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Restoration of the eutrophic Lake Eymir, Turkey, by biomanipulation after a major external nutrient control I

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Abstract

Nutrient loading in lakes is recognized as a serious threat to water quality. Over 25 years of raw sewage effluent discharge shifted Lake Eymir from a state dominated by submerged plants to a turbid water state. Successful effluent diversion undertaken in 1995 achieved 88% and 95% reductions in the areal loading of total phosphorus (TP) and dissolved inorganic nitrogen (DIN), respectively. Furthermore, the reduced load of TP was very close to the suggested threshold areal load (0.6 g m^{-2} yr^{-1}) to attain recovery. Even though diversion also reduced the in-lake TP level by half, the poor water clarity and low submerged plant coverage (112 $\pm$ 43 cm and 2.5% coverage of the lake total surface area, respectively) persisted. Domination of the fish stock by planktivorous tench (*Tinca tinca* L.) and the benthivorous common carp (*Cyprinus carpio* L.) (66 $\pm$ 0.7 and 31 $\pm$ 1 kg CPUE, respectively) appeared to perpetuate the poor water condition. A substantial fish removal effort over 1 year achieved a 57% reduction in the fish stock which led to a 2.5-fold increase in Secchi disk transparency. This increase occurred largely because of a 4.5-fold decrease in the inorganic suspended solid concentration, and to some extent, a decrease in chlorophyll-*a* concentration. A strong top-down effect of fish on the large-sized grazers was evident as density and the body size of *Daphnia pulex* de Geer increased significantly after the fish removal. Even though the spring and annual euphotic depths occurred well above the maximum and mean depths of the lake, respectively, re-development of submerged plants was poor (6.2% coverage). A weak re-establishment of submerged plants might be attributed to an insufficiently viable seed bank, inappropriate chemical conditions of the sediment (severe oxygen deficiency), or to the high coot (*Fulica atra* L.) density. However, the top-down effect of fish appeared to be of great importance in determining water clarity, and in turn, conditions for submerged plant development in a warm temperate lake as recorded in the north temperate lakes. Furthermore, this study provides evidence for the importance of top-down control of fish, which, in turn, can be effectively utilised as a restoration strategy in warm-temperate lakes as well. More applications, along with long monitoring programs, are needed to develop a better understanding about requirements for biomanipulation success in this climate.

Introduction

Worldwide, lake eutrophication from excessive inputs of phosphorus and nitrogen, leads to water quality deterioration with significant losses of biodiversity, goods and services (Kristensen & Hansen, 1994; Dodson et al., 2000). Eutrophication can also modify water clarity and food web structure. Many shallow lakes exhibit alternative stable states as they shift from a macrophyte-dominated, clearwater state to a phytoplankton-dominated, turbid state in response to nutrient loading, especially phosphorus enrichment

(Scheffer et al., 1993). Reduction of external phosphorus loading is the first crucial step for restoration, which is generally followed by a long resilience due to internal phosphorus loading (Marsden, 1989; Sas, 1989; Jeppesen et al., 1991). Re-development of macrophytes cannot be achieved under such circumstances, consequently turbid water conditions may prevail long after restoration efforts.

Recently, understanding and exploiting trophic cascades provides a successful basis for managing the water quality of eutrophic systems (Hrbácek et al., 1961; Shapiro et al., 1975; Carpenter et al., 1985; McQueen et al., 1986; Benndorf, 1987, 1990). Over 20 years of experience in biomanipulation suggests that success, does not rely solely on the simple fish-zooplankton-algae food chain (Jeppesen et al., 1997, 1999; Hansson et al., 1998; Beklioglu et al., 1999). On the contrary, success is achieved only when fish removal triggers secondary processes, including increases in herbivorous zooplankton (particularly *Daphnia* due to their grazing pressure), the re-establishment of former littoral community structure, reduced fish-mediated resuspension, and reduced internal loading (Carpenter et al., 1985; Benndorf, 1990; Jeppesen et al., 1991, 1997, 1999; Hansson et al., 1998; Meijer et al., 1999).

To best of our knowledge, the present study is the first biomanipulation case undertaken in a warm-temperate Turkish lake. Our objective is to evaluate the efficiency of biomanipulation as a restoration tool in a different climate than is often the case. Following the external nutrient loading control, we tested if biomanipulation could further restore eutrophic Lake Eymir, Ankara. Our results may contribute to understanding the governing mechanisms in the restoration of warm-temperate eutrophic lakes.

Study site

Lake Eymir occurs 20 km south of the capital city, Ankara, Turkey (39° 57′ N, 32° 53′ E) (Fig. 1). The lake is relatively shallow (Z_{mean}: 3.1 m) and large (125 ha) with a long hydraulic retention time (1.8–23 years) (Table 1). Lake Eymir owes its origins to the alluvial damming of the Imrahor River Valley, which led to the formation of two lakes, the upstream Lake Mogan and the downstream Lake Eymir. Lake Mogan empties into Lake Eymir at the southwest corner, forming the main inflow of Lake Eymir, which we named Inflow I (Fig. 1). Inflow 2, which dries up in summer, reaches the lake at the northern end.

The semi-arid dry climatic condition of Central Anatolian region influences Lake Eymir. The climate typically includes cold winters and hot summers. Fifteen-year average (1984–1999) of the annual precipitation measured 390 $\pm$ 76 mm with the maximum precipitation recorded in December and May, and the minimum recorded in August (EIE, 2001). Throughout the study period, Lake Eymir displayed a monomictic state. Nearly half of the lake (about 47%) underwent thermal stratification in summer as the thermocline occurred at the depth of 3.5–4 m in early summer, which further deepened to 4.5 m, leaving the hypolimnion with a depth of 2–1.5 m (Table 1 and Fig. 1). Lake Eymir with >1 ‰ salinity and > 2 mS cm^{-1} conductivity can be classified as a hard water lake (Moss, 1998) (Table 1). In addition, the lake is alkaline because of the high pH values (8.5) (Table 1).

