

**CONSEQUENCES
OF BIOMANIPULATION
FOR FISH AND FISHERIES**



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by

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ABSTRACT

The main goal of biomanipulation by fish reduction is not a change in the fish community but a change in the aquatic ecosystem. Fish reduction is a method to push the system in another state, usually a shift from algae domination to macrophyte domination. Intensive fish removal is done by one of the following methods: seining (the Netherlands, Germany, UK), trawling (Sweden, Finland), use of rotenone (Norway, USA, Poland) and stocking of piscivorous fish (USA, Germany). If circumstances allow it (reservoir, ponds) draining is combined with seining (the Netherlands, UK, Poland). The intensity and duration of fishing differs per case, but is quite important for the way the system changes. Fishing may be combined with stocking of predatory fish, mainly pike and pikeperch (or walleye). Stocking is only successful when piscivore catch restriction is introduced (catch limit per day; high minimum size; careful handling of piscivores such as using barbless hooks). If the measure is successful the fish community develops into a different direction with usually a lower biomass but more diverse community. The dominance of bream and/or roach in most European waters becomes less pronounced and makes way for species associated with macrophytes such as tench and rudd. Generally commercial fishermen are pleased with biomanipulation because it increases their income. The extra income comes from the reduction fishery itself, which is usually also done by commercial fishermen. In many biomanipulated lakes commercial fishery is absent and it is sometimes necessary to educate people how to use seines and/or trawl or other fishing methods because skilled people are not always available. Anglers fish on most of the lakes and, if well-organized, they are powerful enough to stop or change biomanipulation plans. Usually it is the local, provincial or national governments who initiate biomanipulation for restoration purposes and if anglers associations own the fishing rights they have to negotiate with them. In the north-western Europe and the USA biomanipulation results in improved fishing conditions for anglers, especially when predatory fish are stocked. In the central and eastern Europe fishing conditions are valued differently and the objective for biomanipulation and lake restoration may differ from that of the other European countries. Biomanipulation should be considered in relation to the whole ecosystem and is only one of the options for restoration. Using fish for biomanipulation may require a continual, sustained removal effort and may be efficient only when applied in tandem with other nutrient control and reduction mechanisms.

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1. INTRODUCTION

The use of biomanipulation as tool for water management started in the 1970s in small lakes and because of its success it was also applied in large lakes in the 1990s. Shapiro and Wright (1984) originally defined biomanipulation as “the deliberate exploitation of the interactions between the components of the aquatic ecosystem in order to reduce the algal biomass”. It was known from work by Hrbáček *et al.* (1961) and Brooks & Dodson (1965) that planktivorous fish affect the zooplankton community and indirectly influence the phytoplankton community. Until the 1980s ecosystem thinking was largely in terms of bottom-up effects in the food chain, particularly as in the 1970s the phosphates were found to play a major role in the process of eutrophication. Lake and reservoir managers concluded that the only way back was the reduction of the phosphate loads. In the 1980s it became clear that the functioning of ecosystems was not a simple one-way up the food chain but a more complex web of interactions with feed backs because of top-down effects. It was hypothesized that between certain limits of P-loads the ecosystem could have alternative stable conditions (Jeppesen *et al.*, 1991; Scheffer, 1993): either a high biomass of algae, high turbidity and large fish biomass, or a low biomass of algae, large abundance of macrophytes, clear water, and a different fish community, but not necessarily a low biomass (Fig. 1).

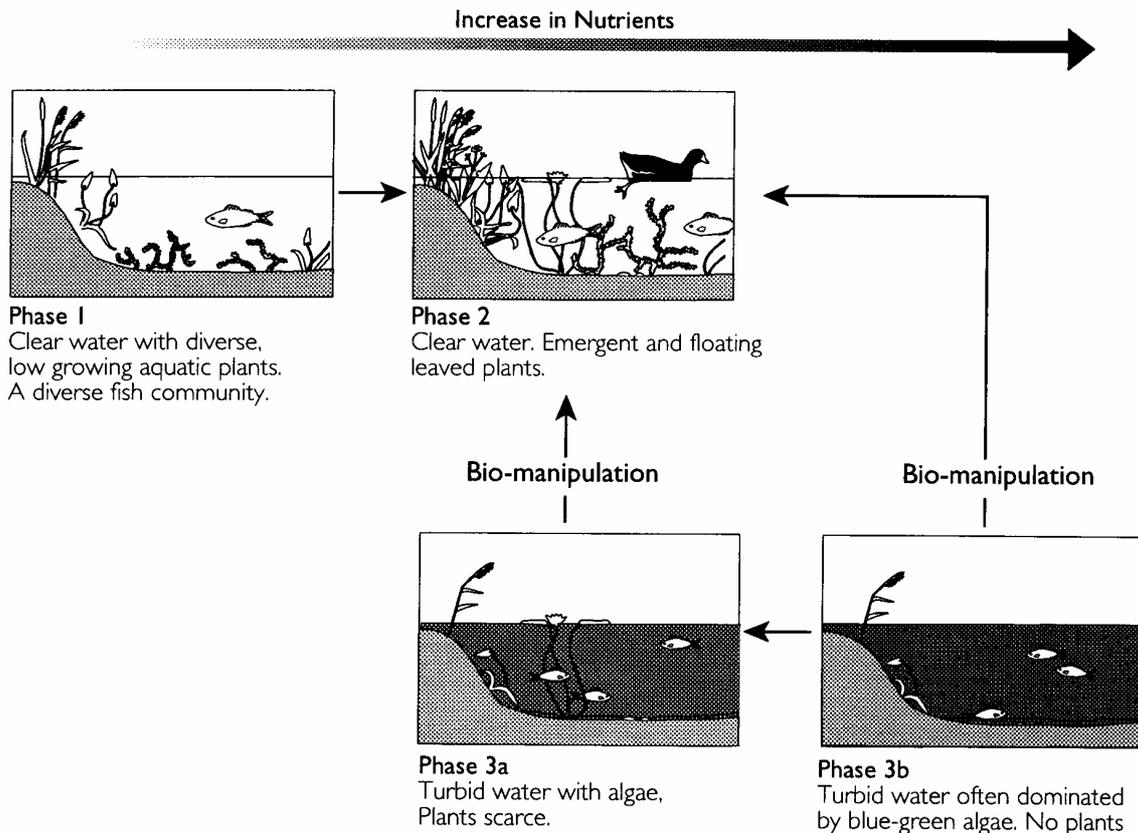


Figure 1. Schematic representation of a shallow lake in vegetation dominated clear state (upper left) and in a turbid phytoplankton dominated state in which submerged plants are largely absent (lower right) and an intermediate stage with two alternative states (from Madgwick, 1999, p. 319, figure 4, with kind permission from Kluwer Academic Publishers).

Although it was clear that the P-load had to be reduced it was obvious that biomanipulation was a practical additional tool in water management bringing a water body more quickly in the alternative stable state. Considering the most important interactions in lakes and reservoirs (Fig. 2) nutrients, fish and water depth are the only variables which can be controlled by the water manager.

