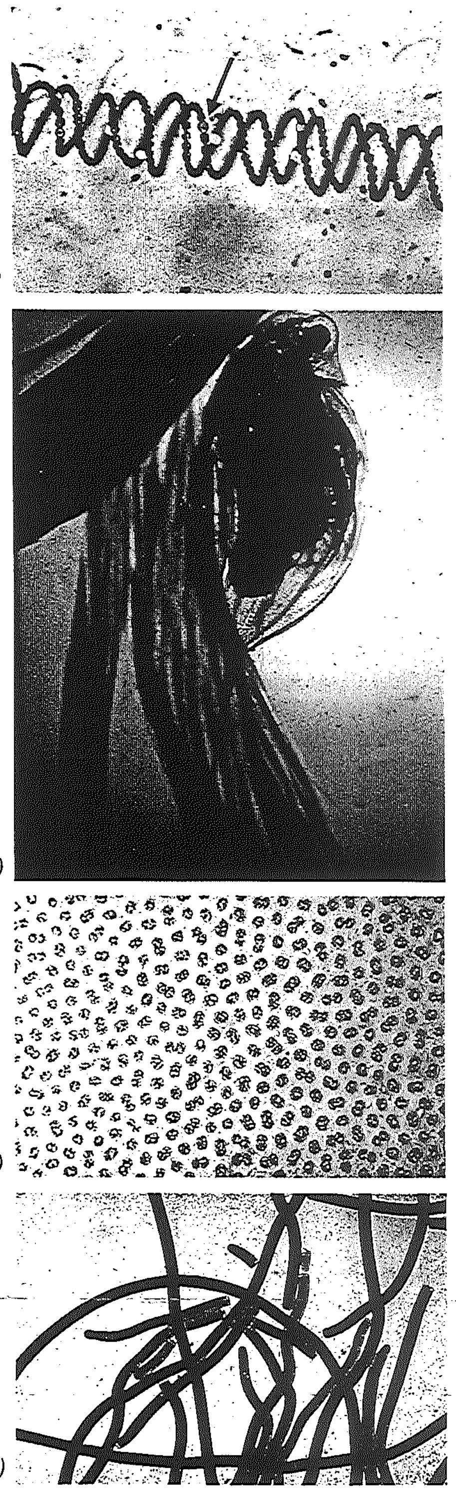
Blue-green Algae
in Eutrophic Fresh Waters

Val H. Smith

Why Do They Dominate and What Can I Do About It?

Freshwater phytoplankton communities naturally may include one or more species of blue-green algae, or cyanobacteria. These cyanobacteria tend to be rare, or present only in very limited abundance, in waterbodies having low levels of fertility. However, cyanobacteria frequently dominate the phytoplankton communities of surface waters receiving high nutrient inputs from their watershed. Extreme growths of cyanobacteria can create highly undesirable water quality conditions, and for the general public these blooms are probably the most commonly recognized symptom of eutrophic lakes, reservoirs, and rivers worldwide.

The phytoplankton communities of eutrophic waters may contain representatives from three especially notorious cyanobacterial genera: *Anabaena*, *Aphanizomenon*, and *Microcystis* (see Figures 1a-c). Water quality professionals, who often refer to them as "Anny," "Fanny," and "Mike," have studied species from these bloom-forming genera with great interest since the early 1900s. Another major cyanobacterial genus, *Oscillatoria* (Figure 1d) is also particularly noteworthy because its occurrence in European lakes was considered clear evidence of deteriorating lake water quality. The appearance of *Oscillatoria* in Lake Washington (Seattle) was an alarm to W.T. Edmondson that stimulated efforts in the metropolitan Seattle area to fund the diversion of incoming wastewater in 1963-1968. These efforts eventually led to the restoration of highly acceptable water quality in the lake.



