Fisheries Management and Ecology, 2004, **11**, 261–275

How to link biomanipulation and sustainable fisheries management: a step-by-step guideline for lakes of the European temperate zone

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Abstract Biomanipulation, the reduction of planktivorous fish to enhance filter-feeding zooplankton, has been used to rehabilitate eutrophied lakes. However, efficacy and long-term success were dependent on nutrient load, lake morphometry and biomanipulation measures. The ongoing focus on sustainable use of aquatic resources offers the chance to perform lake rehabilitation using a combined strategy of nutrient load reduction and traditional inland fisheries management techniques. Particularly in Central and Western Europe where piscivorous fish are the target species of most commercial and recreational fisheries, an enhancement of the piscivores by stocking and harvest regulations may act successfully in the co-management of ecosystem and fisheries. Guidelines are presented on how biomanipulation can be used as in lake rehabilitation by considering the objectives and constraints of traditional fisheries management. Alternatives in the decision tree are elucidated by examples from

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biomanipulations and lake management programmes in the temperate zone of Europe and North America. It is suggested that biomanipulation may support many lake rehabilitation programmes where fisheries' stakeholders are the principal user groups.

KEYWORDS: biomanipulation, fisheries, lake ecosystems, management practice, nutrients, sustainability.

Introduction

According to Mehner, Benndorf, Kasprzak & Koschel (2002), biomanipulation is a widely accepted and frequently applied ecotechnology to improve the environmental quality of standing waters. In this context biomanipulation refers to a reduction of planktivores, followed by an increase in the abundance and size of zooplankton (predominantly large *Daphnia* species). As a consequence, the grazing pressure on phytoplankton is enhanced, thereby leading to clearer water. In theory, the reduction of planktivory may be achieved by either manual removal of the numerous zooplanktivorous fishes, or by creating an abundant piscivorous fish community by stocking and protection measures to increase predation losses of planktivorous fish.

The latter alternative offers some potential to combine water quality management and sustainable fisheries management by biomanipulation (Kitchell 1992; Barthelmes 1994; Lammens 1999; Mehner, Kasprzak, Wysujack, Laude & Koschel 2001; Wysujack, Laude, Anwand & Mehner 2001). The combination may be particularly successful in those regions or states where commercial and recreational fisheries target piscivores. Although guidelines exist on how to apply biomanipulation in general or in particular water bodies (Hosper & Meijer 1993; Benndorf 1995; Moss, Madgwick & Phillips 1996; Perrow, Meijer, Dawidowicz & Coops 1997; Benndorf & Kamjunke 1999; Perrow, Hindes, Leigh & Winfield 1999a; Jeppesen & Sammalkorpi 2002), there are no comprehensive guidelines for biomanipulation with respect to the objective of sustainable fisheries management. In particular, because of a lack of human dimensions research in Europe (Aas & Ditton 1998), interests of recreational fisheries, a sector which increasingly dominates inland fisheries in developed countries (Welcomme 2001; Arlinghaus, Mehner & Cowx 2002), have not been explicitly considered. Here a step-by-step decision tree on how to manipulate fish communities in eutrophic standing waters of the European temperate zone to take into consideration the interests of both fisheries and water quality managers is presented. In addition to a graphical representation demonstrating the decision flow, the approach of Welcomme (1998) to formulate the decision questions similar to a faunistic key, with Yes and No answers guiding to the next questions was followed. For all steps, detailed explanations and reference to the main literature and experience from world-wide biomanipulations which lasted at least 5 years are given (Fig. 1).

The guidelines

The guidelines are based on the supposition that the lake to be managed has been rendered eutrophic by anthropogenic influences, and that phosphorus is the limiting nutrient (excess of nitrogen). In the few waters where nitrogen is limiting the autotrophic potential, the thresholds for phosphorus given below do not apply.

1. Is water quality improvement desired?

In some cases, management of the fisheries resources may be required or desired which are not commensurate with increased water clarity, e.g. enhancing populations of bream, *Abramis brama* (L.), and roach, *Rutilus rutilus* (L.), for fishing competition purposes.