Previous state of the lake

The earliest study carried out on Lake Eymir took place in 1946 and 1947 (Geldiay, 1949). The study revealed that the lake originally occurred in a clear-water state, with summer Secchi disk transparency averaging >4 m, including a maximum value of 6 m recorded in June 1947. Moreover, the lake possessed a wide littoral zone where submerged plants had 6–7 m of outer depth of colonisation out of 8 m of maximum water depth. The recorded submerged plants included five angiosperm species and two species of Charophytes (*Chara vulgaris* L. and *Nitella opaca* C. A. Agardh). Charophytes occurred widely and formed a large meadow. The same study recorded nine Cladocera species including three species of large-bodied daphnids (*Daphnia magna* Straus, *D. pulex* de Geer and *D. longispina* Müll.), and three species of plant-associated zooplankters (*Simocephalus vetulus* O.F. Müller, *S. expinosus* Koch and *Alona affinis* Leyding). During the same study, three species of planktivorous fish occurred in the lake (*Cobitis taenia* L., *Noemachilus angorae* Steindachner and *Varicorhinus tinca* L.). Plant-eating coot dominated the 50 waterfowl species observed in the lake.

The Middle East Technical University has owned the lake since 1958. The lake served as the main drinking water supply for the campus until 1990. The lake started experiencing eutrophication from the 1970s onward as a consequence of the increasing discharge of raw sewage effluent from the nearby town

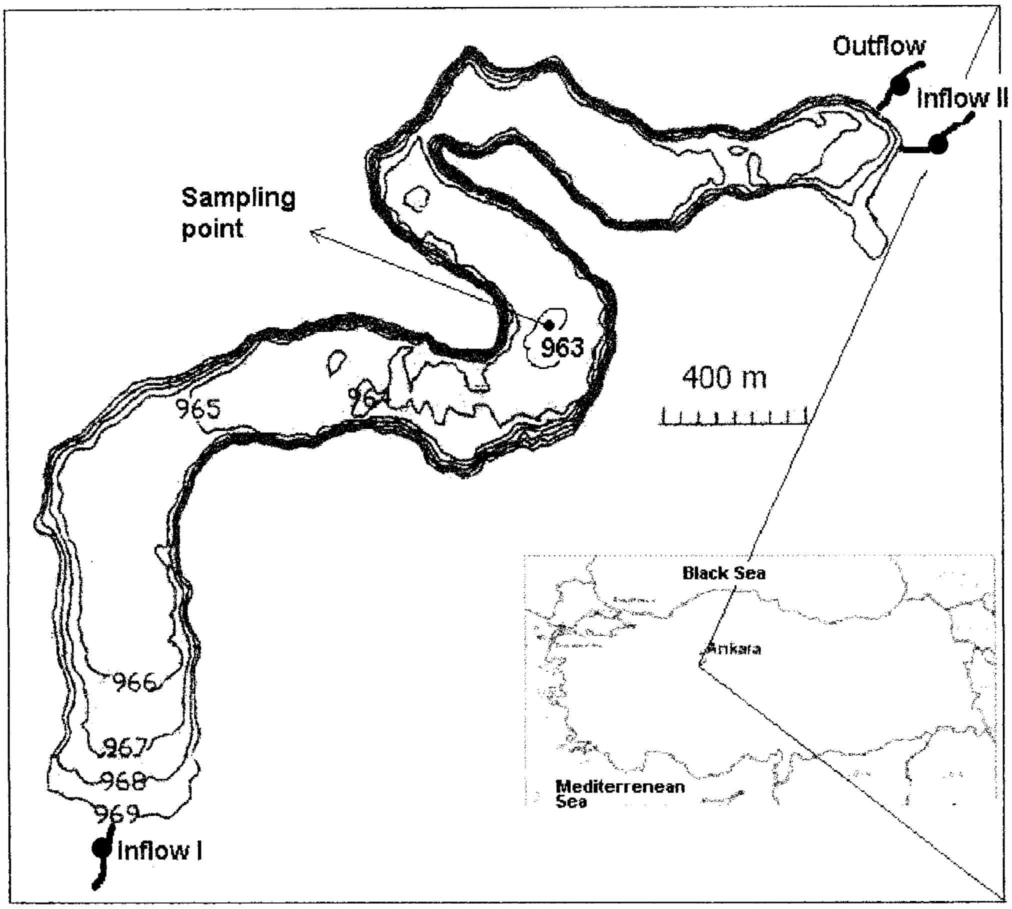

Figure 1. Bathymetric map of Lake Eymir (taken from Altinbilek et al., 1995). Depths shown equal metres above the sea level (m.a.s.l.). Solid round symbols indicate the sampling points in this study.

Table 1. Some hydrological, physical and chemical features of Lake Eymir

Volume (10^6 m^3)	Surface area (ha)	Catchment area (km^2)	Max./mean depths (m)	Hydraulic retention time (y)	Summer water temperat. Epilim./hypolim. (°C)	Salinity (‰)	Conductivity (mS cm^{-1})	pH
3.88	125	971	6/3.1	1.8–23	$23 \pm 0.3/16 \pm 0.7$	1.1 ± 0.05	2.1 ± 0.1	8.5 ± 0.2

(25 000 inhabitants) into Inflow I. A study from 1993 to 1995 revealed the eutrophic characteristics of the lake with high concentrations of TP, DIN, chlorophyll-*a*, and suspended solids in addition to low Secchi depth (727 $\pm$ 433 μg l^{-1}, 1.49 $\pm$ 0.82 mg l^{-1}, 27 $\pm$ 22 μg l^{-1}, 38 $\pm$ 18 mg l^{-1} and 56 $\pm$ 19 cm, respectively) (Table 2) (Altinbilek et al., 1995). The areal load estimation based on their data produced by the same study yielded very high TP, soluble reactive phosphate (SRP) and DIN areal loads into Lake Eymir via Inflow I (5.02, 1.87 and 22.7 gm^{-2} yr^{-1}, respectively) (Table 2). To prevent further eutrophication of the lake, in 1995, diversion of the sewage effluent to the outflow of the lake occurred. However, Inflow I still received poorly-treated, nutrient-rich effluent (TP: 2579 ± 310 μg l^{-1}, SRP: 1522 ± 534 μg l^{-1} and DIN: 3.7 $\pm$ 1.4 mg l^{-1}) from the sewage treatment plant of the TEAS residency with a population of 5000 people (TEAS, STW).

