A review on the Control of Eutrophication in Deep and Shallow Lakes

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Abstract: There has been a much debate about the relative importance of the determination of phytoplankton crops by nutrients (bottom-up control) or by zooplankton grazing (top-down control). Wide acceptance of the importance of nutrient concentrations in water quality deterioration has brought about external nutrient control by which eutrophication is, to some extent, reversible, and which has been proved its effectiveness mostly in deep lakes. In shallow lakes its effectiveness has not been as pronounced, owing to internal nutrient loading. Because the non-linearity of responses of biological systems is much more accentuated in small and shallow lakes. The use of profound effects of lop level consumers, such as fish, is called biomanipulation and is generally regarded as a feasible technique in aquatic management, specifically for the control of algal biomass through the trophic pyramid in addition to external nutrient control. However, in deep and large lakes, biomaniplation is less likely to result in improved water quality than in shallow lakes owing to the weakened top-down effect near the bottom of food web. In shallow lakes, if increased water clarity through fish removal was associated with redevelopment of dense macrophytes, sustainable water quality improvement would be achieved due to clear water stabilizing mechanisms of macrophytes.

Key Words: Deep lake, shallow lake, phosphorus, biomanipulation, fish, macrophyte.

Derin ve Sığ Göllerde Ötrofikasyon Kontrolü Üzerine Değerlendirme

Özet: Tatlı sularda, fitoplankton yoğunluğunun belirlenmesinde suda bulunan besin tuzlarının (özellikle, azot ve fosfat) yoğunluğu (aşağıdan-yukarıya kontrol) ve zooplanktonun (*Daphnia* spp.) (yukarıdan-aşağıya kontrol) rolleri uzun zamandır tartışılmaktadır. Su kalitesinin bozulmasında veya aşırı fitoplankton üremesinde besin tuzlarının yoğunluğunun yüksek olmasının öneminin yaygın olarak kabul edilmesi; tatlı sulara ulaşan besin tuzları (özellikle, fosfat) uzaklaştırılmasının ötrofikasyonun kontrol edilmesinde önemli yöntem olarak yaygın uygulanmasına neden olmuştur. Bir çok çalışmanın bulguları, besin tuzlarının uzaklaştırılması derin göllerde oldukça etkili olurken sığ göllerde ise yetersiz kaldığını göstermiştir. Çünkü sığ göllerde göl tabanından uzun süre devam eden besin tuzları salınımı su kalitesinin sadece bu yöntemle iyileşmesini engellemiştir. Üst tüketicilerin, örneğin planktivor ve piskivor balık, besin zincirinin alt gruplarını kontrol etmedeki rolü esasına dayanan "biyomanipülasyon" tekniği, besin tuzlarının kontrolü ile birlikte ötrofik sığ göllerde fitoplankton biyomasının kontrolünde çok etkili olmuştur. Sığ göllerde plantivor balık biyomasının azaltılması bir başka deyişle biyomanipülasyonu ile artan su kalitesi, ışık geçirgenliği, ötrofikleşme ile yok olan göl içi bitkilerinin artamasını sağlamakta ve su altı bitkilerinin artan biyoması sistemi sahip oldukları kontrol mekanizmaları ile su kalitesindeki iyileşmeyi kararlı hale getirmektedir. Derin ve büyük göllerde biyomanipülasyon tekniğinin, etkili olması sığ göllere göre daha zıyıf bir olasılıktır, çünkü derin göllerde fitoplankton biyomasının yukarıdan-aşağıya kontrolü zayıflayarak etkisizleşmektedir.

Anahtar Sözcükler: Derin göl, sığ göl, fosfat, biyomanipülasyon, balık, su bitkisi.

