transition zone limits the transport of oxygen from surface to bottom waters (BACC 2008). The depth where the halocline is formed varies, but in the Baltic Proper and Gulf of Finland it is around 50 to 80 meters (BACC 2008). In the 1300s the Lake Müllaren got isolated from the Baltic Sea, due to the ongoing land uplift after deglaciation, and contributed to the founding of the city of Stockholm (Lindström et al. 2000).
There are irregular intervals between major inflows of high saline oxygen-rich deep water, which mainly occurs in autumn and winter (Wulff et al. 1990). These sporadic inflows of saline water replenish the oxygen in the deep water layers which leads to sequestration of phosphorus in the sediment, and therefore counteracting eutrophication (HELCOM 2007b). About 85 million people are today living in the drainage area and nine countries have a Baltic Sea coastline i.e. Denmark, Estonia, Finland, Latvia, Lithuania, Poland, Russia, Sweden and Germany. Since beginning of the 1900s the phytoplankton production in the Baltic Sea has almost doubled due to eutrophication (Elmgren 1989).

**Himmerfjärden and Himmerfjärdsverket**

A sewage treatment plant named Himmerfjärdsverket started in 1974 and purifies water from municipalities of Botkyrka, Nykvarn, Salem, Södertälje and parts of Huddinge and the southwestern area of Stockholm. It is the third largest sewage treatment plant in the Stockholm region and there were around 314 100 people connected to Himmerfjärdsverket in 2014 (SYVAB 2014). The purified wastewater is emitted in Himmerfjärden’s inner basin (Franzén et al. 2011), see Figure 1 where the recipient is marked as “H5”. Himmerfjärden receives a minor part of Lake Mälaren’s freshwater outflow and the local catchment consists of c. 530 km$^2$ of forests (57 %), agricultural land (33 %), urban areas (5 %) and lakes (4 %). The salinity in Himmerfjärden is just a bit lower than in the open Baltic Sea.

Since 1976 the area has been used to study the environmental impacts of nutrient discharge (Johnsson 2003). The supply of nutrients to the recipient varies between years, partly due to natural variation in precipitation and changed amounts of discharge from the sewage treatment plant (Elmgren & Larsson 1997). Between the years 1977 to 1985 the discharge of nitrogen increased, excluding years 1983 and 1984, while emissions of phosphorus varied. In 1985 another sewage treatment plant, Eolshälls reningsverk, was merged with Himmerfjärdsverket, and the effect became an increased discharge of nitrogen and phosphorus in the recipient Himmerfjärden. Projects started in the end of the 1980s to attempt nitrogen reduction in wastewater and was introduced as full-scale continuous operation in 1991. One year later, in 1992, the nitrogen discharge decreased to the same level as it was in the end of the 1970s. The amount of phosphorus was at the same year, 1992, measured lower than it was in the end of the 1980s (Elmgren & Larsson 1997).

One of the sampling stations in Himmerfjärden area, called “H4”, used for environmental monitoring (Elmgren & Larsson 1997) was consequently chosen for this study, and is marked on the map in Figure 1.

**Diatoms**

Diatoms are unicellular eukaryotic organisms and belong in the Kingdom Protista (Jones 2013). Their size varies between 2.5 µm and 2 millimetres, and the oldest reliable fossil record is from the early Jurassic about 185 million years BP (Kooistra & Medlin 1996). They can be found in most aquatic habitats, except the most hypersaline and hottest waters. They can also grow as subaerial
forms on terrestrial soils, damp rock faces and also on plant leaves that is growing in damp environments. There are over 100 000 diatom species and they are the most species-rich group of algae; micro algae. The majority of the species are photosynthetic but there is a few species that are facultative or obligate heterotrophs, which means that they are feeding on other organisms (Jones 2013).

Diatoms are made of two halves, so-called valves, with a silica based cell wall. They have a box-like structure and the upper valve is slightly larger than the lower valve, and they have girdle bands which links them together. The siliceous outer shell of the diatom cell is called frustule. Their shape varies and is usually round or boat shaped, but can also be in a square-, triangular-, or elliptical shape (Jones 2013). The diatom’s morphology is used to identify and determine species. Three classes of diatoms are proposed by Round et al. (1990): the Centrics, Pennates without raphe and Pennates with a raphe.

