Phytoplankton and Water Quality Characterization: Experiences from the Swedish Large Lakes Mälaren, Hjälmaren, Vättern and Vänern

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Phytoplankton and Water Quality Characterization: Experiences from the Swedish Large Lakes Mälaren, Hjälmaren, Vättern and Vänern

Phytoplankton and environmental variables have been monitored in the large Swedish lakes Mälaren, Hjälmaren, Vättern and Vänern since the 1960s. Measures to reduce phosphorus input and industrial waste products were taken during the 1970s. The phosphorus loading was then reduced by 90–95% resulting in a halving of the phosphorus concentrations in the most affected basins. The phytoplankton community reacted rapidly with decreased biomasses of cyanobacteria in summer as well as decreased biomasses of spring diatoms and cryptophycean flagellates. Other reactions were a contracted period of waterbloom, an increased taxon richness, an increased evenness in the biomass over the growth season, and a change in the species size structure within the phytoplankton community. Furthermore, the species richness in the large lakes is compared in relation to lake characteristics. A presentation of the occurrence of toxic cyanobacteria in the lakes is also given. Maximum–minimum values of 13–0.1 µg microcystin L^{-1} are established in connection with waterblooms in Hjälmaren and Mälaren. The use of phytoplankton as a monitoring variable to detect water-quality changes is outlined and assessment criteria are presented.

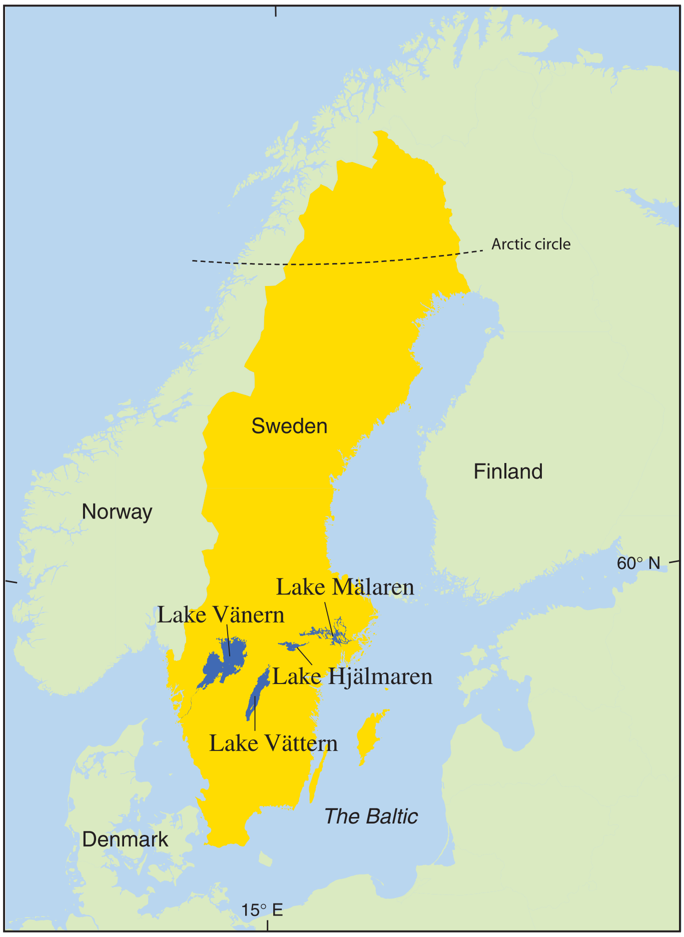

Figure 1. The location of the four largest lakes in Sweden.

INTRODUCTION

Since the early 20th century, phytoplankton has been used in Sweden for water-quality characterizations and for classification of lakes. Pioneers in this respect were Naumann (1), Teiling (2, 3), and Thunmark (4), who all made comprehensive studies, mainly concentrated to lakes in the southern part of the country. These regional limnological investigations, which comprised data on phytoplankton associations in various kinds of lakes in combination with a selection of physical and chemical variables, form basic information still usable as reference material. The taxonomic competence of microalgae in the country has predecessors like Lagerheim (5), Nordstedt (6), Lemmermann (7), and Borge (8) whose investigations of net plankton covered many ecoregions in Sweden from the alpine belt to the southern nemoral zone. Their checklists are now considered in the ongoing work on checklists of Swedish microalgae prepared by the *Swedish Threatened Species Unit* (9). After World War II, Heinrichs Skuja inspired a new generation of students to work with microalgae by his excellent descriptive talent documented in 3 floras illustrating algae from central and northern Sweden (10–12). This new generation of phycologists directed their interest into the practical use of phytoplankton in the work with nature conservation issues and water-quality assessment (13). The technique used for this purpose was developed in Germany by Utermöhl, and involved quantitative estimations of the content of organisms per water volume (14, 15). This technique, which is still in use, facilitates numerical evaluation (estimates of biovolumes) of various taxon levels from species, classes, and phyla to total phytoplankton biomass. In this way the phytoplankton community can be directly compared and linked to other compartments of the pelagic foodweb as well as with the physical and chemical environment. The early use of this technique in Sweden is attributed to Arnold Nauwerck and Torbjörn Willén whose work founded a school for quantitative phytoplankton ecology (16, 17).

Phytoplankton organisms react rapidly to changes in water-quality. This is the reason why phytoplankton was considered an important biological variable to study from the very start of the investigations of the large Swedish lakes in 1964. The aim of the plankton investigations was to get an idea of the biotic response to the successively increased nutrient loadings during the 20th century. Mälaren and Hjälmaren were the first lakes to be studied. These two lakes are situated in densely populated areas in the central part of Sweden (Fig. 1).