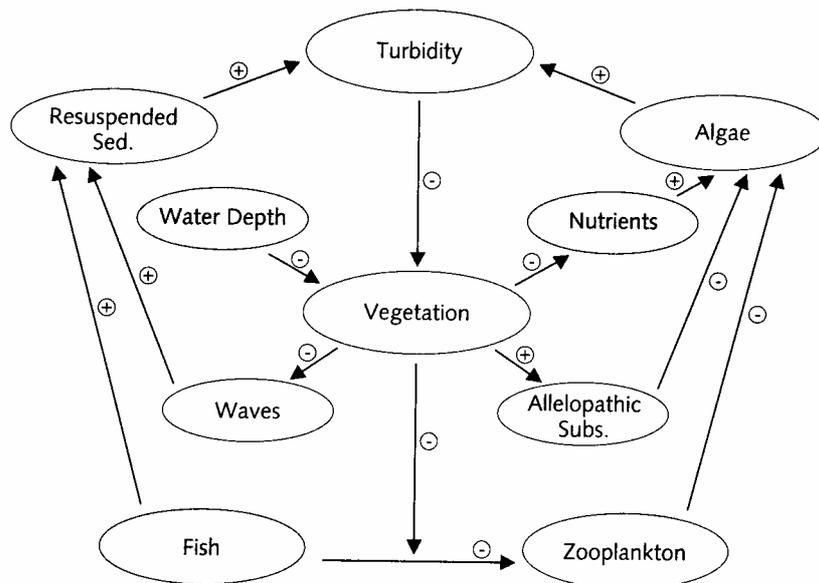


Figure 2. Interactions in shallow, eutrophic lakes with a key role of the submerged vegetation (from Scheffer, 1998, p. 259, figure 5.33, with kind permission from Kluwer Academic Publishers).

In most European countries eutrophication resulted in a change in fish community from a highly varied community with pike (*Esox lucius*) and/or perch (*Perca fluviatilis*) as main predators to one dominated by roach (*Rutilus rutilus*) and/or bream (*Abramis brama*) and mainly pikeperch (*Stizostedion lucioperca*) as predator (Lammens, 1986). This shift to more pikeperch replacing perch and pike was advantageous for the commercial fishery. The conditions for eel (*Anguilla anguilla*) are not sufficiently known, but probably they improved by eutrophication. For anglers the fishing shifted from a variety of species including tench (*Tinca tinca*), crucian carp (*Carassius carassius*), rudd (*Scardinius erythrophthalmus*) and pike to mainly bream, roach and pikeperch. Restoring the lakes and reservoirs to the former mesotrophic conditions will change the catch and the way of fishing of commercial fishermen and anglers just because the water bodies return to the old situation or to an alternative state.

This document reviews different applications of biomanipulation in lakes and reservoirs of Europe and North America and how these have affected the fish populations and the fishing conditions of commercial fishermen and anglers.

2. METHODS OF FISH REMOVAL

Biomanipulation with regard to fish always involves methods to remove fish. Fish may be removed by nets or poison or by stocking predatory fish. These techniques may be combined but the extent and the period of time in which they are applied may differ considerably. As this measure results in a drastic change in the fish community the water manager first has to consult the owner of the fishing rights and has to agree on a fishery plan.

2.1 Fishery Techniques

The fishery techniques usually used are:

- *draining or pumping out*: if a water body is only a few hectares and connected to drainage system the most efficient way of fishing is draining or pumping out the water and removing the concentrated fish with seines. This technique has been used in lake Zwemlust, Maltanski reservoir and Great Linford and the fishstock was completely removed.
- *seining*: the most common way of fishing used to reduce the fish stock (*Fig. 3*). In most European countries this technique is applied when the fish stock has to be reduced by more than 50%. In the Netherlands seines up to 600 meter long, pulled by winches, are used in the larger lakes such as Breukeleveen (180 ha), Wolderwijd (3000 ha), the Frisian lakes (100-2000 ha), and Haussee (136 ha).

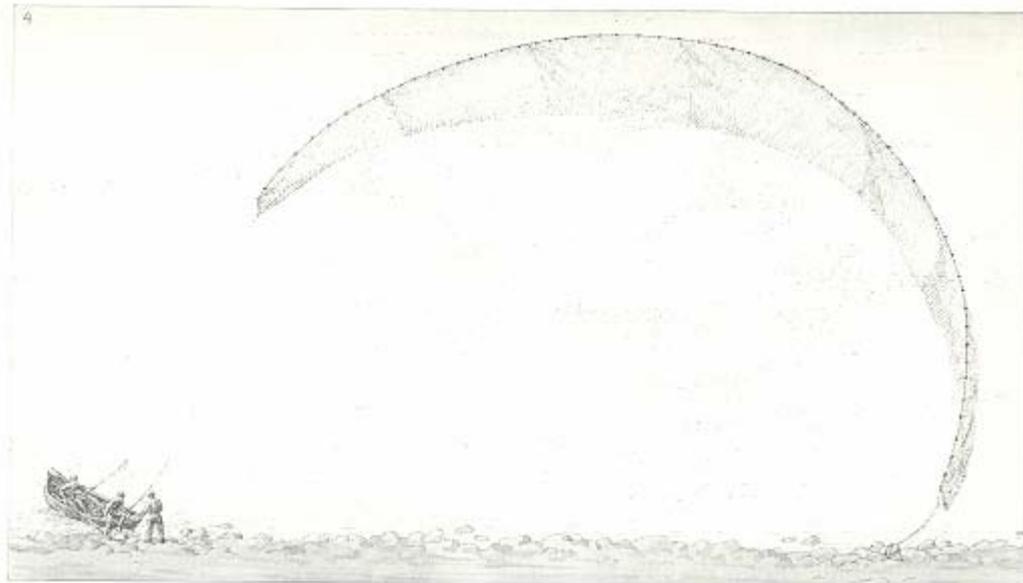


Figure 3. A seine as it was used at the beginning of the 20th century (from Dorleijn, 1987, p. 85, with kind permission from Stichting voor bevolkingsonderzoek in de drooggelegde Zuiderzeepolders).

- *trawling*: trawling is mainly applied in the Scandinavian countries in large lakes (Fig. 4). As it is less effective than seining, the fishing has to be continued for several years (e.g. Finjasjön, Vesajärvi, Koyliönjärvi, Tuusulanjärvi and Enäjärvi).