In Snoeij et al. (1993-1998) the diatoms main life-forms and substrates are presented as follows:

**PELAGIC DIATOMS** – Plankton diatoms. Living in the open water.

**BENTHIC DIATOMS** – Littoral diatoms. Living attached to or associated with different substrata. The benthic diatoms are subdivided in:

- **EPIPELIC DIATOMS** – Unattached, motile diatoms in and on sediments.
- **EPIPSAMMMIC DIATOMS** – Diatoms attached to sand-grains.
- **EPiphytic DIATOMS** – Diatoms attached to plants.
- **EPILITHIC DIATOMS** – Diatoms associated with rock surfaces

In the Baltic Sea diatoms have an important role as a key algal group in the primary production and food web dynamics (Weckström et al. 2007). Nitrogen and phosphorus are together with silica the most important nutrients needed for diatom growth (Bernes 2005). Increased load of the nutrients phosphorus and nitrogen, for example, affects diatom life forms and diversity (Jonsson et al. 1990). However, the nutrient conditions are not only dependent on anthropogenic inputs but also climatic influences, for example rainfall and river run-off (HELCOM 2007a). Another factor that also influence the availability of nutrient for phytoplankton growth is remineralization. In the bottom water of deep basins, during anoxic conditions, phosphorus and silica is released from the sediment, while nitrate is largely denitrified in anoxic sediments (HELCOM 2007a). The nutrients are transported to the upper water layers, with help of convective and diffuse processes, where they promote phytoplankton growth.

Diatoms are sensitive to environmental change and the composition of the diatom flora can be controlled by physical or chemical changes. Temperature, turbulence and light are included in the physical controls, while salinity, pH and nutrients is included in the chemical controls. The siliceous frustules of diatoms are quite resistant to degradation which makes them preserved generally well in sediments, depending on environmental conditions (Jones 2013). Diatoms can be used to gain information about past ecological and environmental changes, e.g. eutrophication, acidification, water pollution, climatic and lake-level changes. However, biological controls as parasitism and grazing
can also control the composition of the diatom flora. Fossilized diatoms can be used on a range of time scales from decadal to millennial, according to records of environmental changes (Jones 2013). Some diatom species are characterized as having an Arctic distribution and they can therefore be utilized in diatom assemblages as indicator species, showing records of colder climate with ice cover (Snoeijs et al. 1993-1998, Hasle & Syvertsen 1990).

**Figure 1.** The maps shows the location of Himmerfjärden in the Baltic Sea (red box, left picture). The location of the sampling station, “H4”, is marked as a red square (right picture) and the yellow square shows the recipient “H5”. The sewage treatment plant Himmerfjärdsverket is highlighted as an orange polygon.

**METHODS**

This study is part of the ongoing project UPPBASER at Södertörn University (Södertörn University, Research) and is performed by diatom analysis on a sediment core from Himmerfjärden estuary. Analyses and laboratory studies were performed with tutorial by Elinor Andrén.

Naturvårdsverket’s report by Elmgren & Larsson (1997) was used to find information about the Himmerfjärden area and history. Snoeijs et al. (1993-1998) and Krammer & Lange-Bertalot (1986, 1988, 1991a, 1991b) were used for identifying the diatom taxa.

The study has been delimited by just analysing level 0 to 294 cm, which was determined after the $^{14}$C-dating of the microfossils. This is because the lower levels, from 314 to 500 cm, were too old.
and not considered relevant for answering the research questions in this study. Furthermore, not all diatom species/taxa we found were determined to species level, only the most important and relevant for this study were selected. A diatom diagram was constructed, including inter alia a time model (which was the best time model that could be created with the dating’s used in this study).

**Sampling**

A sediment core, named “pc1208”, was cored in August 2012 in one of the deepest part of Himmerfjärden. Coring equipment used was a 5-m long piston corer. Total length of the core was 505 centimetres. To facilitate transport to laboratory the core was divided into four shorter sections, see Table 1 in *Results*. The core sections had been stored for three years in a cold room at Södertörn University, until August 2015, waiting for later analysis.

A visit to the site took place in August 2015 when an additional sampling was made just outside Himmerfjärden. My reason to join this field trip was to get more profound understanding how the coring technique is performed. The sediment core sampled in August 2015 was not examined in this study.

**Lithology**

Sediment type and lithological description of pc1208 was determined with visual examination by expert help from Thomas Andrén, lecturer and associate professor at Södertörn University. The core examination took place approximately one hour after the opening. It is important to perform visual examination as soon as possible after opening since there is a risk for the lamination to become less clear when being exposed to oxygen. Munsell soil-color charts (Munsell 2009) was used to determine soil color.

**Sample analysis and diatom preparation**

The sampled sediment core pc1208 was opened at Södertörn University in August 2015. The core sections were described with lithological characteristics, i.e. type of sediment, lamination, and other visible structures. The colors were determined with Munsell Color Chart. The core was also documented by photography and subsampled for diatom analysis.

Four macrofossil findings, evenly distributed in the core, were collected and then washed with distilled water to get rid of sediment. They were placed into four small plastic sample containers in an oven to dry in 60°C for 24 hours. The dried macrofossils were individually weighed and sent to BETA analytic Inc, USA for radiocarbon (14C) dating.