Table 2. The changes (mean ± SD) in the variables measured before sewage effluent diversion (1993–1995), before biomanipulation (1997–August 1998) and during biomanipulation (August 1998–1999) in Lake Eymir. Significance of differences was tested using one-way ANOVA and Tukey's honestly significant difference (HSD) test. The spring Secchi depth included the measurement of the variable from March to June. Algal volumes units are in million of μ m^3 ml^{-1} The annual areal TP, SRP and DIN loadings unites equal g m^{-2} yr^{-1}. Values in brackets represent% contribution of total inputs for a given period. $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$, ns $p > 0.05$. *The data collected during the period of 1993–1995 were taken from Altinbilek et al. (1995)

	Before Sewa. E. D. 1993–1995*	Before Biomanipul. 1997–August 98	During Biomanipul August 1998–99	One-way ANOVA	Tukey's HSD test
TP (μg l^{-1})	727 ± 43	324 ± 31	381 ± 21	**F:12 *p*:0.000**	93_95-***–97, 99; 97-**- 99
SRP (μg l^{-1})	369 ± 22	187 ± 24	284 ± 18	**F:7, *p*:0.003**	93_95-***-97; 99-*-97
DIN (mg l^{-1})	1.49 ± 0.82	0.103 ± 0.14	0.27 ± 0.31	**F:31, *p*: 0.000**	93_95-***97, 99; 97-***-99
NH_4-N (mg l^{-1})	0.86 ± 0.47	0.052 ± 0.02	0.16 ± 0.06	**F:23, *p*:0.000**	93_95-***-97, 99; 97-*-99
NO_3-N (mg l^{-1})	0.68 ± 0.5	0.051 ± 0.02	0.09 ± 0.03	**F:18, *p*:0.00**	93_95-***-97, 99; 97-*-99
Suspended solids (mg l^{-1})	38 ± 18	–	9.4 ± 6	**F:22, *p*:0.000**	–
Chlorophyll-*a* (μg l^{-1})	27 ± 7	19 ± 3.	11.4 ± 2.6	**F:4.6, *p*:0.016**	99-*-93_95 & 97
Secchi depth (cm)	56 ± 6	101 ± 43	262 ± 145	**F:20, *p*:0.000**	99-***-93_95 & 97
Spring Secchi depth (cm)	48 ± 15	95 ± 49	413 ± 91	**F:14, *p*:0.000**	99-***-93_95 & 97
InflowI TP load	5.02 (89%)	0.61 (90%)	1.78 (96%)	**F:7.4, *p*:0.002**	93_95-***97, 99
Inflow I SRP load	1.87 (90%)	0.32 (94)	1.36 (100%)	**F:7.2, *p*:0.002**	93_95-**-97; 97-*-99
InflowI DIN load	22.7 (83%)	1.16 (66%)	2 (95%)	**F:5.7, *p*:0.001**	93_95-**-97, 99
Bacillariophyta	–	0.036 ± 0.004	0.027 ± 0.004	F:0.15, *p*:0.86	–
Chlorophyta	–	1.1 ± 0.05	0.9 ± 0.04	F:0.1, *p*:0.89	–
Cryptophyta	–	0.22 ± 0.4	0.21 ± 0.27	F:0.38, *p*:0.76	–
Cyanobacteria	–	0.052 ± 0.13	0.24 ± 0.3	F.0.37, *p*:0.68	–
Dinoflagellate	–	0.036 ± 0.1	0.13 ± 0.25	F:0.9, *p*:0.4	–
A. bacillifer (ind.l^{-1})	–	1.2 ± 0.3	5.2 ± 0.9	**F:5.6, *p*:0.003**	–
D. pulex (ind.l^{-1}	–	2.1 ± 0.7	11.3 ± 3.2	**F:2.7, *p*:0.05**	–
Daphnid size (mm)	–	1.25 ± 0.1	1.4 ± 0.11	**F:7.5, *p*:0.013**	–
Ceriodaphnia sp. (ind.l^{-1})	–	1.4 ± 0.5	5 ± 3.6	**F:2, *p*:0.053**	–

Materials and methods

We estimated the fish stock once in May 1998, prior to biomanipulation, and once during the biomanipulation in 1999 using multiple mesh-sized gill nets (18, 36, 40, 50, 60, 70 mm). The length and the depth of each section of the net measured 100 m and 3.5 m, respectively. We placed the nets along the shoreline in the littoral zone and perpendicular to the shoreline from the littoral zone to open water and left them overnight to then collect on the following morning. To cover the whole lake, each fishing effort lasted a week. We expressed fish abundance obtained from overnight catches in multiple mesh-sized gill nets as catch per unit effort (CPUE), measured total fish length from mouth to the end of the tail fin, and weighed the specimens. Moreover, we estimated young-of-the-year (YOY) fish stock once in summer 1999 by using a micro-mesh seine net (50 m long, 2 m deep, 2.5 mm mesh-size). YOY CPUE included three sweeps of the micromesh seine net. Moreover, to achieve a recovery in piscivorous fish pike (*Esox lucius*, L.), licensed angling, which was very selective for pike, was banned as from May 1998 as an extra measure on fish stock manipulation.

We sampled at monthly intervals between March 1997 and December 1999. However, in summer 1999, sampling occurred at weekly intervals. We measured temperature and dissolved oxygen concentration at half meter increments using a WTW oxygen meter (to a precision of ± 1%) and recorded Secchi disk transparency using a 20 cm diameter Secchi disk at the deepest point from a fixed buoy. We collected a water sample at the same point from the epilimnion using a weighted length of polyethylene hose and took water samples from Inflow I and II, just before they reach the lake. We monitored conductivity and salinity using an Orion conductivity meter (to a precision of ±1%) and analysed TP, SRP and total oxidised nitrogen (nitrite and nitrate: NO_2-N + NO_3-N) using the methods described by Mackereth et al. (1978), to precisions of ±3%, ±8% and ±8%, respectively. Ammonium-nitrogen (NH_4-N) measurements followed the methods of Chaney & Morbach (1962) to precision of ±4%. During this study, we only measured suspended solids (SS) (APHA, 1998) in 1999, not before the fish removal during the period of 1997–1998. However, Altinbilek et al. (1995) measured SS concentration during the period of 1993–1995 and we used their data to substitute for SS concentration before fish removal (1997–1998). We estimated TP, SRP and DIN aerial loads from Inflows to the lake by multiplying the volume of the water entering from the inflow by monthly mean nutrient concentrations per area of the lake. Inflow II dried out during most of the study period, reducing the significance of its areal contributions. Therefore, we do not include Inflow II in our discussion. Furthermore, we were able to use the data collected during the period of 1993–1995 on Secchi disk, water chemistry and chlorophyll-*a* concentration by Altinbilek et al. (1995).

