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Lake and Reservoir Management 23:xx-xx, 2007

Danish and other European experiences in managing shallow lakes*

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Abstract

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For a century eutrophication has been the most serious environmental threat to lakes in the densely populated or agricultural areas of Europe. During the last decades, however, major efforts have been used to reduce the external nutrient loading, not least from point sources. Despite these comprehensive efforts, lake eutrophication remains a major problem. Today, the highest pollution input is derived from diffuse sources mainly from agricultural land in lake catchments. We describe the actions taken to reduce the external nutrient loading and the lake responses to these actions as well as the use of additional methods to reinforce recovery, such as biomanipulation. We further discuss resilience and short and long-term responses. We highlight the Danish experiences, but add several examples from

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*This paper is dedicated to our great friend and collaborator Jens Peder Jensen, who died in March 2006

restoration measures taken elsewhere in Europe. We also briefly discuss how a potential change in climate may affect lake responses to diminished nutrient loading.

For 50–100 years eutrophication has been the most serious environmental threat to lakes in the densely populated or agricultural areas of Europe. However, during the last 10–40 years major efforts have been made and vast amounts of money dedicated to reduce the external nutrient loading, not least from point sources, leading to improved water quality and ecological state of many lakes (for reviews see Sas 1989, Marsden 1989, Jeppesen *et al.* 2005b). Despite these comprehensive efforts, lake eutrophication remains a major problem. Today, the highest pollution input is derived from diffuse sources, mainly from agricultural land in lake catchments. The diffuse sources constitute the majority of the nitrogen (N) and phosphorus (P) loads from the 1.6 million-km^2 supra-national catchment to the Baltic Sea. Diffuse loads from mainly agriculture represent 86% and 73% of the total loads (including point sources) for N and P, respectively (Bøgestrand *et al.* 2005). The dominant role of agricultural land as the major contributor to nutrient loading to freshwater systems is also documented for several European river basins because N loads from agricultural sources amount to 54% of total loads in the Po River, 62% in the Vistula River, 57% in the Elbe River and 55% in the Rhine River (Behrendt 2004).

Persistence of eutrophication caused by high P levels in lakes may be attributed to continuously too high external loadings or to internal loadings from a sediment pool of P accumulated in the past (Marsden 1989, Van der Moelen and Portielje 1999, Søndergaard *et al.* 2003). Also, resistance in the biological community (such as a fish community dominated by cyprinids or absence of submerged macrophytes) may play a role (Sas 1989, Jeppesen and Sammalkorpi 2002, Meijer *et al.* 1999, Jeppesen *et al.* 2005b). To accelerate lake recovery, a number of chemical, physical and biological lake restoration methods have been applied to European lakes. In this paper we describe the actions taken to reduce the external loading and the lake responses to these actions as well as the use of additional methods to reinforce recovery. We also briefly describe how a potential change in climate may affect lake responses to diminished nutrient loading. The presentation is based on Danish experiences, but with added examples from restoration measures taken elsewhere in Europe.

Table 1.-Action plans and their major elements adopted in Denmark to combat N pollution from agriculture (updated from Kronvang *et al.* 2005).

Action Plans	Year of adoption	Major implemented measures to combat diffuse nutrient pollution
Action Plan to reduce nitrogen, phosphorus and organic matter	1985	Elimination of direct discharges from farms Livestock quota at farm level
Action Plan on the Aquatic Environment I	1987	9 month storage facility for slurry 65% of fields to be winter green Crop and fertilizer plans
Plan for Sustainable Agricultural Development	1991	Standard N fertilisation values for crops Standard values for N in animal manure Required utilisation of N in animal manure (30-45%) Fertilizer plans at farm level
Action Plan on the Aquatic Environment II	1998	Demands for an overall 10% reduction of N application to crops Demands for catch crops Demands for transforming 16,000 hectares farmland to wetlands Reiterated demands for utilisation of N in animal manure (40-55%)
Action Plan on the Aquatic Environment III	2004	Halving the surplus of phosphorus in Danish agriculture before 2015 Establishment of 50,000 ha crop-free buffer zones along all watercourses and larger lakes before 2015 Establishement of an extra 4,000 ha wetlands

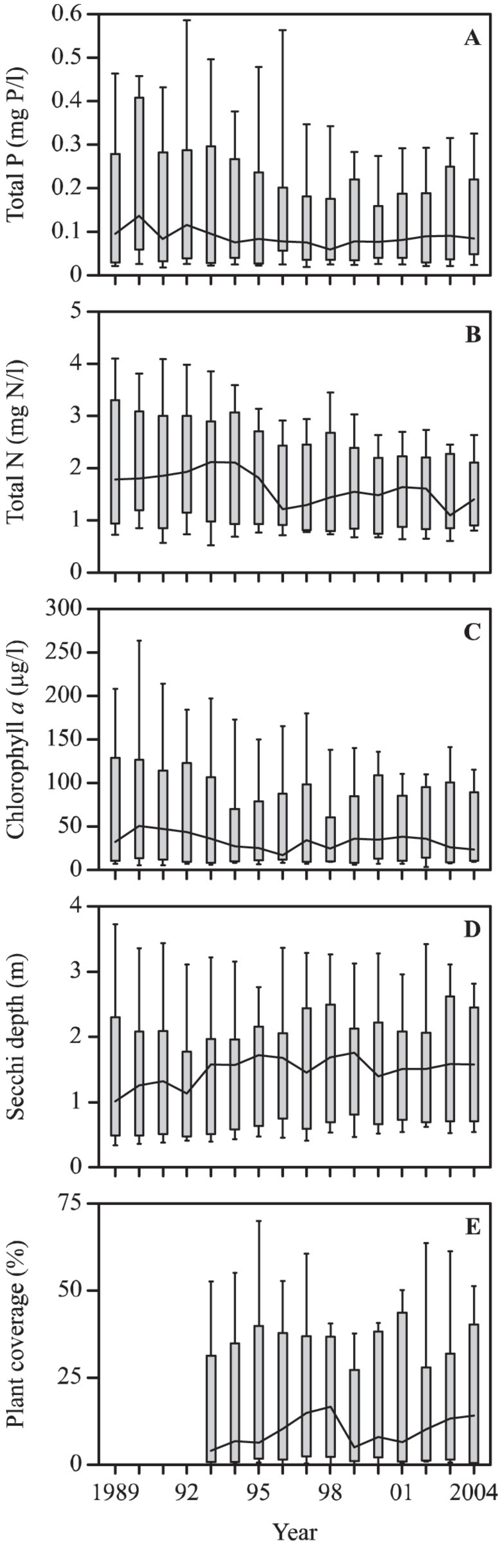

Figure 1.-A–D: Summer mean (May–September) concentrations of various variables in 20 intensively studied Danish lakes during 15 years. E: Coverage of submerged macrophytes in August in the subset of the 20 lakes that host submerged plants. No data were available before 1994. Included are 10, 90, 25 and 75% percentiles, and the line goes through the median.