For diatom preparation 30 small sediment samples were sub-sampled. Following levels were used for sampling (centimeters): 2, 10, 14, 15, 23, 33, 44, 59, 79, 99, 119, 138, 158, 174, 189, 209, 229, 249, 273.5, 294, 314, 334, 354, 374, 394, 415, 438, 459, 479 and 500.
Sediment samples were prepared for diatom analysis according to the method described in Battarbee (1986). Small sediment samples were placed in 100 mL beakers and processed with 10% HCl to remove carbonates. About 25 mL 30% hydrogen peroxide H$_2$O$_2$ was added to oxidise organic matters. The samples were carefully heated on a hot plate in a fume cabinet until boiling. They were left calmly boiling for approximately two hours until the hydrogen peroxide had oxidized all organic matter.

To get rid of the clay sized particles and make as pure diatom slides as possible a process of several cleaning-decanting steps was initiated. 50 mL distilled water was added and the samples were left to rest four hours so the silt sized particles containing also the diatoms, would sink to the bottom. After four hours one could clearly see it as a white coating on the bottom. About 75 mL of the water in the samples was decanted, without letting any of the siliceous matter out. A solution of H$_2$O and NH$_3$ was added to the samples to purify from clay particles. When the water is clear it is clean from clay particles. The samples were thereafter placed into plastic cup containers.

The next step was to apply the solution on to the microscope coverslips, using a Pasteur pipette. Two samples consisting two different concentrations from each level were made. Reason for this is to increase the chances of receiving a sample to analyse with, and for counting, suitable amount of diatom valves on the coverslips. One new disposable pipette was used on each level to avoid mixing material from the other samples. The coverslips were air-dried for 48 hours in room temperature for the diatoms to settle and to let the water evaporate. Subsequently the coverslips were mounted on glass slides with Naphrax™ resin for high refractive index.

Qualitative analyses were performed with a light microscope OLYMPUS BX51 with x1000 magnification using oil immersion. Altogether 19 levels were analysed.

Schrader & Gersonde’s (1978) counting convention was used, and for identifying the taxa the floras of Snoeij et al. (1993-1998) was utilized. Valve counts per sample were >300, except in two levels where valve counts were about 250. Selection of diatom species was done by overviewing all the samples to find out which species that was important to distinguish to species level. Other diatom species were categorized as centric spp. or pennate spp. Chaetoceros spp. includes Chaetoceros resting spores and vegetative cells. Epithemia spp. includes Epithemia sored and Epithemia tur-gida. All counted taxa were furthermore divided in to pelagic or benthic species, based on their life-forms (see Appendix A. for further information). A simplified subdivision was made where all centric species were counted as pelagic and all pennate species were counted as benthic.

A diagram was constructed using the program Tilia version 2.0.38 (Grimm 2013) including all taxa with a relative abundance of more than 2% at any level. A zonation was created using the cluster analysis CONISS included in the Tilia program. Furthermore, a graph with the Arctic species was added which includes Fragilariopsis cylindrus, Melosira arctica, Pauliella taeniata and Thalassiosira baltica.
RESULTS

Sampling

The core pc1208 was sampled in Himmerfjärden, position N 58°59.616’. E 17°43.295’. Water depth on the location was 44.1 meters. The four shorter core sections consists of the following levels (Table 1):

Table 1. Shows the four core sections and level of sediment depth.

<table>
<thead>
<tr>
<th>Section</th>
<th>Sediment depth (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>380-505</td>
</tr>
<tr>
<td>2</td>
<td>255-380</td>
</tr>
<tr>
<td>3</td>
<td>130-255</td>
</tr>
<tr>
<td>4</td>
<td>0-130</td>
</tr>
</tbody>
</table>

The four core sections were opened in August 2015 at Södertörn University. Liner 2 was slightly skew sawn. Between section 1 and 2 (380 cm) about 2 cm sediment was lost when it flowed out at bottom of section 2.

Dating

The returned $^{14}$C-datings of the macro fossils were calibrated with IntCal 13.14C (Reimer et al. 2013) in the program Clam v.2.2 (Blaauw 2010). It is known that $^{14}$C years do not directly equate to calendar years, thus a calibration is required (Reimer et al. 2013). Atmospheric $^{14}$C concentration varies through time because of e.g. changes in the production rate and the carbon cycle (Reimer et al. 2013).

The macrofossils found in level 139, 218 and 320 cm were shell residues, probably from the clam species *Macoma balthica*. The macrofossil found in the lowest level 447.5 cm was plant residue, though it was not clear if it was a terrestrial or aquatic plant.
Table 2. Results from calibrated $^{14}$C dating of retrieved macrofossils.