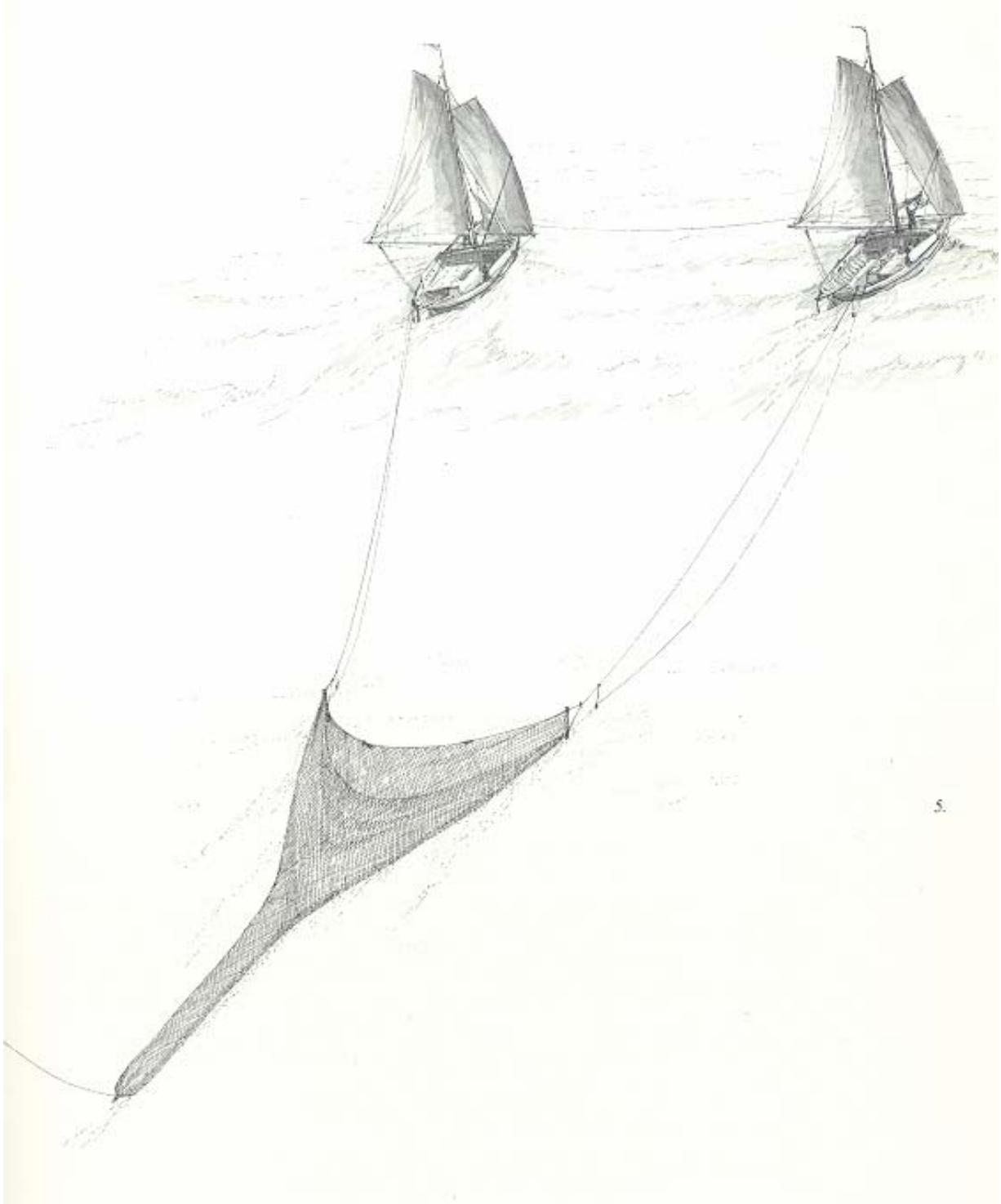


Figure 4. Trawl as used in shallow lakes in the beginning of this century (from Dorleijn, 1982, p. 83, with kind permission from Stichting voor bevolkingsonderzoek in de drooggelegde Zuiderzeepolders).

- *combined fishing with gill-nets, seines, fykes, and electro-fishing*: if there are many hiding places and seines and trawls are difficult to use passive methods may be effective during the periods when fish are locally active, especially during the spawning time when adult fish are concentrated in their spawning grounds. Fykenets and electro-fishing are quite efficient. In winter when young fish are concentrated in ditches and harbours and adult fish in the deeper places seines in combination with echo-sounding are most effective (Noorddiep, Bleiswijk, Wirbel, Danish lakes, Ormsby).
- *gill-nets*: gill-nets may be used for 'fine-tuning' the pike or pikeperch population in order to control the number of large individuals which would control the young of the same species. The fishery is intended to remove individuals > 60 cm to increase the survival chances of the size-group of 10-25 cm, and has been applied in Frisian lakes.
- *poisoning*: the most commonly used poison is rotenone (Norwegian lakes, American lakes, Poland). This method is not allowed to be used in the United Kingdom. Although it is quite effective and the side-effects are difficult to demonstrate, there is a general aversion from the public to apply it.

2.2 Intensity of Fishing

Rapid reduction

A rapid and drastic (> 75% of total biomass) reduction is preferred because the effect is immediate and chances of success are quite high. Especially when dealing with large benthivorous and planktivorous fish with long lifespan the chances for lasting effect will be high. If the fish reduction is successful the large *Daphnia* populations recover quickly and bottom sediments are much less resuspended by the feeding activity of benthivorous fish. Already in the first spring following the measure a clear-water phase occurs and may last the whole summer. For the development of vegetation this is necessary. If technically feasible and if vegetation is wanted this measure is recommended. A rapid reduction can only efficiently be done if the lake is small (< 100 ha) and isolated. Poisoning, draining or seining may remove the fish stock completely in a few days and if the lake is isolated the new fish stock has to be developed by restocking (Zwemlust).

Slow reduction

When the lake is large (> 100 ha) or difficult to fish, or fishing meets with a lot of public resistance, rapid reduction is usually not possible and the fish reduction programme may last for several years (Haussee, Finjasjön, Vesajärvi, Koyliönjärvi, Tuusulanjärvi and Enäjärvi, Frisian lakes, Wolderwijd, Ormsby). On a yearly basis the reduction of the fish varies between 25% and 75% and only the predatory fish is returned. In these cases the fish community becomes 'rejuvenated' and fast growing fish are favoured to develop. Particularly for predatory fish these conditions are good. In Finland almost 100 lakes are biomanipulated in such a way and in most cases both the water quality manager and fishermen are pleased with the measure.

2.3 Stocking Piscivorous Fish

If the fishery is too expensive, technically not feasible or just not wanted, an alternative is stocking with piscivorous fish to reduce the planktivorous and benthivorous fish (Bautzen reservoir, Lake Mendota). Chances for success are lower or less immediate because it takes time for the population to develop and the reduction of the planktivorous population may be too inefficient for the recovery of the *Daphnia* populations. If the lake is very large and/or vegetation is not particularly wanted such a stocking programme may be an option. An advantage of stocking of piscivorous fish is that it is appreciated by anglers and that they will cooperate in such a programme. The stocking may involve young, juvenile and adult piscivorous fish.

Pike and pikeperch/or walleye (*Stizostedion vitreum*) are most easy to breed and most commonly used for stocking. Also in combination with a reduction fishery stocking is often additionally applied, for example, in Zwemlust, Wolderwijd, Noorddiep, Bleiswijk, Haussee, Wirbel, Danish lakes. Only in Lake Mendota and Bautzen See stocking was the main measure. In these lakes particularly anglers were pleased with this measure as their catches increased strongly and therefore the number and size of fish which were allowed to be removed had to be restricted.