Actions to reduce external loading

In Denmark, a multifaceted approach has been applied to reduce the external nutrient loading of lakes, first from point sources and more recently from nonpoint sources. These actions include P stripping and N removal at sewage works, increased use of phosphate-free detergents, the establishment of regulations concerning storage capacity for animal manure, improved animal manure application practices, prohibition of winter spreading of animal manure, fertilisation plans, and green cover in winter (Table 1). The latest Action Plan on the Aquatic Environment passed by the Danish Parliament includes for the first time measures directed against diffuse losses of phosphorus from agricultural land (Table 1). In addition, various measures have been implemented to enhance the nutrient retention of lake catchments by re-establishment of wetlands. A recent effort is the posssibility of establishing 10-m wide crop-free buffer zones along watercourses to mitigate the substantial percentage of Danish wetlands, lakes and streams that have disappeared during the last 150 years due to land reclamation (Iversen *et al.* 1993). During this period most of the remaining streams had culverts installed or were channelized, and 'hard-handed' maintenance was introduced (dredging and mechanical weed control) to enhance the drainage capacity. Also, stream beds were lowered and stream widths enhanced to diminish the risk of flooding (Iversen *et al.* 1993). These steps resulted in a significant reduction in the hydraulic retention time and, thus, loss of nutrient retention capacity. A number of projects have recently been initiated or are underway, aiming to re-establish wetlands, streams, ponds and lakes and re-meander channelized streams (Kronvang *et al.* 1998, Pedersen *et al.* 2006).

Simultaneously, more gentle maintenance practices have been introduced in watercourses. Weed control is now undertaken manually with scythes in many public streams (Madsen 1995), increasing the nutrient retention capacity during summer (Svendsen and Kronvang 1993). While temporary retention in streams does not affect the annual TP transport to lakes, it is significant to their environmental state during summer, especially in rapidly-flushed lakes (Kristensen *et al.* 1990). The new, more environmentally sound weed-clearance practices together with the re-meandering of streams and the raising of stream beds have increased the frequency of flooding, thereby increasing the hydraulic retention time and, consequently, the N loss through denitrification. Flooding also enhances retention of the particulate P transported by the streams because P associated with sediment particles settles out in the floodplains where water velocities are reduced (Kronvang *et al.* 2007). This has a marked effect on the P transport because particulate P typically constitutes 35–77% of the TP transport in Danish streams (Kronvang 1992, Svendsen *et al.* 1995, Kronvang *et al.* 2005).

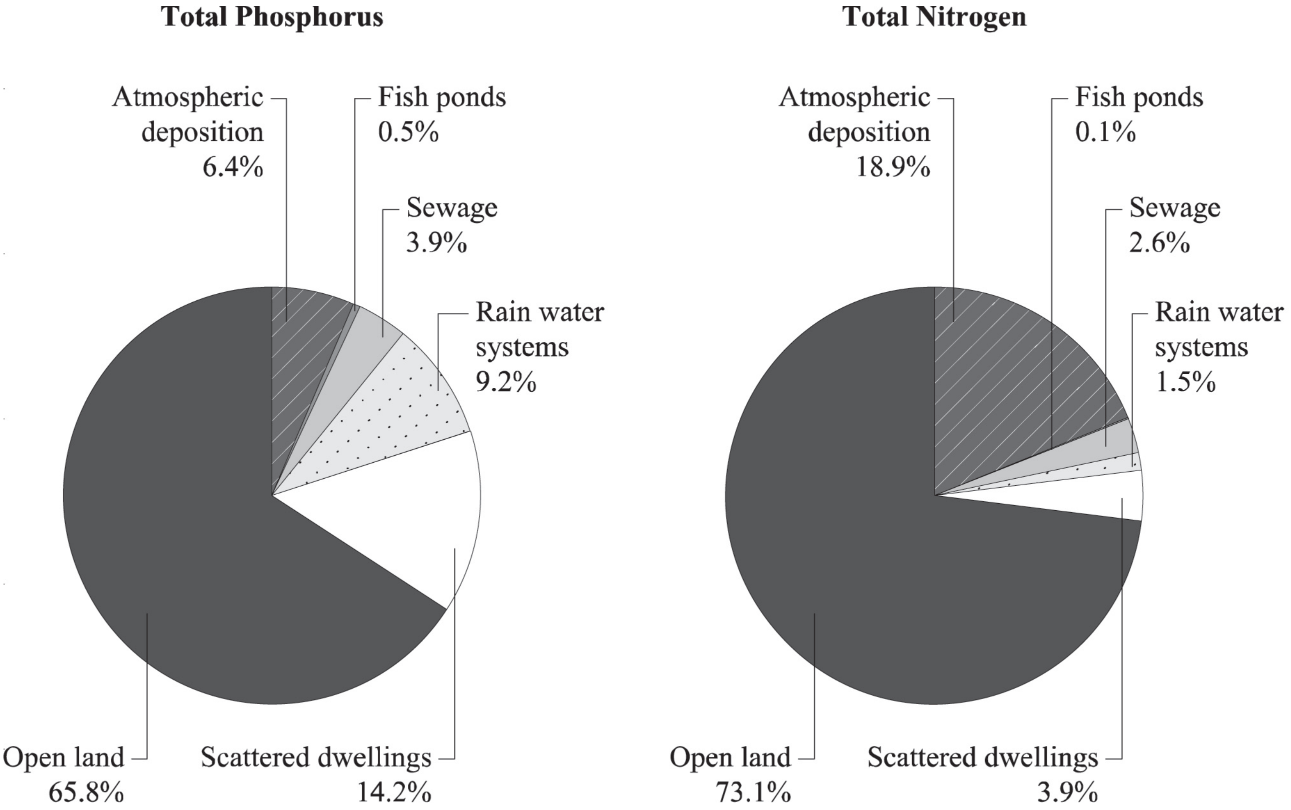

Figure 2.-Pie showing the percentage contribution of various sources to the annual mean total loading of phosphorus and nitrogen to 20 intensively studied Danish lakes. DRP is dissolved reactive phosphate.