The main problem in Mälaren and Hjälmaren was an accelerating eutrophication or fertilization of the water environment. The answer from the lakes was the formation of dense waterblooms of cyanobacteria (blue-green algae) in the most affected areas, close to population centers, and extensive growth of filamentous algae in littoral zones. The growth of microalgae also influenced fishing activities by clogging the fishing-nets,

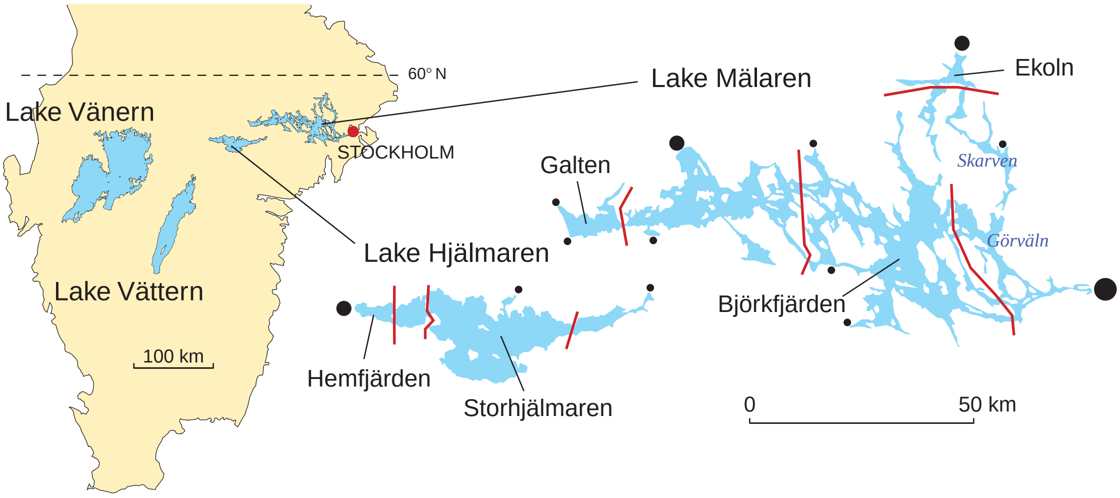

Figure 2. Mälaren and Hjälmaren and their main basins.

and the drinking-water plants by clogging raw-water strainers. So, unlike the use of fertilization in agriculture the fertilization of the lakes restricted both professional and outdoor activities. Rather soon, in 1967–1968, the oligotrophic water of L. Vättern, known as Europe's largest clearwater body situated in southern Sweden, also showed signs of increasing growth of planktonic algae, as well as of attached algae along the shores. Various species of filamentous algae, and especially a planktonic strain of the cyanobacterium *Planktothrix* expanded in the lake. With the experience gained later from the oligotrophic L. Mjøsa in Norway where serious taste and odor troubles occurred, caused by an excessive growth of a species of a related genus, the problems in L. Vättern were fortunately halted by early interference (18). With the aim to investigate the water quality in relation to nutrient contents, and pollution of colored matter from pulp and paper industries in the northern part of L. Vänern, regular phytoplankton monitoring in this lake, the largest of the four, was initiated in 1973. One of the main aims for all lakes was to identify "normal values" and to recognize weather-induced variations among investigated variables, as well as to pinpoint to authorities and the general public water-quality changes induced by excessive nutrient discharge. An important goal was also to establish a biological indicator system, preferably of countrywide use, based on the structure and abundance of various organisms.

In the mid-1970s the phosphorus loading to all lakes from municipal sewage works was reduced by 90–95%, financed by governmental support. This reduction caused a halving of the phosphorus concentrations in the most polluted lakes and basins and a reduction by somewhat smaller proportions in less affected basins. In addition to an extension of the sewage treatment in population centers, also industries in the catchment of the lakes had to restict their discharge of nutrients and harmful substances (19). When these achievements were fulfilled, focus of the limnological investigations in the large lakes was directed towards water-quality improvement and the biotic response.

Among the many results achieved from these long-term studies, this presentation will focus on:

– a characterization of the phytoplankton flora and the species richness in the large lakes and some reasons governing the variation;
– a presentation of harmful algae which cause both health effects and economic losses;
– an evaluation of phytoplankton as a response variable to water-quality changes and a discussion of its indicator value.

CHARACTERIZATIONS OF THE LARGE LAKES IN SWEDEN

Early Studies

Investigations of the phytoplankton flora have earlier been performed in all the large lakes with varying degrees of effort. The oldest publications of good quality date back to early 1900 in L. Vättern (7, 20, 21) and some decades thereafter (22–24).

L. Vänern's summer plankton was documented in 1921 and later in the 1950s (25, 26). In L. Mälaren surveys have been made in 1911 and thereafter with varying frequency up to the 1960s when the still ongoing comprehensive monitoring program was initiated (e.g. 7, 27–30). In L. Hjälmaren a thorough phytoplankton investigation was performed in the 1940s (31), although evaluations of the water quality were stated earlier based on the occurrence of heavy water blooms (32).

The assessments from these works were allocated to the lakes based mainly on their phytoplankton abundance and species composition through 1900–1950:

L. Vänern; conspicuous waterblooms in bays outside population centers. In general, the water quality is stated as moderately nutrient-rich when evaluating the community composition, but the total biomass characterizes oligotrophy.

L. Vättern; waterblooms do not occur although mass-development of the green alga *Botryococcus* sometimes drifts to the shores and colors the surface water reddish. Ultra-oligotrophic conditions prevail and the status of the lake is compared with conditions in Arctic waterbodies.

L. Mälaren; waterblooming algal masses float to the shores in some basins, while large central areas and the lake's outlet at Stockholm have a clean water plankton composition. However, the lake cannot be evaluated as a whole as there are too many divergencies between the separate basins. The basins are ranked from a mesotrophic to a eutrophic state.

L. Hjälmaren; already several hundred years ago the lake was considered as highly productive. Water blooms of cyanobacteria occur during the summer and the spring and autumn development of diatoms is considerable.

Present Characteristics of Lakes and Basins

From the 1960s onwards, results from three distinctly different basins of L. Mälaren and one central basin of L. Hjälmaren are chosen for presentation of species richness and water-quality alterations (Fig. 2). L. Vättern and L. Vänern, which have a rather uniform water quality over large areas, are each treated as single units. The morphological and physicochemical characters of the lakes are presented in Table 1(a, b).

The characteristics of the basins under discussion in L. Mälaren and L. Hjälmaren are as follows (Table 1b):

L. Mälaren

Galten; a westernmost eutrophic and shallow basin (mean depth 3.4 m), without a stratified watermass. It receives 60% of the water discharged *via* inflows to L. Mälaren. Two small towns and several population centers are situated along the shores of this basin.

Björkfjärden; a deep (mean depth 19.7 m), stratified and centrally located basin of mesotrophic character. This basin is the least affected one in the whole lake. It receives a major part of its water from the westerly basins and a rather small portion from the surrounding land. A substantital part of the raw water supporting the Swedish capital Stockholm derives from this basin.

Ekoln; the northeasternmost basin is deep (mean depth 15.4 m) stratified and eutrophic. It receives approximately 12% of the inflowing river water to the whole lake. The large town of Uppsala borders the northern part of this basin (Fig. 2).

