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# EUTROPHICATION AND MASS PRODUCTION OF BLUE-GREEN ALGAE IN THE BALTIC

Ulrich Horstmann
Institute of Marine Research, 23 Kiel, FRG

Mass occurrences of the blue-green algae *Aphanizomenon flos-aquae* and *Nodularia spumigena* have been observed more often in the Baltic proper during the last few years. The present paper touches on some questions connected with the mass production of Cyanophyceae, such as the origin of the blue-green algae blooms, their limitation by nutrients, their nitrogen fixation and their role as nitrate suppliers. The agglomeration of blue-green algae is shown to be a biotic community, and some relations of these algae in the food web are examined. Some results of *in situ* experiments and recent laboratory investigations are given.

When Prince Albert of Monaco was sailing through the Gulf of Finland on his famous yacht »L'Hirondelle» in summer 1884, he observed »une grande quantité de petites algues». Since that time blue-green algae blooms, which is what he most probably saw, have been reported in the Baltic, in coastal areas, especially in the firths, haffs and river mouths (Apstein 1902, Ostenfeld 1931, Välikangas 1926, Gessner 1957). The plankton blooms were generally caused by *Aphanizomenon flos-aquae* and *Nodularia spumigena*, but *Anabaena* species were occasionally observed. Though the central Baltic phytoplankton populations were investigated on various expeditions (Trahms 1939, Bandel 1940), we have found very few early reports of mass occurrences of blue-green algae (Hensen 1887, Apstein 1902). In the last few years, extensive mass occurrences of blue-green algae have been repeatedly observed in the central Baltic, mainly during the summer; *e.g.* on the expeditions of »F.K. Alkor» in late summer 1969, 1971 and early summer 1970 and 1972.

Blue-green algae can be observed in two different but merging forms. In the inner archipelago of the Swedish and Finnish coast as well as in the southern firths, in the haffs and river mouths, they stain the water olive green, while in the outer archipelago and in the open Baltic, the algae occur as whitish-yellow flakes.

Mainly in calm weather, the trichome bundles of the blue-green algae tend to drift to the watei surface. They can sometimes be so dense that they form a yellow-whitish pulp. Particularly in the late summer one can travel for several hours through more or less concentrated patches of these Cyanophyceae.

The algae can form bands extending between less than 100 m and several km, at right angles to the direction of the wind. They reveal the occurrence of slicks, an effect of internal waves which occur in the thermohaline layer.

Mass occurrences of blue-green algae were observed by us south of the Åland islands, and also during various voyages in the Baltic proper, and in the Belt Sea as far as the southern Kattegat.

Inshore, the vertical distribution of blue-green algae usually extends throughout the euphotic zone. Offshore, the depth distribution of Cyanophyceae seems to be strongly influenced by wind-dependent turbulence. In calm weather bundles of algal trichomes concentrate close to the surface. With increasing wind and depending on wave height, they can also be found evenly distributed higher or lower in the water column.

*Aphanizomenon flos-aquae* and *Nodularia spumigena*, the two species of blue-green algae most often responsible for blooms in the Baltic, almost always occur together. The cells of *Aphanizomenon flos-aquae*, formerly termed *Limnochlide flos-aquae*, are 4—6 $\mu$m wide and 5—15 $\mu$m long. *A. flos-aquae* has heterocysts which are scarcely larger than the vegetative cells. The trichomes stick together to form a rhombus-like structure. Sometimes they grow in cushion-shaped bundles, which can be more than 1 mm long and equally wide.

The vegetative cells of *Nodularia spumigena* are 10—16 $\mu$m wide and 8—14 $\mu$m long. The heterocysts are slightly larger than the vegetative cells.