<table>
<thead>
<tr>
<th>Depth in core (cm)</th>
<th>Dated Item</th>
<th>$^{14}$C age</th>
<th>Calibrated age, Cal yr BP</th>
</tr>
</thead>
<tbody>
<tr>
<td>139</td>
<td>Macrofossil, shell, probably from <em>Macoma balthica</em></td>
<td>220 ±30 $^{14}$C-years</td>
<td>191</td>
</tr>
<tr>
<td>218</td>
<td>Macrofossil, shell, probably from <em>Macoma balthica</em></td>
<td>560 ±30 $^{14}$C-years</td>
<td>582</td>
</tr>
<tr>
<td>320</td>
<td>Macrofossil, shell, probably from <em>Macoma balthica</em></td>
<td>1620 ±30 $^{14}$C-years</td>
<td>1490</td>
</tr>
<tr>
<td>447.5</td>
<td>Macrofossil, plant residues (terrestrial or aquatic)</td>
<td>3000 ±30 $^{14}$C-years</td>
<td>3200</td>
</tr>
</tbody>
</table>

**Lithology**

The 505 cm long sediment core displayed changes, such as color, texture and lamination. In the upper part of the core there are clear lamination, as in level 0 to 93 cm. The texture of the mud varies; from more loose and moist in the upper level to more solid/compact and dry in the lower level. The sediment contained of only mud, no sand or gravel. No shell were found in the laminated parts, which probably is an evidence that the sediment was deposited under hypoxic conditions.

Table 3. Lithology of pc1208.

<table>
<thead>
<tr>
<th>Sediment depth (cm)</th>
<th>Sediment description</th>
<th>Munsell color code</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-93</td>
<td>Distinct laminated mud. From two centimeters thick lamination down to a few millimeters. 42-49 cm has some disturbed laminae. No macrofossil was found.</td>
<td>10 G 3/1 - Very dark greenish gray 10 Y 2,5/1 - Greenish black 10 Y 3/1 - Very dark greenish gray</td>
</tr>
<tr>
<td>93-193</td>
<td>Weakly laminated mud. Millimeters thick lamination. Macrofossil was found at level 193 cm.</td>
<td>10 G 3/1 - Very dark greenish gray 10 Y 2,5/1 - Greenish black 10 Y 3/1 - Very dark greenish gray</td>
</tr>
<tr>
<td>193-340</td>
<td>Homogeneous mud with very subtle sulfide banding. Macrofossils were found at level 218 cm and 320 cm.</td>
<td>5 Y 4/1 - Dark gray</td>
</tr>
<tr>
<td>340-505</td>
<td>Homogeneous mud. Elements of silt increases with depth. Macrofossil was found at level 447-448 cm.</td>
<td>5Y 4/2 - Olive gray</td>
</tr>
</tbody>
</table>
Figure 2. Sediment core pc1208, showing sediment depth 0 to 380 cm. Section 4 (top of the photo) shows 0 to 130 cm. Section 3 (in the middle) shows 130 to 255 cm. Section 2 (bottom) shows 255-380 cm.

Figure 3. The four retrieved macrofossils from pc1208, placed in small glass containers.
Figure 4. The figure shows the diatom diagram constructed for pc1208, showing all taxa with a relative abundance of more than 2% at any level. Furthest to the left is an age scale showing calibrated 14C dates of the retrieved macrofossils and the three included dates. Next to it is the linear primary scale showing depth below sediment surface (cm), and to the right of it is lithology of the core shown. To the right of the counted diatom taxa is graphs showing pelagic / benthic ratio and Arctic species. A zonation was created using cluster analysis, showing three Diatom Assemblage Zones (DAZ) as horizontal dashed lines.
Diatom record

Three zones have been created statistically, using cluster analysis, to show diatom assemblage zones, DAZ. The results from the constructed diagram are as follows:

DAZ 1 - In zone1, which is the lowermost zone representing level 294 cm to 158 cm, the pelagic diatoms taxa are dominant and their abundance is never less than 50 %, as seen for example in level 189 cm. *Pauliella taeniata* is the most abundant taxon in almost every level. However, in level 158 cm *Thalassiosira levanderi* is more abundant. *Pennate spp.* has three peaks in zone1 and it also has significantly more counted taxa in this zone than further up in the stratigraphy. The species with low abundance in zone1 is for instance *Chaetoceros spp.*, *Melosira arctica*, *Fragilariopsis cylindrus*, *Skeletonema costatum*, *Thalassiosira baltica*, *Coscinodiscus granii* and *Ctenophora pulchella*. The abundance of Arctic species varies throughout this zone; from around 20 % to 60 %.

DAZ 2 - The middle zone is representing level 138 to 23 cm, and is dominated by an increase of pelagic taxa. *Chaetoceros spp.* is peaking in level 23 and 33 cm and is representing almost 55 % of all counted taxa at this level. This is also the zone where *Chaetoceros spp.* is markedly more abundant than in the other zones. The most dominated counted taxon in zone2 is *P. taeniata*, with exception at level 23 cm where *Chaetoceros spp.* is more abundant. *P. taeniata* is peaking at level 59 cm where it represents almost 60% of all counted taxa. This is the zone where the Arctic species *Melosira arctica* has higher abundance than in the other zones. The abundance of *Thalassiosira proschkiniae* and *Thalassiosira levanderi* varies up and down, but is never representing more than 25 % of all counted taxa. The Arctic species varies from c. 25 % in level 138 cm and increases to almost 80 % at level 59 cm.