The main water flow direction in L. Mälaren runs from the west to the east: from the Galten Basin *via* Björkfjärden to the outlet in the Baltic Sea at Stockholm. Another flow runs from the Ekoln Basin southwards to Stockholm where it mixes with the west–east flow.

L. Hjälmaren

Storhjälmaren occupies almost 80% of the total lake area. This basin is large and almost always subject to a considerable wind-stress. In spite of a maximum depth of 20 m, its water-mass is practically constantly unstratified, due to the large lake area in relation to the mean depth, which is about 7 m (Table 1b). The most complete dataset is derived from this basin although another basin, Hemfjärden, has been the first recipient of sewage water from the town Örebro, situated at the westernmost shore of L. Hjälmaren (Fig. 2). The water from Hemfjärden is however not continuously monitored, but its function as a filter for pollutants from the Örebro town area is obvious. Storhjälmaren is less affected than Hemfjärden by human pollutants, but still very eutrophic.

PHYTOPLANKTON DIVERSITY

Two examples of a complete taxonomic evaluation of phytoplankton species will be quoted here: that from L. Vättern where slightly more than 300 species were recorded, and that from L. Hjälmaren with 400 documented species (36, 37). Only picoplankton (< 2 μm) and species deformed by preservatives were not included. This level of analysis is however impossible to undertake in routine monitoring projects. The two lakes are each other's antithesis. Hjälmaren is rarely stratified, nutrient-rich, and reaches much higher water temperatures in summer than Vättern. Vättern is stratified and nutrient-poor with cool water of a large transparency (Table 1a). The difference in size between the two lakes is another deviating feature. Vättern is 4 times the size of Hjälmaren. The difference in species structure applies especially to cyanobacteria, dinoflagellates, diatoms, and green algae, which are more numerous in Hjälmaren than in Vättern as would be expected in nutrient-rich environments (38). The number of chrysophyte species is 40% larger in Vättern compared to Hjälmaren, which is relevant for oligotrophic waters (39). The richer species number recorded in Hjälmaren is explained by a frequent disturbance by wind and wave actions in this rather shallow lake, which allows many species to co-exist (40, 41). Another important difference between the two lakes is the higher degree of shoreline irregularity of Hjälmaren with extended areas of shallow littoral water. These areas function as inoculation zones for many algae (42).

For a comparison of the species richness in the large Swedish lakes where it has not been possible to perform such a thorough analysis as that referred to above, an alternative method has been used consisting of similar efforts of analysis of quantitative samples throughout the growth season (Box 1).

The Galten basin in L. Mälaren deviates from all the other basins and lakes in a distinct way by being particularly species-rich, which to a large extent is explained by the disturbance caused by the mixing regime (Fig. 3). The Mälaren Basin, Ekoln, deviates on the other hand by its scarcity of species. This could possibly be explained by its position as a first basin in a water-flow direction, where little mixture of algal species from adjacent basins occurs. The species richness of the other lakes and the Björkfjärden Basin of L. Mälaren seem to be of a similar magnitude. The relationship between

Table 1a. Morphological and physicochemical characters of the large Swedish lakes.

	Lake Vänern	Lake Vättern	Lake Mälaren	Lake Hjälmaren
Lake area (km^2)	5650	1890	1120	480
Maximum depth (m)	106	120	66	20
Mean depth (m)	27	40	12.8	6.2
Water volume (km^3)	153	77.6	14.4	3
Drainage area (km^2)	46830	6359	22603	4053
Mean water residence time (year)	9	58	3	3.5
Total nitrogen concentration ($\mu g\ L^{-1}$)	825	690	625–1920	730–1720
Inorganic nitrogen concentration ($\mu g\ L^{-1}$) (NO_3–N, NH_4–N)	555	480	200–1150	155–1210
Total phosphorus concentration ($\mu g\ L^{-1}$)	8.5	6.5	20–55	40–75
Secchi depth, m	5.0	11.0	0.9–3.2	0.5–2.7
Maximum length (km)	141	135	110	63
Length of shoreline including islands (km)	2668	655	2218	353
Length of shoreline except islands (km)	2000	460	960	290
Number of islands >100 m^2	9585	813	1645	1062
Height above sea level (m)	44.5	88.5	0.7	21.9

Morphometric data from (33–35). Nutrient concentrations represent growth season mean values during 1985–1995.

Table 1b. Morphological and physicochemical characters of the basins Galten, Björkfjärden and Ekoln in L. Mälaren and the basins Hemfjärden and Storhjälmaren in L. Hjälmaren.

	Lake Mälaren			Lake Hjälmaren	
	Galten	Björkfjärden	Ekoln	Storhjälmaren	Hemfjärden
Lake area (km^2)	61	340	30	377	25
Maximum depth (m)	19	60	50	22	3
Mean depth (m)	3.4	19.7	15.4	7.2	1.0
Water volume (km^3)	0.2	6.7	0.5	2.6	0.02
Drainage area/lake area	140	4	100	4	62
Mean water residence time (year)	0.08	2	2	3	0.05
Total nitrogen concentration ($\mu g\ L^{-1}$)	870	625	1920	730	1720
Inorganic nitrogen concentration ($\mu g\ L^{-1}$) (NO_3–N, NH_4–N)	260	215	1150	155	505
Total phosphorus concentration ($\mu g\ L^{-1}$)	50	22	55	45	75
Secchi depth, m	0.9	3.2	1.7	2.7	0.5

lake area and species richness in the large lakes is not conspicuous. The following seem to be the overriding determinants.

Mixing regime; lack of stratification in summer favors species richness.

Nutrient state; somewhat higher number of species occurs with increasing availability of phosphorus up to moderate levels of eutrophy.

Shoreline irregularity; a lake with many bays/basins supports more species from littoral areas, and invasion from adjacent basins enhance species richness as compared to lakes with regular shorelines without bays/basins and islands.

A comparison of phytoplankton species richness in these large lakes with smaller lakes in Sweden (area 0.1–1 km^2) may however indicate an areal relationship, although a more detailed evaluation of influencing factors has to be carried out. The smaller lakes contain a median number of 85 species, which corresponds to the species richness in the species poorest basin Ekoln of L. Mälaren.

The species richness calculated for different seasons is generally at its highest in August–September, and at its lowest in June. For a large number (n = 113) of Swedish lakes assessment of species richness of phytoplankton over several years has been made from August samples. Lakes scored with an intermediate richness have 40–55 recorded taxa, a number valid also for the Björkfjärden Basin and L. Vättern in August. The lakes Vänern, Hjälmaren, and the Galten Basin of L. Mälaren would be scored as having a high species number in late summer, 55–69 species, while the Ekoln Basin is regarded as fairly species-poor, 30–39 species. A very low species number, < 15 in late summer, only occurs in depauperized acidified lakes in Sweden, a problem which does not affect any of the large lakes.