Yes → *2*
No → *Guidelines cannot be applied*

2. Are any potential stakeholders involved in fisheries?

Fisheries-related stakeholders may be commercial fishermen, anglers, or fisheries-related sectors upstream or downstream of the principal fishery (Welcomme 2001). It is necessary to develop a detailed management plan with clearly established objectives for the manipulation (Barber & Taylor 1990; Jeppesen & Sammalkorpi 2002).

Yes → *4*
No → *3*

3. Let other stakeholders help define the rehabilitation and management objectives

Biomanipulation may contribute to water quality improvement even if no fisheries-related interests have to be considered. In that case, the management

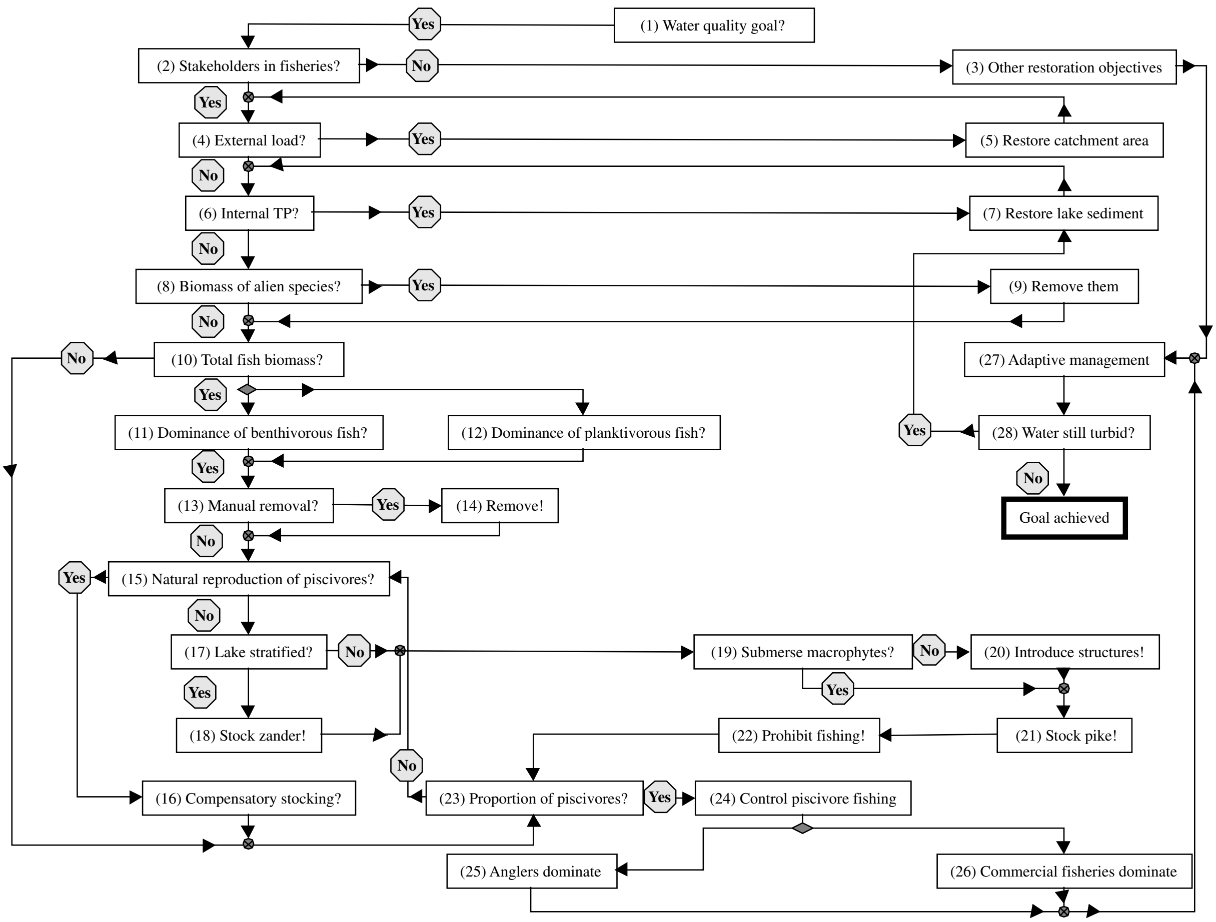

Figure 1. Graphical presentation of the step-by-step guideline. The numbers in the boxes correspond to the numbered questions in the text. Circles and rhomboids in the pathways indicate confluences and branches, respectively.

objectives may differ from those that are set if fisheries have to be considered explicitly. Then, a set of general national (or regional) fisheries-related stakeholder criteria may be used in the absence of direct local stakeholders. These criteria could consider the use of lakes for fisheries purposes in the future as well as other uses, e.g. swimming or protection for water-fowl.