Total chlorophyll-*a* represented that present in 300 ml of epilimnion water after ethanol extraction (Jespersen & Christofferson, 1987). We immediately preserved phytoplankton samples in Lugol's solution, counted to a precision of ±20% with an inverted microscope (400×) and determined biovolumes from the measurements of the linear dimensions of 10 preserved cells of each taxon, using formulae for appropriate geometric shapes (Wetzel & Likens, 1991). Calculation of biovolume density of each species (μm^3 ml^{-1}) simply entailed the multiplication of average cell volume by cell population density. Community biovolume density represented the sum of the values for all species.

We collected zooplankton samples simultaneously with samples for chemical analyses by vertical tows from the epilimnion using a 45-μm mesh-sized, nylon plankton net (50 cm length and 12.5 cm mouth opening). We also fixed these samples with Lugol's solution and subsampled (using a wide-bore pipette) for counting under a stereomicroscope (minimum of 100 individuals of the dominant zooplankton species) (Bottrell et al., 1976). For each sampling date, we measured (with a precision of 0.04 mm) the body size as the distance from eye to tail spine of the adult *Daphnia pulex*. The body size of the smallest egg-bearing females (1.1 mm) represented the reference size to distinguish juveniles and adults.

We surveyed aquatic plants twice: in July 1998, before biomanipulation, and during biomanipulation in August 1999. During the survey carried out in 1998, we divided the lake into 20 transects with >100 m between each. An average of five observations occurred for each transect. During the 1999 survey, we selected eighteen transects with >120 m distance, each also with an average of five sampling points. Plant occurrence determined from a boat at each sampling point using a glass viewer was plotted on detailed map (1:2500). Furthermore, plants were sampled using a grapnel for identification using Haslam et al. (1982). Percent cover of submerged plants was estimated from a weighed photocopied image of the vegetation map.

Results

Fish stock

Biomanipulation started in August 1998, and stopped in December 1999. Over a year of vigorous selective removal of the planktivorous fish using gillnets led to overall 57% reduction of the fish stock. Planktivorous fish tench and benthivorous common carp dominated the fish stock in Lake Eymir (66 ± 0.7 and 31 ± 1 kg CPUE, respectively) in 1998 (Fig. 2). The 3^+ and 4^+ year classes of tench comprised 85% of the population with the total length ranging from 20 to 33 cm. Large individuals also dominated the common carp stock (the total length: 64 ± 6 cm). Following the stock estimation of 1998, we selectively removed both carp and tench from Lake Eymir. The biomass of tench and carp decreased to 36.2 ± 0.2 and 5.2 ± 0.8 kg CPUE, respectively. Consequently, the fish removal achieved a large reduction in both tench and carp biomasses (45% and 83%, respectively). The 1998 stock estimation found a low biomass biomass of pike (*Esox lucius* L.) (0.54 ± 0.2 kg CPUE) (Fig. 2). The fish stock estimation in 1999 revealed a great recovery in the biomass of pike which increased to 7.9 ± 1.5 kg CPUE (Fig. 2). Large-sized individuals dominated the pike stock (45 ± 5 cm) in both estimations. The YOY estimation carried out in summer 1999 using micro-mesh seine nets yielded 2300 ± 262 individuals CPUE. Tench and carp with lesser contribution, comprised most of the YOY stock.

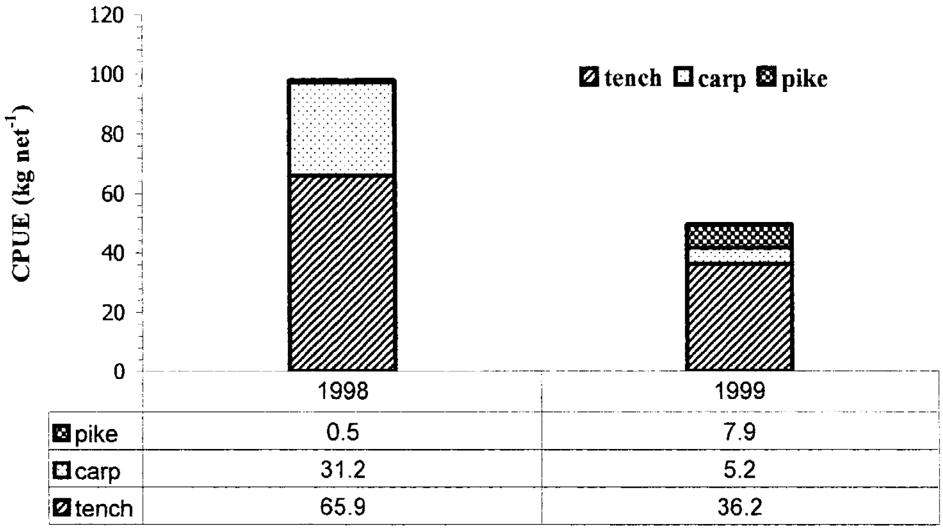

Figure 2. The biomass of fish kg net^{-1} (CPUE) caught using multiple mesh-sized gill-net ranging from 16 to 70 mm conducted in 1998 and 1999 in Lake Eymir.

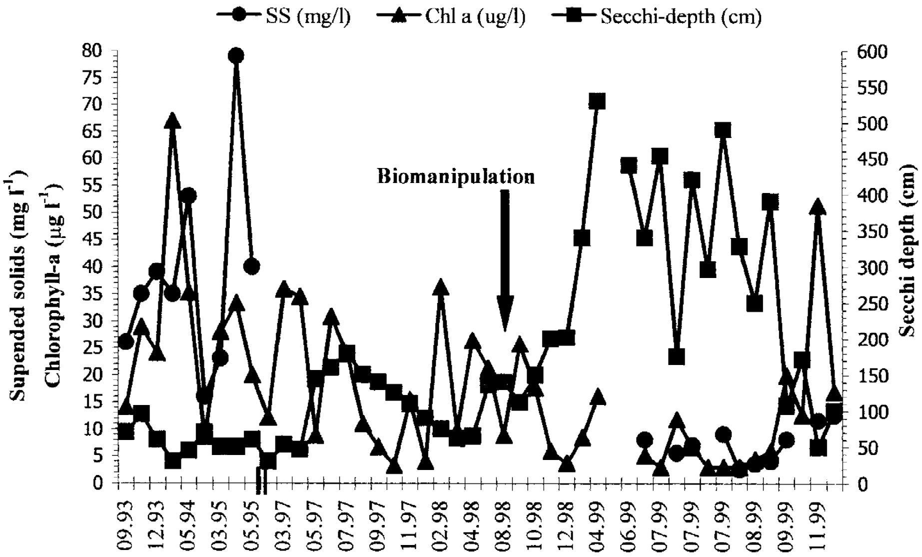

Figure 3. Changes in the concentrations of chlorophyll-*a* (chl *a*) and inorganic suspended solids (SS), and the Secchi depth transperancy (Secchi) in Lake Eymir from 1993 to 1995 and 1997 to 1999. The data collected during the period of 1993 to 1995 are from Altinbilek et al. (1995). The arrow indicates the start of biomanipulation.