An overview of dominating taxa in the large Swedish lakes during 2 successional stages (spring and late summer) is given in Table 2. In all lakes, the diatom *Aulacoseira* is a dominant spring alga, a taxon common in situations of deep mixing, and nutrient replete situations, also in many other large lakes of the world, i.e. Lakes Ladoga and Onega, L. Bajkal, L. Ontario, L. Michigan, and several of the large Rift Valley lakes (44–48). Summer taxa are characterized by flagellated species in nutrient-poor or mesotrophic situations of large lakes/basins together with colonial cyanobacteria, chrysophytes or green alga. In eutrophic basins, filamentous and large-celled colonies of cyanobacteria are frequent. Many diatoms also develop during summer. The diatoms need mixing, and large lakes always have considerable wave actions stirring up the water.

Box 1.
Simplified analysis of species richness in routine countings of phytoplankton by use of the Utermöhl method and an inverted microscope.

Analysis is made in samples preserved with iodine solution supplemented with acetic acid (43).

The size of the chosen settling chamber is determined by the abundance of 100 individuals of the most frequent nanoplankton (20–25 µm) that covers 2 transects in a high magnification (ca. 400x). All other and less frequent nanospecies are then enumerated over the same area. Larger species, which often occur in smaller numbers are counted over the whole chamber bottom in the same chamber size but at a smaller magnification (ca. 100x). Many rare and large species usually caught by net hauls are not recorded with this method.

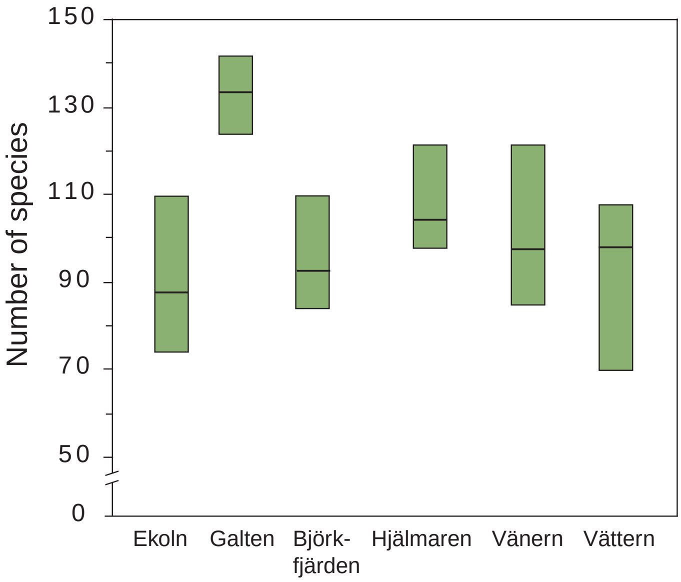

Figure 3. Species richness, median values and the min-max-values in the large lakes of Sweden during the growth season May–October. In L. Mälaren three different basins are illustrated—Ekoln, Galten, and Björkfjärden.

OCCURRENCE OF HARMFUL ALGAE

Mass development of harmful algae are recurrently occurring in many lakes, and the large lakes are no exception in this respect.

Clogging Algae

Complaints about algae that clog fishing-nets, filter-beds and micro-strainers in waterworks are numerous. Many large lakes support a number of professional fishermen whose economy to a small or large extent depends on the outcome of the catches. This is also the case in Vänern, Vättern, Mälaren, and Hjälmaren. Slimy masses of diatoms, in these cases mainly of *Aulacoseira* species, are stuck to the fishing-nets, which reduce the catches and make fishing temporarily impossible, forcing many fishermen to go on the dole (Fig. 4). The same clogging phenomena applies to waterworks and their various strainers. Other taxa than *Aulacoseira* may also be distressing like *Asterionella*, *Diatoma*, *Didymosphaenia*, *Fragilaria*, and *Tabellaria*. Clogging diatoms and those adhering to bridges and boats are usually in a physiologically dormant stage visible by a condensed protoplasm and a thick organic coating (Fig. 5) (49). This coating facilitates the clogging ability. Such a period occurs in the large lakes usually from November to March. The adhesion of algae to various substrates is not necessarily connected to poor water-quality or eutrophication, but the problem usually accelerates with increasing nutrient availability.

Taste- and Odor-producing Algae

Many algal classes have representatives that cause taste and odor problems to household- and drinking water as well as to fish and crayfish. Special complaints from consumers come during developments of the golden algae *Dinobryon*, *Synura*, and *Uroglena*, which also in moderate amounts produce aldehydes or ketones that give an unpleasant taste and cod-liver-oil-like smell. Such complaints have been recorded from L. Vättern during summer, as well as from L. Mälaren and L. Hjälmaren in spring. Diatoms and cryptophycean algal developments also contribute substantially to taste- and odor events recorded, among others, in L. Mälaren, where one of the waterworks, in the Görväln Basin, which supports some 500 000 persons in the Stockholm area with drinking water, has considerable problems related to algal development (Fig. 2). More conspicuous problems are related

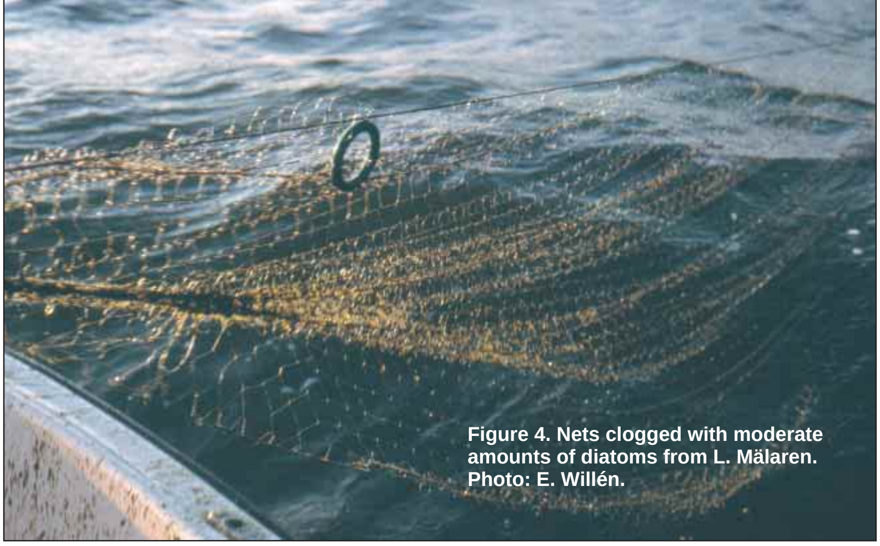

Figure 4. Nets clogged with moderate amounts of diatoms from L. Mälaren. Photo: E. Willén.