DAZ 3 - The uppermost zone represents level 2 to 14 cm and is also dominated by pelagic taxa. *T. prosckinae* is the most dominated counted taxon, followed by *T. levanderi*. Thereafter, they are followed by *Cyclotella choctawhatcheeana* which is significantly more common in zone3 than in the other zones where it had quite low abundance. Both *P. taeniata* and *Chaetoceros spp.* were showing a high abundance in zone1 and 2, but is now representing <15 % each in level 2, 10 and 14 cm. There is also a low abundance of Arctic species which are less than 20 % at any level in zone3.

The most dominating taxon throughout the stratigraphy is *P. taeniata* which was found in every level from 2 to 294 cm. The highest relative abundance of this taxon is found in level 273.5 cm where it represented 56.8 %. The lowest relative abundance is found in level 10 cm where it only represented 2.6 % of all counted taxa.
INTERPRETATION and DISCUSSION

Marine eutrophication of estuaries and coastal waters is a major problem around the world (Nixon 1995) and in the Baltic Sea the increased nutrient load has led to marked changes in the ecosystem. The more closed coastal ecosystems are a focus for management efforts since they are more susceptible for nutrient load and thus gets more affected compared to ecosystems in the open sea (Weckström 2006). The recent European Water Framework Directive (WFD) (Anonymous 2000) requires that all European surface waters fulfills the criterion of “good ecological status” by the years 2015-2027. This means that the biological and chemical status in these waters should diverge only slightly from undisturbed baseline conditions. It is therefore important to gain more knowledge about present biogeochemical nutrient cycles in coastal waters, and also how nutrient concentrations have varied through time together with the chemical and ecological background conditions (Weckström 2006). Palaeolimnological studies, similar to this study, can help to assess ecological changes in coastal waters over centennial timescales and give us information about background conditions. Consequently they are valuable as management tool for ecosystem protection in addition to ecosystem restoration (Weckström 2006).

The assumption made in this thesis, concerning the time model, is that the top of the core is representing present time. There is however a risk that this time model may not be fully accurate. It is likely that some sediment in the top got lost, or flown out, when doing the sampling with the piston corer. The uppermost sediment is unconsolidated and flows out on the deck when the piston is removed. This means that up to 20 cm sediment in the top may be missing. The risk of sediment loss can be minimized by analysing a short gravity core with undisturbed sediment from the top, done separately from the long piston corer. But in this study there was no time for analysing a short parallel core. However, a comparison was made with the well dated sediment core analysed in the EU MOLTEN project (Conley 2003). That core, which was sampled on the same site in Himmerfjärden as core pc1208, shows that 20 to 30 cm sediment in the top are equivalent to five to ten years, at most. The Himmerfjärden site has a high sedimentation rate and therefore a maximum of five to ten years may be lost in my time model, which is negligible in the interpretation. We have thus assumed that level 0 cm in sediment core pc1208 is representing present time. Furthermore, we have assumed constant sedimentation rate between the three dated levels in the core. However, the sediment gets more compact and contain less water further down in the sediment, and therefore a linear age scale between the dates does not necessarily have to be correct, but it is the best assumption that can be made with the current dated material. Three macrofossils that we found in the sediment core were from an aquatic organism, Macoma balthica. It would though have been preferable to date a terrestrial residue, e.g. plant or seed. This is because aquatic organisms pick up and store old carbon from the ocean, which can give them inaccurate age when radiocarbon dating them, so called marine reservoir age (Lougheed et al. 2013). However, the marine reservoir age is corrected in the program Clam v.2.2 (Blaauw 2010) when doing the calibrations. These problems, which I just have discussed throughout this section, are the main inaccuracies in this study.

The interpretations that will follow in my discussion is under the premise that the time model is correct. The results have been interpreted and put in context regarding the known historical changes. The work with this time model is under improvement, but it can already be used as a very good method when studying environmental changes using diatom stratigraphy.
The sediment of core pc1208 analysed in this study started to deposit around c. 1300 to 1490 cal yr BP. The $^{14}$C dating shows that the lower part of the sediment, zone1, was deposited approximately between 240 to 1490 cal yr BP. In this zone, the benthic diatom taxa is slightly more abundant than it is higher up; in zone2 and 3. When the abundance of planktonic diatom species are increasing, due to nutrient input, the water column gets more turbid and transmit less sunlight, which causes a decrease in the abundance benthic diatom species. Furthermore in zone1, one can see that there is a major increase in the abundance of *Cyclotella choctawhatcheeana*. This species grows under high nutrient conditions and is thought to be an indicator of anthropogenic perturbation in brackish water (Cooper, 1995). The increase of *C. choctawhatcheeana* starts around 25-30 years ago and may correspond with an incident in 1984 when Himmerfjärdsverket increased the load of phosphorus in to the bay for experimental purposes. Another incident that may be connected to the increase of *C. choctawhatcheeana* was when sewage from Eolhälls reningsverk was directed to Himmerfjärdsverket in 1985. This led to a 40 % load increase (Elmgren & Larsson 1997).