Introduction

During the latter half of this century, there has been increasing concern over the increasing nutrient status, or eutrophication, of many lakes because the eutrophication of temperate lakes leads to increase in algal biomass (including potentially toxic cyanophytes) and changes in a community's structure. These changes can be summarized as production of much more algal material in a eutrophic lake than can be used by the herbivores (e.g. *Daphnia*). This surplus accumulates in the lake until decomposed by bacteria. This leads to a progressive decline in dissolved oxygen and, in extreme cases, to anoxia and release of accumulated nutrients from the sediment. An increase in pH is observed following the consumption of CO_2 by photosynthesis. These variations in the chemical environments provoke modifications in the biological community. Stenotype fish species such as salmonoids and coregonids are gradually replaced by more tolerant cyprinids; in the phytoplankton, green algae are replaced by blue-green. The zooplankton populations also undergo

a profound structural change passing from large-Cladocera to small-Cladocera dominance (e.g., *Daphnia* to *Cyclops* and rotifers dominance). More generally speaking, at this level of the food chain there is a gradual shif to smaller species which are less efficient at utilizing the available food particles, and eutrophication sets a wider gap between the primary production and algal biomass utilization by herbivorous zooplankton (1). Due to wide recognition of the problems caused by increased algal biomass in water quality deterioration, much research has focused on factors that may limit phytoplankton populations (2, 3, 4) and numerous investigators have used algal species composition as indicators of trophic state of lakes (5, 6, 7). Cyanophyta appear to be common algal taxa associated with poor water quality in eutrophic deep lakes and are recognized as a major water quality problem worldwide (8). Several competing hypotheses have been proposed to explain the seasonal and geographical incidence of cyanophytes, including high water temperature (9), low light (10), low N:P, the role of buoyancy in Cyanophyta dominance (10) and, lastly, low CO_2/high pH (11). These form a base for understanding the mechanisms for controlling the eutrophication or cyanophyte problems of water bodies but are generally the result of intensive studies on large, deep lakes. More recently a great deal of researh has been carried out in shallow lakes, where the significance of zooplankton grazing has become apparent for controlling algal crops (12-16), though not necessarily cyanophytes.

Bottom-up & top-down forces in water bodies

There has been much debate about the relative importance of the determination of phytoplankton crops by nutrients (bottom-up control) or by zokoplankton grazing (top-down control) (17-20). It has widely become accepted that the control of algal biomass and species is determined by both top-down and bottom-up forces (14, 21). In an environment that is free of any population limiting effects of predators or controlled just by nutrient availability (bottom-up forces) (Figure 1, left panel), the pattern of trophic level abundance and species composition with respect to nutrient availability would primarily be determined by competition. At the bottom of the food web, algal biomass would increase with increased nutrient concentrations (22). Furthermore, the percent composition of grazable algae would decrease and total algal biomass would increase. With the incerasing nutrient availability, the percent composition of calanoids might decrease and cladocerans and specialist microzooplankton might increase. Among the fish, planktivores would be expected to be increasingly abundant and piscivores less abundant (23).

On the other hand, in an environment where changes have been controlled by top-down or prey-predator (Figure1, right panel), the driving force in both abundance and species composition is predation. At the top of the food web, piscivore fish would have strong effects on planktivore fish (24). At the planktivore-zooplankton link, large zooplankton species would always be controlled by planktivore. At the zooplankton-algae link, grazable algae would be sharply decreased by zooplankton grazing (25).

Because top-down and bottom-up forces both affect abundance and species composition, it is very difficult to isolate the mechanisms that determine algal biomass. The holistic model (23) (Figure 1, middle panel) suggests that as nutrient concentrations increase, predator abundance increases in response to increased prey availability and then decrease in response to nutrient-mediated habitat degradation. Planktivore increase with nutrients. Zooplankton biomass also increase with increasing nutrient, but planktivore abundance eventually reduces the biomass of large-bodied grazers (*Daphnia*), increasing in turn, algal biomass (26).

