

The potential causes of cyanobacterial blooms in Baltic Sea estuaries

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Abstract

Nodularia spumigena Mertens, *Aphanizomenon flos-aquae* (L.) Ralfs and some species of the genus *Anabaena* are the dominant cyanobacterial taxa occurring in the Gulf of Gdańsk. The heterocystous cyanobacteria use dissolved molecular N₂ as an additional nitrogen source, and this allows them to bloom during the summer when growth of other phytoplankton species is normally nitrogen-limited. Although cyanobacterial blooms have been reported in the Baltic Sea since the mid-19th century, the extent and intensity of blooms have recently increased due to anthropogenic sources of eutrophication. Increased river phosphorus input and changes in the phosphorus to nitrogen ratio are implicated as causal factors. After us the initial cause of the cyanobacterial bloom is a low N:P ratio, which indicates phosphorus excess, i.e. favourable nutrient conditions for nitrogen-fixing algae. An N:P ratio of 10 has been considered an approximate value for the N:P requirements of Baltic phytoplankton. For several years this ratio has been lower than 10.

The mean annual value of the N:P ratio for the water of the Gulf of Gdańsk ranged from 3 to 7. Differences in the intensity of blooms observed in different years could be linked to temperature. During hot summers, when the seawater temperature increased to 20°C, large blooms were noted. For the cyanobacterial blooms in the Baltic Sea, the low N:P ratio is the primary factor and high temperature is a starting point.

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INTRODUCTION

An increase in productivity of natural sea and inland waters has been observed over the past few decades. Toxic blooms of phytoplankton, a result of natural water eutrophication, are a common phenomenon. The primary producers of toxins in seawater are dinoflagellates and chrysophytes, while in freshwater – blue-green algae (currently called the cyanobacteria). One of the first cases of acute poisoning of humans with water contaminated with a cyanobacterial bloom reported in the medical literature occurred in England in 1842. Currently, reports of toxic cyanobacterial blooms are increasingly frequent and originate from various continents. It is believed that in many cases the impact of algal toxins is still unknown due to erroneous diagnostics and the lack of awareness of cyanobacteria and algal toxin existence; algal toxins cause symptoms similar to those occurring from pesticide poisoning (Cook et al. 1989).

A large cyanobacterial bloom is a characteristic phenomenon, typical for many water bodies, including: lakes, ponds, slow-flowing rivers, lagoons, bays, and open waters of the Baltic Sea (Pliński et al. 1998). Blooms change the water color to blue-green, and may also change water consistency to resemble thick paint. Furthermore, during these mass occurrences cyanobacteria may create foamy layers on the water surface. Piles of these foamy layers are usually blown by the wind towards the shore of the water body. Both the blooms and the foamy layers may pose a threat to human and animal health, because many algal species involved in these blooms are capable of producing toxins (Carmichael 1992; Bell, Codd 1994). Cases of domestic animal poisoning, large numbers of dead fish, and perished birds related to cyanobacterial blooms and toxins created by these bacteria were reported worldwide in the previous century. Deaths of animals including, cattle, sheep, horses, pigs, dogs occurred only after drinking water containing cyanobacterial toxins (Beasley et al. 1989). In the case of dogs, the poisoning may have occurred following consumption of a hardened blanket an animal found on the shore after a bloom or during fur cleaning after coming out of bloom-containing water (Codd et al. 1992, Edler et al. 1985).

In Europe, toxic cyanobacterial blooms have been observed in at least 20 countries, including Poland. Such blooms do not always produce toxins. However, based on surveys conducted in Finland, Norway, Sweden, Great Britain, and Australia, it was concluded that at least 50% of blooms tested positive for toxicity (Codd 1992). Such a high probability of poisoning requires that measures be undertaken with the assumption that every bloom is toxic, even if this turns out not to have been the case. The reported isolated cases of animal poisoning do not challenge the above guidelines, because the problem

remains unresolved due to imprecise description of the phenomenon, incomplete research, and insufficient information concerning blooms.

An increase in intensity of “red tide” phenomena has been observed in the marine environment, particularly in coastal waters. This phenomenon is caused by mass single-species blooms of flagellates, including dinoflagellates. In most cases, these are toxin-producing species. They are a component of phytoplankton and constitute a food source for marine animals, especially bivalves, crustaceans, and fish. Having entered the alimentary canal, they undergo digestion; the released toxins accumulate in the animal body, which, when consumed, pose a health hazard, in many cases causing human death. Therefore, algal toxins constitute a serious health and above all economic problem, especially for seafood growers. Furthermore, the toxins constitute an ecological problem, because they are also responsible for deaths of marine mammals that feed on contaminated food.