Physical and chemical parameters

In Lake Eymir, removal of 57% of omnivorous fish resulted in a great recovery in the Secchi disk transparency and the concentration of inorganic suspended solids and chlorophyll-*a* (262 ± 15 cm, 9.4 ± 6 mg l^{-1} and 11.4 ± 2.6 μg l^{-1}, respectively), which significantly differed between the pre-biomanipulation and pre-diversion periods (Table 2 and Fig. 3). The fish removal resulted in 4 and 1.7-folds reductions in the concentration of suspended solids and chlorophyll-*a*. Furthermore, the fish-removal induced 4.3-fold recovery in the spring Secchi disk transparency, which included the Secchi disk transparency from March to June (Table 2 and Fig. 3). On the other hand, sewage effluent diversion did not lead to a significant recovery in either the annual or the spring Secchi disk transparencies and in chlorophyll-*a* concentration (Table 2 and Fig. 3). The euphotic depths (estimated by multiplying the Secchi depth with 1.7) (Moss, 1998) occurred at 190 and 471 cm for the periods of pre- and during biomanipulation, respectively. Thus, the fish removal resulted in a large increase in the euphotic depth, which occurred well above the mean depth. Furthermore, the fish removal especially increased the spring euphotic depth to 702 cm from 162 cm, which was recorded during pre-biomanipulation. The spring euphotic depth recorded during biomanipulation occurred well above the maximum depth of the lake.

In Lake Eymir, the inputs from the sewage effluent via Inflow I, as a percentage of the total external inputs, measured 89% for TP and 90% for SRP. Effluent diversion undertaken in 1995 led to 88 and 83% reductions in the areal loading of the TP and SRP, respectively, which significantly decreased (0.61 and 0.32 gm^{-2} yr^{-1}, respectively) from previous period (Table 2). A significant decrease of the in-lake concentration of TP and SRP clearly reflected the significant reduction in the external loads of these nutrients. Their concentrations lowered by half during the period of pre-biomanipulation (324 $\pm$ 31 and 187 $\pm$ 24 $\mu g\ l^{-1}$, respectively) compared to the concentrations recorded during pre-diversion (727 $\pm$ 43 and 369 $\pm$ 23 $\mu g\ l^{-1}$, respectively) (Table 2 and Fig. 4). However, the in-lake concentration of TP and SRP increased during the fish removal in 1999 (381 $\pm$ 22 $\mu g\ l^{-1}$ and 284 $\pm$ 18 $\mu g\ l^{-1}$, respectively) (Table 2 and Fig. 4). This increase coincided with the increase in the external loads of TP and SRP via Inflow I (1.78 and 1.36 gm^{-2} yr^{-1}, respectively); however, we found the increase only statistically significant for the SRP areal loading (Table 2).

In Lake Eymir, a significant input of DIN in terms of percentage of the total external input (83%), came from the sewage effluent via Inflow I (22.7 gm^{-2} yr^{-1}) (Table 2). Effluent diversion resulted in 95% reduction in the areal loading of DIN, which significantly decreased (Table 2 and Fig. 5). The decrease in the external load resulted in significant decrease in the in-lake concentration of NH_4-N, NO_2+NO_3-N and, in turn, in DIN (Table 1 and Fig. 5). In Lake Eymir, the inorganic nitrogen concentration showed typical seasonal fluctuations with the high winter and the low summer concentration (Fig. 5). However, during biomanipulation, the concentration of NH_4-N, NO_2+NO_3-N and DIN significantly increased and included higher winter peaks compared to those recorded in pre-biomanipulation period (Table 2 and Fig. 5). This coincided with the large increase in the areal loading of DIN via Inflow I (Table 2). Nevertheless, this increase in the external load did not meet the criteria for statistical significance (Table 2). In Lake Eymir, the ratio of DIN to TP remained low (<1) throughout most of the sampling period (Table 2, Figs 4 and 5).

Phytoplankton community

In Lake Eymir, the phytoplankton community biovolume did not significantly differ between pre-biomanipulation and during biomanipulation, even with lower biovolume in the pre-biomanipulation period (Table 2). Chlorophyta biovolume dominated the community and the biomasses of Cryptophyta and cyanobacteria made large contributions (Table 2 and Fig. 6). The biovolume of Chlorophyta species, *Crucigenia tetrapedia* Kirch. and *Kirchneriella lunaris* Kirch., dominated the phytoplankton community during early spring before biomanipulation (Fig. 6). The biovolume of Cryptophyta, mainly *Cryptomonas ovata* Ehrenberg increased, in June and July 1997, followed by small peaks of cyanobacteria (*Anabaena* sp.) and dinoflagellates (*Ceratium hirundinella* (O. F. Müell.)) in late summer 1997 (Fig. 6). The species of Chlorophyta appeared again and persisted in 1998 and up until summer 1999. A bloom developed by *C. hirundinella* and cyanobacteria (*Merismopedia* sp.) contributed the most to phytoplankton biovolume in late summer 1998 during the beginning of the fish removal (Fig. 6). In 1999, the total phytoplankton biovolume largely contained *Oocystis crassa* Wittrock and *O. parva* West & West (Chlorophyta) and also *C. ovata* (Cryptomonad) (Table 2 and Fig. 6). In summer 1999, the contributions made to the community biovolume by cyanobacteria and dinoflagellates remained as low as recorded in 1997 and before biomanipulation (Table 2 and Fig. 6).