Control of eutrophication by external nutrient control (bottom-up)

Wide acceptance of the importance of nutrient concentrations in water quality deterioration has brought about an approach in which eutrophication is, to some extent, reversible in that algal crops can be reduced if nutrient additions are restricted. Since the 1960s in North America and the 1970s in Europe, there has been a pressure to mitigate the effects of eutrophication. The first question that arises is which nutrient or nutrients to remove. To gain increased algal production, both nitrogen and phosphorus supplies must be increased. Reducing the algal crop of a lake, however, should require reduction in a single nutrient, phosphorus, because it can be radily controlled (27). Nitrogen is not easily controlled, as its compounds are too soluble, they enter waterways from many diffuse sources and there is also a potential source of it from the atmosphere through nitrogen fixers. Phosphorus, on the other hand, is readily precipitated, enters mostly from a relatively point sources and there is no atmospheric reserve of it (28, 29, 30).

External nutrient control in deep lakes

The isolation of lakes from concentrated phosphorus sources such as urban sewage effluents or external nutrient loading is thus often considered to be the first an main step in reversing the adverse effects of eutrophication (31-34). Therefore, lake restoration techniques have traditionally focused on reduction in
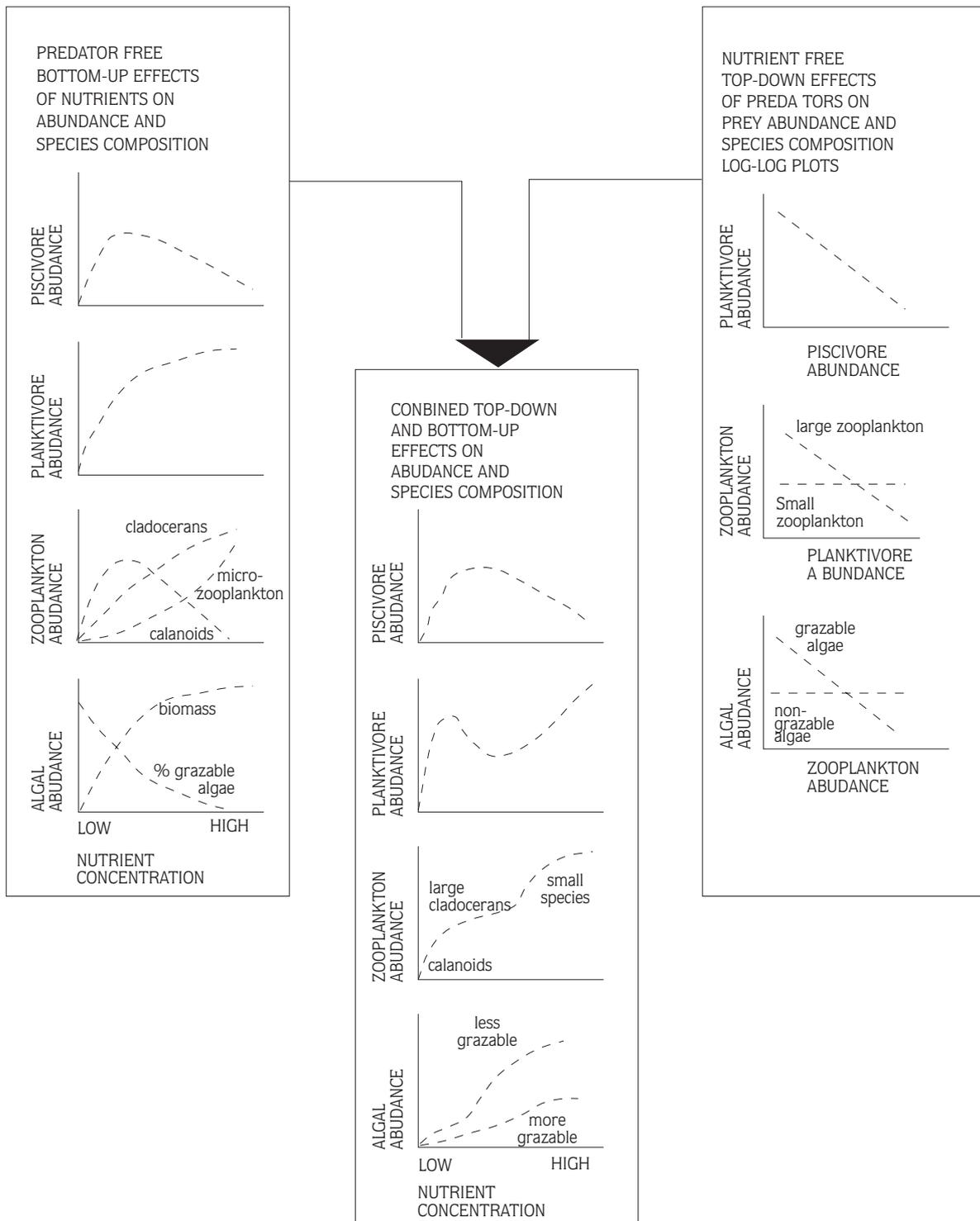
Figure 1. The isolated effects of nutrient concentrations (left panel) and predation pressure (right panel) and the interaction effects (middle panel) of these two factors together. A detailed explanation is given in the text (taken from McQueen, 1990).

