Removal of Surface Blooms of the Cyanobacteria Nodularia spumigena: A Pilot Project Conducted in the Baltic Sea

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Removal of Surface Blooms of the Cyanobacteria *Nodularia spumigena*: A Pilot Project Conducted in the Baltic Sea

Blooms of Cyanobacteria are a major concern during the summer period in the Baltic Sea Proper. The nitrogen-fixing *Nodularia spumigena* forms massive toxic blooms in the surface layers, with a concentration of biomass in the uppermost 1-m water layer. This pilot study describes the construction and test of a *Nodularia* collecting device during the summer of 2006. Oil booms were modified so that their dragging skirt was replaced with a water-permeable forming fabric used in the pulp and paper industry. The results showed that the modified oil booms worked and operated in an effective way when towed in the sea. Calculations showed that the collecting device used in this study has a theoretical capacity of cleaning 0.055 km^2 (5.5 ha) of sea surface hr^{-1}, compared with the 6600 km^2 of the Baltic Sea that were covered by *Nodularia* blooms during the summer of 2005. Future possibilities for *Nodularia* harvesting are discussed.

INTRODUCTION

Harmful Cyanobacteria blooms occur worldwide in fresh water, drinking water, recreational water, estuaries, and marine water. The first literature reference to toxic Cyanobacteria was in 1878 when a cattle and sheep mortality event from the brackish water Cyanobacteria, *Nodularia spumigena* was reported from Australia (1). A combination of increased loads of nutrients and global warming may favor the growth of Cyanobacteria and they may well be an increasing global problem in the future (2).

In the brackish Baltic Sea, high levels of phosphorus and nitrogen inputs from various sources, in combination with increased surface water temperature, are causing regular and intensive blooms of Cyanobacteria. The 2005 summer bloom of the toxic Cyanobacteria *N. spumigena* was one of the worst ever recorded, with negative effects on tourism, recreation, and fisheries (3).

The Baltic Sea is a relatively small inland sea, but is the largest brackish sea in the world. Its drainage area includes 14 countries and is approximately four times larger than the sea itself. This is a large and densely populated area with intensively cultivated regions that load the Baltic Sea with large quantities of pollutants of anthropogenic origin (4).

Due to the mix of fresh water and salt water in the Baltic Sea, the number of species is lower there than in saline oceans or freshwater lakes (5). The salinity gradient, which progresses from lowest in the north to highest in the south, also affects the occurrence of species. In addition, the Baltic Sea is divided by a halocline at a 70-m depth, with lower salinity above this depth and higher salinity below it (6). Due to the limited exchange of waters with the North Sea, the turnover time for the Baltic Sea is very long. This is an important aspect as it hampers the replenishment of oxygen. The limited exchange of water also means that toxins and nutrients stay for a long period of time in the Baltic Sea (4).

The Baltic Sea is a water body under great environmental stress. Over time, a combination of natural conditions that render the sea sensitive to environmental alterations and large environmental impacts caused by human activities has altered the conditions within the sea. During recent years, these alterations have developed into severe environmental problems. At present, eutrophication is one of the most serious environmental threats to the Baltic Sea (7, 8).

There are several sources of eutrophying nutrients, including point sources, such as industries or communities with inadequate or no water treatment, and nonpoint sources, such as atmospheric deposition and leakage from the agricultural and forestry sectors (9). The greatest nutrient load to the Baltic Sea comes with drainage water mainly originating from agricultural sources (10).

There is an ongoing discussion about whether nitrogen or phosphorus is the limiting factor for eutrophication in the Baltic Sea. Studies have shown that the limiting factor is area-specific and changes over time. A bay can be nitrogen-limited in the spring, but phosphorus-limited in the summer (4).

The problems of eutrophication in the Baltic Sea began to be addressed in the 1980s, when the countries surrounding the sea decided to cut the nutrient loads in half by 1995. However, despite the measures taken in order to decrease the amount of nutrients reaching the sea, the nutrient input remained the same. This shows that the Baltic Sea needs time to recuperate and that the time lag before a reduction in nutrient input produces any visible results is extensive (7).

These facts show that, in addition to long-term measures aimed at combating the sources of eutrophication and reducing the nutrient input to the Baltic Sea, other direct-action, short-term measures are needed to fight the actual effects of the eutrophication process.