(a) (b) (c) (d)

Figure 1 (all at left): (a) Anabaena flos-aquae. *Note lighter green heterocysts (see arrow). Photo by J. Kann; (b)* Aphanizomenon flos-aquae. *Note the large flake-like colonies, which are too large to ingest by the* Daphnia pulex *shown in this picture. Photo by E. Swain; (c) (interior of a colony). Photo by F. deNoyelles. (d) Oscillatoria sp. Photo by F. deNoyelles.*

Unique Features of Cyanobacteria

As a group, cyanobacteria exhibit a number of unique features. Unlike other phytoplankton, many species of cyanobacteria are buoyant because their cells contain tiny gas-filled vesicles that allow them to float in the water column. As a result, buoyant cyanobacterial cells can accumulate in unusually high numbers at the water's surface, creating highly unsightly scums. In exceptionally eutrophic lakes, these scums can be up to several feet thick! When cyanobacterial blooms die in lakes, the death and decay of the blue-green cells can create severe odor problems, and also may cause significant depletion of dissolved oxygen from the water column. Summer fish kills can sometimes result from cyanobacterial blooms as well.

Many cyanobacteria are also capable of producing and releasing substances that can impart strong tastes and odors to drinking water, and their growth can create very costly taste and odor problems in bodies of water that are used for municipal water supplies. Moreover, several cyanobacterial species can produce organic compounds that can cause death in domestic animals and livestock, and health problems in humans. Some of these toxins are even more potent than cobra snake venom (Table 1)! Cyanobacteria also tend to be much less edible by zooplankton than other phytoplankton, and their dominance in a waterbody potentially can reduce the efficiency of fish production.

Why do blue-greens become dominant in some waterbodies and not in others? The answer to this question is somewhat complex, because many potential factors contribute to cyanobacterial blooms. These conditions can be grouped into three general categories: physical factors, chemical factors, and biological factors.

Physical Factors: The Contribution of Stable Water Column Conditions

Cyanobacteria appear to be well-adapted to eutrophic waters characterized by periods of thermal stratification and stagnation when climatic and nutritive factors favor their growth. Surface accumulations of cyanobacteria in particular often tend to occur after a period of hot, still weather, when the intensity of sunlight has been high, and the water's surface has been calm. If large numbers of cyanobacteria already exist in the water column, a period of calm weather allows these cells to rise to the surface and to concentrate there as a scum or surface bloom, which may persist for days or weeks. Favorable physical factors cannot be the sole cause of nuisance cyanobacterial blooms, however. Calm weather conditions can only allow the surface accumulation of buoyant cyanobacterial cells that are already present in the water column, and these cells can only have arisen as a result of active growth and reproduction. Such growth can only be supported by ample nutrient supplies.

Chemical Factors: The Key Role of Nutrient Availability

In order to generate the large cell numbers that lead to nuisance blue-green blooms, a waterbody must contain the nutrients necessary for abundant growth. As is true of each plant species in a farmer's pasture, each particular phytoplankton species has somewhat unique requirements for nutrient resources. Each species requires carbon dioxide (CO_2) and sufficient supplies of inorganic nutrients for their growth, just as the many different plant species that grow in a farmer's pasture do. However, carbon dioxide itself is rarely growth-limiting for extended periods because it can be rapidly re-supplied from the atmosphere soon after it is used by algal growth.

What nutrients *do* limit algal growth in lakes? For almost 150 years agricultural chemists have known that two principal nutrients, nitrogen and phosphorus, potentially limit the growth of plants in a farmer's field. Moreover, the final yield of a farmer's crop is often proportional to the amount of nitrogen and phosphorus fertilizer that is added. Nitrogen and phosphorus (N and P) have also been found to be the two primary limiting nutrients in surface waters worldwide. As was observed over half a century ago by C.N. Sawyer in his classic studies of the Madison (Wisconsin) chain of lakes, both the summertime yield of algae and the likelihood of nuisance algal blooms in lakes are typically proportional to their phosphorus content. Sawyer's work has been confirmed by hundreds of researchers during the past 50 years, and this knowledge has led to development of the phosphorus-based eutrophication management frameworks that now used globally.