external phosphorus loading where urban effluent (point source) has been the main source of phosphorus. The classic cases are Lake Washington and the St Lawrence Great Lakes in North America and the alpine lakes of Italy and Switzerland. Where diffuse sources dominate and the lakes are deep and large (30). Lake Washington is perhaps the best example of restoration by external effluent reduction. In 1955 a blue-green alga, *Oscillatoria rubencens,* became prominent in the plankton, and the lake was receiving sewage effluent (24 200 m^3 per day) and the effluent was providing about 56% of the total phosphate load into lake. In 1967 almost all of the effluent was piped to the sea. The transparency of the water increased from 1 to 3 m and chlorophyll a concentrations decreased from 38 to about 5 µg l^{-1}. The lake responded very quickly to the diversion and since the early 1980s has improved even more (35, 36).

There are also some lakes, for example, the deeper, ground water-fed Shropshire meres, UK (14, 37), which may retain naturally high concentrations of phosphorus and in which nitrogen in the key limiting nutrient. These cases require different approaches.

External nutrient control in shallow lakes

The scenario of external P reduction in shallow lakes has been very different from that of deep lakes, which is almost complete resilience or long delayed recovery (34, 38, 39). Control of phosphorus inputs at nearly 200 lakes in Holland has proved to be inadequate (40) and similar problems have been experienced in the Norfolk Broadland, UK (41). Despite very low external P loading to shallow Danish lakes, due to very stringently control, resilience to recovery has been long-lasting (42). However, release of phosphorus from the sediment appears to be a factor in many shallow lakes from the P-pool accumulated in the lake sediment during the time when loading was high (34, 39, 41, 43-47). The duration of resilence depends on conditions such as the magnitude and duration of loading, hydrological retention time and iron inputs (34, 45, 48). Flushing rates of water bodies are importanted for recovery because under such high flushing rates, fast reduction in concentrations of limiting nutrients (dilution) has been recorded (49, 50). However, the period of resilience may be long-lasting, even in fast-flushed lakes (51).

Biological homeostasis is another factor affecting interanal P loading and has an important role in the resilience of eutrophic shallow lakes. Trophic interactions in which plantivorous and benthivorous fish seem to contribute significantly to biological resilience in shallow lakes by feeding on large zooplankton and stirring up sediment when foraging on benthic invertebrates (45, 52-56).