In the Baltic Sea, blooms of filamentous cyanobacteria are reported regularly every year in late summer. The most intense blooms occur during windless summer periods, usually at the end of July and beginning of August. These blooms have been reported since the mid-nineteenth century. It has been observed that this phenomenon has increased with time, and intensification of these blooms is related to the increased eutrophication of Baltic waters (Horstman 1975). The coastal regions, such as Gdańsk Bay, have been particularly exposed to strong human pressure for an extended period. This exposure has resulted in considerable cyanobacterial blooms and especially in the reduction of biodiversity (Wiktor and Pliński 1992).

CYANOBACTERIAL ECOLOGY

Cyanobacteria, also called blue-green algae, are taxonomically most closely related to bacteria, and belong to the common group, prokaryotes. Ecologically, most species of cyanobacteria are characterized by a wide adaptive range. These bacteria have the ability to utilize a wide light spectrum, they are resistant to poor oxygen conditions, endure high pH values, and are generally of considerable size, which makes them inedible by zooplankton. Furthermore, they are able to grow in water with a low nitrogen to phosphorus ratio due to the ability to fix free atmospheric nitrogen under conditions of deficiency of nitrate and ammonium salts. Cyanobacteria can also accumulate nitrates and phosphates in their cells. The characteristic feature of cyanobacteria is the presence of gas vacuoles in cells, which enable them to change their specific gravity and move vertically in the water column. As a result, the cyanobacteria are able to take advantage of optimal light conditions, which, when

accompanied by an excess of macronutrients, creates favorable conditions for their intense proliferation (Kononen 1992).

Cyanobacterial blooms are usually observed in the second half of the year. Proliferation of cyanobacteria is slow due to the low growth index, which is strongly correlated with temperature and quantity of daylight (short days with high temperature). Therefore, in moderate latitudes, cyanobacterial blooms occur later than blooms of other groups of phytoplankton. Spring blooms of diatoms and early summer blooms of golden algae or green algae use up the available phosphorus, nitrogen, and in the case of diatoms, silica and, after dying, deposit them in the benthos. If not all sources of phosphorus in the water were utilized, or the water body was fertilized, the cyanobacteria may intensify their growth and “explode” in a bloom. A deficiency in nitrate salts (nitrates and ammonium salts) caused by growth of diatoms and other algal groups is compensated for through the fixation of atmospheric nitrogen, which is performed by cyanobacterial species capable of producing toxins. The low ratio of nitrogen to phosphorus (total N/total P < 29) creates favorable conditions for cyanobacterial growth; however, this simple explanation is insufficient to account for all cyanobacterial blooms, which also include species that are incapable of fixing atmospheric nitrogen. The sole increase of macronutrient content in water is not a sufficient cause for intensified proliferation of cyanobacteria; however, without this process the proliferation certainly would not occur. An extended period of warm and sunny weather is necessary for the development of a bloom. These weather conditions have been present in Poland and in the rest of Europe for the past few years (Pliński and Józwiak 1995).

CYANOBACTERIAL BLOOMS IN THE BALTIC SEA

Based on the results of paleolimnological studies, Bianchi et al. (2000) concluded that blooms of nitrogen fixing cyanobacteria occurred in the present Baltic proper as early as 7000 B.C. when the Ancylus Lake was transformed into the saltwater Litorina Sea. Because this event took place long before anthropogenic water eutrophication, cyanobacterial blooms in the Baltic Sea can be considered a natural phenomenon. According to Finni et al. (2001) *Nodularia* originally occurred in the Baltic Sea in the demersal zones of slightly salty bays and estuaries. The presence of *Nodularia* as a prevailing species in the open sea was reported for the first time at the end of July and the beginning of August of 1939. In the 1960s, mass blooms of this cyanobacterial species occurred regularly in the proper and southern sections of the Baltic, primarily as a result of eutrophication. It is estimated that between 1950 and 1980 the amount of nitrogen discharged into the Baltic increased four-fold and that of phosphorus, eight-fold. Additionally, at the end of the 1960s and in the 1970s,