The appearance of the trichomes varies. In waters with low salinity, in the inner archipelago and in the firths and haffs, the trichomes of *Nodularia spumigena* are mostly stretched and can grow to several centimetres long. In the outer archipelago and in the open Baltic the trichomes are mainly twisted spirally (Fig. 1) and can form an agglomeration in which the chains of cells measure several centimetres. Under a microscope such a *Nodularia* agglomeration is seen to be a biotope for countless sessile and planktonic organisms (Fig. 2). Diatoms of the *Navicula* type stick to the trichomes together with vorticells and Bryozoa. Different species of Cyanophyceae, Peridineae and numerous diatom species can be found in these flakes, their appendices and bristles entwined with the chains of blue-green algae. Large numbers of flagellates and planktonic ciliates occur as well as rotifers and adults and larvae of crustaceans.

*In situ* experiments with blue-green algae were carried out in August 1972 at the Askö Laboratory in the Swedish archipelago, 60 km south of Stockholm. In this area the salinity is approximately 8 ‰ and conditions are favourable for the growth of blue-green algae. Attention was mainly paid to the effects of the phosphate and nitrogen concentrations, since they influence the growth of blue-green algae as well as the number of heterocysts. The experiments were started shortly after the height of a blue-green algae bloom, when *Nodularia spumigena* was predominant over *Aphanizomenon* (Horstmann 1973). Twelve plastic bags in 2 frames containing 800 l were filled with the surrounding water. In six bags the plankton had been concentrated five times with a net (56 $\mu$m pores). During an experimental period of 3 weeks, the concentration of blue-green algae and the heterocyst number,

TABLE 1. Growth rate of a plankton population (*Nodularia spumigena* dominant) held in plastic bags for 18 days.

| Plankton population | Not concentrated | | | | | | | | | Concentraten with net c. 4 x | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Nutrient supply | Control | | | $PO_4$ | | $NO_3$ | | $PO_4+NO_3$ | | Control | | | $PO_4$ | $NO_3$ | $PO_4+NO_3$ | |
| | $PO_4$ | $NH_3$ | $NO_3$ | | | | | | | $PO_4$ | $NH_3$ | $NO_3$ | | | | |
| Initial concentration of nutrients μg at/l | 2.8 | 5.5 | 6.0 | 26.5 | | 70.5 | | 48.5 | 82.0 | 2.1 | 6.5 | 8.3 | 28 | 78 | 48 | 70 |
| Chlorophyll concentration μg/l | a | | c | a | c | a | c | a | c | | a | | a | a | a | |
| 1st day | 3.5 | | < 1 | 4.0 | < 1 | 3.4 | < 1 | 3.9 | < 1 | | 15.3 | | 14.4 | 17.3 | 18.0 | |
| 3rd day | 3.0 | | » | 7.2 | » | 4.6 | < 1 | 2.4 | < 1 | | 8.4 | | 18.1 | 12.3 | 12.2 | |
| 6th day | 1.2 | | » | 25.4 | » | 3.1 | < 1 | 28.5 | 2.0 | | 18.4 | | 32.1 | 12.0 | 25.8 | |
| 12th day | 2.9 | | » | 42.6 | » | 12.8 | 4.7 | 66.8 | 3.1 | | 20.6 | | 74.3 | 22.6 | 44.6 | |
| 18th day | 5.4 | | » | 52.4 | < 2 | 28.3 | 8.4 | 56.6 | 6.4 | | 22.8 | | 42.1 | 24.2 | 122.3 | |
| Final concentrations of nutrients μg at/l | 0.5 | 1.5 | 0.6 | 8.0 | | 7.0 | | 19.0 | 0.4 | 0.2 | 0.5 | 0.6 | 6.5 | 2.5 | 19 | 0.8 |