It is known that the mortality among fish smaller than 10 cm is very high and that stocking is most effective when the predatory fish is larger than 10 cm (Bautzen reservoir), but the cost to raise the fish to a size of >10 cm is usually too high to be attractive.

3. CASE STUDIES

These are limited to the reasonably well documented experiments with good results. They are based on literature information, which in all cases has been supplemented by additional information about the fishery obtained directly from the authors.

3.1 The Netherlands

3.1.1 Lake Zwemlust

Lake Zwemlust was the first lake in the Netherlands to be biomanipulated. The lake is only 1.5 ha, 1.5 meter deep and it suffered from high algal biomass and regular algal scum of *Microcystis* (Van Donk *et al.*, 1989, 1998). The fish community was dominated by a high biomass (ca. 1000 kg ha⁻¹) of poorly growing bream. The lake was used as swimming pool and only one fisherman exploited the eel population. The provincial water board decided to use biomanipulation as a restoration measure and paid all costs. The reduction was 100% because the lake was drained and the concentrated fish could easily be removed by seining. The fisherman received all eel and glass-eel were stocked after refilling the lake as compensation. In the first year after the measure the lake was stocked with 1500 pike of 4 cm and 140 adult rudd as a new start for the new fish community. The lake became clear and after one year aquatic macrophyte vegetation developed and the fish community reached a few hundred kg ha⁻¹. Because the new fish community was adapted to the vegetation and clear water conditions the new fish community did not pose threat to revert the system to the old situation. The biomanipulation also did not cause a threat to the fisherman, who was compensated. Angling was not allowed. As the lake was a swimming pool the success of the measure was evaluated according to the number of visitors before and after the measure. A cost-benefit analysis showed that the restoration of the pond was economically viable as the income from the extra number of visitors compensated for the costs incurred by the whole operation.

3.1.2 Lake Breukeleveen

Lake Breukeleveen was the first large lake in the Netherlands to be biomanipulated. The lake has a surface area of 180 ha, it is 1.5 meter deep and it suffered from a high turbidity because of resuspended sediment and a high algal biomass, mainly consisting of filamentous cyanobacteria (Van Donk *et al.*, 1990). The fish community was dominated by poorly growing bream and some pikeperch and roach (ca. 150 kg ha⁻¹). The pikeperch and eel stocks were exploited by one fisherman and some anglers, but the fisherman had the fishing rights and issued licenses for fishing. Other important recreation was sailing. The provincial water board decided to apply biomanipulation as a restoration measure and paid all costs. The fish was removed by seining, the seine being 550 meter long. The fisherman cooperated as he was paid for the job and received all the pikeperch. The fish stocks were reduced by 60% and the following summer the stock increased to its original size both by natural growth and by immigration, because the fish barrier did not function well. The experiment was a failure, with the fisherman having a nice profit but the local community paying the costs.

3.1.3 Lake Wolderwijd

Lake Wolderwijd is the largest biomanipulated lake in the Netherlands. The lake covers 2650 ha, mean depth is 1.5 m. The lake suffered from high algal biomass consisting of mainly filamentous bluegreen *Planktothrix agardhii* (Meijer and Hoesper, 1997). Prior to biomanipulation the fish community was dominated by bream and roach (205 kg ha⁻¹). The lake is used for sailing, bathing and fishing. A commercial fisherman exploited the eel population and anglers fished for bream and roach. The water manager decided to use biomanipulation as a restoration measure and paid all costs. Using seining, the fish stocks were reduced by 75%. As the fishing rights for all fish except eel belonged to the anglers, they were financially compensated for the fish loss. The commercial fisherman cooperated in the fish reduction programme. In the first year after the seining the lake was stocked with 217 pike fingerlings ha⁻¹. In spring 1991 the lake cleared as a result of grazing by *Daphnia galeata*. The clear-water phase lasted for six weeks. Macrophytes did not respond as expected and most of the young pike died. However, from 1991 the submerged vegetation gradually developed and in 1999 more than 50% of the lake was covered with stonewort (*Chara*). Initially there was some recovery of fish, but as soon as the stonewort started to develop the fish biomass started decreasing, eventually reaching 50 kg ha⁻¹. The number of species increased from 10 to 22. An evaluation of cost-benefit should not only consider the fishery, but also an increase in visits made by birds and recreating people, which resulted from the biomanipulation and restoration of the aquatic habitat.

3.1.4 Lake Noorddiep and Lake Bleiswijkse Zoom

Biomanipulation measures in the Netherlands are usually a combination of a drastic fish stock reduction and an introduction of pike fingerlings. In Noorddiep and Bleiswijkse Zoom these measures resulted in a clear-water state and the development of macrophytes (Meijer *et al.*, 1994, 1995). After the measures the fish community developed differently because of the new physical and biological conditions. Results from the biomanipulation of lake Noorddiep and lake Bleiswijkse Zoom showed that the fish community became more diverse. Bream and carp became less dominant and were partly replaced by roach and perch. The importance of the main predator pikeperch was strongly reduced as it was replaced by pike and perch. The share of piscivorous fish in the total fish stock increased. The recruitment of young-of-the-year was similar or even higher in the clear overgrown areas than in the turbid water before the measures, but the recruitment of young-of-the-year to older fish differed between the species. Predation by pike and perch could not control the young-of-the-year cyprinids, but their predation may have contributed to the shift from bream to roach, because of selective predation on bream in the open water, while roach was hiding in the vegetation. The macrophytes provide new refugia and feeding conditions that favour roach and perch, but offer relatively poor survival conditions for bream and carp.

3.1.5 Frisian Lakes

The Frisian lakes are an interconnected system of lakes with a surface area of ca 10,000 ha, mean depth 2 m. They suffer from high algal biomass represented mainly by the filamentous bluegreen *Planktothrix agardhii*. Prior to biomanipulation, the fish community was dominated by bream, ruffe, smelt and roach with pikeperch as main predator (Lammens 1986, 1999). The total biomass amounted to 180 kg ha⁻¹. The lake is mainly used for sailing and fishing. About 30 commercial fishermen exploit the eel

population and anglers fish for pikeperch and bream. The anglers and commercial fishermen decided to start a fishery programme for a period of 5 years in order to increase the catches of eel for the fishermen and the catches of pikeperch by anglers. Part of the bream population was yearly removed to improve the food condition for eel. Pikeperch > 60 cm was removed to improve the survival chances of pikeperch < 20 cm and to keep the pikeperch population young. It was a biomanipulation experiment with a different goal than water management. The annual seining removed 25-30% of the bream stocks. The pikeperch > 60 cm was caught both with gill-nets and seines. Pikeperch was sold and used to finance the whole operation. During the fishery experiment the water quality improved as clear-water phases occurred more frequently and lasted longer and aquatic vegetation started to colonize the lakes. The fish community changed only with respect to size composition and year classes: the average age and size of most fish species decreased, but the total biomass hardly changed. Considering the positive results for both anglers and commercial fishermen, and the improvement of water quality the benefits exceeded the costs.