several considerable inflows of salt water from the North Sea occurred, which enriched the Baltic water in macronutrients. Studies demonstrated that a significant increase in pigment concentration characteristic for cyanobacteria was observed in sediments during that period, including myxoxanthophyll, echinenone, and zeaxanthin (Poutanen and Nikkilä 2001). While in the 1980s the toxic species *Nodularia spumigena* constituted ca. 17% of the total biomass, between 1997 and 2003, its fraction was estimated to equal over 50% (HELCOM). Thus, eutrophication contributed not only to a change in the phytoplankton biomass, but also had a tremendous impact on community structure; it caused a significant reduction in biodiversity. Currently, blooms of *Aphanizomenon flos-aquae* and *Nodularia spumigena* are typical phenomena for waters of the Baltic proper; whereas, *Anabaena lemmermannii* occurs primarily in coastal waters. *Aphanizomenon flos-aquae* and *Nodularia spumigena* have many common features, but they differ in their required temperature conditions; therefore, they can co-dominate in the same ecological niche. In the Baltic, *N. spumigena* is the primary phytoplanktonic organism producing toxins. To date, the Baltic strain of *A. flos-aquae* has not been found to contain any of the toxins produced by the freshwater strains of this species. In the Baltic, hepatotoxins from the cyclic heptapeptides group are produced by cyanobacteria from the genera *Anabaena* and *Microcystis* (Mazur and Pliński 2003, Karlsson et al. 2005).

Satellite data and surveys conducted during monitoring cruises, for example as part of the [Alg@line](#) project, confirm the constant increase of cyanobacterial biomass in the Baltic. This process progresses despite the fact that concentrations of macronutrients do not increase, and are even decreasing in some regions in comparison with the 1980s (Łysiak-Pastuszak et al. 2004). Large blooms of cyanobacteria are not only a manifestation of intensified eutrophication, but are also a result of equilibrium disturbance in the aquatic ecosystem. According to the Declaration signed in 1988, the states located on the Baltic Sea committed themselves to reducing phosphorus and nitrogen compounds that are discharged into the sea by rivers by 50%. The quantity of harmful compound discharge has been reduced by 35% over a relatively short period (ca. 7 years), (Neumann and Schernewski 2005), but further reduction of the N and P discharge has proved much harder to accomplish. The reduction of N discharge during the short period contributed to the proportional reduction of the DIN content in the water (attributed to the process of denitrification, especially in oxygenated sediments). However, reduction of the DIP content proceeds much more slowly. According to Łysiak-Pastuszak and Drgas (2001 a, b), the phosphate concentration has decreased in Gdańsk Bay by only 5% since 1990, which was concurrent with a much greater reduction in nitrate concentration. Depletion of P in water occurs only through deposition of this

element in the sediment. However, under conditions of oxygen deficiency, Fe undergoes reduction, which frees P from organic matter and in turn increases the DIP content. Therefore, the reduction of macronutrient discharge indirectly contributed to a decrease in the N/P ratio. Thus, favorable growth conditions were created for nitrogen fixing cyanobacteria. A low value of N/P in itself does not determine the development of the cyanobacterial blooms, but it creates unfavorable growth conditions for organisms that compete with them for space in the ecosystem. Neumann and Schernewski (2005) maintained that the upward trend in cyanobacterial blooms is a temporary phenomenon (following the 35% reduction of macronutrient discharge) and will last until the Baltic ecosystem reaches a new state of equilibrium. It is believed that the reduction of DIP content to the level of DIN may take ca. 20-30 years.

For filamentous cyanobacteria from the *Nostocales* and *Stigonematales* the essential element for adaptation to environmental nitrogen deficiency are heterocysts. These are specialized cells, within which the process of molecular nitrogen fixation (N_2) from the atmosphere occurs. In *N. spumigena*, heterocysts constitute approximately 5% of all cells in the filament. Due to the smaller numbers of heterocysts (1%), *A. flos-aquae* fixes N_2 less effectively. The occurrence and growth of filamentous cyanobacteria is not limited by concentrations of dissolved forms of nitrogen. Furthermore, it is estimated that in the Baltic proper, cyanobacteria alone yield from 30 to 430×10^3 of N annually (Rahm et al. 2000, Larsson et al. 2001). This quantity of nitrogen is comparable to that discharged into the Baltic Sea by rivers. In this situation, the primary element limiting the growth of N_2 fixing cyanobacteria is phosphorus (e.g. Moisander et al. 2003). Based on measurements of P concentration in water, or essentially the excess of P in relation to N (considering the demand of phytoplankton for these elements, N:P 16:1), it was possible to determine the probability of occurrence of a cyanobacterial bloom as early as February. The authors of the most recent prognostic models pay special attention to the DIP content (dissolved inorganic phosphorus) on around June 15, that is, after the spring algal blooms and before the summer cyanobacterial blooms (Laanemets et al. 2006). However, a cyanobacterial bloom may occur even if there are no dissolved phosphorus compounds in the second half of June. These compounds may appear in the surface water as a result of an intensive mixing of water masses or upwelling. It is also known that cyanobacteria accumulate reserves of P, which allow them to survive and proliferate in the case of a temporary deficiency of this element in the environment.