Zooplankton community

Before the fish removal, Lake Eymir contained a low abundance of zooplankton, especially large-bodied species such as *Daphnia pulex* and *Arctodiaptomus bacillifer* Liéven (2.1 $\pm$ 0.7 and 1.2 $\pm$ 0.3 Ind l^{-1}, respectively) (Table 2 and Fig. 7). Small cladocerans, we also found *Bosmina* sp., *Ceriodaphnia* sp., *Diaphanosoma* sp. and *Chydorus* sp., although at low abundances. Fish removal led to a significant increase in the densities of *D. pulex* and *A. bacillifer* (Table 2 and Fig. 7). Furthermore, fish removal resulted in a significant increase in the size of adult *D. pulex* compared to the mean size recorded during pre-biomanipulation (1.4 $\pm$ 0.1 and 1.25 $\pm$

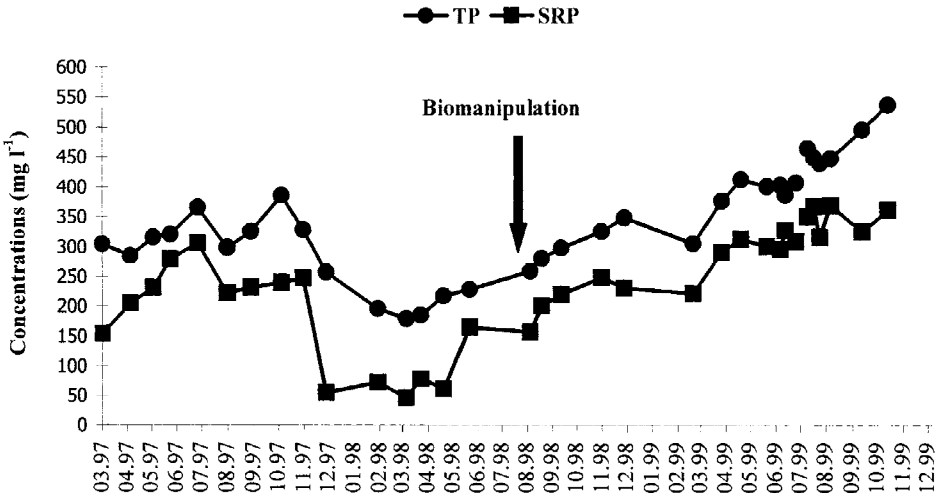

Figure 4. Changes in the concentrations of soluble reactive phosphate (SRP) and total phosphorus (TP) in Lake Eymir from 1997 to 1999. The arrow indicates the start of biomanipulation.

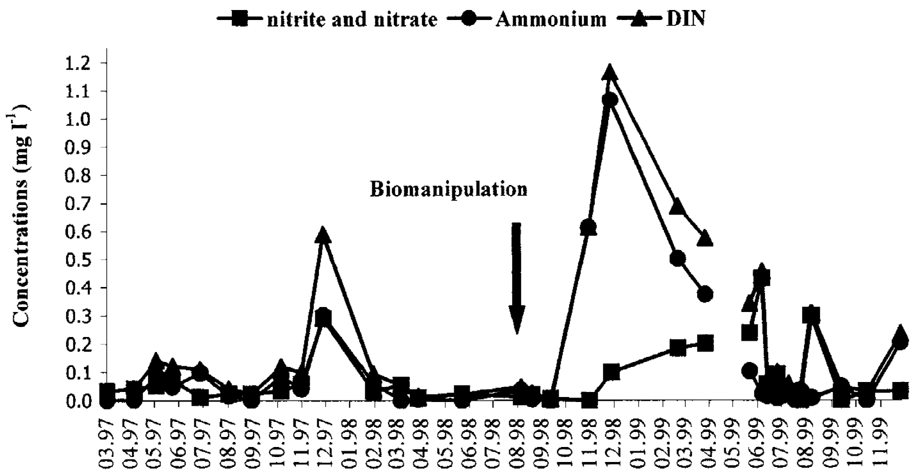

Figure 5. Changes in the concentrations of ammonium-nitrogen (NH_4-N) and total oxidised nitorgen (NO_2-N + NO_3-N) in Lake Eymir from 1997 to 1999. The arrow indicates the start of biomanipulation.

0.1 mm, respectively) (Table 2 and Fig. 7). The densities of small cladocerans did not noticeably change during the fish removal. Only *Ceriodaphnia* sp. produced some occasional peaks, which accompanied a decrease in the density of *D. pulex* (Fig. 7).

Aquatic plants

Our plant surveys carried out before the fish removal in 1998 and during the removal in 1999 recorded *Myriophyllum spicatum* L., *Ceratophyllum demersum* L., *Potamogeton pectinatus* L., *Najas marina* L., and *Najas* sp.. Overall, we found low surface coverage of the submerged plants, only about 2.5% of the total surface area of the lake before the fish removal in 1998. Coverage slightly increased to 6.2% in 1999 during the fish removal. Furthermore, we saw little evidence of dense plant growth. Throughout the study period, the dominant emergent plant, *Phragmites austrialis* L., covered the whole shoreline as a belt with a width of 15–25 m, and with an average of 10–12% of the lake's total surface area.

Discussion

In Lake Eymir, we achieved 57% reduction in fish stock with a vigorous fish removal effort lasting over 1 year. Overall, our results for nutrient concentrations

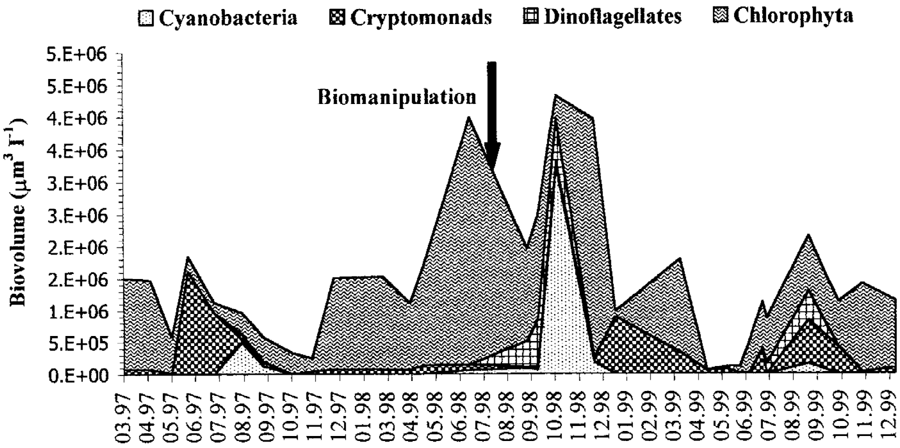

Figure 6. Changes in the biovolume of dominant phytoplankton taxa in Lake Eymir from 1997 to 1999. The arrow indicates the start of biomanipulation.