3.2 Germany

3.2.1 Bautzen Reservoir

Bautzen Reservoir was the first large biomanipulation project in Germany. The lake covers 533 ha, is 7.4 m deep and it regularly suffered from algal scum formed by *Microcystis* (Benndorf *et al.*, 1988; Benndorf, 1995). The fish were dominated by planktivores and benthivores (ca. 200 kg ha⁻¹), with only few predatory fish. The reservoir was fished mainly by anglers. The university of Dresden decided to start a long-term biomanipulation experiment and the anglers assisted with the stocking of the predatory fish (pikeperch, pike and eel) and accepted the catch restrictions for piscivores. The programme was financed by research funds and by the angler association. The response of the lake was slow and in the first years the total fish biomass and the water quality hardly changed. After ten years the predatory fish stock increased by more than 50% and the total fish biomass dropped to ca. 100 kg ha⁻¹. Pike showed the highest increase in biomass as the conditions for this fish gradually improved, but pikeperch and eel stocks also eventually stabilized at a higher biomass. The anglers were initially sceptical, but quite pleased with this project as the fishing conditions considerably improved. It is difficult to make a sound cost-benefit analysis as the lake is only used for recreation. A cost-benefit analysis considering both the benefits for anglers, for recreation in general and enhancement of the scientific knowledge would probably show beneficial results of the biomanipulation approach. Plans are made for a new project in Saidenbach (drinking water) reservoir.

3.2.2 Lake Haussee

Haussee was another large biomanipulation project in Germany (Kasprzak *et al.*, 1995). The lake covers 136 ha and has a mean depth of 6.9 m. The lake suffered from algal blooms although the P-load was reduced to 0.1 g m⁻² yr⁻¹. Initially the fish community was dominated by planktivorous and benthivorous fish, mainly roach and bream (ca. 400 kg ha⁻¹), with only a few predatory fish. The lake was fished by anglers and commercial fishermen. The Department of Limnology of the Academy of Sciences (of the former East Germany) started a long-term biomanipulation experiment and the anglers and commercial fishermen actively cooperated in the programme. The biomanipulation was a combination of fish reduction by seine fishing, which removed

ca. 25% of the total biomass, and stocking of predatory fish (pikeperch, pike, eel, catfish and perch). The programme was mainly paid by the water manager. The response of the lake was slow. In the first years the total fish biomass hardly changed and the water quality improved only slightly. But after 10 years the predatory fish increased to more than 20% of the total, while the total fish biomass dropped to ca. 100 kg ha⁻¹. Aquatic macrophyte vegetation started to develop in 1995. Although the anglers and commercial fishermen were sceptical in the beginning, particularly because of the fishery restrictions, after a few years they became more enthusiastic with the increase of predatory fish.

3.3 Poland

3.3.1 Maltanski Reservoir

Maltanski Reservoir (Goldyn *et al.*, 1994, 1997) is the largest restoration project in Poland. The lake covers 64 ha, with a mean depth of 3.1 m. The reservoir had a high fish biomass of 438 kg ha⁻¹, mainly bream, roach and perch, with 45 kg ha⁻¹ of the total represented by pike and pikeperch. The reservoir suffered from high algal biomass, mainly filamentous cyanobacteria. Recreation activities on the reservoir included canoe tracking and to meet the international standards for canoe tracking transparency had to be improved. The reservoir was drained, all fish were harvested, sediments were removed and waste water sources were diverted. The reservoir was refilled in 1990. In the two following years some pike were stocked. Only in the first year there was a clear effect on water quality. In the second year cyanobacteria (particularly *Planktothrix agardhii*) formed a strong water bloom. Therefore the water manager decided to repeat the draining and fish removal at the end of 1992. 398 kg ha⁻¹ was removed of which only 10 kg were pike and pikeperch. In this second phase (1993-1996) predatory fish stocking was intensified, but the effect was more or less similar to the first experiment. The aquatic macrophytes did not develop and therefore the fish stocks returned to the old situation. The easy immigration of fish from the river Cybina accelerated this process. In both experiments the commercial fishermen participated by fishing. Anglers had mixed feelings as angling was banned in the second period.

3.3.2 Lake Wirbel

Lake Wirbel is a small lake of only 11 ha, 2 meter deep and regular algal scum (Prejs, 1997). The fish community was dominated by roach and bream. Some 10-15 kg ha⁻¹ yr⁻¹ was caught by anglers. The university of Warsaw decided to use biomanipulation as an experimental restoration measure for 6 years and paid for the costs. The programme started with the introduction of pike during the first 3 years, together with a simultaneous reduction of large bream and roach. As this was not effective rotenone was used and all fish were removed. Following the fish removal the water quality improved. The effect was persistent for three years when repeated stockings of pike fry and fishing were used to control immigration and reproduction of planktivores. After the stocking and fishing terminated the lake quickly reversed to the old situation as no vegetation developed. The experiment showed the importance of the development of vegetation for the stabilization of the new situation.

3.4 Sweden

3.4.1 Lake Finjasjön

Finjasjön was the first large lake in Sweden to be biomanipulated. The lake covers about 1000 ha, is 4 meter deep and it suffered from high algal biomass in summer and from toxic algal scum of *Microcystis* (Annadotter *et al.*, 1999). The fish stocks were dominated by a high biomass (ca. 400 kg ha⁻¹) of roach and bream. The lake was mainly used as a drinking water reservoir and for recreation. The municipality of Finjasjön decided to use biomanipulation as a restoration measure when it became clear that removal of the mud had no effect on the blooms of toxic cyanobacteria. The municipality paid all costs. The reduction fishery was performed by trawling over a period of several years. Two boats were built and fishermen were paid to do the job. After two years the lake became clear and vegetation started to develop. The fish community was reduced to ca. 50 kg ha⁻¹ and consisted of roach, perch and pike. The development of the vegetation stabilized the lake. In the beginning there was resistance of the anglers, but soon they changed their attitude because the angling conditions improved with better fish growth rates. As water quality improved in the rehabilitated lake this offered better opportunities for recreation. The success of the measures could be evaluated taking into consideration lesser costs needed for water purification for drinking purposes and the increased number of visitors.

3.5 Finland

3.5.1 Lake Vesijärvi, Enonselkä

The Enonselkä basin of Lake Vesijärvi was subjected to a large-scale (2600 ha) biomanipulation trial in Finland (Horppila and Kairesalo 1990; Horppila 1998). The fish removal lasted five years (1989-1993) and there was also a large scale stocking of pikeperch (1987-1994), brown trout (*Salmo trutta*) (1987-1992) and salmon (*Salmo salar*) (1992-1994). The lake suffered from summer blooms of blue-green algae (*Aphanizomenon*, *Microcystis*). High biomass of roach was considered to play an important role in maintaining high algal productivity and biomass in the lake water. The fish community was dominated by a high biomass of roach (180 kg ha⁻¹ in 1989) and smelt (75 kg ha⁻¹). The municipality decided to use biomanipulation as a restoration measure and paid all costs. In a period of 5 years in total 423 kg ha⁻¹ were removed. The roach biomass was reduced to ca. 50 kg ha⁻¹ and smelt to 12 kg ha⁻¹ by trawling. Professional fishermen from the larger Lake Päijänne were paid for fishing. Water transparency increased, nutrient concentrations decreased, blooms of cyanobacteria vanished and submerged macrophytes recovered since 1990. Fishery was stimulated after the biomanipulation as evident from increased catches of pikeperch, salmonids and crayfish. In the waters of the City of Lahti (1100 ha) 1000 gill-net licenses are sold annually. The cost of the project was 2.4 million \$ and the estimated increase on land value on the shores of the lake was 6.8 million.