The experiments of Vuorio et al. (2005), which measured the impact of low values of N/P with increasing concentrations of P, did not confirm the decisive role of these factors. Cole et al. (1993) argued that in the case of cyanobacteria that fix molecular nitrogen, molybdenum, the element that is an integral part of

nitrogenases, might also be a factor limiting growth. Molybdenum occurs in seawater in the form of molybdate, which are structural analogues of sulfates; in the Baltic Sea, this does not limit the growth of cyanobacteria. However, high concentrations of SO_4^{2-} in the environment may cause poorer assimilation of MnO_4^{2-} and, in turn, hinder the activity of nitrogenase – an enzymatic complex that takes part in nitrogen fixation (Stal et al. 2003). A significant reduction of nitrogenase activity in *N. spumigena* was observed at a SO_4^{2-} concentration exceeding 9 mmol dm^{-3} , which corresponds to the salinity of ca. 9 PSU. Biological concentration of an accessible form of Fe in seawater is low, but demand for this element in such cyanobacteria as *Nodularia* is considerable. Iron is a component of both nitrogenase and ferredoxin, which is an electron donor for nitrogenase.

Poor water exchange in the Baltic results in the development of a salinity gradient from 9 PSU in the southern part of the Sea to 1-2 PSU in the northern part of the Gulf of Bothnia. The salinity of deep water is greater than that of surface water and reaches 10-13 PSU for the Baltic proper. After a period of extensive water exchange with the North Sea through the Kattegat Strait, the salinity of bottom water in the area of the Bornholm Basin may even reach 20 PSU. It is believed that salinity is one of the most important abiotic factors that determines the structure of phytoplankton communities and the development of cyanobacterial blooms. The studies conducted have demonstrated that the salinity level optimal for growth and nitrogen fixing of *N. spumigena* is 5 – 13 PSU (Sivonen et al. 1989). Blooms of this cyanobacterium do not occur in the Kattegat Strait or in the northern part of the Gulf of Bothnia, that is, in waters with salinity levels above 20 PSU or below 3 PSU. Growth of *A. flos-aquae* is significantly hindered in waters with over 10 PSU; optimal growth for this species was observed at salinity levels of 0-5 PSU (Lehtimäki et al. 1997). It is believed that salinity affects the bacterial growth directly by curbing physiological processes and indirectly by changing the impact of other environmental factors (Moisander et al. 2002, Mazur-Marzec et al. 2005). Freshwater species *Microcystis aeruginosa* shows slight growth and decelerated CO_2 fixation in an environment with salinity above 2 PSU. Numerous species of cyanobacteria are capable of adapting to salinity fluctuations due to the production of osmotically active organic substances, active transport of ions into and out of the cell, or production of stress proteins. The energy required for these processes, which help to retain the proper osmotic potential in the cell, is utilized for growth. Higher levels of salinity decrease the nitrogenase activity, the enzyme that plays a key role in N_2 fixation.

Water temperature, in addition to the concentration of biogenic salts, is an important determinant of mass growth of cyanobacteria from the *Nodularia* genus. When the water temperature reaches 16°C the maturation of akinete -

endospore forms begins, which facilitate cyanobacteria survival in unfavorable conditions. Although upwelling enriches surface water with biogenic substances, it does not have a positive impact on cyanobacterial growth because of the described temperature requirements. The water temperature within an upwelled area is approximately 4-6°C lower and usually does not exceed 16°C. Furthermore, temperature indirectly affects the blooms by contributing to water column stratification, which has a stabilizing effect and restricts water mixing. Wasmund (1997) noted the role of temperature in the acceleration of phosphorus remineralization in sediments. This factor is of essential importance, especially in shallow waters. The optimal temperature for *A. flos-aquae* is slightly lower and ranges from 16 to 22°C. This species also occurs in the Baltic Sea in winter.