Farmers and agronomists are also very aware that the nutrient requirements for optimal growth differ significantly for different plant species. For example, legumes such as peas and clover have very high demands for soil phosphorus; peas and clover also can fix atmospheric nitrogen and use it for growth, while wheat or corn cannot. Similar differences in N and P requirements occur among phytoplankton. Like peas, cyanobacteria appear to have very high growth requirements for phosphorus, and their growth is strongly stimulated if their phosphorus supply is increased. The summer abundance and dominance of cyanobacteria have been found to depend very strongly on the concentration of total phosphorus in the water column, although this response to phosphorus appears to be altered somewhat in deep lakes.

All phytoplankton require nitrogen for their growth, but mounting scientific evidence suggests that under conditions of nitrogen limitation, cyanobacteria may be better competitors than are other phytoplankton. Like terrestrial legumes, several species of cyanobacteria have a specialized structure called a "heterocyst" that can be used to fix molecular nitrogen gas (N_2) dissolved in the water. In contrast, other phytoplankton species are only able to use dissolved inorganic nitrogen in the form of nitrate or ammonia, just as non-legume terrestrial plants do.

Nitrogen:phosphorus (N:P) ratios less than about 10:1 by weight in a waterbody's nutrient supply create conditions of nitrogen limitation, and these low N:P loading ratios have been found to strongly favor dominance by heterocystous cyanobacteria. Extensive evidence worldwide supports this N:P ratio hypothesis, even when it is extended to *all* species of cyanobacteria. Other recent studies, including one ➠

Table 1. Comparison of the toxicities of three cyanobacterial toxins. The LD_{50} represents the approximate dose of toxin needed to kill 50% of lab animals receiving injections of each toxin. These data were derived from Figure 2 in Skulberg et al. (1984).

Toxin	*Source*	*LD_{50}, micrograms per kilogram*
Muscarine	*Amanita* mushroom	1,100
Anatoxin	*Anabaena*	250
Microcystin	*Microcystis*	60
Neurotoxin	cobra snake venom	20
Aphantoxin	*Aphanizomenon*	10

by B.G. Kotak and colleagues in Alberta, Canada, have also concluded that low N:P ratios can contribute to the development of toxic blooms of *Microcystis*. Although a large body of evidence supports the N:P ratio hypothesis, other factors also are clearly important and may be overriding in some systems, however. These factors include differences in food web structure.

Biological Factors: The Role of Grazing Zooplanktons and Their Predators

Phytoplankton do not live alone in our surface waters, but instead are members of complex food webs that include a diverse community of microscopic consumers (zooplankton), and that can also include fishes. Evidence has accumulated during the past several decades that the food web structure of lakes can have important effects both on the total abundance of phytoplankton in lakes, and dominance by cyanobacteria.

For example, Jacob Kann has recently concluded that hypereutrophic Upper Klamath Lake (Oregon) is a shallow, well-mixed lake that lacks large fish populations because massive algal growth causes extremely stressful variations in pH and oxygen levels in the water. In the absence of significant fish predation, the zooplankton community of Upper Klamath Lake is dominated by large *Daphnia pulicaria*. Dominance of the zooplankton by this large grazer creates very high death rates for edible species of phytoplankton, but the presence of *Daphnia* also unfortunately appears to cultivate nuisance blooms by the inedible cyanobacterium *Aphanizomenon flos-aquae*. As can be seen in Figure 1b, the flake-like colonies of this colonial cyanobacterium can become too large for the *Daphnia* to eat, and under such conditions *Aphanizomenon* tends to be the only phytoplankton species that can persist when large *Daphnia* are present in high abundances in hypereutrophic lakes.