Figure 5. *Aulacoseira islandica* in a resting stage with a condensed protoplasm. Photo: E. Willén.

Table 2. Dominating taxa during the vernal and late summer period in the large Swedish lakes. Lakes and basins are ordered from ultra-oligotrophy to eutrophy. Species are ordered in declining abundance.

Lake/Basin	Vernal phytoplankton dominants	Late summer phytoplankton dominants
Vättern	*Aulacoseira islandica* *Chrysophycean flagellates* *Rhodomonas lacustris* *Cyclotella* spp. *Tabellaria flocculosa* *Asterionella formosa* *Nitzschia intermedia f. actinastroides*	*Cyclotella* spp. *Cryptophycean flagellates* *Ceratium hirundinella* *Uroglena* spp. *Woronichinia compacta* *Asterionella formosa*
Vänern	*Aulacoseira islandica* *Aulacoseira subarctica* *Cryptophycean flagellates* *Aphanizomenon flos-aquae* *Stephanodiscus* spp. *Tabellaria flocculosa v. asterionelloides*	*Woronichinia naegeliana* *Cryptophycean flagellates* *Aphanizomenon flos-aquae* *Ceratium hirundinella* *Chrysophycean flagellates* *Anabaena* spp. *(lemmermannii, planctonica, crassa)*
Mälaren, Björkfjärden	*Aulacoseira islandica,* *Aulacoseira subarctica* *Stephanodiscus* spp. *Gymnodinium uberrimum* *Cryptophycean flagellates* *Diatoma tenuis*	*Cryptophycean flagellates* *Ceratium hirundinella* *Woronichinia naegeliana,* *Woronichinia compacta* *Aphanizomenon flos-aquae* *Stephanodiscus* spp. *Sphaerocystis schroeteri*
Hjälmaren, Central basin	*Aulacoseira islandica,* *Aulacoseira subarctica* *Stephanodiscus* spp. *Gymnodinium helveticum* *Pseudosphaerocystis lacustris*	*Actinocyclus normannii f. subsalsa* *Stephanodiscus* spp. *Microcystis* spp. *(aeruginosa, viridis, wesenbergii, flos-aquae)* *Woronichinia naegeliana*
Lake Mälaren, Galten	*Aulacoseira* spp. *(islandica, subarctica, ambigua, granulata)* *Cryptophycean flagellates* *Stephanodiscus* spp. *Diatoma tenuis*	*Aphanizomenon flos-aquae* *Aulacoseira granulata,* *Aulacoseira ambigua* *Woronichinia naegeliana* *Microcystis aeruginosa* *Stephanodiscus binderanus*
Lake Mälaren, Ekoln	*Aulacoseira islandica* *Stephanodiscus* spp. *Cryptophycean flagellates* *Diatoma tenuis* *Synedra ulna* *Melosira varians*	*Aulacoseira granulata, A.granulata v. angustissima* *Diatoma tenuis* *Microcystis* spp. *(aeruginosa, botrys, wesenbergii)* *Aphanizomenon flos-aquae* *Asterionella formosa*

to the occurrence of cyanobacteria. They produce odorous substances such as geosmin and 2-methylisoborneol, which give the water and the fish a muddy, earthy or musty odor/taste. In the large Swedish lakes such problems are especially connected to the more nutrient-rich basins of Mälaren and Hjälmaren.

Toxin-producing Species

Toxin-producing cyanobacteria are recorded in all of the large lakes also in the ultraoligotrophic L. Vättern (50). In such a lake, with a large open-water area, cyanobacteria may occur in small amounts in the surface water, but they drift and accumulate in larger amounts in wind-exposed bights, where toxin concentrations then amount to deleterious levels. Sites in the large lakes where toxic cyanobacterial blooms have been documented either by mouse bio-assays, immunological methods (ELISA-test) or by high pressure liquid chromatography (HPLC) are illustrated in Figure 6.

Cyanobacterial toxins may cause problems of a serious health character. The toxins can be separated into 3 classes according to their mode of action: neurotoxins affect the transmission of neural impulses, hepatotoxins interfere with transduction mechanisms in the cells, and dermatotoxins cause skin irritations. Hepatotoxins (called microcystins after the species from which they first were documented) may cause serious liver damage and also promote tumours in skin and liver (53). The seriousness of this toxin has been the cause of special attention in the aquaculture industry, in the Swedish National Food Administration, which is responsible for drinking-water quality, and among tourist organizations. Neurotoxins have immediate and devastating effects on cattle and pets drinking and swimming among toxic cyanobacterial masses. In the case of serious intoxication the animals die, and such events are reported annually. People may suffer from headache, stomach cramps, nausea, and diarrhea after exposure during swimming or accidental ingestion. The dermatotoxins cause allergic reactions among human beings as well as hot fever-like symptoms (54).

Events of Hepatotoxicity in the Large Swedish Lakes

The highest concentration of microcystins has been measured in L. Hjälmaren where 13 $\mu g\ L^{-1}$ is attained, which is considerable as the lake is a drinking-water source for several population centers. However, after treatment which includes sedimentation, flocculation and activated carbon processes, the concentrations in drinking water are zero or very low. Bearing in mind the comparatively short duration of waterbloom events, the provisional guidelines set up by the World Health Organisation, of 1 $\mu g\ L^{-1}$ of microcystins as a daily lifetime intake is not exceeded in Sweden's large lakes (53).

The main taxa attributed to toxin production in L. Hjälmaren are *Microcystis* spp. (*aeruginosa*, *botrys*, *wesenbergii*, *viridis*) and *Anabaena flos-aquae*. The microcystin concentrations in L. Mälaren vary between 0.1–4.3 µg L^{-1}, and the highest concentration is assigned to the occurrence of *Planktothrix prolifica*, which form red-colored metalimnetic waterblooms in summer and below-ice blooms in winter (51). The most widespread species connected to toxic waterblooms at many sites in this lake is otherwise *Microcystis aeruginosa*. This species has its peak abundance in late summer. The toxin content in Vättern and Vänern have till now only been tested with mouse bio-assay, which does not give quantitative results comparable to chromatographic and immunologic tests. In these lakes, the genus *Anabaena* and usually the species *lemmermannii* is a main toxin-producer.