Cyanobacteria have developed a range of mechanisms that enable them to adapt to fluctuations in light intensity. This factor determines the development of blooms to a significant degree, especially in the case of nitrogen fixing organisms. This process requires a large amount of energy. The disappearance of blooms was observed when the intensity of photosynthetically active radiation was reduced by 50% and wind velocity exceeded 5 m s⁻¹. The optimal range of light intensity for the growth of *N. spumigena* and *A. flos-aquae* equals 105-155 and 25-45 μmol photons m⁻² s⁻¹, respectively (Konoshina et al. 2003). Under conditions of low sun radiation intensity and decelerated photosynthesis, cyanobacteria accumulate extra material in the form of polysaccharides, which results in the reduction of osmotic potential in a cell. This state is responsible for the increased production of gas bubbles, which cause the cells to rise in the water column. Windless weather (wind velocity below 4 m s⁻¹) and poor mixing of water masses are necessary conditions for development of surface clusters of cyanobacteria. If such conditions prevail, it is estimated that *Nodularia* aggregates may move towards the surface with a speed of 36 m per day (Walsby et al. 1995). An increase in wind velocity above 6-8 m s⁻¹ results in dispersion of these clusters; cells are transported to greater depths, where lower light intensity reduces photosynthesis and nitrogen fixation rates, which hinders cyanobacterial growth.

In recent years, cyanobacterial blooms were observed in the Baltic Sea annually. However, their intensity and ranges varied each year. The heterogeneous nature of this phenomenon substantially hinders monitoring conducted by conventional methods of sample collection.

FACTORS RESPONSIBLE FOR PRODUCTION OF CYANOBACTERIAL TOXINS

Cyanobacterial toxins are liberated into the water only when cells die or age and lose their contents. Animal poisoning usually occurs when an entire

cyanobacterial organism is consumed. Poisoning may also occur when an animal drinks water contaminated with released toxins. The mechanism by which cyanobacteria release toxins into the water remains unknown. Maximal production of cyanobacterial toxins occurs in different periods and may vary in the same water body from year to year. Experiments have demonstrated that optimal growth of *Microcystis aeruginosa* cells and toxin production occurs in the presence of Zinc. *Microcystis aeruginosa* is one of the most common species of cyanobacteria and forms extensive blooms in various types of water bodies. In the presence of non-toxic concentrations of Al, Cd, Cr, Cu, Mn, Ni, and Sn, a significant increase in *M. aeruginosa* cell proliferation and toxin production was not observed. However, when the concentration of iron is very low ($< 2,5 \mu\text{M}$) or absent, the cells grow very slowly but produce 20-40% more toxin.

Therefore, environmental stress factors are responsible for the production of toxins by cyanobacteria. Among the physical factors, temperature and light intensity are the primary determinants. It was found that one of the *M. aeruginosa* strains grows at the highest rate at 32°C, while the toxicity of these cells reaches a maximum at 18-25°C (ca. 50% higher than the toxicity of cells growing at 32°C). *Aphanizomenon* cultures reach their thermal optimum for production of toxins at 26°C; whereas, for *Anabaena*, the highest production occurs at 22.5°C. Light has a considerable impact on the growth rate of *M. aeruginosa*; however, it does not affect the toxicity of this species. Among the chemical factors, tests have included the impact of pH and macronutrients on the growth rate and toxicity of *M. aeruginosa*. It was found that the highest growth rate of this species occurs at pH = 9.0, and toxicity increases at lower and higher values of pH. Low concentrations of nitrogen and phosphorus significantly reduce the growth rate of *M. aeruginosa*, but this factor has a relatively small impact on toxicity. Removal of phosphorus from culture medium does not affect the cell toxicity, but the reduced concentration of nitrogen or inorganic carbon causes a ca. ten-fold increase in toxicity. It was observed that the quantity of cyanobacterial toxins is positively correlated with phosphorus levels in lacustrine waters and the abundance of *M. aeruginosa*, and negatively correlated with nitrogen content in water. Therefore, it seems probable that the most effective method for prevention of cyanobacterial blooms is the reduction of phosphorus compound discharge into the water.