3.5.2 Lake Vesijärvi, Paimela Bay

Paimela Bay (390 ha) is part of Lake Vesijärvi and had the same problems with cyanophyta as the Enonselkä basin. The municipality and state paid the costs to reduce the fish biomass in order to improve the water quality. The total catch of fish removal with seine and fykenets was 445 kg ha⁻¹ (95 % cyprinids) in four years (1992-

1995) (Sammalkorpi *et al.*, 1995; Turunen, 1997). Water transparency increased, nutrient concentrations decreased, blooms of cyanobacteria vanished, and submerged macrophytes recovered since 1994. There was no commercial or recreational fishing in the lake and a commercial fisherman was paid for seine fishing and advising on the use of fykenets.

3.5.3 Lake Koyliönjärvi

Lake Koyliönjärvi is a large, highly eutrophic lake (1250 ha) and because of increasing blooms of (sometimes toxic) cyanobacteria a restoration programme was launched. To achieve an improvement in water quality the lake was subjected to biomanipulation for 8 years (Sarvala, 1998). The programme was paid for by the local municipality, voluntary associations and companies, and regional authorities. The high fish stocks of Lake Koyliönjärvi (mainly roach, bream and smelt) were reduced from 414 kg ha⁻¹ in 1991 to about 80 kg ha⁻¹ in 1998 by removal fishing and pikeperch was stocked. After eight years changes in plankton were relatively small, but blooms of cyanobacteria disappeared. Fishermen from a lake nearby were paid for fishing and the fish was sold for the production of animal food. Angling and commercial fishing is not important in this lake, there is only some gill-netting by local inhabitants, who complained that large bream disappeared.

3.5.4 Lake Tuusulanjärvi

Lake Tuusulanjärvi (595 ha) was highly eutrophicated as a result of discharges of municipal sewage until 1979, but due to internal phosphorus loading and the still high external loading from agriculture it remained highly eutrophic until the 1990s (Pekkarinen, 1990). The fish community of the lake is dominated by cyprinids and smelt. Severe blooms of cyanobacteria in summer of 1997 led to the start of biomanipulation to improve water quality. The removal of fish and much of the research is funded by municipalities. Also anglers invested time in the project. The total biomass of fish removed was 125 kg ha⁻¹ in 1997 and 101 kg ha⁻¹ in 1998. The water quality in 1998 was the best since 1981. The biomanipulation led to no adverse effects on the fisheries. Local fishermen were positive about the fishery as only cyprinids were removed. In the beginning the public was very suspicious about the fate of pikeperch, but their suspicion disappeared as the project progressed. The biomanipulation continues.

3.5.5 Lake Enäjärvi

Lake Enäjärvi (508 ha) was highly eutrophicated and had a poor water quality. The fish community of the lake was dominated by roach and the municipality started a restoration project by fish reduction. Between 1993 and 1997 373 kg ha⁻¹ was removed (mainly roach) with seines and fykenets (Lempinen, 1998). The water quality considerably improved in 1996 and 1997 which was expressed in a decrease of cyanobacteria, decrease of chlorophyll-a and increase in transparency. External commercial fishermen did most of the work. Local anglers and fishermen were pleased with the measure as the fishing conditions improved resulting in higher perch catches.

3.6 Denmark

At least 16 lakes have been biomanipulated in Denmark (Søbo, Dallund, Arreskov, Hvidkilde Sø, Skanderborg, Ramten, Lading, Viborg Nørresø/Søndersø, Hale, Klejtrup, Maribo, Engelsholm, Væng, Skærsø, Ejstrup and Rørbæk). The number of well described experiments is relatively low (Jeppesen *et al.*, 1990, 1991) and the information presented here is based mainly on communications with water management personnel. In most lakes turbidity caused by a high algal biomass is the reason why the water manager starts the biomanipulation. In most lakes (13) the fish is only exploited by anglers and in three cases by commercial fishermen. In only one case there was resistance of commercial fishermen, sufficient for the biomanipulation to fail. In most lakes 80-100% of the fish biomass was removed and piscivores (usually pike) stocked. In most lakes the fish community changed and the fish biomass declined. In two of the three cases where commercial fishing was involved the fishermen cooperated and fishing conditions improved. The evaluation of the fishing conditions and the satisfaction of the anglers was more difficult and showed more mixed feelings. In three cases they cooperated, in two they strongly resisted and in the rest they were neutral. In all cases the people involved said that it was not possible to make a cost-benefit analysis. The main reason for that is that only fishery can be expressed in cost-benefit terms. Water quality is more difficult to express in economic dimensions if it is not used for drinking water or industrial purposes.

The following persons provided information on the Danish lakes: Gudrun Krig, Kjeld Sandby, Karsten Fugel, Paul Nordemann-Jensen, Mads Ejby Ernst and Simon Marsbøll.

3.7 Norway

3.7.1 Lake Haugatjern

Lake Haugatjern was biomanipulated in 1979 because of algal blooms and periodical oxygen deficit (Reinertsen *et al.*, 1990). An experimental research project was set up to study the effect of the total elimination of fish (by rotenone) on the algal biomass. The experiment resulted in a fourfold decrease in the algal biomass and the share of daphnids in the total zooplankton increased from 49-63% during 1979-80 to 74-90% during 1982-84. The total fish community was replaced with char (*Salvelinus fontinalis*) by stocking. The improved fishing conditions satisfied both anglers and commercial fishermen. The water quality improved. A cost-benefit analysis could be made on the basis of costs and profits for the fishery.

3.7.2 Lake Asklundvatn

Lake Asklundvatn was biomanipulated by total elimination of fish using rotenone (Reinertsen *et al.*, 1997). The main reason for it were frequent algal blooms and periodical oxygen deficit. The lake was mainly used by anglers. After the use of rotenone the lake was stocked with brown trout. Thereafter the algal biomass decreased and the trout population thrived. The project was a research project but as the fishing conditions improved it also gave satisfaction to the anglers. A cost-benefit analysis could be made from the costs and profits for the fishery.

3.7.3 Lake Vikvatn

Lake Vikvatn covering ca. 460 ha and 7.6 m deep suffered from summer algal blooms. The fish community was dominated by brown trout, eel (*Anguilla anguilla*) and three-spined stickleback (*Gasterosteus aculeatus*). The lake was mainly used for fish farming (Koksvik and Reinertsen, 1991). To study the effects of total fish removal on the water quality the University of Trondheim decided to use biomanipulation as a restoration measure. The fish community was completely removed using rotenone. After the measure the algal biomass decreased and remained low when fish farming started again. A cost-benefit analysis was not done.