Cyanobacteria are single-celled microscopic organisms that are commonly found in fresh or brackish waters. These bacteria possess the ability to photosynthesize sunlight, which is why they are commonly referred to as blue-green algae. There are several species within the family Cyanobacteria, of which some possess the ability to fix nitrogen. The nitrogen-fixing Cyanobacteria in the Baltic Sea are dominated by three families: *Nodularia*, *Aphanizomenon,* and *Anabaena* (11).

The vertical distribution of the coexisting nitrogen-fixing *N. spumigena* and *Aphanizomenon* sp. is very different. *N. spumigena* prefers near-surface water in the top 5 m of the water mass, while *Aphanizomenon* sp. has its maximum biomass at around a 10-m depth (12).

Even though Cyanobacteria only constitute a small fraction of the algal production within the Baltic Sea, these microbes have attracted a comparatively large share of attention. *N. spumigena* (Fig. 1) has been the cause of particular concern (14). The ability of this species to fix nitrogen, which makes it independent of the growth-limiting nitrogen pool in the water, its ability to float, its rapid growth rate, and its ability to produce toxic substances contribute to the large impact it has on human environments. When the growth conditions are right, these bacteria form massive, poisonous blooms on surface waters, which pollute coastal areas at prime vacation time with

Figure 1. *Nodularia spumigena*. (Source: HELCOM [13] with permission).

negative impacts on both economic conditions and recreational activities (11).

Studies of Baltic Sea sediments show that blooms of nitrogen-fixing Cyanobacteria have been a natural event in the Baltic Sea for thousands of years (15). A recent increase in their occurrence has been reported in several studies (16, 17), accompanying an increase in the nutrient load to the Baltic Sea Proper (7).

Cyanobacteria in the Baltic Sea fix nitrogen in specialized cells called heterocysts, where the enzyme nitrogenase catalyzes the assimilation of nitrogen, in the form N_2, to ammonia (NH_3) in an oxygen-free environment (18). Cyanobacteria that fix nitrogen can continue to grow when other phytoplankton are nitrogen-limited.

Cyanobacteria may also be one of the most important sources of new nitrogen to the Baltic Sea (19). Estimates show that the cyanobacterial nitrogen fixation in the Baltic Sea Proper results in the addition of 180 000–430 000 t nitrogen y^{-1}. The upper limit of these estimates almost equals the entire riverine load and is twice as great as the atmospheric load (11).

In the brackish Baltic Sea Proper, noxious blooms of Cyanobacteria are a common phenomenon (20). High supply rates of phosphorus relative to nitrogen favor the growth of nitrogen-fixing Cyanobacteria (21). After the spring bloom, the extremely low ratio of dissolved inorganic nitrogen (DIN) to dissolved inorganic phosphorus (DIP) in surface water, in combination with a period of calm and sunny weather that increases the stability of the water column, leads to a nutrient-depleted euphotic zone that is isolated from the nutrient-rich water mass below. These conditions favor the nitrogen-fixing Cyanobacteria species *N. spumigena*, *Aphanizomenon* sp., and *Anabaena* spp. (12). A long-term series of measurements shows the highest abundance of Cyanobacteria in the southern part of the Baltic Sea (20).

This paper presents the results of a pilot study that tested the feasibility of physical collection of surface blooms of Cyanobacteria. The main objective of the study was to test and optimize a method that allows for physical collection of surface blooms of the Cyanobacteria species *N. spumigena*. Further aims of the study were to assess the importance of the method with regard to the removal of Cyanobacteria masses, hereafter referred to as "algal blooms," in areas of recreational and economic importance and the nutrient status of the Baltic Sea.

MATERIALS AND METHODS

Study Area

This field study was carried out at the Askö marine field station, which belongs to Stockholm Marine Research Centre, during a period of 6 weeks, from 25 July until 1 September 2006. The field station is located on the island of Askö in the Trosa archipelago, about 80 km south of Stockholm in the north-western Baltic Sea Proper (22).