The impact of biological factors on toxin production has not been satisfactorily explained. It has been observed that consumption of *Microcystis aeruginosa* by *Daphnia* spp. took place when the number of colonies did not exceed five; however, alternative data demonstrate that the death of both juvenile and adult forms of this zooplankter occurred under similar conditions.

Toxic cells of *Anabaena affinis* affect zooplankton selectively: they limit growth rate of populations of large forms of Cladocera, but this reaction is not observed in small forms of both Cladocera and Rotifera. It is still unclear if animals possess a selective feeding mechanism, and if so, to what extent. This mechanism would enable an animal to react selectively to toxic cells of cyanobacteria and could be considered a factor for interspecific competition in zooplankton (Tarczyńska, Zalewski 1994).

METHODS OF CONTROL AND REDUCTION OF CYANOBACTERIAL BLOOMS

Cyanobacteria inhabiting a water body and developing blooms are difficult to eliminate from the ecosystem. Both endospore and vegetative cells produced by cyanobacteria may survive in sediments for many months and even years. Application of technical methods, such as constant artificial aeration or destratification of the water column may prevent development of the bloom foam or foam layers floating on the water surface, but is expensive and ineffective, especially in the case of large water bodies.

Researchers are investigating methods that would directly remove the cyanobacteria through their consumption by protozoa, fungus parasites or bacteria and cyanophages, which cause lysis of cyanobacterial cells. It has been found that certain macrophytes (*Ceratophyllum* sp., *Myriophyllum* sp., *Lemna minor*) and filamentous algae (*Cladophora* sp., *Pitophora oedogonium*) are capable of making substances that inhibit growth of *Microcystis aeruginosa* and *Anabaena* sp. even when nitrogen is a factor limiting phytoplankton growth.

Certain countries apply a method of bloom control in drinking water reservoirs quite often. In this method, copper sulfate is added to the water, causing lysis of algae cells. This method, however, results in the sudden release of toxins into the water, and the water becomes undrinkable for several weeks. Furthermore, treating water with copper sulfate reintroduces large quantities of macronutrients into circulation, which previously were accumulated in cells. This process is a result of the disintegration of cell walls. For that reason, this method proves to be ineffective and even harmful, and as such should not be recommended.

Alternative methods for controlling cyanobacterial blooms should be based on the prevention of algal bloom development rather than on their elimination; in other words, the methods should focus on removing causes and not effects in the form of excessive proliferation of bacteria. The techniques for limiting blooms should therefore be based on controlling the most essential factors that determine bacterial growth, that is, phosphorus. Both the amount of phosphorus discharged into the water body and the amount of phosphorus released into the circulation from sediments should be controlled. A safe and effective method of

controlling the cyanobacterial blooms involves treating water with calcium, which does not disintegrate the algal cells, but limits their development through fixing easily assimilable forms of phosphorus. Furthermore, experiments have demonstrated that treating cyanobacterial blooms with calcium results in the release of very small quantities of toxins into the water; in some cases, the concentration of cyanobacterial toxins was lower than in the control. On the other hand, the side effects of calcium treatment can be increased pH and a lack of free CO₂, which prevents the growth of other planktonic algae - potential competitors of cyanobacteria (Chorus, Bartram 1999).

To recapitulate, it should be stressed that cyanobacteria pose a potential threat to every water body. They are particularly dangerous for reservoirs that are used for recreation and whose water is intended for human consumption. The effects of cyanobacterial blooms in fish ponds and other economically viable reservoirs are not without significance. The current state of knowledge regarding conditions for cyanobacterial bloom development as well as mechanisms of toxin release and production is very unsatisfactory. It is known that the same species, in the same water body, and under the same environmental conditions can be toxic or non-toxic at different times. Furthermore, all methods of bloom control applied to date in order to neutralize cyanobacterial toxins have proved to be ineffective. These methods require extensive further research and implementation.