As a result of these multiple approaches, the P loading of freshwaters has decreased considerably since the implementation of the various Danish Action Plans on the Aquatic Environment. The average TP concentration in 20 intensively studied lakes has decreased (Fig. 1) from 0.181 mg P L^{-1} in 1989–1995 to 0.106 mg TP L^{-1} in 2004 (Lauridsen *et al.* 2005). However, internal P loading remained important because net retention of P was negative in one-third of the study lakes in 2004. So far the decline in external P loading can mainly be ascribed to improved sewage treatment. Today, point sources only account for 14% of P loading to the 20 lakes studied intensively as part of the Danish lake monitoring programme, while loading from arable land and scattered dwellings accounts for as much as 80% of the P input (Fig. 2). In addition, the N loading and N concentrations in streams and lakes (Fig. 1) have declined, with diffuse source controls being the key mechanisms, although N removal on the large treatment plants have also contributed in some catchments. Stream concentrations of both P and N are now highly influenced by the proportion of agricultural land in the catchment (Fig. 3). The loading reduction of nutrients has resulted in a decrease in chlorophyll *a* in the lakes, while Secchi depth and the coverage of submerged macrophytes have increased in several of the lakes (Fig. 1; Lauridsen *et al.* 2005). In the vast

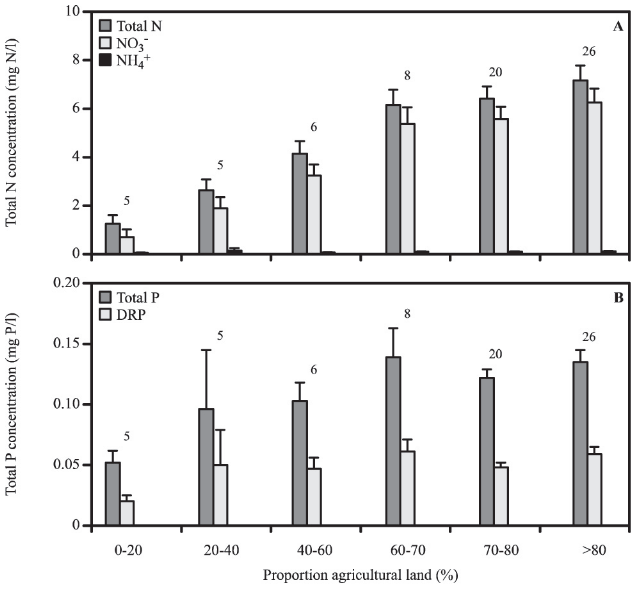

Figure 3.-Annual mean (discharged weighted) concentration of various nitrogen and phosphorus components in Danish streams running in catchments with contrasting proportions of agricultural land. Numbers in the graph represent number of streams included.

Box 1.-Catchment management and farmer commitment - Lake Pyhäjärvi, Finland.

Lake Pyhäjärvi is mesotrophic with a mean depth of 5.4 m, a maximum depth of 25 m, a lake area of 155 km^2, and a catchment area 615 km^2. The eutrophication of Pyhäjärvi started decades ago and accelerated in the 1990s due to high external P loading deriving mainly from agriculture and nonpoint pollution sources in the lake's catchment area. Present knowledge shows that to effectively combat eutrophication, P loading should be decreased by 50%. During the exceptionally dry years of 2002 and 2003 the external P loading was only half that of the mean loading in the 1990s (Fig. 4), and an immediate reduction in lake water TP was recorded (Fig. 5).

Since the early 1990s, water protection measures have been applied in the Lake Pÿhäjärvi catchment area to permanently decrease the nutrient loading. Large-scale protection started in 1995 when the Pyhäjärvi Protection Fund was established by local municipalities, industry and nongovernmental organisations.

Different methods have been used to reduce the nutrient loading, especially the agricultural input. Buffer strips and protective zones have been established along rivers and streams to prevent surface runoff loading. Wetlands, settlement ponds, and a series of small dams have been constructed to increase the sedimentation of solid particles in the water and to bind dissolved nutrients to the vegetation. Also, sand filtration has been implemented to reduce the nutrient loading of ditch water. Because the ultimate goal of all these efforts is to reduce the nutrient runoff from fields, cultivation methods have been optimized, and especially erosion has been reduced with the introduction of conservation tillage. All farmers in the catchment area are encompassed by the European Union's agri-environmental programme and are thus obliged to introduce basic water protection measures, such as reduction of fertilizer use. Recently, the EU has emphasized the need for maintaining and restoring existing water protection measures to ensure continued P removal.

Waste water produced by sparsely populated communities is also a significant source of external nutrient loading. Several research projects have produced recommendations for wastewater treatment methods. Finnish legislation on wastewater treatment has recently been tightened, and sewer networks are today under construction in sparsely populated areas.

Citizen participation and education are important aspects in the effort to encourage the commitment of the local population in the important task of water protection. This commitment intensified substantially in the years of the Pyhäjärvi LIFE Project (1996–2000) when the first village water protection plans were created. These plans were based on suggestions from the local population as to desirable water protection measures for their particular village, and many of these suggestions have in fact been implemented.

Further information is available in Ventelä and Lathrop (2005) and Ventelä *et al.* (2007).

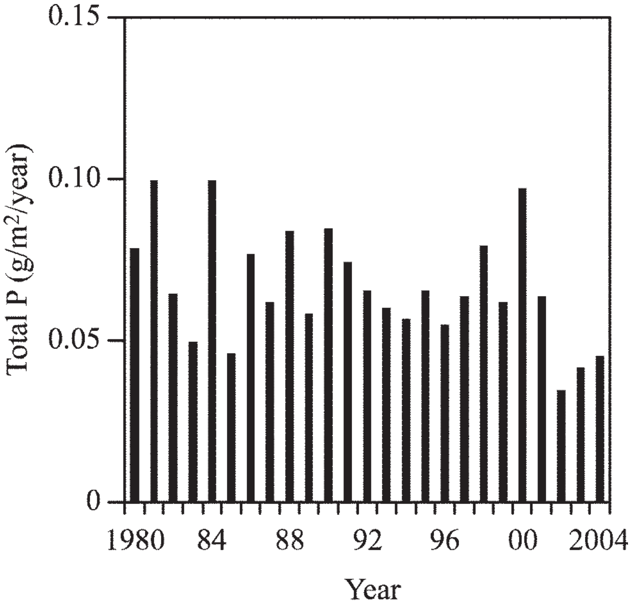

Figure 4.-Total annual P load from 2 major rivers entering Lake Pyhäjärvi, Finland during 1980–2004.

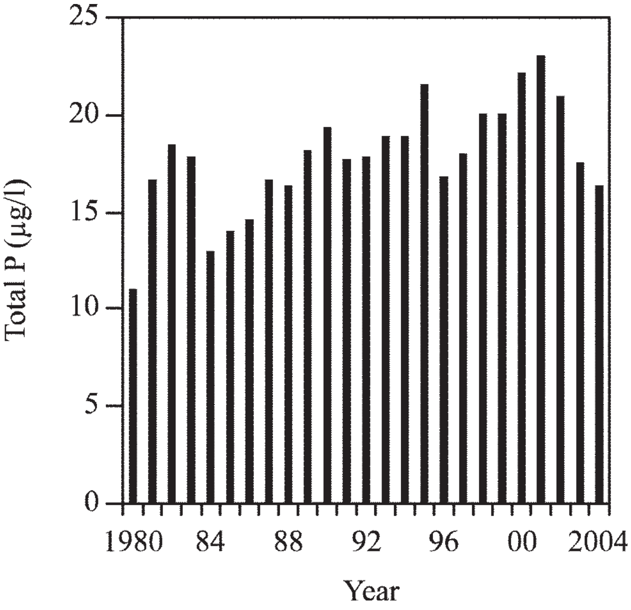

Figure 5.-Total P concentration in Lake Pyhäjärvi, Finland during the 1980–2004 open water season.

majority of the lakes the target ecological state is, however, not yet met (Lauridsen *et al.* 2005).