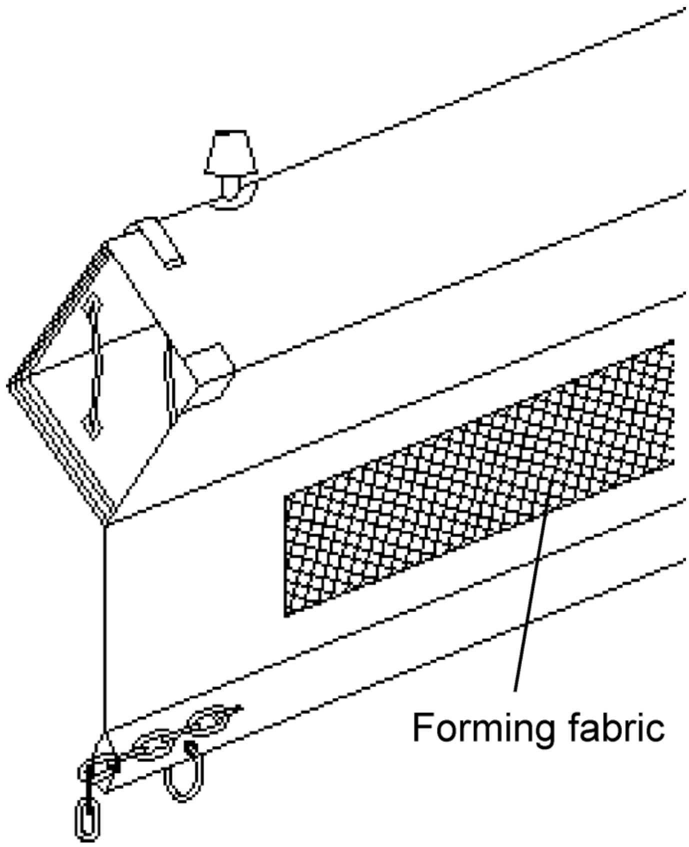

Figure 2. Outline of an oil boom with forming fabric attached.

Askö marine field station was chosen as the study site due to *i)* its location in the outer archipelago with easy access to algal blooms in the Baltic Sea Proper, and *ii)* the facilities available at the station, including vessels, boats, and other tools necessary for the project.

Project Design

The field study was divided into two practical experiments, the first examining the optimal characteristics of the forming fabric (a water-permeable polyester weave) that was to be used for the collection of algal blooms of *N. spumigena*. The second experiment was a small pilot study in which a prototype of the microbe collection device was constructed by replacing part of the fabric of the oil boom with water-permeable forming fabric.

Experiment 1. Forming fabric (Fig. 2) is used in the pulp and paper industry for paper forming, pressing, and drying. The fabric is composed of one or several layers of polyester threads joined together in a fine-meshed weave (23). Forming fabrics possess qualities such as strength and durability which, along with their filtering qualities, make the material a good option for the construction of a microbe (Cyanobacteria) collecting device.

In order to identify the type of forming fabric that would be most suitable for the collection of Cyanobacteria blooms, a small-scale experiment was conducted in which five different types of forming fabric were tested (Table 1). These fabrics differed in yarn diameter, number of yarns cm^{-1}, and number of layers (L. Johansson pers. comm.).

Experiment 2. The aim of the second experiment was to study the extent to which surface blooms of *N. spumigena* could be collected by an oil boom towed by two motor vessels. In

Table 1. Characteristics of the five different types of forming fabrics that were included in the experiment. The letters to the right in the designations indicate other characteristics of the fabrics, including number of shafts, number of layers, and sets of weft yarns.

Designation	Yarn diameter (mm)	Yarns cm^{-1}
dw 20 – OPB	0.50	18
dw 19 – N	0.30	36
dw 16 – N	0.17	62
dw 16 – OP	0.17	62
dw 22 – GPT	0.15	72

order to reduce the resistance caused by the water pressure on the boom, and thus the possibility of Cyanobacteria escaping the oil boom, part of the fabric of the oil boom was replaced by water-permeable forming fabric.

An oil boom (Figs. 2 and 3) is a floating barrier normally used for combating oil spills floating on the surface of the sea and can be found in various types and sizes (24). In principle, all oil booms consist of a floating device connected to a subsurface skirt, which prevents oil from escaping under the boom. In order to keep the boom upright in the water, some type of ballast is attached to the hanging skirt.