In less nutrient-rich lakes, the opposite effect appears to occur, however. Dick Osgood showed that in mesotrophic Square Lake (Minnesota), large *Daphnia pulicaria* effectively controlled the entire phytoplankton population, and *Aphanizomenon* was not present. Similarly, J. Elser and his colleagues added piscivorous fish to an experimentally fertilized lake in Ontario (Canada); after the piscivore additions, minnows were decimated and the zooplankton became dominated by large *Daphnia pulex*. At the same time that *Daphnia* became dominant in Lake 227, the total abundance of all phytoplankton was drastically reduced, and dominance by cyanobacteria was eliminated for the first time in 15 years!

A Proposed Pathway to Noxious Cyanobacterial Blooms

Elser (1999) has recently presented a synthesis of our knowledge that captures the major features of each of the critical factors discussed above. He has proposed a conceptual diagram (Figure 2) that asks three key questions:

1. Is the nutrient loading to the waterbody high?
2. Is the N:P ratio of the nutrient loading low?
3. Are hydrodynamic and light conditions favorable?
4. Does food-web structure inhibit *Daphnia* dominance?

If the answer to each of these four questions is *yes*, then Elser concludes that conditions overall are sufficiently favorable that noxious cyanobacterial blooms are very likely to occur. The answer to item number four may be conditional upon the trophic state of the lake, however, because *Daphnia* dominance can lead to blooms of *Aphanizomenon* in exceptionally nutrient-rich lakes.

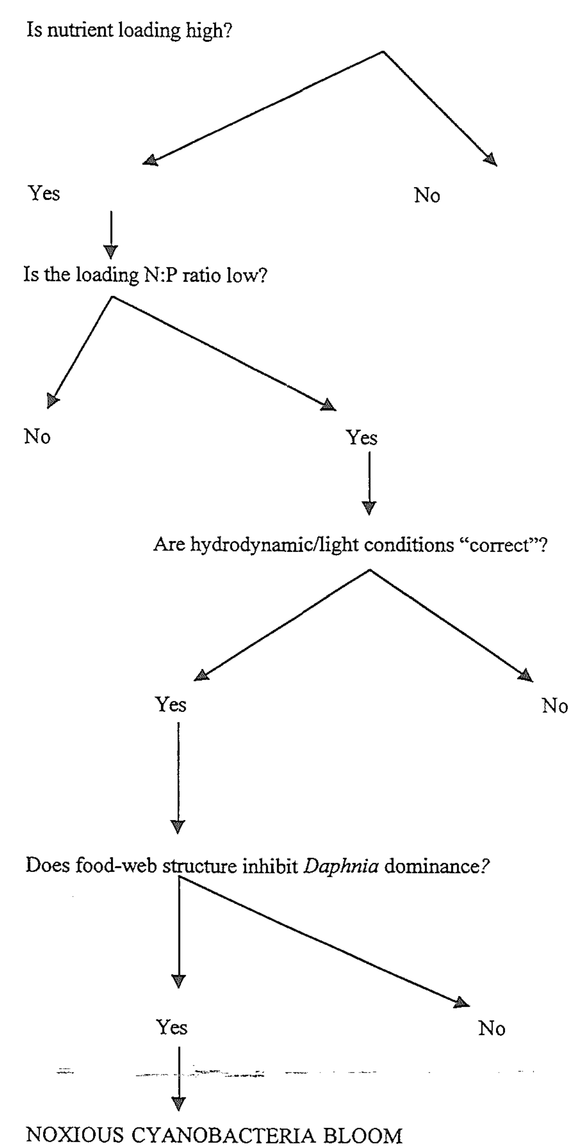


Figure 2. Pathway to dominance by nuisance cyanobacterial blooms proposed by Elser (1999).

How Can I Prevent or Minimize the Occurrence of Nuisance Blue-green Blooms in My Waterbody?