Multi-approaches to reduce external loading have been introduced in several other European countries. A notable example of this is the Finnish Lake Pyhäjärvi project in which farmers and NGOs were actively involved. Both comprehensive actions at catchment level and in-lake measures (biomanipulation) were taken to improve the ecological state of the lake (Box 1). Establishment of a 90 km^2 wetland area (Kis-Balaton) upstream one of the largest lakes in Europe, Lake Balaton, Hungary (Box 2), is another large-scale restoration project that has led to a reduction in external P loading, at least in the short term, and to enhanced N loss by denitrification in a long-term perspective.

Recovery of shallow Danish lakes after reduced external loading

In the shallow Danish lakes, reductions in TP and chlorophyll *a* were first observed in spring and autumn, and later in summer as well (Søndergaard *et al.* 2005, Jeppesen *et al.* 2005a), even though external loading reduction from point-source controls was evenly distributed over the season. This response indicates that internal loading primarily declines during cold periods in the early recovery phase. During this period a gradually reduced exchangeable P pool in the sediment entails lower release, then lower phytoplankton production, less algal sedimentation, and thus improved redox conditions favoring P retention in the sediment. With lower phytoplankton biomass, benthic algae production may increase, which in turn reinforces the P retention and puts further constraints on phytoplankton growth (Jeppesen *et al.* 2005c). However, during summer, high temperatures reduce the capacity of the sediment to retain P, thereby stimulating a phytoplankton dominated state in the early recovery phase. Eventually the release during summer was also reduced.

Higher improvement rates in cold seasons have also been observed in Lake Barton Broad in England (Phillips *et al.* 2005) and some other European lakes (Köhler *et al.* 2005, Anderson *et al.* 2005). In Müggelsee, Germany, however, where not only P but also N loading was markedly reduced, chlorophyll *a* also declined substantially in summer, even in the early phase of recovery (Box 3; Köhler *et al.* 2005).

The duration of the period with excess internal loading after a P-loading reduction varies among lakes depending on the extent and duration of the period with high loading, retention time and depth (Jeppesen *et al.* 1991, Søndergaard *et al.* 2003). However, even one of the most heavily polluted Danish lakes, Lake Søbygård, is now showing clear signs of recovery following an external loading reduction in 1982 (Box 4), though in this case more than 30 years will likely pass before the lake is in equilibrium with the new and lower external loading. A recent meta-analysis of European and North American case studies has shown that a new equilibrium adapted to the lower loading often occurs after 10–15 years (Jeppesen *et al.* 2005b).

While the decline in phytoplankton biomass and the increase in transparency are evidently associated with the decline in nutrients, cascading effects from the top of the food web have most likely been a contributory factor to the observed improvements. Hence, fish captured with multiple mesh-

Box 2.-Establishment of a large upstream wetland to restore a large shallow lake – Lake Balaton, Hungary

Lake Balaton is the largest shallow lake in Central Europe (596 km^2) and is primarily used for recreational purposes. During the past 30 years, the lake's biota has been heavily impacted by human activities. High point-source loading, resulting from the rapid increase in the application of fertilizers and from sewage discharge, has led to eutrophication and, with it, cyanobacterial blooms during summer and massive repeated fish kill events (Bíró 2000). To combat eutrophication, the Hungarian government has initiated several action plans aimed at reducing the external nutrient loading and nutrient retention. During the past 100 years, the wetland area located at the main inflow (the River Zala) to Lake Balaton gradually disappeared because of drainage. However, between 1986 and 1991 efforts were made to reconstruct about 90 km^2 of this wetland area. The Kis-Balaton Water Protection Reservoir, KBWPR, consists of 2 parts and was constructed for nutrient control of Lake Balaton (Tátrai *et al.* 2000).

Action plans and wetland re-establishment have in combination led to a >70 % reduction in the external P loading from point sources, and since the beginning of 1990s a reduction of the internal P loading has been observed. At present, the KBWPR retains about half of the suspended solids, corresponding to more than one-third of TP, more than two-thirds of phosphate-P, only one-tenth of TN, but more than 50% of nitrate (Fig. 6). A 16 km^2 area of the second part of the wetland has been operating experimentally since 1991. Here, approximately 75% of the suspended solids (mostly of algal origin) coming from the first part is retained, but P retention is low due to the sediment P release (Istvánovics *et al.* 2002). Until 1994 there were no significant differences in the monthly means of the chlorophyll *a* concentration in the western part of Lake Balaton. However, since 1994 chlorophyll *a* has decreased by an order of magnitude. This decrease may be the result of the combined effects of weather conditions (*e.g.*, lower temperature, rainfall, hydrological regime) and reduced nutrient availability.

Further information is available in Bíró (2000); Istvánovics *et al.* (2002) and Tátrai *et al.* (2000).