The distinct lamination in the core between 0 to 93 cm, indicate that there has been hypoxic conditions in Himmerfjärden estuary approximately the latest 120-130 years. It is worth noting that no macrofossil was found in this part, which most likely has to do with the oxygen depletion.

The sediment layers in the laminae are coloured by sulphides and appear distinct gray or black (Table 3; Fig. 4). This occurs when there are no micro organisms to decompose organic matter. The black layers indicate more organic deposits, usually a result of the spring and summer blooms. It also contains bacteria that can live without oxygen and form the toxic gas hydrogen sulphide. Oxygenated sediments remain the color light brown and the annual layers of deposited sediments are mixed to a homogeneous mass by bioturbation. Further down in the sediment, from level 193 to 294 cm, the lithology shows that the homogeneous mud with weak sulphide banding contains no lamination and are thus an indication of a non-hypoxic period in Himmerfjärden estuary. The period with homogeneous mud extends over c. 1000 years – from c. 480 cal yr BP to 1490 cal yr BP.

It is not clear when humans started to affect the ecosystem in the Baltic Sea. Zillén et al. (2008) propose that human impact on the bottom-conditions in the Baltic Sea started about 750 AD, around the onset of the Medieval Warm period. Earlier studies shows that several lakes around Europe have been eutrophicated since the onset of Middle Ages (Zillén et al. 2008). At that time the population increased and there was improved agriculture techniques together with more intense land-use which led to nutrient leaching. Due to decreased population during the plague/Black Death in the 1300s the hypoxic conditions were reduced and the bottoms got oxygenated again (Zillén et al. 2008).

There are some small, but significant, changes throughout the diatom stratigraphy in this study. It shows that there is no major change in the diatom assemblage thus it is dominated by pelagic diatom taxa throughout the entire stratigraphy. However, the benthic diatom taxa has a peak in level 189 cm where it almost reaches 50 %. But there is never a shift towards a dominance of benthic taxa. The reason for creating a chart of pelagic/benthic ratio is because a shift can be an indication of environmental changes, inter alia eutrophication. For example, an increase in the abundance of pelagic diatoms can indicate worse water quality, e.g. turbidity in the water column, which decrease the abundance of benthic diatoms. A shift from dominance of benthic species to dominance of pelagic species can consequently indicate on more turbid water (Weckström 2006). But the fact that
there is never a shift towards a dominance of benthic diatoms in my study is not surprising since the core pc1208 was sampled on a site with great water depth. Further, the Himmerfjärden estuary has a steep bathymetry with only a narrow shallow zone suitable for phytobenthic growth. This means that the area where benthic diatoms can grow and live is restricted due to deficiency of sunlight. Most of the benthic diatoms found in the sample site have probably been transported/moved to the bottom after they died.

The diatom assemblage shows that *Pauliella taeniata* has the highest abundance in almost every level. *P. taeniata* is an Arctic species that lives attached to ice and since the late 1980s to the early 1990s the abundance has decreased markedly due to warm winters and few ice-days in the Baltic Sea (Snoeijjs & Weckström 2010). *P. taeniata* is an indicator of ice-winters and also climate changes. This species have dominated the diatom assemblages during the 1900s in the deep sediments of the Baltic Sea, mainly in Gulf of Bothnia and Gulf of Finland. During the latest 20 years it has though been less common in many parts of the Baltic Sea because of warm winters without ice cover (Snoeijjs & Weckström 2010). In the constructed diagram one can find that the abundance of *P. taeniata* has decreased dramatically in Zone3, which corresponds with the latest 20 to 30 years of warm winters.

Diatoms from the Arctic flora in the Baltic Sea occur less frequently in the spring bloom when ice cover is limited. They can therefore be used as markers for increases and decreases in ice cover over an area, caused by climate change (Snoeijjs & Weckström 2010). The Arctic species that were used in this study are: *Fragilariopsis cylindrus*, *Melosira arctica*, *Pauliella taeniata* and *Thalassiosira baltica*. *T. baltica* is common in the Baltic plankton (Hasle & Syversten 1990). The diatom diagram (Fig. 4) shows that the highest abundance of Arctic species in this study is found at level 59 cm, approximately 75 %. Changes in phytoplankton biomass and species composition reflect the effects of eutrophication and also climatic change (HELCOM 2007b). Warming will inhibit cold-water species, such as some diatoms, and may stimulate warm-water species as the bloom-forming toxic cyanobacteria *Nodularia spumigena* (HELCOM 2007b). There is also a risk that new species, originating from warmer seas, would establish in the Baltic Sea and displace native species. If spring blooms will begin earlier during spring, due to reduced ice cover and earlier stabilization of the water column, it would affect food supply for zooplankton and, thus, the entire food web. As mentioned in the background, Baltic Proper has a permanent salinity stratification where the deep saline water is separated from the surface brackish water by a halocline. Stronger vertical stratification of the water column would reduce vertical transport processes, such as exchange of nutrients and dissolved gases, upward transport of cysts/spores, sedimentation and vertical migration of plankton (HELCOM 2007b), and is a situation that may benefit cyanobacteria.