3.8 United Kingdom

3.8.1 Great Linford

Great Linford is one of the famous projects in the U.K. where biomanipulation was applied as a measure of nature conservation (Giles, 1992). The lake covers ca. 37 ha, is ca. 1 meter deep and in the past it suffered from high algal biomass and lack of macrophytes. The fish community was dominated by bream and roach (ca. 400 kg ha⁻¹). The question was raised whether these gravel pits could be used as breeding sites for mallard ducks to repopulate adjacent wetlands. The Game Conservancy decided to use biomanipulation in order to investigate if fish affect the breeding opportunities for diving and dabbling ducks in freshwater habitats. The lake was pumped down and the fish of >10 cm were removed with seine nets. The reduction was almost 100% for fish >10 cm because the lake was drained and the concentrated fish could easily be removed by seining. The fish was sold to angler clubs. The lake became clear, vegetation developed, and the food supply for mallards and tufted ducks increased. This was confirmed in experimental ponds (Giles, 1995). Because of the development of vegetation the fish community changed to a dominance of tench and pike. A cost-benefit analysis cannot be done in fishery terms, but only in conservancy terms if it is possible to give some value to a breeding place of mallard.

3.8.2 Ormsby Broad

Ormsby Broad is one of the larger lakes of the Norfolk Broads. It has a surface area of 54 ha and is on average ca. 1 m deep. The Broad used to have a rich aquatic vegetation community, which disappeared at the beginning of this century. The fish community was dominated by bream and roach (>153 kg ha⁻¹) with only few pike and tench present. The Broads Authority decided to choose Ormsby Broad to demonstrate biomanipulation as a tool for water management in the broads after a series of experiments in other broads (Perrow *et al.*, 1997; Moss *et al.*, 1996). The fish was removed with seine nets and electrofishing during the winter when the small fish were aggregated in ditches and the large fish concentrated in schools. The anglers were at first not very pleased with the experiments, but agreed after two special meetings and were convinced that they would also profit from a change in the fish community with more pike and tench. After the fish removal the water cleared almost instantly and the vegetation came back. A cost-benefit analysis cannot be done in fishery terms, because no professional fishery is present, but as the water is also used by a drinking water supply company the cost of removal of the summer high algal biomass can be estimated. In terms of angler fish catches and as site for nature conservancy the proper criteria for evaluation are still lacking.

3.9 United States of America

3.9.1 Round Lake

Round Lake was the first lake in the U.S.A. to be biomanipulated. The lake suffered from scum algae during summer and the water manager decided to use biomanipulation as a restoration measure and paid the costs for the restoration programme. Rotenone was applied to eliminate predominantly planktivorous and benthivorous fish. The lake was subsequently restocked with a higher population density of piscivores. The abundance of phytoplankton was much lower after biomanipulation and *Daphnia*, rare in 1980, became the dominant genus in 1981 and 1982, and a shift to progressively larger-bodied *Daphnia* species was observed. The fish community was different and the biomass lower after the treatment. The main fishery in the lake is angling and the anglers cooperated in the programme as fishing conditions would improve. Mainly because of the increased abundance of piscivores the anglers were satisfied with the project.

3.9.2 Lake Mendota

Lake Mendota was the first large lake in the United States to be biomanipulated. The lake covers 4000 ha, with a maximum depth of 25.3 m. It suffered from scum algae during summer and the diversity of macrophytes has declined steadily (Carpenter *et al.*, 1993). The fish community has become less diverse because of the great loss in habitat due to the decline of macrophytes. The dominant fishery in the lake is angling. The water manager decided to use biomanipulation as a restoration measure and paid the costs for the introduction of walleye and pike during a period of 3 years. During the project period the water clarity in the lake was remarkably good. The high stocks of piscivorous fish attracted many anglers. The catch of the anglers increased several-fold and the anglers were very pleased with this measure. A cost-benefit analysis was not made but according to the researchers it was clear that the costs of the whole operation were fully recovered.

3.9.3 Lake Christina

Lake Christina is a shallow prairie lake of 1619 ha, with mean depth of 1.5 m. Because of high turbidity and lack of macrophytes the water manager decided to use biomanipulation as a restoration measure (Hanson and Butler, 1990, 1994). The complete fish community was killed in 1987 by rotenone and piscivorous fish largemouth bass (*Micropterus salmonoides*) and walleye were subsequently stocked. The lake responded quickly to the treatment: water transparency increased and submerged macrophytes expanded. Initially anglers were quite pleased with the results of the treatment as their catches were quite good. Eventually the lake managers opted for more restrictive angling as they were afraid that anglers would overexploit the predatory fish. After 12 years the lake is still clear and seems to have established a new steady state. The anglers have mixed feelings because of the changed fishing regulations.

3.9.4 Lake Denham

Lake Denham is a hypereutrophic lake (104 ha, 1.4 m deep) in Florida. It suffered from high algal biomass and regular algal scums (Beaver *et al.*, 1994). The fish community was dominated by gizzard shad (*Dorosoma cepedianum*) (ca. 500 kg ha⁻¹). The state of Florida funded the project to determine if biomanipulation of fish populations would cause a measurable change in water quality (or food web structure) in this lake and Florida lakes in general. Therefore almost the complete fish community was eliminated (ca. 425 kg ha⁻¹). The lake is mainly used for recreation by anglers and yachtsmen. Anglers resisted this project as they expected the fish to disappear, but they cooperated when the fish community changed to a composition that was more attractive for anglers.

3.9.5 Como Lake

Como Lake, a shallow hypereutrophic 29-ha lake in Minnesota, was biomanipulated using rotenone in September 1985, to reduce algal standing crop, improve aesthetics, and increase its recreational use (Noonan, 1998). The restoration was paid by the government and county. After the treatment with rotenone macrophytes became abundant within two years and the fish community redeveloped after stocking of large mouth bass, blue-gill and walleye. The recreational fishing increased 4-5 times. "Top-down" influences were not stabilized, but appeared to have dampened with time due to decreased effectiveness of sportfishing regulations and fish stocking, along with partial winterkill due to aerator failure, to maintain piscivore abundance. Monitoring results suggest that future management efforts in Como Lake should emphasize fisheries again.

4. BIOMANIPULATION IMPACT ON FISH STOCKS

Fish stocks in eutrophic lakes and reservoirs are usually dominated by cyprinids in Europe and sunfishes and shads in North America (see the case study summaries in this report). The main predatory fish in these eutrophic waters are walleye (in North America) and pikeperch (in Europe), which are well adapted to open turbid waters and avoid clear water rich in vegetation. Eel is another commercial valuable fish which thrives in eutrophic water (De Nie, 1988). Perch and pike are less adapted to live in these conditions than the above-mentioned fish (Persson *et al.*, 1993; Grimm and Backx, 1990) but have more chance to develop if pikeperch and/or walleye are absent (Lammens, 1986). If the habitat changes because of restoration measures, the fish community will change as well. Measures can be a drastic nutrient reduction, change in the water level fluctuation, change in the morphology of the lake, or a drastic fish reduction or/and predator stocking. If these measures are effective the habitat changes from turbid open water to clear water structured by vegetation (Gulati *et al.*, 1990; Hoesper, 1997, 1998; Lammens *et al.*, 1990; Meijer, 1995). Depending on the type of vegetation the habitat may be further differentiated. The changes in the fish community are only to a small extent related to the fishery itself, as they are determined largely by the changes of the habitat.