The most approach to releasing large quantities of phosphorus has been the very expensive removal of the sediment or physical or chemical sealing of it (57). Dredging involves disposal as well as removal and the costs can reach millions of ECUs for moderately sized lakes. Physical sealing involves dumping blankets of fly ash and chemical sealing, and the injection of aluminum salts or ferric chloride and sodium nitrate (58). The latter binds phosphorus in an oxidizing environment. The problem is that there are as yet no examples of the long-term success of any of these treatments, and sealing is undesirable in lakes of importance for conservation and wildlife because plant root growth may be inhibited.

Control of eutrophication by biomanipulation (top-down)

Lake systems consist of numerous components, which are not linked through a unidirectional flow of influence from nutrients to phytoplankton to zooplankton and finally to the fish. The eutrophication of a lacustrine enviroment does not proceed according to a linear relationship between nutrient load and algal growth or vise versa, but displays rather a sigmoid trend with delay. Biological systems show a marked resistance to variation, both when an nutrient load is increased and when it is reduced (34). This non-linearity of response is much more accentuated in small and shallow lakes owing to internal nutrient loading. This is probably the main reason for the long resilience of eutrophicated shallow lakes to external nutrient loading reduction. Thus, many studies have focused on the profound effects of top level consumers, such as fish, on the lower levels of the aquatic community, in addition to external nutrient control. The experimental work by Shapiro *et al.* 1975 (59) led to many subsequent studies of what he called biomanipulation and which is generaly regarded as a feasible technique in aquatic management, specifically for the control of algal biomass through the trophic pyramid (52). There are different definitions of the objectives of biomanipulation. All of them concentrate more or less on water quality management aspects. Probably the best of them is suggested by Moss (60): "Biomanipulation is a kind of biological engineering which attempts to reconstruct the ecosystem by using biological as well as, or instead of, nutrient reduction to reduce the algal crop." This top-down effect is also termed cascading trophic interaction (61). Most approaches have focused on the removal of zooplanktivorous fish to stimulate zooplankton populations in order to increase grazing

pressure on phytoplankton (24, 25, 54, 62-64). Some studies have involved a reduction of zooplanktivorous fish biomass by piscivore stocking (61, 65). Despite the apparent potential of piscivore manipulation, there may be drawbacks to this approach in that improved water quality will only be possible when zooplanktivore yields are reduced to such low levels that the piscivores can not be maintained (21). A complete or a near complete removal of planktivorous fish either through piscivore enhancement or removal of plantivores might yield to increased predation pressure of large carnivorous invertebrates (*e.g. Chaoborus, Leptodora*) on large *Daphnia;* therefore, a complete removal of planktivorous fish will not lead to optimal conditions for daphnids to establish and stabilize (66). On the other hand, if the biomass of plantivorous fish exceeds a certain critical level, the large crustacean herbivores will neither be able dominate nor regulate phytoplankton biomass.

Biomanipulation in deep lakes

Studies on food web manipulation or biomanipulation indicate a difference in lake responses between large-deep and small-shallow water bodies (66-71). For deep and large lakes, all of the published reports (21, 26, 52, 65, 66) suggest that long-term effects of biomaniplutaion are strongly dependent upon the probability of non-grazable algal bloom development which is determined by many factors (chemical and physical and grazer-related) which modify the impact that grazers have on phytoplankton biomass. In deep lakes, therefore, successful fish manipulations may only be effective when chemical and physical factors are altered to produce an algal species composition (non blue-green algae or Cyanophyta) that permits strong top-down control of prey by predators or large-bodied grazers (21). Also, due to different turnover times of the organisms a new and stable equilibrium may require several years to develop. For planktivore and zooplankton, the different turnover times are much greater than for piscivores and plantivores so that when planktivore biomasses are high, large zooplankton species may be reduced, but often small species show compensatory increases and piscivore populations track one another with a predictable time lag and show strong inter-annual correlations. For zooplankton and phytoplankton, the differences in turnover time are also large. This means that phytoplankton can respond quickly to predation losses (69). It appears that top-down effect is stronger at the top but weaken near the bottom of the food web (24).