The oil boom used in the present experiment was 25 m long and protruded about 0.5 m into the water column. The buoyancy of the boom was provided by self-inflatable air chambers, and a chain was attached along the bottom of the fabric of the skirt to keep the boom vertical in the water (Fig. 2). This type of oil boom can be folded up, which makes it easy to transport to where it is needed.

Equipment

Experiment 1. Segments (1.0 m x 0.35 m) of all five types of forming fabrics were cut out and nailed onto a wood framework. The Cyanobacteria *N. spumigena* was collected from the Baltic Sea and concentrated into tanks (1.0 m × 0.40 m × 0.40 m).

The experiment was conducted by manually pulling the forming fabrics through the tanks (Fig. 4). The capacity of each fabric to collect *Nodularia* was assessed by taking a sample of Cyanobacteria from each fabric and examining it under the microscope to determine the proportion of *N. spumigena* in the collected fraction.

Figure 3. Trial of the oil boom: forming fabric construction. (Photo: F. Gröndahl)

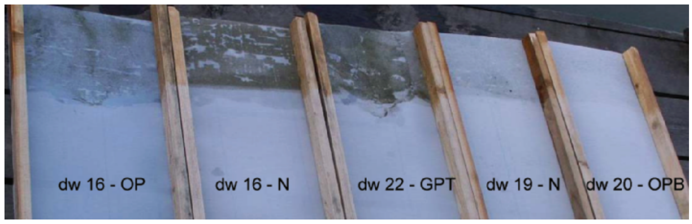

Figure 4. The forming fabrics after being pulled through microbe-rich water.

Experiment 2. A 20-m long segment of 0.40-m depth was cut out of the oil boom skirt. A piece of forming fabric (type dw 20 – OPB) was cut to fill and overlap the gap in the oil boom skirt and was placed on the boom. The forming fabric was joined to the oil boom skirt using bolts and plates (Fig. 2).

A second oil boom was constructed using segments from all five fabric types. Four different segments of 0.8-m length were placed in the central part of the oil boom skirt. A 3.5-m long segment of type dw 20 – OPB was also attached to the oil boom. This fabric has the biggest mesh size and was also the type used on the first oil boom. It was predicted to be the most appropriate fabric.

The oil boom–forming fabric construction was tested on three separate occasions. Two 10-m long ropes were attached to the bottom part of the skirt at the very ends of the oil boom. The oil boom was towed in the water by two boats, thus adopting a U-shaped form (Fig. 3).

The performance of the first oil boom was tested for about 1 hr using two larger vessels (Figs. 3 and 5). The second oil boom was then tested for a slightly shorter time using two small, open boats with outboard motors. On all occasions, the weather conditions were good and the water was calm. The average speed of the boats was 1.5 to 2 nautical miles hr^{-1}, where a nautical mile is 1852 m.

RESULTS

Experiment 1

The first experiment provided information about the capacity of each forming fabric to collect Cyanobacteria (i.e., *N. spumigena*) concentrated in tanks. The use of a microscope revealed that many *Nodularia* cells were joined together in threads. However, the cells had not formed bundles in the way that is normally seen in massive Cyanobacteria blooms. The capacity of each forming fabric is shown in Table 2.

Experiment 2

During testing of the modified oil booms, the following observations were made:

– The oil boom–forming fabric construction was stable and was not obstructed by the pressure exerted by the water.
– The oil boom skirt adopted the desired vertical position in the water.
– The water flow through the forming fabric was good.
– The maximum speed under prevailing conditions was estimated at 2–3 nautical miles hr^{-1}.
– The ropes used in the tests were too short. At least double the length (20 m) is required in order for the oil boom to adopt a good position behind the boats. Longer ropes would also facilitate maneuvering of the boats.
– Large and powerful vessels are needed to maneuver the oil boom. The outdoor motor boats used in the second trial

Figure 5. Trial of the oil boom: forming fabric construction. (Photo: F. Gröndahl)

were too weak. The vessels used also need to be of equal motor capacity.

Capacity of the Modified Oil Booms

When calculating the capacity of the method, the arc of the oil boom is important. In practice, this arc is never static, and therefore an approximate value of 30 m is used for a boom with a total length of 50 m. If a boom is dragged through the water with a speed of 1 nautical mile hr^{-1}, this leads to a capacity of 0.055 km^2 (5.5 ha) hr^{-1} in use. To place this in context, the normal spread of surface accumulations of algal blooms for 2004 was 5400 km^2, while for 2005 it was 6600 km^2 (25).