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REFERENCES

- Beasley V.R., Coppock R.W., Simon J., Ely R., Buck W.B., et al., 1989, *Algae intoxication in livestock and waterfowl*, *Clinic. Toxicol.*, 5: 345-61
- Bell S.G., Codd G.A., 1994, *Cyanobacterial toxins and human health*, *Rev. Med. Microbiol.*, 5: 256-64
- Bianchi T.S., Engelhaupt E., Westman P., Andrén T., Rolff C., Elmgren R., 2000, *Cyanobacterial blooms in the Baltic Sea: Natural or human-induced?*, *Limnol. Oceanogr.*, 45(3): 716-26
- Carmichael W.W., 1992, *Cyanobacteria secondary metabolites and the cyanotoxins*, *J. Appl. Bact.*, 72: 445-59
- Chorus I., Bartram J., 1999, *Toxic cyanobacteria in water*, E & FN Spon, London and New York, pp. 416

- Codd G.A., 1992, *Eutrophication, Blooms and Toxins of Cyanobacteria (blue-green algae), and health [in:] Proceedings of the fourth diaster prevention and limitation conference. The changing face of Europe: Diasters, pollution and the environment.* Aquatic problems, vol. 4, Keller A.Z., Wilson H.C. (eds.), University of Bradford, pp. 33-62
- Codd G.A., Edwards C., Beattie K.A., Barr W.M., Gunn G.J., 1992, *Fatal attraction to cyanobacteria?*, Nature, 359: 110-111
- Cole J.J., Lane J.M., Marino R., Howarth R.W., 1993, *Molybdenum assimilation by cyanobacteria and phytoplankton in freshwater and salt water*, Limnol. Oceanogr., 38: 25-35
- Cook W.O., Beasley V.R., Lovell R.A., Dahlem A.M., Hooser S.B., Mahmood N.A., Carmichael W.W., 1989, *Consistent inhibition of peripheral cholinesterases by neurotoxins from the freshwater cyanobacterium Anabaena flos-aquae: studies of ducks, swine, mice and a steer*, Environ. Toxicol. and Chemistry, 8: 915-22
- Edler L., Ferno S., Lind M., Lundberg R., Nilsson P.O., 1985, *Mortality of dogs associated with bloom of the cyanobacterium Nodularia spumigena in the Baltic Sea*, Ophelia, 24: 103-9
- Finni T., Kononen K., Olsonen R., Wallström K., 2001, *The history of cyanobacterial blooms in the Baltic Sea*, Ambio, 30(4-5): 172-78
- Hallegraeff G.M., 1995, *Harmful algal blooms: A global overview [in:] Manual on harmful marine microalgae*, IOC of UNESCO, Manuals and Guides, 33: 1-22
- Horstmann U., 1975, *Eutrophication and mass production of blue-green algae in the Baltic*, Merentutkimuslait. Julk./Havsforskningsinst. Skr., 239: 83-90
- Karlsson K.M., Kankaanpää H., Huttunen M., Meriluoto J., 2005, *First observation of microcystin-LR in pelagic cyanobacterial blooms in the northern Baltic Sea*, Harmful Algae, 4: 163-66
- Kononen K., 1992, *Dynamics of the Toxic Cyanobacterial Blooms in the Baltic Sea*, Finnish Marine Research, 261: 1-36
- Konoshina I., Lips U., Leppänen J.-M., 2003, *The influence of weather conditions (temperature and wind) on cyanobacterial bloom development in the Gulf of Finland (Baltic Sea)*, Harmful Algae, 2: 29-41
- Laanemets J., Lilover M.J., Raudsepp U., Autio R., Vahtera E., et al., 2006, *A fuzzy logic model to describe the cyanobacteria Nodularia spumigena blooms in the Gulf of Finland, Baltic Sea*, Hydrobiol., 554: 31-45
- Larsson U., Hajdu S., Walve J., Elmgren R., 2001, *Baltic Sea nitrogen fixation estimated from summer increase in upper mixed layer total nitrogen*, Limnol. Oceanogr., 46: 811-20
- Lehtimäki J., Moisander P., Sivonen K., Kononen K., 1997, *Growth, nitrogen fixation, and nodularin production by two Baltic Sea cyanobacteria*, Appl. Environ. Microbiol., 63: 1647-56
- Lysiak-Pastuszek E., Drgas N., 2001a, *Nitrogen compounds [in:] Environmental conditions in the Polish zone of the southern Baltic in 2000*, Krzemiński W., Łysiak-Pastuszek E., Miętus M. (eds), Mater. Oddz. Mor. Inst. Meteorolog. Gosp. Wod., Gdynia, pp. 102-113, (in Polish)
- Łysiak-Pastuszek E., Drgas N., 2001b, *Phosphorous compounds [in:] Environmental conditions in the Polish zone of the southern Baltic in 2000*, Krzemiński W., Łysiak-Pastuszek E., Miętus M. (eds), Mater. Oddz. Mor. Inst. Meteorolog. Gosp. Wod., Gdynia, pp. 89-96, (in Polish)
- Łysiak-Pastuszek E., Drgas N., Piątkowska Z., 2004, *Eutrophication in the Polish coastal zone: the past, present status and future scenarios*, Mar. Pollution Bulletin, 49: 186-95
- Mazur H., Pliński M., 2003, *Nodularia spumigena blooms and the occurrence of hepatotoxin in the Gulf of Gdańsk*, Oceanologia, 45: 305-16

