SHALLOW LAKES: EFFECTS OF NUTRIENT LOADING AND HOW TO REMEDY EUTROPHICATION

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Contents

Summary

When the nutrient loading of lakes increases, substantial changes in the environmental state often occur. The lakes change from a clearwater state with high abundance of submerged macrophytes, relatively low abundance of planktivorous fish, and many predatory fish to a turbid state characterized by high abundance of phytoplankton, many planktivorous fish, and no or only few submerged macrophytes. There is, though, resistance towards such a shift due to various feedback mechanisms, especially related to the presence of submerged macrophytes. When nutrient loading is again reduced, there is likewise resistance against a shift to the clearwater state conditioned by both chemical and biological factors. At intermediate nutrient levels, either clearwater, or turbid state may occur, and because of the feedback mechanisms major perturbations (natural or human-made) are needed to shift the lake to the other state. A turbid state may be shifted to the clearwater state via fish stock manipulation, by removal of planktivorous fish and/or stocking of predatory fish. The designation of this method is “biomanipulation.” If such an intervention is to have a long-term effect, a nutrient reduction equivalent to a lake water concentration below 0.05–0.1 mg P L^{-1} (in equilibrium) is required; protection of submerged macrophytes against bird grazing or transplantation of plants may also be needed. Biomanipulation offers a great potential but its long-term effects are only poorly elucidated. Greater knowledge of the biological interactions in and restoration possibilities for Arctic/Antarctic, tropical, brackish, and saline lakes is still needed.

1. The Eutrophication Process

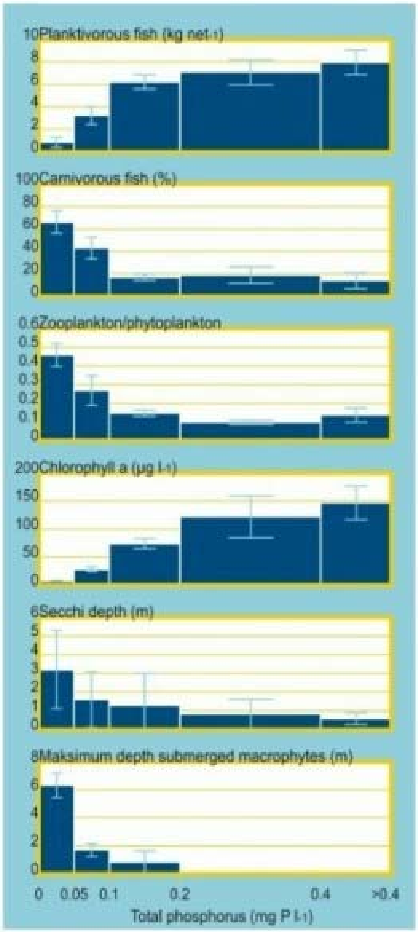


Figure 1. August biomass of zooplanktivorous fish (measured as catch per unit effort (CPUE), catch in multiple mesh size gill nets, 14 different mesh sizes 6.25–75 mm) versus summer mean lake water concentrations of total phosphorus (*n* = 65). Also shown are the percentage of carnivorous fish, summer mean (May to October 1) of zooplankton:phytoplankton biomass ratio, chlorophyll *a* concentration, Secchi depth, and the maximum depth of submerged macrophytes versus the lake water concentration of total phosphorus. Mean ± standard deviation (SD) of the five total phosphorus groups is shown. The impact of changes in total phosphorus on biological structure and physico-chemical variables is thus particularly high at low phosphorus concentrations, while only small changes occur when total phosphorus is higher than 0.1–0.2 mg P L^{-1}. (Modified from Jeppesen *et al.*, 1999, *Hydrobiologia* **408/409**, 217–223.)

Shallow lakes are the most widespread lake type in the world and have a great impact as habitat and refuge for wildlife and as a recreational resort. Palaeoecological studies of lake sediments have shown that anthropogenic activities such as afforestation and early agriculture have long affected the nutrient state of lakes and their ecology.