The diatom assemblage shows a high abundance of *Chaetoceros spp.* in Zone 2 at level 23 cm and 33 cm, which is approximately 25 to 40 years ago. That time correspond with the opening of Himmerfjärdsverket around 40 years ago. Peaks in the abundance of *Chaetoceros* resting spore can indicate a very high productivity in nutrients (Andrén et al. 2000). From this period and forward the ice-diatom *Pauliella taeniata*, together with the other Arctic species, are decreasing. This has most likely to do with a warm period which implies less ice. As discussed earlier in this study, the composition of microalgal communities changes when eutrophication occurs and initially enhances diatom growth (Snoeijjs & Weckström 2010). It is known that during the last century the anthropogenic
nutrient load of phosphorus and nitrogen into aquatic ecosystems has increased markedly. In fact, the Baltic Sea has now eight times more phosphorus load and about four times more nitrogen than a century ago (Elmgren 1989). This has led to, inter alia; a 500 to 1000 % increase in the sedimentation of organic carbon and into a pelagic regime shift (Snoeijs & Weckström 2010).

The two lowermost levels in the stratigraphy, 294 cm and 273.5 cm, are where the valve counts per sample were <300 because of scarce amount of diatoms. These levels of the sediment were deposited around 1050 to 1280 cal yr BP. The lithology shows (in Fig. 4) that homogeneous sediment is present at these levels in the core and therefore indicating a period of oxygenated bottoms (Zillén et al. 2008). This means that other organisms lived in the bottoms and thus mixing the sediment. This can lead to poor preservation of the diatoms frustules as the nutrient silica is dissolved and recirculated. Another interpretation, regarding the scarce amount of diatoms in the lowest levels, is that this may have been a period with low primary production.

The main focus in this study was to investigate if there was any records on eutrophication in Himmerfjärden since the start of the nearby sewage treatment plant Himmerfjärdsverket. The constructed diatom diagram shows that in zone 3 there is an increase in the planktonic taxa that are favoured by nutrient input, such as Thalassiosira levanderi, Thalassiosira prosckinae and Cyclotella choctawhatcheana. This indicates that there has been environmental changes in Himmerfjärden, possibly from the opening of Himmerfjärdsverket 1974. This study show some similar results in the diatom stratigraphy as the results from the EU MOLTEN project from 2001 (Conley 2003), implying that c. 20 cm of the upper sediment from pc1208 is lost. As I mentioned earlier (on page 14) that sediment core was sampled in the same site as pc1208, and it shows similar fluctuation patterns for e.g. P. taeniata and T. proschkinia, mainly in the upper levels in the sediment.

The other main question for my study was if there were any signs that the opening of Södertälje Canal may have affected Himmerfjärden bay. The construction of Södertälje Canal and sluice was ready in 1819, and if there were any records of freshwater forcing or increased nutrient discharge from the opening one would might be able to see a change in the diatom stratigraphy around 200 cal yr BP. The stratigraphy in this study shows some signs indicating that this might be true. Around level 150 cm, in the scale showing depth below sediment surface, there is an increase in the abundance of pelagic species. There is also a major increase in the abundance of Chaetoceros spp. in this level and throughout zone 2. Peaks in the abundance of Chaetoceros resting spore can indicate a very high productivity in nutrients (Andrén et al. 2000). These results can be interpreted as Himmerfjärden may have been affected by the opening of Södertälje Canal and sluice.

Finally, this study could be a part of the process of working towards a “good environmental status” in the Baltic Sea. There are needs for further studies regarding past and recent ecological changes in the estuaries and coastal zones around the world. Studies similar to this thesis could be used for increased understanding of eutrophication and environmental change, and therefore be a valuable management tool for ecosystem protection. However, this study requires continued and improved work for further and more accurate interpretations, for example; an improved time model with more precise dating, created with more close/dense sub-samples and Pb-dating. This could, together with
more precise diatom analyses, improve the interpretation with historical records and environmental change.

CONCLUSIONS

- $^{14}$C-datings shows that the sediment core of pc1208 started to deposit around c. 1300-1490 cal yr BP. The lowermost part of the sediment, zone1, shows that the benthic diatom taxa is more abundant in this zone than it is higher up, in zones 2 and 3.