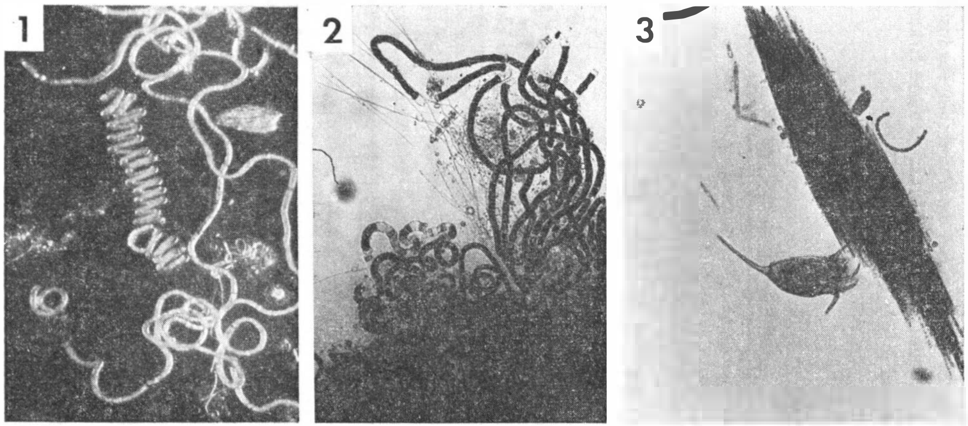


Fig. 1. 1) *Nodularia spumigena*. Trichome twisted spirally, as it appears in the outer archipelago and in the open Baltic. 2) Agglomeration of *Nodularia spumigena*. 3) *Keratella cochlearis recurvispina* picking up single cells from a trichome bundle of *Aphanizomenon flos-aquae*.

which is nutrient-dependent, were examined. Besides the oxygen content, the chlorophyll and nutrient contents of the plastic bags were measured (Table 1). At the beginning and shortly after the end of the experiment the nitrogen-fixation capacity of the blue-green algae was determined. It can be seen that blue-green algae grow considerably when phosphate is added. This growth can only be exceeded when both phosphate and nitrate are added. When only nitrate is added, there is a small increase in production as compared with the control, but this is due to the blooming of a diatom population, as is shown by the chlorophyll *c* values.

The index used to test the influence of the nutrient supply on the development of heterocysts was the number of vegetative cells per heterocyst (Table 2). The results agreed with the observation made by Stewart *et al.* (1969) in *in vitro* experiments that nitrogen causes a deficit of heterocysts in blue-green algae. An increase in heterocysts could be observed as soon as nitrogen became deficient.

The nitrogen-fixation ability was also significantly higher in populations with a greater number of heterocysts. The determination was made by the method of Steward *et al.* (1971) as modified by Granhall *et al.* (1971), whose measuring apparatus (flame ionization detector) we were kindly allowed to use. The samples were incubated at five standard depths for 2 hours at noon (Table 3). It is not possible to draw general conclusions from these values with regard to the N-fixation per m² and year for Baltic areas, but we found that, for instance, at station 1, our values were about 10 % below those obtained by Granhall *et al.* in Lake Erken in August 1972. Granhall calculated an annual rate of around 3 g N/m² for Lake Erken.

TABLE 2. Influence of nutrient supply on the development of heterocysts. Heterocyst frequency expressed as number of vegetative cells per heterocyst.

| Plankton population | Not concentrated | | | | Concentrated with net c. 4 × | | | |
|---|---|---|---|---|---|---|---|---|
| Nutrient supply | Control | $PO_4$ | $NO_3$ | $PO_4+NO_3$ | Control | $PO_4$ | $NO_3$ | $PO_4+NO_3$ |
| Initial number 31 .. | 29 | 7 | 30 | 28 | 14 | 10 | 16 | 32 |

TABLE 3. Relative nitrogen fixation ability of a plankton population (*Nodularia spumigena* dominant) after being held in plastic bags for 18 days in different nutrient concentrations; and of a natural *Aphanizomenon flos-aquae* bloom at three different stations.