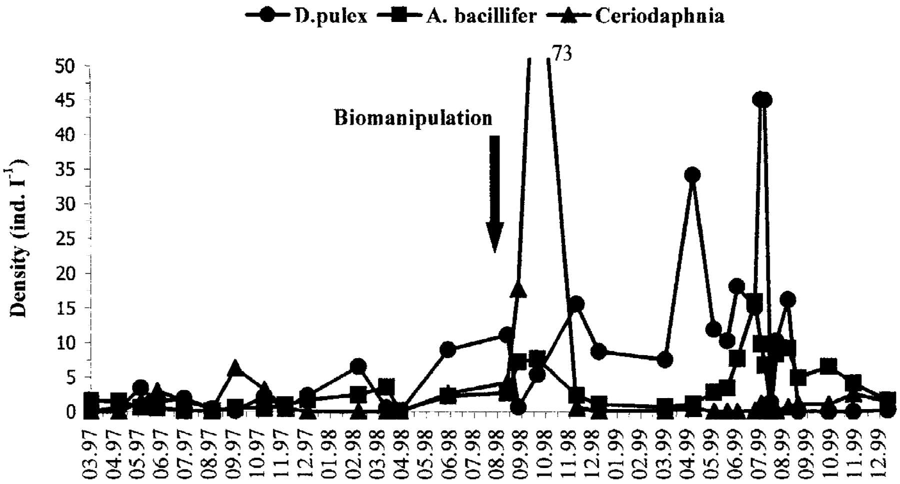

Figure 7. Changes in the density *Daphnia pulex*, *Arctodiaptomus bacillifer* and *Ceriodaphnia* sp. þn Lake Eymir from 1997 to 1999. The arrow indicates the start of biomanipulation.

and food web composition demonstrate that methods used to restore north temperate shallow lakes may also be applicable to warmer systems. Our successful efforts to help restore the lake can be seen in 2.5 fold increase in the Secchi disk transparency after fish removal. This increase occurred largely due to the 4.5 fold decrease in the inorganic suspended solid concentration and to some extend chlorophyll-*a* concentration. Reduction in fish biomass, and thus their feeding-induced resuspension, likely contributed the greatest improvement in the water clarity.

In Lake Eymir, removal of the common carp, which was dominated by enormously large-sized individuals (total length: 64 ± 6 cm), significantly helped improve lake water clarity. A recent review on five Turkish shallow lakes suggested that the turbidity in the lakes were caused largely by carp-feeding induced high suspended solid concentration because common carp dominated the fish stock by 90% of contribution (Beklioglu et al., 2001). Several studies illustrate that, in shallow lakes, high benthivorous fish stock can be responsible for more than 50% of the turbidity induced by sediment resuspension through stirring up sediment while fish feeding (Meijer et al., 1990; Breukelaar et al., 1994). Furthermore, carp-feeding induced resuspension may even act as a catastrophic disturbance causing a shift to the turbid water state from the clearwater state (Zambrano et al., 2001).

Besides sediment resuspension, top-down control of phytoplankton acts as a major driving force for inducing water clarity (Shapiro et al., 1975; Benndorf, 1990: Jeppesen et al., 1997; Hansson et al., 1998; Meijer et al., 1999). In Lake Eymir, the increase in *D. pulex* density and size probably helped control phytoplankton and may have played a role in reducing the concentration of the suspended solids. Jeppesen et al. (1999) demonstrated the importance of grazer control over the concentration of suspended solids in shallow lakes. Nevertheless, the reduction in the concentration of suspended solids through carp removal is the most likely important trigger for clearwater in Lake Eymir.

Fish removal produced significant improvements in the spring and annual euphotic depths. Furthermore, Lake Eymir shows the potential to contain a substantial littoral zone, with 13 km long shoreline relative to its total surface area. However, the submerged plant development delayed and the surface coverage of the submerged plants increased only to 6.2% from the 2.5% of the total surface area of the lake in 1999. Several studies showed that re-establishment of viable macrophytes after biomanipulation efforts may be slow, owing to insufficient viable seed banks, to inhospitable sediment chemistry for germination (toxic substances or too much organic matter), or to herbivory exerted by waterfowl and fish (Crivelli, 1983; van Donk et al., 1990; Lauridsen et al., 1993; Meijer et al., 1999). Lake Eymir possessed a 25 year history of a turbid water state without substantial vegetation cover and long history of raw sewage effluent discharge. Therefore, the lack of a sufficient seed bank and the heavy organic content of the sediment (creating a severe oxygen deficiency especially in the thermally stratified areas) might have prevented re-establishment of the plants. The historical data available on the submerged plants indicated a marked decrease in the coverage and the outer depth of plant colonisation which was 6–7 m with the large contribution of Charophytes 50 years ago (Geldiay, 1949).

Waterfowl grazing may also be responsible for slow re-establishment of vegetation (Lauridsen et al., 1993). In Lake Eymir, herbivory exerted by coots (24 ± 4 ind. ha^{-1}) (MB, unpub. data) recorded in summer 1999 was likely to slow the re-development of submerged plants. Though no waterfowl data exist for the period before the fish removal, improvement in the water clarity might have attracted more coots from the upstream Lake Mogan. Lake Mogan lies 1 km away from Lake Eymir, and is an internationally Important Bird Area (IBA) with very high density of the waterfowl, mainly coot. Moreover, mesocosms experiment carried out on the impact of fish feeding in the littoral zone of Lake Eymir suggested that the coot grazing makes a significant impact on plant establishment (MB unpub. data). In addition, tench, and especially carp, could suppress the submerged plant development. Carp can be potentially destructive for the aquatic plants, either directly through grazing, and up-rooting or indirectly through increasing the turbidity (Crivelli, 1983). However, the mechanisms behind slow plant re-establishment remained unclear.