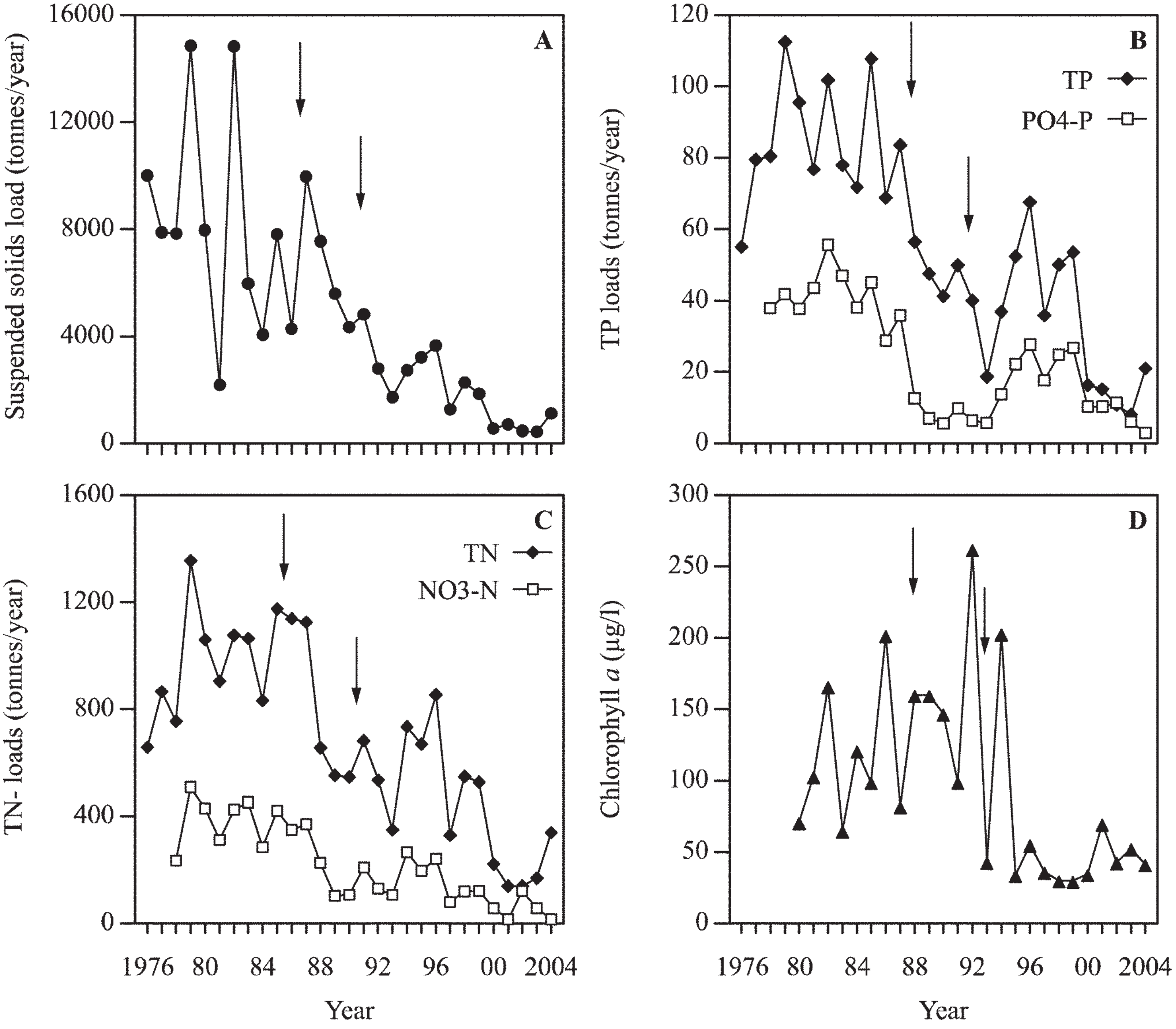

Figure 6.-(A) Annual loads of suspended solids; (B) total P and PO_4-P; (C) total N and NO_3-N reaching Lake Balaton, Hungary, at the entrance to the southwest basin of the lake; (D) maximum summer chlorophyll *a* concentration in the open water of the southwest basin of the lake where the inflow of the Kis-Balaton Water Protection Reservoir (KBWPR) is discharged. Arrows indicate the years of completing wetland reconstruction of part I and II in 1986 and 1991, respectively. (Contribution from the West Transdanubian Water Authority, Kis-Balaton Water Quality Laboratory, Mátyás, K. pers. comm.).

sized gill nets in recovering Danish lakes revealed a shift from dominance by cyprinids (especially bream, *Abramis brama*; and roach, *Rutilus rutilus*) to, in particular, perch (*Perca fluviatilis*). Also, the catch per net per night of more littoral species, such as tench (*Tinca tinca*), rudd (*Scardinius erythrophthalmus*) and pike (*Esox lucius*) increased as an important outcome. The contribution of potential piscivorous fish such as pike, perch and pikeperch (*Stizostedion lucioperca*) increased in lakes with major reductions in summer mean TP, thereby intensifying the top-down control on benthi-planktivorous fish (Jeppesen *et al.* 2005a, 2005b). In addition, the habitat distribution of the fish changed markedly (Jeppesen *et al.* 2006). These changes occurred over a 5–10-year period, which suggests that fish communities and their choice of habitat may change rapidly at lower nutrient levels and, furthermore, that the changes largely follow the trajectory known from lakes undergoing eutrophication. With reduced abundance of planktivorous fish, predation on zooplankton decreased, as was expected. Accordingly, the zooplankton:phytoplankton ratio increased, as did in consequence the grazing on phytoplankton (Jeppesen *et al.* 2005a). Consequently, changes at the top of the food web (fish) also impact phytoplankton biomass in the recovery phase. The meta-analysis of European and North American

Box 3.-Large reduction of external P and N loading – Lake Müggelsee, Germany

Lake Müggelsee is a polymictic lake (mean depth 4.9 m, area 7.3 km^2) in Berlin, Germany. The inflowing lowland River Spree drains a basin of 7,000 km^2. Total phosphorus loading of Lake Müggelsee declined by 52% and TN loading by 68% from the hypertrophic (1979–1990) to the eutrophic period (1997 until present). The effects of lowered nutrient loadings were modified by more intense denitrification and stronger P release from sediments of upstream lakes and impoundments in summer.

Total phosphorus concentrations of Lake Müggelsee declined only during winter and spring. During summer, P release from the sediments was favored by reduced nitrate concentrations. Lake Müggelsee acted as a net P source for 6 years after the external loading reduction despite a mean water retention time of only 0.1–0.16 years. Mean TN concentrations declined steadily in spring, but also in summer. Mean TN:TP ratios fell below the Redfield ratio (7.2 by weight) in August–September in the hypertrophic period and from July–October during the eutrophic period.

Phytoplankton biovolume declined immediately after nutrient loading was reduced. It was significantly correlated to TP in spring and to TN (but not to TP) in summer (Fig. 7). Nonheterocystous cyanobacteria disappeared, but the N-fixing species remained. The abundance of *Daphnia* spp. decreased by 50% in summer; benthic macroinvertebrates (mainly chironomids) declined even stronger. Like phytoplankton, zooplankton was resource-controlled as indicated by significant positive correlations between phytoplankton and zooplankton biomass.

Water transparency in spring increased after nutrient reduction, but recolonization of the lake by submerged vegetation was hampered by periphyton shading and grazing by waterfowl and fish. Mean water temperatures in Lake Müggelsee have increased in winter, early spring and summer since 1979. Warming changed the timing of the development of certain plankton populations, but was less important for the seasonally-averaged total biomass of phytoplankton and zooplankton.

Futher information is available in Köhler *et al.* (2005).