| | Acetylene reduction (n moles $C_2H_4$/sample × 2 hr) | | | | | | |
|---|---|---|---|---|---|---|---|
| | Control | $PO_4$ | $NO_3$ | $PO_4+NO_3$ | *Aphanizomenon* bloom | | |
| Depth (m) | | | | | St. 1 | St. 2 | St. 3 |
| 0 | 0.32 | 1.35 | 0.56 | 0.46 | 0.84 | 0.18 | 0.74 |
| 1 | — | 1.57 | 0.76 | 0.32 | 1.22 | — | 0.69 |
| 2 | 0.21 | 0.43 | 0.84 | — | 0.92 | 0.08 | 0.54 |
| 4 | 0.18 | 0.94 | 0.32 | 0.14 | 0.45 | 0.04 | 0.23 |
| 8 | 0.02 | 0.14 | 0.02 | 0.04 | 0.09 | 0.00 | 0.04 |

The results of the *in situ* experiments yielded some clues but no definite answers to the many open questions about the blue-green algae in the Baltic.

So far, our conclusions regarding the regional origin and distribution of the algae must be based on measurements of hydrographical parameters and various biological facts.

Ostenfeld (1931), who describes *Aphanizomenon flos-aquae* as a fresh-water species, states: »A new invasion takes place every year from the rivers and lagoons bordering the Baltic». Apstein (1902) believes that blooms of *Aphanizomenon flos-aquae* only develop when the fresh water of the lagoons and rivers mixes with the salt water of the sea. He writes that *Aphanizomenon flos-aquae* does not enter fresh water.

Wesenberg-Lund's (1900) observations indicated that *Aphanizomenon flos-aquae* germinates at 12° C, but only begins to increase at 18° C. However, in May 1973 when the water temperature was less than 9° C, we observed a striking bloom of *Aphanizomenon flos-aquae* in the area of Landsort deep, and Wellershaus (1963) found *Aphanizomenon flos-aquae* in the Gotland deep almost throughout the year, its density being relatively high even during the winter.

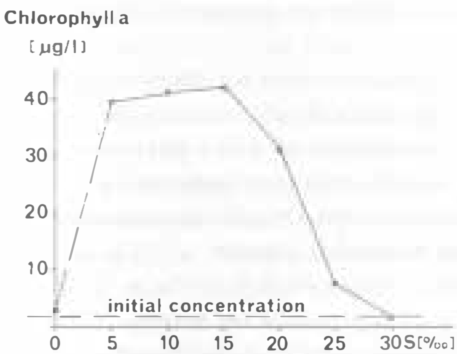


Fig. 2. Growth of pure cultures of *Nodularia spumigena* at different salinities.

As far as the salinity is concerned, at least *Nodularia spumigena* can grow in the entire central Baltic. *In vitro* experiments with pure cultures of *Nodularia* showed good development between 5 ‰ and 25 ‰ S (Fig. 2) of a *Nodularia* stock which was bred at 8 ‰ S. Thrams (1939) even reports *Nodularia spumigena* and *Aphanizomenon flos-aquae* from the North Atlantic and Mediterranean.

The phosphate content appears to be most important for the growth of blue-green algae blooms in the Baltic. Trahms (1939) and Kalbe & Tiess (1963) report *Nodularia* blooms in phosphate-rich waters. Our experiments have shown to what extent the addition of phosphate stimulates the growth of Cyanophyceae. We feel almost certain that the blue-green algae blooms in the Baltic originate mainly from those areas of the coast where large amounts of phosphate can be found in the water. Such are the mouths of the Odra and Weichsel and the strongly eutrophicated firths and haffs, as Apstein (1902) and Ostenfeld (1931) have correctly observed. Today, though, many more sources of phosphate can be found along the Baltic coast owing to the increase in the discharge of sewage.

The Cyanophyceae blooms normally appear after the spring bloom, which mainly consists of diatoms. The time of their occurrence may be determined by their temperature tolerance and low need for nitrate nitrogen. The algae are driven to offshore areas by the land breeze and south-westwards by the Baltic stream, and can certainly develop further as they drift. The production of blue-green algae in offshore areas should not be overestimated; it is more a question of a mass collection of Cyanophyceae than of their mass production.