Biomanipulation in shallow lakes

In general, biomanipulation in shallow lakes and ponds have been more likely to result in improved water quality than biomanipulation in deep lakes. This is partly attributable to the fact that submerged macrophytes are able colonize relatively large areas in shallow lakes (13, 16, 40, 42, 54, 63). The role of biomanipulation in shallow lakes is to overcome resilience caused by biological homeostatis. These studies show that after removal of plantivorous and benthivorous fish, there were increases in cladoceran biomass and mean size and decreases in sediment disturbance and internal P loading associated with reductions in algal standing stocks. This is also associated with macrophyte growth in summer (40). The combined effect of both reduction of external nutrient loading and biomanipulation of the fish community has been successful in reducing phytoplankton populations and creating clear-water in many shallow lakes. The short-term results of these food-web manipulations are encouraging, but there is still much controversy over the long-term stability of the improved water clarity. Sings of deterioration of water clarity of manipulated shallow lakes, in which especially macrophyte regrowth have not been achieved, have already been recorded (20, 47) hinting at possible return to high phytoplankton growth which might be associated with a lack of macrophytes and the significant key-role they may play in maintaining clear water in shallow lakes.

Submerged plants are important components of shallow lakes, and they have disappeared in extreme cases, shaded out by intense growth of overlying planktonic algae (40). Turbid water with phytoplankton dominance (or suspended sediment) and a clear-water state with strong macrophyte dominance seem to be alternative stable states in shallow eutrophic lakes (Figure 2) (53, 70-72). These two states have been reported from different geographical regions and appear to fulfill the requirements of alternative stable states (40, 73-77). Scheffer (53, 70) and Moss (64, 71) have suggested that shallow lakes might have alternative stable states, or bistability, an idea based on the observation that the restoration of turbid eutrophic lakes by means of nutrient reduction seems often to be prevented by ecological feedback mechanisms. Mechanisms proposed for stabilising the clear water state by macrophytes include the provision of refuges against predation pressure for phytoplankton grazers (78, 79), similar linkages for periphyton grazers (80), allelopathy (81, 82), reduction of resusupension of bottom material (83), nutrient limitation of phytoplankton through nitrogen uptake by the plants or denitrification by the microorganisms associated with them (84, 85) and provision of spawning grounds and refuge against cannibalization for
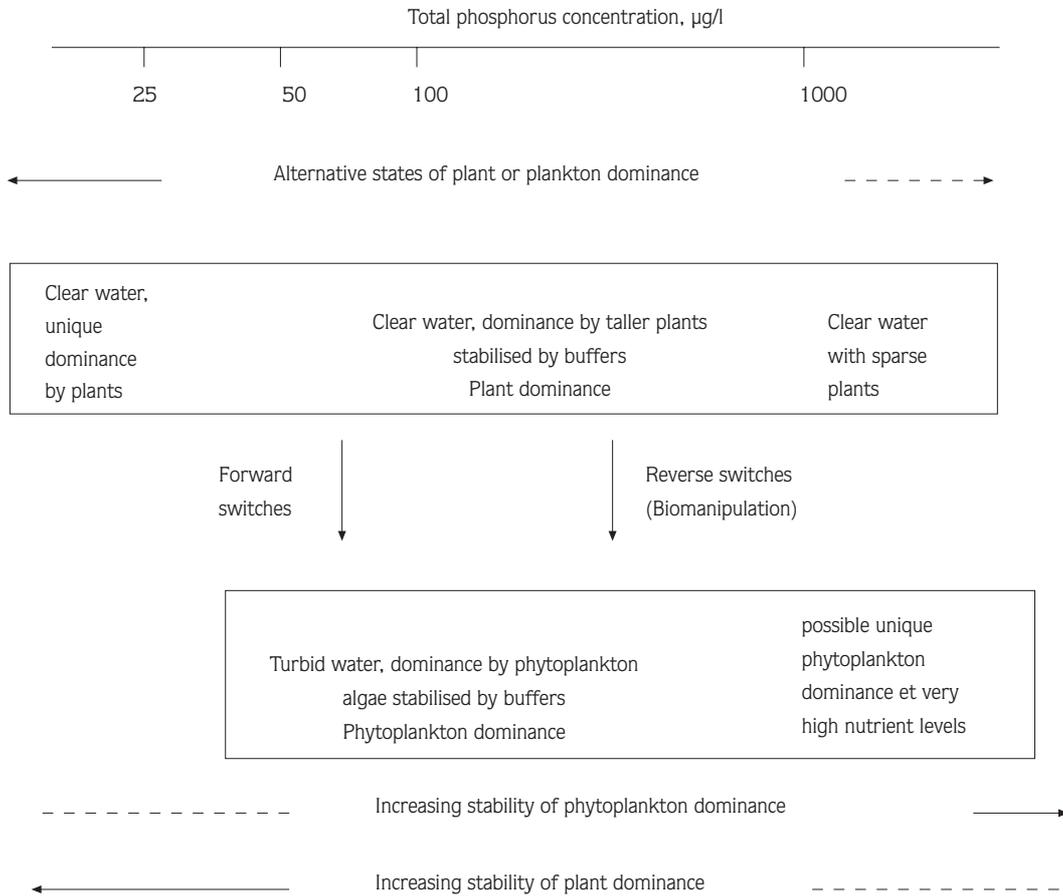
The restoration of shallow lakes