DISCUSSION

Management of coastal eutrophication is of global importance, particularly in estuaries and enclosed seas with reduced water exchange, such as the Baltic Sea. In the Baltic Sea Proper, eutrophication has been a recognized problem for over 30 years (26). In Sweden, management strategies to reduce phosphorus, and later also nitrogen, in discharged treated sewage water have been successful (27). The demands in the European Union Urban Waste Water Treatment Directive to substantially reduce discharged nitrogen may, in some coastal areas in the Baltic Sea, stimulate the growth of nitrogen-fixing Cyanobacteria, particularly when bordering phosphorus-rich open sea areas (26).

In Himmerfjärden Bay, Elmgren and Larsson (25) showed that a drastic reduction in nitrogen load resulted in a substantially increased occurrence of nitrogen-fixing Cyanobacteria. The phosphorus used by the Cyanobacteria bloom in Himmerfjärden Bay is mainly derived from elevated phosphorus concentrations in the bordering open Baltic Sea since phosphorus reduction by the local sewage treatment plant is around 95%. Thus, management of coastal areas may need to account not only for anthropogenic sources from land and atmosphere, but also those from adjacent open sea areas.

During summer in particular, the further reduction of nitrogen in the Baltic Sea Proper may stimulate blooms of toxic nitrogen-fixing Cyanobacteria such as *N. spumigena*, which frequently forms surface accumulations in the open Baltic Sea and sometimes also in the outer coastal areas. Such blooms may reduce the recreational value of a coastal area and may even pose a threat to public health. Counteracting such blooms of *N. spumigena* is thus an important issue for the Baltic Sea.

Table 2. Capacity of the different types of forming fabric tested to collect *N. spumigena*.

Polyester thread fabric	Experimental results
dw 22 – GPT	Fabric fully covered by microbes, no distinction between *Anabaena* sp. and *N. spumigena*
dw 16 – N	Fabric fully covered by microbes, no distinction between *Anabaena sp.* and *N. spumigena*
dw 16 – OP	Fabric covered by a thin layer of microbes
dw 19 – N	Fabric partly covered by a thin layer of microbes
dw 20 – OPB	Mesh size too big to exclude single microbes, with possible distinction favoring *N. spumigena* over *Anabaena* sp. *N. spumigena* form large bundles that are attached to the thread

There is a need for several strategies in order to cope with the problems of eutrophication in the Baltic Sea Proper and the increased occurrence of cyanobacterial blooms during the summer. An important problem is the political situation, as the Baltic Sea catchment comprises a number of countries with major cultural and political differences. The results of actions to prevent eutrophication in the Baltic Sea take time, and we may not see any improvements for several decades. Thus, in the foreseeable future, we may have to live with the problems of eutrophication in the Baltic Sea and an increased frequency of Cyanobacteria blooms during the summer.

This pilot study demonstrated one method to handle the problems, particularly blooms of *N. spumigena*, in the future. This cannot prevent eutrophication, but may be a possible way to preserve recreational values in some coastal areas of the Baltic Sea.

The method studied is specially designed to deal with *N. spumigena*, which prefers near-surface water in the top 5 m of the water mass, with most of the biomass concentrated in the uppermost 1 m of water during the blooms, when *Nodularia* forms floating bundles (12). *N. spumigena* is also the Cyanobacteria species that forms massive poisonous blooms that are periodically discussed in the media. The *Nodularia* blooms can also be observed by satellites and are monitored daily by the Swedish Meteorological and Hydrological Institute during the summer.

This study was conducted during the summer of 2006. There was a very short period of extensive blooms of *N. spumigena* during this summer, from 9 to 16 July (28). During that time, the project was still in its initial phase and the modified oil boom (Figs. 2 and 5) was not ready for testing until the end of July. From that time onward, the project team was on standby waiting for a new *Nodularia* bloom that never occurred. Thus, since the *Nodularia* collecting device (oil boom) has not been tested in the field during a very intensive bloom, no conclusions can be drawn regarding the efficiency of the method. However, some results from the 2006 study can be discussed since they clearly showed that the method has the potential to work during an intensive cyanobacterial bloom.