A blue-green algae bloom behaves completely differently from most of the other phytoplankton blooms, which when not grazed sink to lower water layers or to the bottom after they die. Cyanophyceae drift to the upper water layer as a result of their gas vacuoles. Even after they die, the trichomes can remain there for a long time. It is therefore not surprising that some kind of accumulation has taken place by the second half of the summer, when the strong blue-green algae concentrations in the central Baltic proper are observed. In addition, during this time of the year the weather in this area is normally calm, which favours the emergence of the algae at the surface.

When nutrients are scarce, especially during summer, after the diatom bloom, the occurrence of great quantities of blue-green algae can strongly influence the nutrient content of the upper water layers and the production of other phytoplanktonic organisms. High production has been found in areas with mass occurrences of blue-green algae, and a relatively high chlorophyll *a* to *c* ratio. One of the reasons may be that the chlorophyll *a* molecule in the freely suspended plastids of the blue-green algae is more quickly reduced through damage by light when they rise to the water surface, because the chloroplasts which stabilize the pigments are missing. This may be the explanation of the whitish-yellow appearance of the trichome bundles drifting at the surface.

Dead blue-green algae can thus give rise to blooms of other phytoplankton organisms in oligotrophic areas by passing on nitrogen fixed from the air, and phosphate transported from inshore areas. This applies in particular to the diatoms, for which nitrogen is mostly the limiting factor, since they take up nitrogen and phosphate at a ratio of 15 : 1 (Cooper 1937, 1938).

Observation of fresh material in the microscope shows one way in which the blue-green algae enter the food chain directly. Rotifers of the species *Keratella quadrata* and *K. cochlearis recurvispina* are able to bite single cells from the trichome bundles of *Aphanizomenon flos-aquae* (Fig. 4). We have constantly met very large numbers of rotifers in fresh material, and in our opinion their role in the Baltic has been underestimated. The reason may be that the specimens have been contracted or dissolved beyond recognition in the preservative normally used, as suggested by Lauterborn (1942), who recommended the method of preservation of Rousselett (1902). Many other zooplankton organisms are found in agglomerations of blue-green algae, such as ciliates, radiolarians and larvae of different crustaceans and polychaetes. They quite clearly find an adequate food supply in all the organisms which use the blue-green algae as a substrate and source of nitrogen. It is uncertain whether whole agglomerations of blue-green algae are eaten by fish or fish larvae.

Some blue-green algae species, especially *Nodularia spumigena*, are reported to be toxic to fish, birds and mammals (Fitch & Bishop 1934, Prescott 1948, Schwimmer & Schwimmer 1955).

Kalbe and Thiess (1963) attribute a mass death of ducks in the Jasmunder Bodden to a water bloom of *Nodularia spumigena*. Francis (1878) reports casualties in Australian livestock due to *Nodularia* poisoning — dogs, sheep and even horses. The list of toxic algae compiled by Schwimmer and Schwimmer (1955) is very long and includes *Aphanizomenon flos-aquae*.

It is not quite sure whether these algae species are really toxic, since often small hardly noticeable flagellates or protein decomposition products like hydroxylamine or hydrogen sulphate can be responsible for the poisoning. When pure cultures of *Nodularia spumigena* were given to laboratory mice, even as much as 1.5 g of wet weight did not harm the mice.

It is difficult to prove that the mass occurrence of blue-green algae in the Baltic has increased during the last few years, since there are only scattered records of earlier observations. The determination of fixed blue-green algae is extremely difficult owing to the floating trichomes, so that the Utermöhl method cannot be applied.

However, pollution with phosphate has increased in the Baltic and this nutrient promotes the production of Cyanophyceae.

It should be noted that when blue-green algae are present, eutrophication in the Baltic is not only followed by an increased plankton bloom, but that a process of secondary eutrophication can be induced, since these algae »sediment to the surface», enriching the surface water with their decomposition products, especially with nitrogen, which they fixed from the air.

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