→ 27

4. Is external total phosphorus (TP) load higher than 2 g TP m^{-2} year^{-1}?

This is the approximate biomanipulation-efficiency threshold for phosphorus loading according to Benndorf (1987) and Benndorf, Böing, Koop & Neubauer (2002). Kasprzak, Schrenk-Bergt, Koschel, Krienitz, Gonsiorcyk, Wysujack & Steinberg (2000) give a critical range of 0.6–2.0 g TP m^{-2} year^{-1} for shallow lakes and reservoirs with low water retention time, and a maximum threshold of 0.5 g TP m^{-2} year^{-1} for stratified lakes. Biomanipulation will not be successful or shifts in water quality will not remain stable if loading remains above these thresholds. There is a need to reduce the external P loading from point sources and/or the diffuse catchment loading. If no data on TP loading are available, information on the lake's trophic status can be obtained from other variables (see other guidelines, e.g. Jeppesen & Sammalkorpi 2002).

Yes → 5
No → 6

5. Rehabilitate the catchment area

To decrease external loading, habitat improvement measures in the catchment area are required. Numerous handbooks and overviews describe approaches for catchment improvement (e.g. Sas 1989; Cooke, Welch, Peterson & Newroth 1993; Mehner & Benndorf 1995).

→ 4

6. Is the annual mean concentration of TP in the lake higher than 250 μg L^{-1} for shallow lakes with mean depths <3–5 m, or higher than 50 μg L^{-1} for deep lakes with mean depth >5–10 m?

These thresholds above which biomanipulation alone is probably not successful are detailed by Jeppesen & Sammalkorpi (2002). If external load is below the biomanipulation-efficiency threshold for phosphorus loading (see 4), but mean TP in the lake water is still high, then strong internal nutrient loading from the sediment may prevent rehabilitation success. Significant and sustaining changes in the biological communities and in water transparency of shallow temperate freshwater lakes cannot be expected unless the TP concentration is reduced to below 100 μg P L^{-1} (Jeppesen & Sammalkorpi 2002). For stratified lakes, the supposed threshold of 20 μg L^{1} (Jeppesen & Sammalkorpi 2002) has not been confirmed by empirical studies. In exceptional cases, lake internal P concentration can be higher and manipulation can be successful due to a reduction in P concentration as a consequence of the biomanipulation measures (Hansson *et al.* 1998; Benndorf *et al.* 2002). However, if TP is higher than 500 μg L^{-1}, there is such a high production potential of planktivorous fish, that production is generally beyond control by piscivore predation (Jeppesen, Søndergaard, Kanstrup, Petersen, Eriksen, Hammershoj, Mortensen, Jensen & Have 1994; Perrow, Jowitt, Leigh, Hindes & Rhodes 1999b), and algal (as opposed to macrophyte) production is likely to dominate in any case. In cases where no data on P concentration are available, information on the lake's trophic situation can be derived from other variables (see other guidelines, e.g. Jeppesen & Sammalkorpi 2002).

Yes → 7
No → 8

7. Reduce internal loading, for example by rehabilitation of lake sediments

There is some in-lake chemical resistance against decline of external nutrient load. P-concentrations remain high because of P-release from the sediment pool and the duration of the transition can be as long as 20–40 years (Jeppesen & Sammalkorpi 2002). Numerous handbooks and overviews describe approaches for reduction of internal loading, mainly via sediment restoration, usually combined with catchment rehabilitation (e.g. Sas 1989; Cooke *et al.* 1993; Mehner & Benndorf 1995). However, in shallow and stratified eutrophic lakes a 30–50% reduction in internal TP-concentration was found in the most successful fish manipulation experiments, even when macrophytes were absent (Søndergaard, Jensen, Jeppesen & Lauridsen 2000). In-lake nutrient concentration can be enhanced by high biomasses of benthivorous fish, therefore reduction of such fish stocks is required in addition to the reduction of planktivores (see 11).