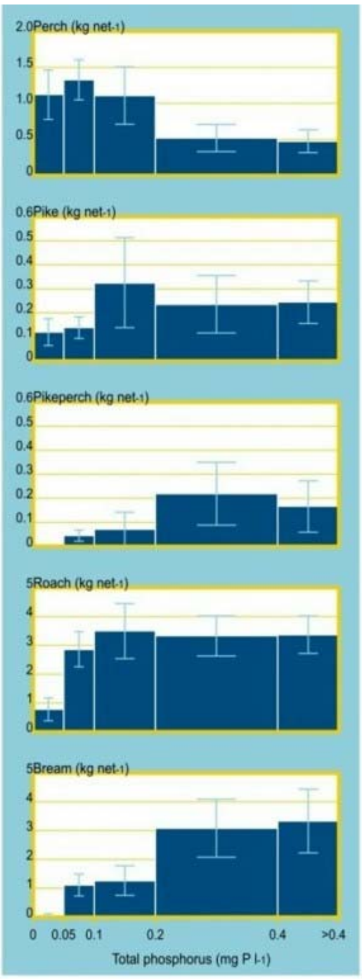


Figure 2. Biomass (CPUE, catch in multiple mesh size gill nets ±SD, cf. Figure 1) of various quantitatively important fish species in Danish lakes versus summer mean total phosphorus concentrations in the lake water. The first three species are carnivorous, while the last two are plankti-benthivorous.

During the past century, increased urbanization and sewage disposal, regulation of wetlands and streams, and more intensive farming practices have increased the nutrient loading to many shallow lakes worldwide, not least in the industrialized part of the world. This has resulted in major changes in biological structure and dynamics of the lakes and often a shift from a clearwater to a turbid state (Figures 1–3). A typical scenario in northern Europe is as follows: At the top of the food chain major changes have occurred in the fish community. At low nutrient concentrations, predatory perch (*Perca fluviatilis*) and pike (*Esox lucius*) dominate the fish community. Synchronously with eutrophication, the biomass of fish increases (Figure 2), and a shift to dominance of cyprinids occurs, especially of roach (*Rutilus rutilus*) and bream (*Abramis brama*) (Figure 3). Roach and bream are zooplanktivorous and their increased biomass results in enhanced predation pressure on zooplankton and thereby reduced grazing pressure on phytoplankton. Changes in size structure of zooplanktivorous fish towards dominance by small specimens further enhance the predation pressure on zooplankton. The biomass ratio of zooplankton to phytoplankton decreases from 0.5–0.8 in mesotrophic lakes to less than 0.2 when phosphorus concentrations are above 0.10–0.15 mg P L^{-1} (Figure 1), the latter figure being so low that zooplankton is not capable of controlling the phytoplankton whose turnover time in eutrophic lakes may be 0.5–2 days. With decreasing grazing pressure by zooplankton and snails and increased nutrient supply, the biomass of phytoplankton increases, resulting in reduced Secchi depth. An increase in fish predation may also reduce snail abundance and thus grazing of epiphytes on plants, which also impoverishes the growth conditions for submerged macrophytes. The plants disappear and the food source for a large number of birds is diminished. The result is a lake with a large biomass of roach and bream, high abundance of phytoplankton, few or no submerged macrophytes and a greatly reduced density of birds dominated by fish-eating species (Figures 1–3).

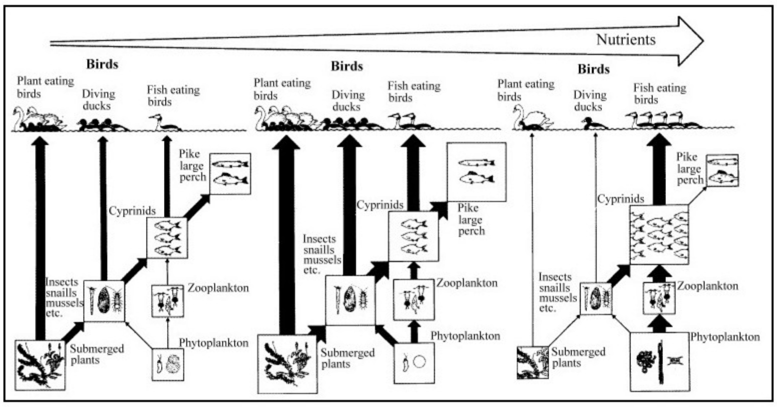
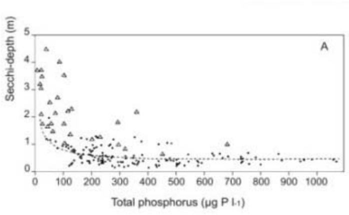