The very strong phosphorus dependence of blue-green growth makes it clear that the primary strategy for cyanobacterial bloom control should be to restrict the supply of phosphorus that enters a waterbody from both point and non-point sources. A study of long-term data from eutrophic Lake Mendota (Wisconsin) by Dick Lathrop and colleagues demonstrates an excellent example of a quantitative method for calculating the phosphorus loading reductions that are needed to control blue-green algal blooms in waterbodies for which nutrient loading can be successfully managed and controlled. In cases where the external loading cannot be controlled, and where money and other resources permit, restoration measures involving physical, chemical, or biological manipulations of the waterbody itself may instead be required.

In contrast to phosphorus input restriction, it is extremely ill-advised to pursue nutrient management strategies that remove nitrogen alone, or to implement nutrient loading control measures that produce N:P loading ratios below ca. 10:1 (by weight) to the receiving waterbody. The ability of heterocystous cyanobacteria to obtain their nitrogen requirements from the atmosphere makes it extremely imprudent to restrict the incoming supplies of inorganic nitrogen unless strong restrictions on phosphorus inputs are made as well. Heterocystous cyanobacteria will tend to be favored by conditions of nitrogen limitation, and these undesirable species will tend to increase in abundance up to the limit imposed upon them by the supply of available phosphorus. For these reasons, Smith et al. (1995) argued against targeted nitrogen loading controls in Lake Okeechobee (Florida). Similarly, a report by LimnoTech (1991) to the Metropolitan Washington (D.C.) Council of Governments recommended that they *not* pursue a strategy of wastewater denitrification if nuisance blooms of cyanobacteria were to be avoided in the freshwater Potomac estuary.

It has also been suggested that the *addition* of nitrate-rich water can reduce or eliminate blooms of cyanobacteria because this might reduce the competitive advantage cyanobacteria have in nitrogen utilization. Dick Lathrop of the Wisconsin DNR explored this method by treating a shallow hypereutrophic Wisconsin lake in 1981 and 1982 with ammonium nitrate fertilizer in order to determine whether these inorganic N additions could prevent the development of summer *Microcystis aeruginosa* blooms. Whole-lake N fertilization proved to be expensive, and did not fully prevent summer *Microcystis* blooms. However, the summer bloom was virtually non-existent during the entire 1982 nitrogen fertilization period. Evidence supporting the use of nitrate fertilizer to prevent blue-green blooms is thus unfortunately still limited, and further tests of this method would be valuable.

For Further Reading

Elser, J.J. 1999. The pathway to noxious cyanobacterial blooms in lakes: The food web as the final turn. Freshwater Biology 42:1-7.

Lathrop, R.C., S.R. Carpenter, C.A. Stow, P.A. Sorrano, and J.C. Panuska. 1999. Phosphorus loading reductions needed to control blue-green algal blooms in Lake Mendota. Canadian Journal of Fisheries and Aquatic Sciences 55:1169-1178.

Limno-Tech. 1991. Evaluation of nitrogen removal eutrophication risk for the freshwater Potomac estuary. Limno-Tech, Inc., Ann Arbor, MI. Final report prepared for the Metropolitan Washington Council of Governments, Washington, D.C., USA.

Skulberg, O.M., G.A. Codd, and W.W. Carmichael. 1984. Toxic blue-green algae blooms in Europe: A growing problem. Ambio 13:244-247.

Smith, V.H. 1998. Cultural eutrophication of inland, estuarine, and coastal waters, p. 7-49. In: M.L Pace and P.M. Groffman (editors). Successes, Limitations and Frontiers in Ecosystem Science, Springer-Verlag, New York.

Smith, V.H., V.J. Bierman Jr., B.L. Jones, and K.E. Havens. 1995. Historical trends in the Lake Okeechobee ecosystem. IV. Nitrogen:phosphorus ratios, cyanobacterial biomass, and nitrogen fixation potential. Archiv für Hydrobiologie Monographische Beitrage 107:69-86.

***Val Smith** can be reached at the Department of Ecology and Evolutionary Biology, Haworth Hall, University of Kansas, Lawrence, KS 6045, e-mail: <valsmith@falcon.cc.ukans.edu>.*