The experiment testing the forming fabric (Fig. 2) clearly demonstrated the collecting capacity of the various polyester fabrics tested (Fig. 4). Even though the concentration of Cyanobacteria in the tanks was high, the physical qualities of the Cyanobacteria in the test differed greatly from those of *Nodularia* found in field blooms, where the Cyanobacteria form large bundles of several cm in diameter (11). The most efficient forming fabrics proved to be dw 16 – N and dw 22 – GPT (Table 2). However, fabric parameters such as mesh size are believed to be of minor importance in large-scale use of polyester fabric for the collection of algal blooms of *N.*

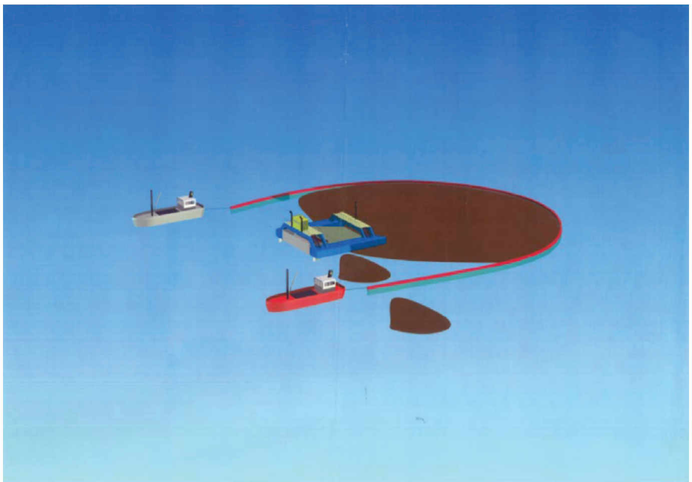

Figure 6. Oil boom transporting a *N. spumigena* bloom toward the harvesting station. (Drawing: P. Selberg).

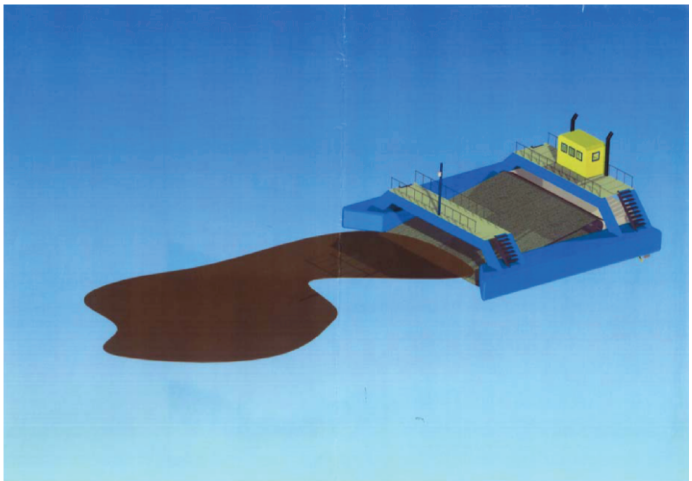

Figure 7. A harvesting station for Cyanobacteria (e.g., *N. spumigena*). (Drawing: P. Selberg).

spumigena since, in the field, this species forms large bundles. Thus, the project team decided to use the larger mesh size, dw – 20 OPB, for the operative oil boom because the experiment showed a possible distinction favoring *Nodularia* cells and bundles over other Cyanobacteria cells. It may be important to have a selective factor in order to avoid collecting algae or cyanobacterial cells that are not harmful and thus avoid a negative impact on the pelagic ecosystem. This selective factor is probably of minor importance. A more important factor is that a larger mesh size will allow longer hauls before getting clogged and reducing the efficiency of the oil boom.

The experiments provided useful information and experiences about the qualities of the forming fabrics. Following the first experiment, a decision was made to extend the pilot project by constructing a second, additional, oil boom with sections of all five forming fabrics.

On three different occasions, the operative oil boom was tested in the field without any extensive *Nodularia* blooms (Figs. 3 and 5). The results showed several positive properties of the modified oil boom. For example, the oil boom skirt (Figs. 2 and 5) adopted the desired vertical position in the water, and the forming fabric construction was stable and not obstructed by the pressure exerted by the water. The water flow through the fabric was good, indicating that the forming fabric is a useful material for the construction. The operational speed of the oil boom under the prevailing conditions was 1.5 to 2 nautical miles hr^{-1}. The field experiment also provided valuable practical experiences regarding rope length and the need for stronger and larger vessels in order to maneuver the oil boom (Fig. 3).