Our restoration efforts produced impacts through the food web in Lake Eymir. Fish removal significantly increased the density and size of daphnids, although the increase in density *D. pulex* found in the epilimnion appeared lower than recorded elsewhere (Beklioglu & Moss, 1996; Hansson et al., 1998; Jeppesen et al., 1999). We may have underestimated actual grazer density in the lake, as a zooplankton survey carried out a year after biomanipulation showed diel vertical migration (DVM) of large-sized daphnids, with 2–3-fold higher daytime density in the hypolimnion than that of epilimnion (Muluk, 2001). Nonetheless, *D. pulex* density showed signs of instability during summer, perhaps due to the recruitment of YOY. We expected high YOY recruitment following fish reduction due to enhanced spawning and fecundity of adults (Hansson et al., 1998). In Lake Eymir, we report an estimated abundance of the YOY almost an order of magnitude lower than recorded elsewhere (Hansson et al., 1998). Our seine net possibly did not catch all individuals (T. Lauridsen, pers. comm.), however, one should also consider the role of the increased pike biomass in suppressing YOY abundance (Hansson et al., 1998).

Cyanobacteria and dinoflagellate contributed greatly to the summer phytoplankton biomass in 1997 and especially in 1998, as recorded in other eutrophic lakes especially under nitrogen-limited conditions (Ganf & Oliver, 1982; Smith, 1983). In Lake Eymir, availability of nitrogen appeared to severely limit phytoplankton. The species of both taxa are strong competitors under nitrogen limitation (Ganf & Oliver, 1982; Smith, 1983). These species apparently also thrived under weak top-down control of the large grazer *D. pulex.* Furthermore, in summer 1999 during biomanipulation, the biovolume of phytoplankton community, especially the contribution made by cyanobacteria, decreased but the phytoplankton biovolume mirrored the pre-biomanipulation period. Therefore, it is rather difficult to draw a conclusion on top-down effect of zooplankton grazing on phytoplankton community. However, during biomanipulation, grazing-resistant green algae, *O. crassa* and *O. parva,* dominated the phytoplankton community. A gelatinous sheet allows these algae to pass through the grazer's gut without being digested (Reynolds, 1984). Lack of grazers' effect on Crytopmonads, *C. ovata* might have been due to high growth rate of the species that compensated for the grazing loss (Reynolds, 1984). The change in the species composition of phytoplankton towards to grazing-resistant and r-selected species may also hint at the significance of grazer control (Reynolds, 1984).

Due to the worldwide acceptance of phosphorus as a limiting nutrient for phytoplankton production (Schindler, 1971) lake restoration traditionally focuses on reducing the external phosphorous loading. Reducing nutrients proves effective in some cases, especially in deep basins (Edmondson, 1985) but not as much in shallow basins (Marsden, 1989; Sas, 1989; Jeppesen et al., 1991; Beklioglu et al., 1999). In Lake Eymir, 88% of reduction in the TP areal loading by effluent diversion proved significant and efficient as the reduced load was close to, the suggested threshold areal load (0.6 g m^{-2} yr^{-1}) needed to attain recovery (Benndorf, 1987, 1990). We expected considerable resilience in the in-lake TP concentration due to prolonged internal phosphorus loading (Marsden, 1989; Sas, 1989; Jeppesen et al., 1991). However, in Lake Eymir, a major reduction in external TP loading resulted in a significant decline in the in-lake TP concentration 3 years after the diversion, even though the reduced concentration was still high enough to maintain eutrophic conditions. Although diversion induced recovery in the in-lake TP concentration, the turbid water conditions persisted until the fish removal as the alternative stable state hypothesis predicts ineffectiveness of the nutrient control alone in shallow lakes (Scheffer et al., 1993).

In Lake Eymir, we also expected a high contribution of internal P loading to the in-lake TP concentration because of the high fish biomass (particularly benthivores), near anoxic oxygen level in the hypolimnion associated with relatively warm water temperature, and a long history of raw sewage discharge (Boström et al., 1982; Sas, 1989). However, this contribution remained lower than the expected values, as 47% of the total lake water mass remained thermally stratified. In turn, the hypolimnion likely trapped about half of the released phosphorus. Consequently, effluent diversion reduced the in-lake TP to the half of its original level because of the actual low contribution of internal phosphorus loading under thermal stratification. This agrees with findings on the effectiveness of the external nutrient control in thermally stratified deep basins (Edmondson, 1985). Moreover, in Lake Eymir, following the 95% reduction in the DIN areal loading through effluent diversion, an enormous decrease in the concentration of nitrogen occurred as expected. Internal nitrogen loading appears to be an unimportant resilience factor in lake recovery owing to little accumulation of inorganic nitrogen in the sediment, perhaps due to denitrification (Jeppesen et al., 1991; Beklioglu et al., 1999).

Cascading effects of fish removal accompanied with re-development of vegetation often results in a large decrease in the total P concentration, especially due to stabilizing buffer mechanisms of the aquatic plants (Scheffer et al., 1993). However, the high planktivorous fish biomass adds significantly to the resilience of shallow lakes (Carpenter et al., 1985; Jeppesen et al., 1991; Hanson et al., 1998). However, in Lake Eymir significant increases in the concentrations of TP, SRP and DIN during the fish removal coincided with the increase in external nutrient loading, which became slightly higher than the suggested threshold load to attain recovery (Benndorf, 1990). Moreover, the in-lake TP concentration reached well above the threshold below which shallow lakes are usually in a vegetated state (Jeppesen et al. 1991, 1997). Such increase in the availability of the nutrients could jeopardise the success of biomanipulation in Lake Eymir, because an effective external nutrient control for successful biomanipulation is an indispensable prerequisite for long-term recovery (Benndorf, 1990; Jeppesen et al., 1991). However, because Lake Eymir suffered from severe nitrogen limitation, such level of TP might have been tolerable under nitrogen-limited conditions. Nevertheless, in some biomanipulation cases, attaining clearwater and re-development of submerged plants seems to be independent from nutrient levels (Beklioglu & Moss, 1996; Meijer et al., 1999).

In conclusion, this study presents results of the first biomanipulation application in a warm-temperate eutrophic Turkish lake after an efficient external nutrient control. Fish removal achieved a shift to increased water clarity accompanied by a 4.5-fold decrease in the inorganic suspended solid concentration, and to some extent, a reduction in the chlorophyll-*a* concentration. Submerged plants did not immediately re-established though the reasons for such delay remained unresolved. Furthermore, this study provides evidence for importance of top-down control fish, which, in turn, can be effectively utilised as a restoration strategy in warm-temperate lakes as well. More applications, along with long monitoring programs, are needed to develop a better understanding about requirements for biomanipulation success in this climate.

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