- The pelagic taxa is dominant throughout the stratigraphy, but is decreasing to a bit above 50% around level 189 cm. It is not surprising that there is no shift towards a dominance of benthic taxa, inter alia since the core was sampled on a site with great water depth.

- The uppermost layer of the core shows distinct lamination between 0 to 93 cm, which indicates that Himmerfjärden area has suffered from hypoxia during the latest 120-130 years.

- The constructed diatom diagram shows that in zone3 there is an increase in the planktonic taxa that are favoured by nutrient input, e.g. Thalassiosira levanderi, Thalassiosira prossckinae and Cyclotella choctawhatcheeana. This indicates that there has been environmental changes in Himmerfjärden, possibly due to the opening of Himmerfjärdsverket 1974.

- Arctic diatoms can indicate periods with ice cover. Pauliella taeniata is an Arctic species that lives attached to ice but and is an indicator of ice-winters and climate change. Since the late 1980s to the early 1990s the abundance has decreased markedly, due to warm winters and few ice-days in the Baltic Sea, which can be seen in the diatom diagram in this study.

Acknowledgements

I would like to thank my supervisor Elinor Andrén at Södertörn University – first of all for this interesting thesis proposal, and also for all your time dedicated to help me, give me ideas and guidance throughout this study. I especially enjoyed the practical work in the lab and the diatom analyses with microscope, and also the field trip I got to go on with you and your team. This study has given me lots of new knowledge! Furthermore, I would like to thank Lena Norbäck Ivarsson for all your help during this time – from laboratory work to the diatom analysis in the microscope (and everything in between). Last, but not least, I want to thank Thomas Andrén for your help with the lithology in this study, and for your explanation and demonstration of how the coring technique is performed.
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**Appendix A.**

**Diatom species**

The table in Appendix A are showing the identified diatom taxa and their life-form (Snoeijs et al. 1993-1998):

<table>
<thead>
<tr>
<th>Name</th>
<th>Life-form</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Chaetoceros</em> Ehernberg 1844</td>
<td>Pelagic</td>
</tr>
<tr>
<td><em>Coscinodiscus granii</em> Gough 1905</td>
<td>Pelagic</td>
</tr>
<tr>
<td><em>Ctenophora pulchella</em> (Ralfs ex Kützing)</td>
<td>Epiphytic</td>
</tr>
<tr>
<td>Williams &amp; Round 1986</td>
<td></td>
</tr>
<tr>
<td><em>Cyclotella choctawhatcheeana</em> Prasad 1990</td>
<td>Pelagic sometimes epilithic</td>
</tr>
<tr>
<td><em>Epithemia sorex</em> Kützing 1844</td>
<td>Epiphytic</td>
</tr>
<tr>
<td><em>Epithemia turgida</em> var. westermannii (Ehrenberg) Grunow 1862</td>
<td>Epiphytic</td>
</tr>
<tr>
<td><em>Fragilariopsis cylindrus</em> (Grunow) Krieger in Helmcke &amp; Krieger 1954</td>
<td>Pelagic and on ice</td>
</tr>
<tr>
<td><em>Melosira arctica</em> Dickie 1852</td>
<td>Pelagic and on ice</td>
</tr>
<tr>
<td><em>Pauliella taeniata</em> (Grunow) Round &amp; Basson 1997</td>
<td>Pelagic and on sea ice</td>
</tr>
<tr>
<td><em>Rhoicosphenia curvata</em> (Kützing) Grunow 1860</td>
<td>Epiphytic and epilithic</td>
</tr>
<tr>
<td><em>Skeletonema costatum</em> (Greville) Cleve 1878</td>
<td>Pelagic</td>
</tr>
<tr>
<td><em>Tabularia tabulata</em> (C.A. Agardh) Snoeijs 1992</td>
<td>Epiphytic</td>
</tr>
<tr>
<td><em>Thalassiosira baltica</em> (Grunow) Ostenfeld 1901</td>
<td>Pelagic</td>
</tr>
<tr>
<td><em>Thalassiosira levanderi</em> Van Goor 1924</td>
<td>Pelagic</td>
</tr>
<tr>
<td><em>Thalassiosira proschkinae</em> Makarova 1979</td>
<td>Pelagic, sometimes epilithic</td>
</tr>
</tbody>
</table>
Appendix B.

Photographs of diatoms

The photos below shows some of the diatom species in this study. The photographs are taken by E. Andrén and L. Elander.

*Chaetoceros* resting spore and vegetative cell

*Cocinodiscus granii*
Ctenophora pulchella

Cyclotella choctawhatcheeana
Epithemia turgida

Fragilariopsis cylindrus
Melosira arctica

Pauliella taeniata
Rhoicosphenia curvata

Skeletonema costatum
Tabularia tabulata

Thalassiosira baltica
Thalassiosira levanderi

Thalassiosira proschkinai