The duration of toxic blooms is usually short, and except where *Planktothrix prolifica* prevail, restricted to a period in August–September. Deviations may occur, however, like an incident in October 2000 in L. Mälaren, where toxin concentrations of about 3 µg L^{-1} were measured in an area which supplies the southern parts of the capital Stockholm with drinking water. Also at low concentrations for which effects are not traceable in drinking water, folkstorms may stir up. It is more probable in these cases that cattle and pets may be affected and that a bioaccumulation in fish could occur. It is recommended by water authorities not to eat viscera where especially the liver is a target organ for the toxins.

PHYTOPLANKTON REACTION TO REMEDIAL MEASURES

Already some years before the phosphorus precipitation measures in the large lakes were accomplished, in the mid-1970s, the water quality, especially in L. Mälaren, was perceived as improved by an increased transparency, and a reduced time-span of waterblooms. This amelioration was caused by several years with an extremely low water flow, resulting in decreased discharges of nutrients and organic matter, a period which coincided with the increasing purification in sewage-treatment plants.

The Secchi depth in summer increased after the reductions of nutrients by 0.5 m in the most nutrient-loaded and stratified basins in L. Mälaren, and also in L. Hjälmaren and L. Vättern, while smaller unstratified basins reacted with less changes. The archipelago areas around the capital of Stockholm, close to L. Mälaren's outlet into the Baltic, were interpreted as having a much improved water quality by an increased transparency of about 1 m (55). The water clarity was an easily understandable indicator for the general public reflecting an immediate and apparent success of measures taken. A later following high flow period with reduced transparency did however not conceal the first positive public reaction, which was an important contribution to the approval of the costly remedial step taken. In addition, the phytoplankton answered rapidly with a 40–60% reduction of its biomass in the most affected basins of L. Mälaren (the Ekoln and Galten basins) and with a 35% biomass reduction in L. Hjälmaren and L. Vättern (Table 3). In particular the reduction of cyanobacterial biomass in the most eutrophied parts was obvious in both time and space (Fig. 7).

Long-lasting waterblooms which extended from June to September/October in the 1960s, and from public statements also had done so in the 1950s in several parts of L. Mälaren, and in L. Hjälmaren, were reduced in time to a late summer period, which is a more normal situation for eutrophic but not overloaded lakes.

Another conspicuous feature was the reduction of the vernal diatom peak biomass. This is statistically significant especially in L. Vättern where a 50% decrease is recorded as compared to the period before 1976 and a stabilized postrestoration period

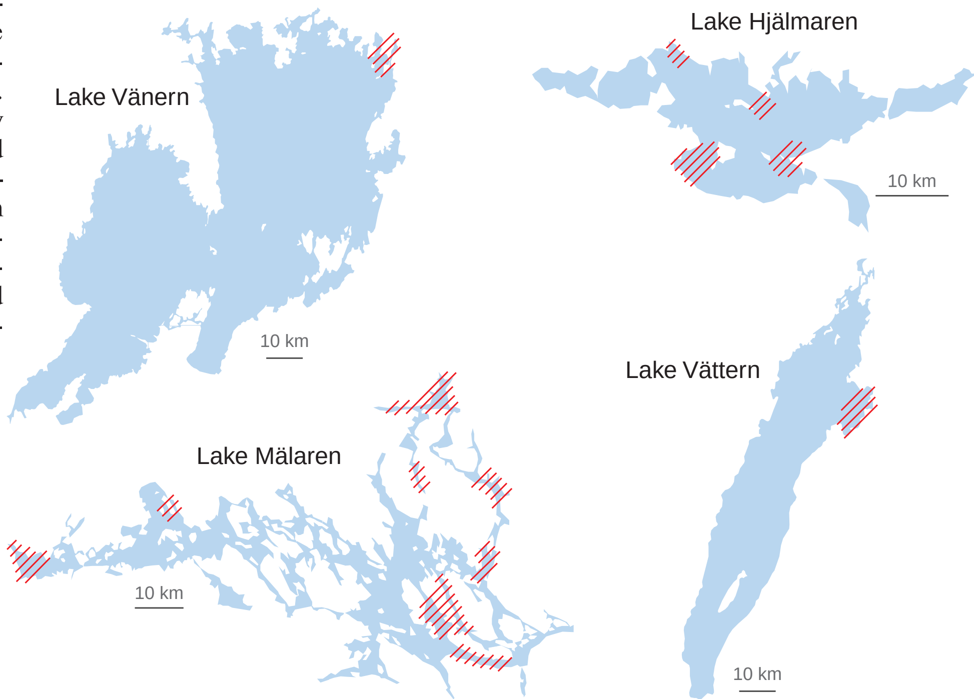

Figure 6. Areas in the large Swedish lakes where occurrence of toxic cyanobacteria are documented by mouse bioassays, by ELISA- or HPLC-tests. Data from (50–52).

Table 3. Growth season (May–Ocotober) means values of total phosphorus (TP) and total phytoplankton volume characterizing the four largest Swedish lakes during a pre- and postrestoration phase with similar water flow

Lake	Mälaren						Hjälmaren		Vättern		Vänern	
Basin	Galten		Björkfjärden		Ekoln		Storhjälmaren					
Pre- and postrestoration period	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Total phosphorus, µg L^{-1}	67	50	30	22	93	55	45*	45*	11	6	12	10
Total phytoplankton volume, mm^3 L^{-1}	6.3	3.9	0.9	0.6	3.1	1.3	2.0	1.3	0.11	0.07	0.4	0.2

Prerestoration periods are: L. Mälaren 1966–1973, L. Hjälmaren 1968–1975, L. Vättern 1970–1976, L. Vänern 1973–1982. Postrestoration period in all lakes is 1985–1995. * Comparable values for the most polluted westernmost basin in this lake (Hemfjärden) are 150 and 75 µg L^{-1}, respectively, but the phytoplankton samplings are here more irregular.

1985 through 1995 (Table 4). The vernal diatom peak was also reduced significantly in some of the eastern basins of L. Mälaren, but in different years rather high biomasses may still occur. The overall impressions, apart from reduced total biomasses and a reduction of certain algal groups, were decreased intra-annual biomass variations. This reflected a general decrease of mass-developments, whether caused by cyanobacteria, diatoms or by other algal groups.