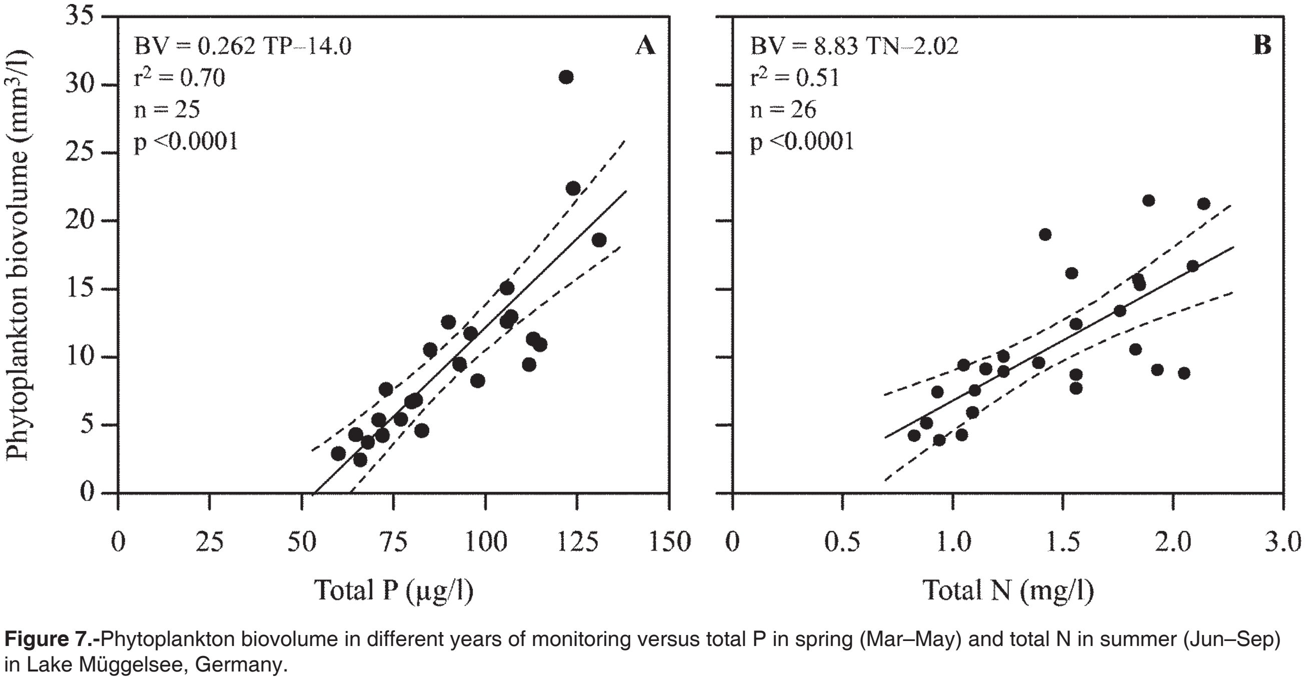

Figure 7.-Phytoplankton biovolume in different years of monitoring versus total P in spring (Mar–May) and total N in summer (Jun–Sep) in Lake Müggelsee, Germany.

Box 4.-Example of long-term resistance to external P loading reduction – Lake Søbygård, Denmark

Lake Søbygård is a small (0.39 km^2) shallow (mean depth 1.0 m, max depth 1.9 m) Danish lake. The hydraulic retention time is short (annual mean 18–27 days). Formerly, the lake received large amounts of only mechanically treated sewage water. In 1976, biological treatment was initiated at the nearby treatment plant, and this led to a 70–90% reduction in loading of organic matter. In 1982, P-stripping was introduced at the plant, and TP loading markedly declined. Despite the significant reduction in TP loading the ecological state improved only slowly (Fig. 8) due to high internal P loading from the P pool accumulated in the high loading period. Today, net retention of P is still negative (*i.e.*, more P leaves the lake than is received via the inlet). Thus, the sediment pool is only slowly reduced (Søndergaard *et al.* 2003), and predictions based on a simple mass-balance model suggest that not until 2016 will the lake reach a new steady state adapted to the present external loading (*i.e.*, 34 years after the loading reduction; Jensen *et al.* 2006). In addition, the biological response has been slow. The fish community remained dominated by cyprinids and the fish biomass (as judged from catch in multi-mesh-sized gillnets) remained high for many years (Fig. 8). Yet, 14 years after the loading reduction, the percentage of piscivorous fish (mainly perch, *Perca fluviatilis*) increased substantially, and the abundance of planktivorous fish, and accordingly algal biomass expressed as chlorophyll *a*, declined. In general, Lake Søbygård is an example of significant chemical resistance owing to high internal P loading following a prolonged period with high external P loading.

Further information is available in Søndergaard *et al.* (1993) and Jeppesen *et al.* (1998).

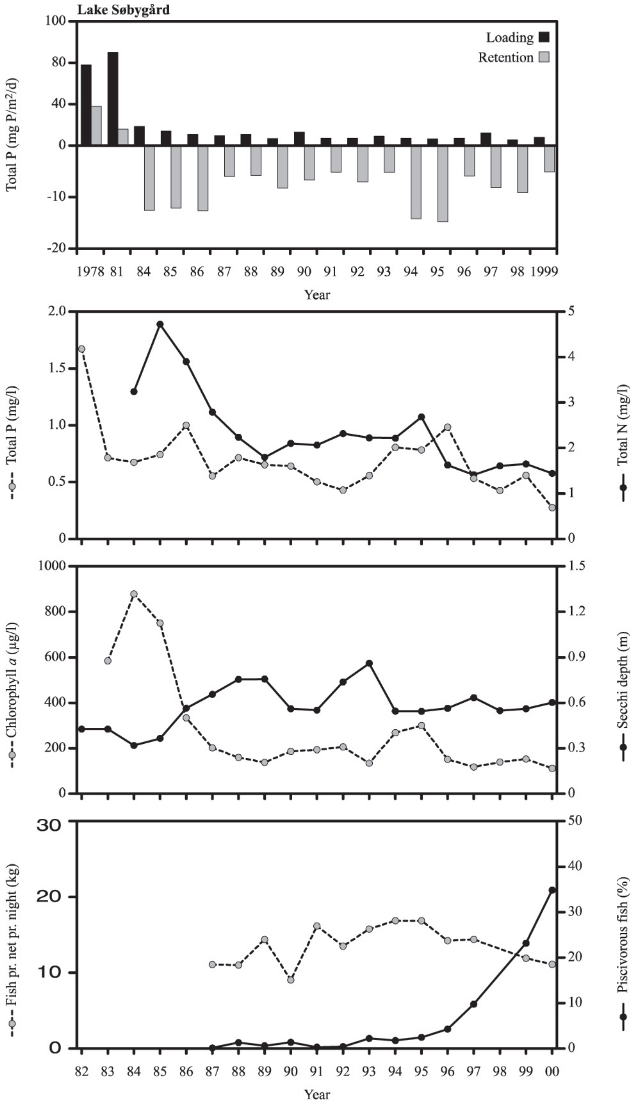

Figure 8.-Top: Annual mean external loading and retention of total P in Lake Søbygård, Denmark 1978–1999. Where retention is negative, more phosphorus leaves than enters the lake. Bottom: Summer mean (May–Oct) concentrations of total phosphorus and nitrogen, algal biomass expressed as chlorophyll *a* and Secchi depth (lake water transparency) in the lake as well as the weight of fish and the percentage of piscivorous fish caught in multiple mesh-sized gill nets (42 m × 1.5 m, 14 different mesh sizes 6.25–75 mm).

lakes described above also showed pronounced changes in fish biomass expressed as a reduction in the benthi-planktivorous fish biomass and an increase in the percentage of piscivores, and often in the zooplankton:phytoplankton ratio as well (Jeppesen *et al.* 2005b).