Total phosphorus concentration, µg/l

| 25 | 50 | 100 | | 1000 |

Alternative states of plant or plankton dominance

Clear water, unique dominance by plants

Clear water, dominance by taller plants stabilised by buffers
Plant dominance

Clear water with sparse plants

Forward switches

Reverse switches (Biomanipulation)

Turbid water, dominance by phytoplankton algae stabilised by buffers
Phytoplankton dominance

possible unique phytoplankton dominance et very high nutrient levels

Increasing stability of phytoplankton dominance

Increasing stability of plant dominance

Figure 2. A diagram of a lake (small-shallow; large-deep) stability (O) in response biomanipulated (-------) and unmanipulated (————) changes. In large-deep lakes, manipulated alterations are less stable, with lower capacity and longer duration, while unmanipulated changes have a longer span and higher stability; in small-shallow lakes the converse is true (taken from Moss, 1996).

piscivorous fish (e.g., pike), which in turn decrease zooplanktivorous and benthivorous fish density (85, 86). The switch from clear to turbid water state can be accomplished by destruction of aquatic plants, bird and mammalian grazing, grass and common carp feeding, which are made easier as nutrient concentrations increase. To restore these lakes to clear water and plant dominance, the switch mechanisms must be removed and the nutrients reduced as far as possible. The lakes must then be biomanipulated (30). The role of aquatic vegetation in shallow lake restoration is predominantly a stabilizing one. Thus, the success of external nutrient

control and biomanipulation may depend on the establishment of strong and diverse vegatiton.

Conclusion

To improve the water quality of eutrophicated deep and shallow lakes, external nutrient control and biomanipulation are invariably in conjunction with each other and they should not be seen as an alternative to each other. The importance of top-down control is also influenced by the strength of bottom up factors. The shallow lake is typically fully mixed throughout the year,

whereas most deep lakes are summer-stratified. This affects nutrient availability for the phytoplankton. Therefore, external P control might have a more pronounced effect in deep lakes than in shallow lakes. Fish and submerged macrophytes seem to play an important role in shallow lakes, and biomanipulation of these two compartments may thus have substantial impact because top-down and bottom-up forces both affect abundance and species composition. It is very difficult to isolate the mechanisms that determine algal biomass. It appears inevitable that there are no tailor-made solutions for a reduction of algal biomass and sustainable improvement in water calirty; nevertheless, phosphorus reduction and fish manipulation are indispensable measures.

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