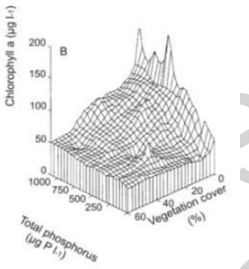
Figure 3. Scheme illustrating how the biological strucutre and dynamics change along a gradient in nutrient loading. At low loading, the lake is in a clearwater state, and owing to numerous feedback buffer mechanisms the clearwater state is maintained at increasing loading, although predation at the various food web levels increases. At a lake-specific threshold, a shift occurs to a completely different state: the turbid state, which also holds a number of stabilizing feedback mechanisms. At intermediate nutrient level, two alternative states may occur: the turbid and the clearwater state, and perturbations (natural climate-mediated or human-made changes) are needed to shift the lake from one state to the other.

2. Resistance to Increasing Nutrient Loading

Frequently, the shift to the turbid state does not occur gradually concurrently with increasing nutrient level, but rather abruptly when a given lake-specific nutrient threshold is reached (Figure 3). Often considerable resistance towards the shift is found. The reasons are various (Box 1). When the nutrient loading increases macrophyte biomass increases, resulting in increased nutrient fixation in macrophytes and epiphytes. During summer, part of the added nutrients is thus not available to the phytoplankton. Moreover, increased abundance of submerged macrophytes may indirectly reduce available nutrients. They reduce sediment resuspension, which otherwise often results in increased nutrient release to the water. Some investigations moreover indicate that the roots and larger surface area contributed by the plants promote denitrification, and hence, nitrogen loss from the lake. Low oxygen concentrations within the macrophyte beds, not least at night, are supposed to have similar effects. Finally, submerged macrophytes may locally diminish phytoplankton by shading.

Submerged macrophytes have a great impact on water transparency in nutrient-rich temperate lakes (Figures 4A, B). The effects may be both direct (plants take up nutrients from the water leaving less nutrients for the algae with increased transparency as the results) and indirect, since the water at a given nutrient level is clearer in lakes with high macrophyte coverage, several factors being involved (Figure 4C).





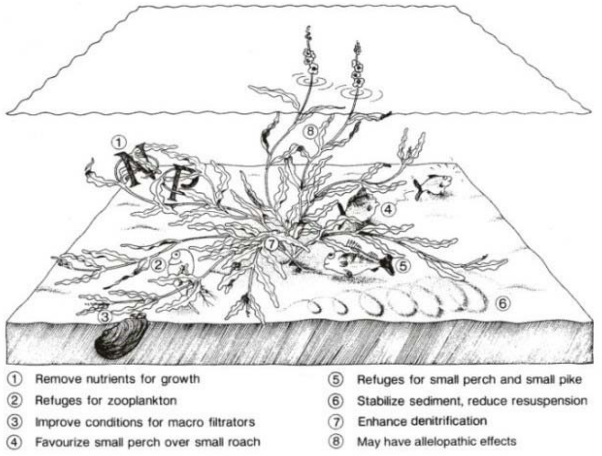


Figure 4A. Summer mean transparency (Secchi depth) in relation to the total phosphorus concentration of the lake water in shallow Danish lakes with (triangles) and without (dots) substantial aquatic vegetation (Jeppesen et al. (1990). *Hydrobiologia* **200/201**, 129–227).

Figure 4B. The concentration of chlorophyll *a* plotted against the TP concentration and submerged macrophyte coverage in 84 Dutch shallow lakes. The surface is interpolated through the data points. In lakes with a high coverage of submerged plants chlorophyll hardly increases with the phosphorus concentrations. At low density of submerged macrophytes, chlorophyll *a* increases (phytoplankton biomass) with increased total phosphorus in consequence, whereas there are no changes in chlorophyll *a* when plant density is high. (From Scheffer (1998). See reference list.)

Figure 4C. Multiple factors explain why temperate nutrient-rich lakes with high macrophyte coverage are maintained in a clearwater state.

Box 1. Submerged macrophytes maintain clearwater conditions

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Biographical Sketches

Erik Jeppesen, Professor, DSc. His main interests are trophic structure and dynamics in temperate and arctic lakes, palaeolimnology including lake responses to reduced nutrient loading, and lake restoration. His has more than 120 scientific publications in international refereed journals and books.

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