Reinforcing recovery

In some Danish lakes, the external P loading is now so low that a shift to the clearwater state ought to have occured but has not. To reinforce recovery, various physical and chemical methods have been employed to combat the internal P loading, including sediment dredging and oxygenation of the hypolimnion with pure oxygen or nitrate (Table 2) in the transitional phase immediately following a reduction of external loading. Such initiatives will stimulate the binding capacity for P in the sediment by increasing the concentration of oxidized iron species. Moreover, aluminium treatments have recently been used in several Danish lakes (Reitzel *et al.* 2005). However, biological tools are the most frequently applied methods of restoration (Table 2), comprising removal of planktivorous fish and/or stocking of piscivorous fish (mainly pike and, in a few cases, perch). Removal of 75–80% of the planktivorous and benthivorous fish stock during a 1–2 year period has been recommended to avoid regrowth and to stimulate the growth of potentially piscivorous perch (Hansson *et al.* 1998, Meijer *et al.* 1999). An alternative or supplementary method to fish removal in Europe is ample stocking of 0$^+$ pike (>1000 ha^{-1}) to control newly hatched plankti-benthivorous roach and bream, though the success of such stockings has only been marginal (Skov *et al.* 2006). Others have used stocking of pikeperch and perch (Benndorf 1995, Mehner *et al.* 2002).

The results of extra in-lake measures to reinforce recovery vary considerably, but often significant short-term effects on water quality have been obtained (Søndergaard *et al.* 2003). However, interpretation of results is rendered difficult by the simultaneous application of in-lake measures with loading reduction. Other complicating factors are sudden changes in keystone organisms such as the recent increase in the abundance of zebra mussels (*Dreissena polymorpha*) in several Dutch lakes, including Lake Veluwemeer, which may markedly alter the trophic dynamics and water clarity of the lakes (Box 5). Moreover, only a few studies have had sufficient duration to allow an evaluation of the long-term effects of restoration. Most fish manipulation studies cover only the first few years following the intervention. The few existing Danish long-term time series indicate that maintaining the often strong initial positive effects on the ecological state in the long term is difficult. The reasons for this remain to be elucidated, but factors such as reinforced internal loading of P, return of planktivorous dominance (particularly roach) and large year-to-year variations in the coverage of the submerged macrophyte community may play a role. However, suspended matter remains lower and Secchi depth higher, likely reflecting an apparent permanent lower bream population (authors' unpublished data). Temperature increase during the past 15 years may also have contributed to a shift back toward the turbid state as higher temperatures stimulate sediment P release and blooming of cyanobacteria (Mooij *et al.* 2005, Jeppesen *et al.* 2007). How climate affects the response of a biomanipulated lake was studied in Lake Eymir, Turkey (Box 6). Initially, a severe drought seemed to stimulate macrophyte growth. In the following period, however, nutrient concentrations increased, which might be

Table 2.-Overview of restoration measures applied in Danish lakes (>10 ha) to reduce effects of anthropogenic eutrophication.

Restoration method	**Number of lakes**
Fish removal (planktivores - benthivores)	42
Stocking of piscivores	48
Hypolimnetic oxygenation	6
Aluminium treatment	2
Sediment dredging	1

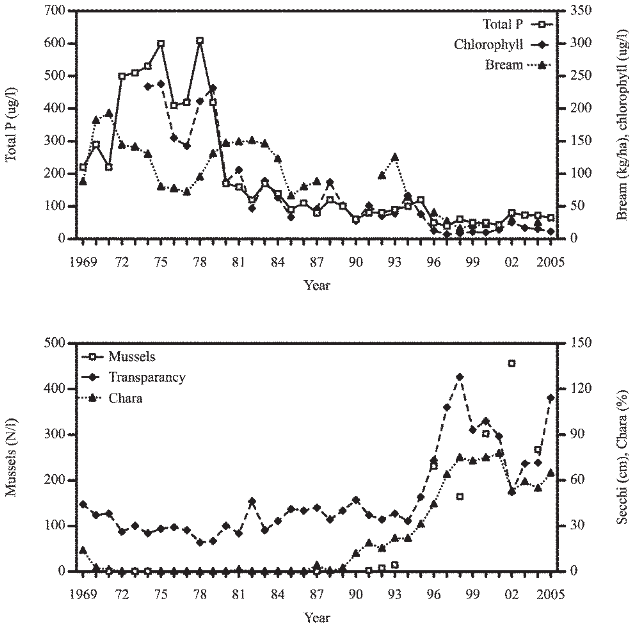

Figure 9.-Top:Total P (average concentration Apr–Sep) and chlorophyll *a* (average concentration Apr–Sep) and the weight of bream (*Abramis brama*) (weight in Aug–Sep) during 1969–2005 in Lake Veleuwemeer, The Netherlands. Bottom: Secchi-depth (cm), density of zebra mussels (No m^{-2}), and *Chara* coverage (%) during 1969–2005 in Lake Veleuwemeer, The Netherlands.

Box 5.-Strong in-lake biological response – Lake Veluwemeer, the Netherlands

Lake Veluwemeer is located in the centre of the Netherlands. It was created in 1957 as a result of land reclamation from Lake IJsselmeer and has a surface area of 34 km^2 with an average depth of 1.5 m. After 15 years the lake was severely eutrophicated and suffered from heavy algal blooms. The restoration took place in 2 steps: first was a P loading reduction at the end of the 1980s. The lake was flushed with relatively nutrient-poor water and, in consequence, TP levels dropped from ~500 $\mu g\ l^{-1}$ to ~125 $\mu g\ l^{-1}$, and the concentration of chlorophyll *a* decreased from ~200 $\mu g\ l^{-1}$ to ~50 $\mu g\ l^{-1}$. The bream population did not exhibit any significant response to the reduction of P and chlorophyll (Fig. 9). The second step was a reduction of the bream population by commercial fishermen (Lammens *et al.* 2002). Over a period of 3 years the bream population was reduced from ~125 kg ha^{-1} to ~20 kg ha^{-1}.

After step 1 of the restoration process, transparency increased from ~30 cm to 40 cm, and at the beginning of the 1990s *Chara* beds started to grow in the shallow parts of the lake where light reached the bottom (Fig. 9). With step 2, the reduction of the bream population, the zebra mussel (*Dreissena polymorpha*) population rapidly recovered, and transparency increased further from 40 cm to ~1 m. In large areas of the lake, light penetrated to the bottom, and *Chara* beds expanded to more than 60% of the lake (Fig. 9). In 2002, transparency temporarily deteriorated, likely due to successful recruitment of bream and roach.