However, if the fishery is not intensive the habitat does not change rapidly. Only the size composition of the fish stocks changes because of the size-selective fishery or the size-selective predation of stocked predatory fish (Frisian lakes, Bautzen reservoir, Haussee, Vesijärvi). Trawling or seining will continuously remove the large individuals or selectively other species and thus change competitive interactions. The same may be true for the impact of stocked predatory fish. The longer this fishery management continues the greater the change in the fish community will be, and the greater the chance that the system will revert to the situation prior to eutrophication (Bautzen reservoir, Haussee). This kind of management is not only beneficial for the water quality, but also for commercial fishermen and anglers. The former are asked to perform the fishery and are paid for the job, and the anglers profit from the high stocking rates of predatory fish.

In many cases the effects of biomanipulation will lead to a situation very similar to the one before eutrophication started, but the description of fish communities before the 1960s is rather poor and usually just anecdotal, which makes difficult any precise comparison. In some cases comparison is not possible, because the reservoirs were built in or after the 1960s and were from the beginning subjected to eutrophication.

5. BIOMANIPULATION IMPACT ON FISHERY

The effects of fish removal and/or predator stocking on commercial fishery and angling have to be subdivided in direct and short-term, and indirect and long-term effects. The most direct and short-term impact on commercial fishery is the participation in the reduction of the fish stock. Particularly in large lakes, not treated with rotenone, the commercial fishermen benefit from the biomanipulation as they are asked to do the job, and their main source of income, i.e. eel, is not negatively affected by the fishery, as in Breukeleveen, Wolderwijd, the Frisian lakes, Haussee, Finjasjön, Vesijärvi, Pyhäjärvi, and Koylionjärvi. In these lakes fishermen fished several years to reduce the fish stocks considerably. In these cases there is a gradual change from short-term (one year in Breukeleveen) to long-term impact (15 years in Haussee). Only in one lake in Denmark commercial fishermen refused to cooperate. Overall, commercial fishermen benefit from the biomanipulation. In small lakes the job is easily done and the benefits are only short term for commercial fishermen.

The short-term effects for anglers are negative if fish stock reduction is the only objective. Only when they are paid to be compensated for the fish loss (Wolderwijd, Frisian lakes) they will have some profit. When the fish community develops in a different direction because of the habitat changes (clear water, vegetation), this change towards a more differentiated fish community with more fish species but lower biomass is more attractive for many anglers. The short-term effects are positive if the fish community changes because of intensive stocking with predatory fish. Anglers are usually pleased in the beginning, but start to complain as soon as regulations are introduced to protect the predator population (Mendota, Christina, Haussee, Bautzen). The main problem is to prevent the overexploitation of piscivores by anglers. The anglers have to be convinced that only enforcing fishery regulations will make the piscivores sustainable and the angling will remain successful (Bautzen, Haussee). In most of the small lakes commercial fishery is absent and usually there is only angling for carp, bream and roach. Lakes dominated by carp and pikeperch are especially favoured by anglers. If the experiment is successful pikeperch and bream populations will almost disappear and be replaced by perch, pike, tench and rudd. Stocking large numbers of pike is usually a compensation measure to please the anglers, but also increases the chances for success of the experiment. Whether the new fish community (usually pike, tench and rudd) is acceptable should be ascertained through discussions with the users of the biomanipulated water body.

It should be mentioned, however, that there are still areas in central and eastern Europe where angling is not just a form of recreation, but an extra source of food. In these conditions biomanipulation may not be wanted as the eutrophic state of the lake has a higher carrying capacity for fish than the mesotrophic state. But as there are no documented biomanipulation cases from these countries there is no evidence for decreasing catches of anglers in such conditions.

6. WHEN IS BIOMANIPULATION AN OPTION?

In most cases reported here the real determining factor leading to the decision to initiate biomanipulation is not quite obvious, i.e. the actual criteria on which this decision was based are usually not evident. In fact these criteria are more or less arbitrary and will depend on the knowledge of the particular lake manager.

Until now the decision of lake managers usually depends on the following questions:

1. how serious is the (eutrophication) problem?
2. what are the chances for success of fish biomanipulation?
3. how will it affect the present users of the lake?
4. is there sufficient support of the present users?

The problem

In general the most important criterion is the level of eutrophication. If the lake has a high concentration of nutrients even after serious reductions in the load of nutrients, and high concentrations of algae, in particular cyanophytes, the lake is considered as a serious candidate for biomanipulation. If nutrient reduction has only little or no effect at all on the recovery of the lake, biomanipulation will speed up the process of recovery (Meijer, 2000).

The chance for success

The chances for success will depend on the strategy adopted, i.e. whether the removal of fish was partial or complete, or if only predatory fish were stocked. The size and depth of the lake are critical for the whole technical operation and will be decisive for success or failure. For technical reasons small lakes are usually easy and large lakes (> 1000 ha) difficult to manipulate (Meijer, 2000).

Effect on present users

When a water manager proposes to biomanipulate a lake or a reservoir for the sake of water quality, then there is usually a lot of resistance coming from different groups of people, all having different interests in the specific waterbody. Anglers and commercial fishermen fear for their catches, nature conservation associations expect the decrease of piscivorous birds, yachtsmen expect problems with aquatic macrophytes. In fact, most people fear changes because they know what they have and are unsure about the potential changes. In a way they are right because it is impossible to predict the changes with 100% security. What we have is empirical evidence and a theoretical framework about the mechanisms involved. This knowledge is used to advise lake managers. The decision of the lake managers could profit from a cost-benefit analysis. In some cases a cost-benefit analysis can easily be made if the main users of the lake have only economic profits, such as drinking water companies or commercial fishermen. In some cases (e.g. Finland) the improvement of the water quality led to an increase in the value of the surrounding land. Improved leisure benefits for anglers, yachtsmen and swimmers, or ecological benefits for flora and fauna, are more difficult to express in economic values. If conditions for angling, sailing or swimming are improved, an infrastructure may be developed that benefits from these conditions and then a cost-benefit analysis may be made. For nature conservation it seems more a matter of appreciation, which is difficult to be translated in economic terms. At the moment it is only possible to provide a qualitative scale for the evaluation of the non-economic changes using the positive, neutral and negative criteria. With the knowledge we have about the various ways of biomanipulation and their effects on the fish

community and the aquatic vegetation we can make a best guess what the score will be for all the users of a water body.

The support of the users

The support of the current users is necessary if they have (legal) rights in the specific waterbody. It implies that biomanipulation in a large lake with recreation, commercial fishing and nature conservation requires a lot of preparatory work in order to receive the support of the users involved. Using fish in biomanipulation will be more effective in small water bodies than in large ones. It should be remembered, however, that in many situations only a continual, sustained removal effort, used in tandem with other nutrient reduction and control mechanisms, will be fully effective (cf. Wetzel, 2000).

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