- Mazur-Marzec H., Żeglińska L., Pliński M., 2005, *The effect of salinity on growth, toxin production, and morphology of Nodularia spumigena isolated from the Gulf of Gdańsk, southern Baltic Sea*, J. Appl. Phycol., 17(2): 171-79
- Moisander P.H., McClinton E., Pearl H.W., 2002, *Salinity effects on growth, photosynthetic parameters, and nitrogenase activity in estuarine planktonic cyanobacteria*, Microb. Ecol., 43: 432-42
- Moisander P.H., Steppe T.F., Hall N.S., Kuparinen J., Pearl H.W., 2003, *Variability in nitrogen and phosphorus limitation for Baltic Sea phytoplankton during nitrogen-fixing cyanobacterial blooms*, Mar. Ecol. Prog. Ser., 262: 81-95
- Neumann T., Schernewski G., 2005, *An ecological model evaluation of two nutrient abatement strategies for the Baltic Sea*, J. Mar. Syst., 56: 195-206
- Pliński M., Józwiak T., 1995, *Dynamics of Heterocystous Cyanobacteria Growth in the Brackish Water*, Abstracts of 7th Intern. Conf. on Toxic Phytoplank., Japan, pp. 101
- Pliński M., Musiał A., Ostrowski B., 1998, *Blue-green algae blooms in the Gulf of Gdańsk and surrounding area*, Oceanological Stud., 27(1): 39-44
- Poutanen E-L., Nikkilä K., 2001, *Carotenoid pigments as tracers of cyanobacterial blooms in the recent and postglacial sediments of the Baltic Sea*, Ambio, 30(4-5): 179-83
- Rahm L., Jönsson A., Wulff F., 2000, *Nitrogen fixation in the Baltic proper: an empirical study*, J. Mar. Systems, 25: 239-48
- Sivonen K., Kononen K., Carmichael W.W., Dahlem A.M., Rinehart K.L., Kiviranta J., Niemelä I., 1989, *Occurrence of the hepatotoxic cyanobacterium Nodularia spumigena in the Baltic Sea and structure of the toxin*, Appl. Environ. Microbiol., 55(8): 1990-95
- Stal L.J., Albertano P., Bergman B., von Bröcel K., Gallon J.R., Hayes P.K., Sivonen K., Walsby A.E., 2003, *BASIC: Baltic Sea cyanobacteria. An investigation of the structure and dynamics of water blooms of cyanobacteria in the Baltic Sea – responses to a changing environment*, Continental Shelf Research, 23: 1695-714
- Tarczyńska M., Zalewski M., 1994, *Toxicity of cyanobacterial blooms in eutrophic reservoirs [in:] The integrated strategy of the protection and the farm implements of water ecosystems*, Bibl. Monitoringu środowiska, pp. 79-89, (in Polish)
- Vuorio K., Lagus A., Lehtimäki J.M., Suomela J., Helminen H., 2005, *Phytoplankton community responses to nutrient and iron enrichment under different nitrogen to phosphorus ratios in the northern Baltic Sea*, J. Exp. Mar. Biol. Ecol., 322: 39-52
- Walsby A.E., Hayes P.K., Boje R., 1995, *The gas vesicles, buoyancy and vertical distribution of cyanobacteria in the Baltic Sea*, Eur. J. Phycol., 30: 87-94
- Wasmund N., 1997, *Occurrence of cyanobacterial blooms in the Baltic Sea in relation to environmental conditions*, Int. Revue ges. Hydrobiol., 82(2): 169-84
- Wiktor K., Pliński M., 1992, *Long-term changes in the biocoenosis of the Gulf of Gdańsk*, Oceanologia, 32: 69-79