Concerning the situation in L. Vänern, where only a slight phosphorus reduction has been recorded so far, there is no statistically significant change in the biomass of phytoplankton, neither totally nor among the dominating algal groups, like diatoms and cryptophycean flagellates. An increased diversity on algal class level has however been recorded, comprised of a larger proportion of cyanobacteria and chrysophytes since the mid–1980s. The appearance of these groups may have been favored by an increment of the water clarity and a reduction of substances with toxic effects. The decreased effluents of organic matter from paper- and pulp industries have raised the Secchi depth from 3 to 5 m since the late 1980s. Simultaneously, the discharge of toxic compounds from these industries has been reduced to a large extent. Poor light conditions and toxic waste-water are both components that depress the primary production which also have been analyzed and discussed in the case of L. Vänern (56).

The strongly reduced phosphorus discharge and the reduction of industrial waste products have displayed great effects on the phytoplankton community of the Ekoln Basin of L. Mälaren (Fig. 7, Table 4). Among the explanations for this apparent reaction are the position of the basin topmost in the flow direction southwards, with little influence of adjacent basins. In addition, the basin is deep and stratified with a fairly long retention time allowing particles to sediment.

There are however other hypertrophic basins in L. Mälaren which have diminished their phosphorus concentrations by 50% and still have not attained a statistically significant phytoplankton reduction, other than a slight decrease of the spring peak of diatoms. An evident example of this is the deep basin of Skarven south of Ekoln (Fig. 2).

Lake areas with much wind-stress and without lengthy stratification seem to need considerable time to restore. Also, if phosphorus concentrations are reduced as in the Galten Basin of L. Mälaren, cyanobacterial biomass in some years may still reach disturbing biomasses (10–20 mm^3 L^{-1}). In general, the total phytoplankton biomass calculated as a mean of several growth seasons is reduced by 40% after the P-precipitation, which indicates a decreased interannual variation (Table 3).

In the basin of Storhjälmaren, the phosphorus levels have still not diminished in spite of the remedial measures taken. The reason for this seems to be a lowered phosphorus retention in the sediments, a matter which needs further clarification. Anyhow, the cyanobacterial biomasses have declined significantly, which may be due to a decrease in the biologically available phosphorus fraction (Fig. 7).

Further comments are given on the reaction to reduced phosphorus discharge in the deep large lakes with a long water retention time, like L.

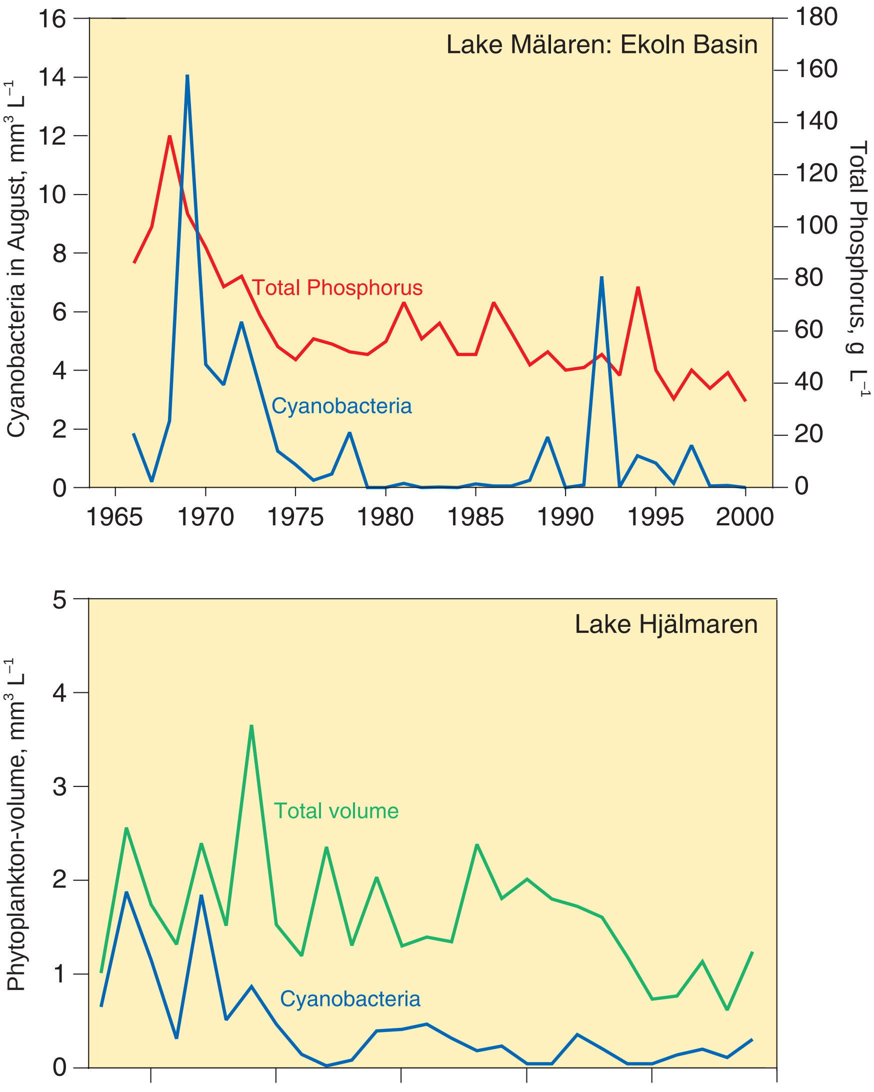

Figure 7. The reduction of cyanobacteria in the Ekoln Basin of L. Mälaren and in L. Hjälmaren following phosphorus precipitation in sewage works of the lakes´ catchment areas.

Table 4. An overview of statistically significant reductions in the three lakes Mälaren, Hjälmaren and Vättern of the biomass of algal indicator groups, which may vary between the lakes, and of total phytoplankton volumes. The period 1966–1976 and the postrestoration phase 1985–1995 are compared. Significance is marked x, tested with Mann-Whitney test (p-level 0.1).

Lake	Mälaren			Hjälmaren	Vättern
Basin	Galten	Björkfjärden	Ekoln	Storhjälmaren	
Total phytoplankton volume (biomass), mean value of growth season (May–October)		x	x		x
Total phytoplankton volume (biomass), peak values of growth season	x	x	x		x
Cyanobacterial biomass, mean value of growth season	x		x	x	
Cyanobacterial biomass, peak values during growth season	x		x	x	
Diatoms, vernal peak biomasses					x
Cryptophycean flagellates, summer peak biomasses	x	x	x		x

Vättern. The reduced load caused decreases of total phytoplankton volumes and the dominant algal groups during their peak periods. The biomass reductions are, however, on a much smaller scale than those of other lakes, because here phosphorus has been a limiting nutrient all the time, and the recorded P-reduction has reverted the water from an oligotrophic to an ultraoligotrophic state (Table 3).