The capacity of the *Nodularia* collecting device was found to be 0.055 km^2 hr^{-1} when the oil boom was towed with a speed of 1 knot. The normal spread of surface accumulations of *N. spumigena* in the Baltic Sea Proper was 5400 km^2 in 2004 and 6600 km^2 in 2005 (25). In order to harvest large surface areas, a capacity of modified oil booms have to be built up. For comparison, Sweden has 10 000 m of smaller coastal oil booms similar to the one used in this study to handle oil spills along the coast (J. Fälteke, pers. comm.). A similar capacity with modified oil booms that could harvest *Nodularia* would increase the capacity to 11 km^2 hr^{-1}. Theoretically, the 2005 surface accumulation of *Nodularia* would be harvested in 50 days (based on a 12-hr working day). The cost for an oil boom is about USD 300 m^{-1}, which means that the total cost would be USD 3 million (J. Fälteke, pers. comm.). A first step can be to build up a capacity in order to protect coastal areas important for swimming and recreation; this could be done for a reasonable cost. The results indicate that the method has the capacity to clear a substantial coastal area over time if the modified oil boom can also function during an intensive bloom of *N. spumigena*.

The idea of using an oil boom to protect a coastal area from intensive blooms of Cyanobacteria has also been tested in Finland offshore from some beaches of recreational value. The results were quite positive but have not been published (E. Bonsdorff pers. comm.). In these studies, the oil boom was not modified with forming fabrics and was not towed through the bloom but only acted as a passive barrier to prevent the bloom from reaching the beach.

Studies have shown that filamentous Cyanobacteria (mostly *Aphanizomenon* sp. and *N. spumigena*) have an internal storage of phosphorous. Nitrogen is also stored within the cells to some extent. The carbon : phosphorus ratio in spring is low, indicating a high uptake of phosphorus, but rises continuously during the summer along with the increase in microbial biomass. During August and early September, when the population reaches its peak, the carbon : phosphorus ratio reaches almost fourfold the Redfield value. The use of internal stored phosphorus during summer reduces the need for filamentous Cyanobacteria to compete for phosphorus, and only a small percentage of daily mineralized phosphorus is sufficient to cover their uptake (19).

Aphanizomenon produce a considerably higher biomass than *Nodularia* and the growth season of *Aphanizomenon* is also longer than that of *Nodularia*. In the northwestern Baltic Sea Proper, *Aphanizomenon* is abundant from June to September, while *Nodularia* is only seen during July and August (29).

Estimates show that cyanobacterial atmospheric nitrogen fixation in the Baltic Sea Proper is 180 000–430 000 t nitrogen y^{-1} and thus can be almost as high as the entire riverine load and twice the atmospheric load. Atmospheric nitrogen fixation is thus an important source of nitrogen to the nourishment of pelagic zooplankton and fish (19).

Further research is needed to establish whether extensive use of modified oil booms harvesting *N. spumigena* during summer will have any effect on the eutrophication process in the Baltic Sea or whether this is only to be considered a cosmetic method for use outside coastal areas of recreational value. The inventor of the oil boom method, Per Selberg, and the author believe that the modified oil boom, in combination with floating harvesting stations (Figs. 6 and 7), could be important in withdrawing nutrients such as phosphorus and nitrogen from the Baltic Sea. The cost estimate for the harvesting station (Fig. 7) is estimated to be around USD 1 million (P. Selberg pers. comm.). The construction and function of the floating harvesting station is a patented construction by P. Selberg and will not be described in this paper. Production of biogas may be a possible way to use the harvested biomass of *Nodularia*. Cyanobacteria are not suitable as fertilizers on farmland because they may contain harmful substances (L. Kautsky pers. comm.). Much research on the topic has to be performed, but the vision is in accordance with similar thoughts on the removal of filamentous algae and blue mussels (*Mytilus edulis*) from the sea in order to decrease the overload of nutrients to the Baltic Sea Proper (30).

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