Further information is available in Lammens *et al.* (2002, 2004).

Box 6.-Restoration of an semi-arid lake by fish manipulation – Lake Eymir, Turkey

Lake Eymir is located 20 km south of Ankara, Turkey (39°57'N; 32°53'E, altitude 900m). The lake is shallow (mean depth 3.1 m) and the surface area is 1.25 km^2. The semi-arid dry climate of Central Anatolia with cold winters and hot summers (annual precipitation: 390±76 mm) influences lake dynamics. Due to 25 years of raw sewage effluents input, the lake changed from a clear state dominated by submerged plants to a turbid state. Sewage diversion in 1995 led to 88% and 95% reductions in the areal loading of TP and dissolved inorganic nitrogen (DIN), respectively. However, water clarity remained poor, and submerged plant coverage low (1.1 m and 2.5% coverage, respectively).

A 55% removal of the density of carp (*Cyprius carpio*) and tench (*Tinca tinca*) resulted in a 78% decrease in the amount of inorganic suspended solids and a 2.5-fold increase in Secchi disk transparency (Fig. 10). This increase was particularly prominent in spring, and transparency remained well above the mean depth. Recolonization of submerged plants (*Potamogeton pectinatus* L. and *Ceratophyllum demersum* L) occurred rapidly; growth remained high and the cover ranged from 45 to 90% of the lake surface area during a 4-year period. Re-establishment of vegetation coincided with significantly reduced concentrations of TP. The abundance of *Daphnia pulex* was low, and it later disappeared from the zooplankton community. However, a severe drought occurred 2 years after the fish removal. The water level decreased significantly (>1 m), while the hydraulic residence time increased (7 yr) (Fig. 11). This complicated the process of recovery because salinity, TP, and especially DIN concentrations rose (Fig. 10), but the vegetation coverage increased to 90%.

Six years following the biomanipulation, the lake shifted to a turbid water state, and the submerged vegetation disappeared despite the fact that the lake water level was as low as in 2001 when the vegetation expanded extensively. The shift was probably due to a significant decrease in spring Secchi depth resulting from a 3- to 4-fold increase in chlorophyll *a* concentration, largely due to excessive growth of cyanobacteria. Thus, TP and DIN concentrations seemed largely regulated by internal processes rather than external loading during the drought periods. Further, during the drought tench biomass increased to prebiomanipulation levels, and the ratio of piscivores (pike (*Esox lucius*)) to planktivores decreased.

The results suggest that biomanipulation is an effective restoration measure in semi-arid climates, at least in the short term. The response of semi-arid and high altitude Lake Eymir to fish removal substantially differs from that of subtropical and tropical lakes, probably due to prominent winter ice cover resulting in a limited fish fauna with abundant piscivore, as in cold temperate lakes. However, the initially high TP concentrations made the clearwater state following biomanipulation somewhat unstable. The drought events, which may occur more frequently in the future due to global warming, seemingly led to significantly increased TP and DIN levels; therefore, the thresholds for nutrient loading must be even lower than those suggested by Romo *et al.* (2004) to obtain a stable submerged vegetation-dominated clearwater state in shallow semi-arid or arid Mediterranean lakes in a future warmer climate.

Further information is available in Beklioglu *et al.* (2003) and Beklioglu *et al.* (in press).

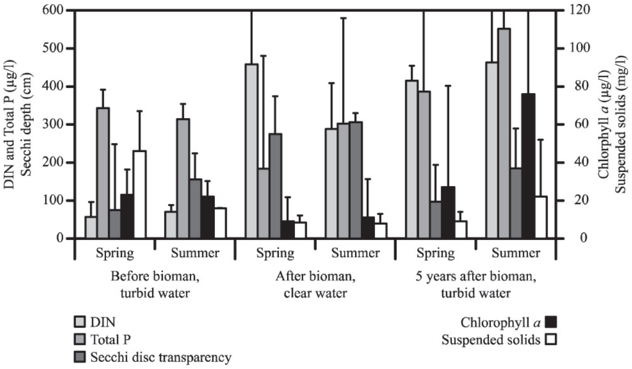

Figure 10.-Mean±SD of selected variables in spring (Mar–May) and summer (Jun–Sep) before, immediately upon, and 5 years after biomanipulation (1997–2005) in Lake Eymer, Turkey.

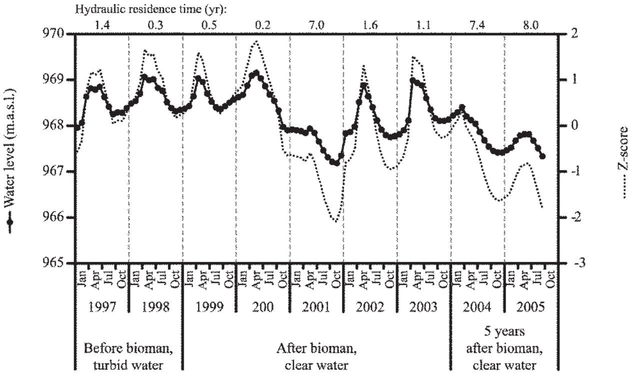

Figure 11.-Changes in water level given in meter above sea level (m.a.s.l) and z-scores measured before, immediately upon, and 5 years after biomanipulation (1997–2005) in Lake Eymer, Turkey. Hydraulic residence time is given for each year. Z-scores were calculated for the water level data by first subtracting the calculated mean from an observation and then dividing this difference by the standard deviation of all the data.

the cause of the observed shift back to a more turbid state with reduced macrophyte coverage.

Clearly more studies are needed to elucidate the long-term effects of in-lake restoration measures and to identify the mechanisms behind the frequently observed poor long-term effects, including the role of climate change. It may be that strategies combining initial intensive measures (*e.g.*, biomanipulation) with subsequent less intensive follow-up actions during a subsequent 5–10-year period are the way forward to stabilize the lake systems.

Acknowledgments

We wish to thank the staff (Jane Stougaard-Pedersen, Lissa Skov Hansen, Birte Laustsen, Karina Jensen and Kirsten Thomsen) at the National Environmental Research Institute, Silkeborg, for technical assistance in the field and laboratory, and Anne Mette Poulsen and Tinna Christensen for editorial and layout assistance. The study was supported by the Danish Natural Science Research Council (research project "CONWOY" on the effects of climate changes on freshwater), the EU EUROLIMPACS project (www.eurolimpacs.ucl.ac.uk) on the effects of climate changes on aquatic ecosystems, the Finnish project CARE and the Danish project CLEAR (a Villum Kann Rasmussen centre of excellence project). We thank G. Dennis Cooke, Peter Kasprzak and Richard C. Lathrop for valuable comments and the latter for the invitation to write this paper.

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