A summary of changes in the planktonic algal community experienced as a result of decreased nutrient availability in the large lakes of Sweden shows:

- decreasing biomasses totally, but especially of cyanobacteria, spring diatoms and cryptophycean flagellates;
- a contracted period with waterblooms;
- decreased biomass variations within the growth season of a year—peak values are reduced but conspicuous peaks may occur in single years under certain weather conditions;
- a change in the size structure of the phytoplankton community—the proportion of small and intermediate-sized species has increased;
- an increased evenness—development of dominant species has decreased;
- taxon richness has increased.

The experiences from the huge effort to reduce input of phosphorus and industrial waste products to the large Swedish lakes, in general, has had a positive effect on the phytoplankton community. The response pattern in wind-exposed, unstratified lakes or basins is however delayed, a condition reported also from other restored, eutrophic and shallow lakes. The storage of phosphorus in the sediments and a successive and variable release from the sediment are limiting factors. An evaluation of the theoretical frameworks and experiences made of nutrient reductions to a spectrum of different lakes is outlined among others by Sas (57), and with a planktonic perspective by Reynolds (58).

From a perspective of large lakes which requires special coordination when performing large-scale restoration efforts, successful results have been reviewed from among others various parts of the Laurentian Great Lakes (59, 60), from L. Washington (61) and from L. Mjøsa in Norway. The reactions in these lakes reflected among phytoplankton have many similarities to those of the Swedish experiences.

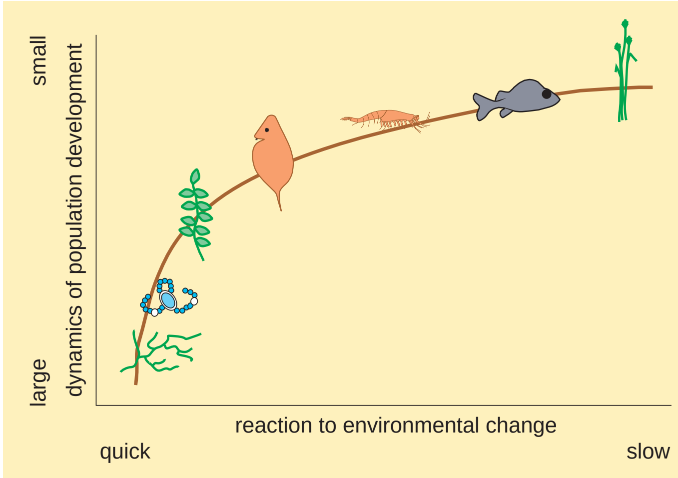

Figure 8. The reaction of attached littoral algae, phytoplankton, submerged macrophytes, zooplankton, benthic invertebrates and emergent macrophytes to water-quality changes. The dynamics in their population development exposed over the year are also considered.

PHYTOPLANKTON AS AN INDICATOR OF WATER-QUALITY CHANGE

What are the advantages and drawbacks of using phytoplankton in water-quality assessment? Among the advantages are the rapid response of this group of organisms to changes in the environment (Fig. 8), its primary role in the foodweb and its influence on other organisms. These circumstances make phytoplankton suitable as an early warning indicator. Additionally, experience has been gained since the late 1800s and early 1900s, of characteristic associations in various trophic gradients and during different seasons, especially in the temperate zone. Such knowledge facilitates interpretations of deviations in community structure and dynamics. During the latest decades much insight has also been achieved into the mechanisms governing fluctuations in phytoplankton communites, which has benefited interpretations of results from applied work (e.g. 62–66). Likewise, with relevant information, successful models have been elaborated for predictions of water-blooms and community structures in relation to successional stages and water quality, although further work has to be done using the many extensive databases which have been compiled during monitoring work in several countries (e.g. 67–70). Such models could then act as guidelines for "expected" phytoplankton biomasses and species associations under a set of environmental conditions.

The disadvantages of the use of phytoplankton in monitoring work are connected with its seasonal changes and interannual variations, which require a fairly extensive sampling frequency. Another disadvantage often referred to, is lack of taxonomic competence, a fact that not only applies to algae but also to many other groups of organisms. In spite of the related difficulties, the use of phytoplankton and algae in general to reflect alterations due to changes in the water-quality has proved to be a sensitive indicator, which also is evidenced by the monitoring of the large Swedish lakes. Its role as an early warning indicator is superior to many other groups of plants and animals.

In recently established water-quality criteria in Sweden phytoplankton is one of the biological variables chosen to assess biological conditions and deviations from a reference state (71). The phytoplankton data used to establish these criteria originate from the monitoring programs in the large lakes and some 100 other lakes from all of Sweden. Assessments involve 2 procedures: *i*) an appraisal of the state of the environment *per se* in terms of the quality of the ecosystem; and *ii*) an appraisal of the extent to which the recorded state deviates from a reference value.

The results of both appraisals are expressed on a scale of 1–5. Assessments that use phytoplankton data comprise the parameters: total phytoplankton volumes (mean values of growth seasons or just August values); biomass (volumes) of spring-peaking diatoms; biomass (volumes) of water-blooming cyanobacteria (late summer values); number of potentially toxin-producing cyanobacterial genera (late summer value); and biomass (volumes) of the invasive species *Gonyostomum semen* in Swedish lakes. Provisional reference values for planktonic algae (total biomass, diatom biomass and biomass of water-blooming cyanobacteria and number of potentially toxic cyanobacterial genera) have been suggested to be able to assess a deviation from a pristine or natural/near-natural condition. Reference values are set for stratified and unstratified lowland lakes, for forest lakes and for mountain lakes. The reference values for lowland lakes are based partly on correlations with total phosphorus, partly on relationships between growth season mean values and late summer values calculated from a large number of lakes in various ecoregions of Sweden. It is assumed that mesotrophic conditions have prevailed in lowland lakes in their pristine state, with a total phosphorus concentration of at most 15 $\mu g\ L^{-1}$. Two reference lakes form the basis for the chosen reference values of forest lakes, and for mountain lakes maximum values from a number of studies are used. Further information on these water-quality criteria are outlined on the internet www.internat.environ.se where details can be found under the heading "legislation/guidelines".

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