→ 6

8. Is density of alien fish species significant?

In some exceptional cases, non-native fish species may be present in high density and may degrade water quality or impact upon the native fish community. In these cases, a strong reduction in the stock size is favoured, although it is not always possible. Examples of such species are the Asian cyprinids, grass carp, *Ctenopharyngodon idella* (Val.), bighead carp, *Hypophthalmichthys nobilis* (Rich.), and silver carp, *Hypophthalmichthys molitrix* (Val.). These species were intentionally or accidentally stocked in several lakes, particularly in the former socialist countries in Central and Eastern Europe. Normally, they do not reproduce under the climatic conditions in temperate regions and thus naturally die off after 15–30 years. However, since they feed on and destroy macrophytes (grass carp) or feed on some proportion of zooplankton (silver carp and bighead) (Barthelmes 1982; Xie 1999; Xie 2001), and thus catalyse the nutrient turnover as well as the nutrient availability, dense stocks are not acceptable (Benndorf & Kamjunke 1999).

Yes → 9
No → 10

9. Remove alien species

This can be a complex and laborious task. For Asiatic carp species, gill netting with large mesh sizes (120–150 mm bar mesh size) made of strong twine diameter may work (compare Predel 1978) if performed intensively (200 gill netting days per year). Alien carp species concentrate near the surface during the warm months and may be detected easily during that season. Catch with active gears (trawls, purse seines, beach seines) may be successful (Predel 1978), but gear avoidance of the species is well known (Predel 1978; Barthelmes 1982). For smaller species, active fishing techniques with small mesh sizes (see below) may work. In some areas, recreational fishing for Asian carps is practised. Residual stocks of up to 10 kg ha^{-1} may be tolerable, as this biomass has little or no effect on the ecosystem.

→ 10

10. Is total fish biomass higher than 50–100 kg ha^{-1}?

Fish biomasses less than 50 kg ha^{-1} are sufficiently low to have only a minor negative impact on water quality, although thresholds for juvenile planktivores may be lower (Mills & Forney 1983; Benndorf 1995; Hülsmann & Mehner 1997; Kasprzak *et al.* 2000). Some impact on water quality may be expected at fish biomass between 50 and 100 kg ha^{-1}, but success of biomanipulation may depend on the situation in the particular lake. Rough estimates of fish biomass are required and may be performed by echosounding, trawling or seining (Cowx 1996) or converting CPUE data into biomass. In particular, a simultaneous sampling in littoral and pelagic habitats is recommended. If the fish community has not been managed intensively during the previous years, a correlation between nutrient concentration and fish biomass may be expected (Hanson & Leggett 1982; Jeppesen & Sammalkorpi 2002):

Fish biomass $= 2.17\ TP^{0.78}$; valid for deep, stratified lakes

Fish biomass $= 9.42\ TP^{0.62}$; valid for shallow lakes,

with fish biomass in kg ha^{-1}, TP in $\mu g\ L^{-1}$ (from Jeppesen & Sammalkorpi 2002).

Yes → if benthivorous fish dominate → 11
Yes → if planktivorous fish dominate → 12
No → 23

11. Benthivorous fish dominate in the lake

Benthivorous fish, such as bream or common carp, *Cyprinus carpio* L., stir up the bottom when feeding, enhancing turbidity and impairing recolonisation and growth of macrophytes (Breukelaar, Lammens, Klein Breteler & Tatrai 1994; Lammens 1999). Even biomasses of around 50 kg ha^{-1} can lead to complete removal of *Chara* (Ten Winkel & Meulemans 1984). In some cases, the feeding habits of benthivores were found to cause greater deterioration in water quality than feeding of planktivores (Hansson *et al.* 1998). In these cases, substantial reduction of benthivores is required.

→ 13

12. Small planktivorous fish dominate in the lake

Cyprinids such as roach and bleak, *Alburnus alburnus* (L.), and small-sized perch, *Perca fluviatilis* L., are often the dominant planktivores in eutrophic lakes (Persson, Diehl, Johansson, Andersson & Hamrin 1991). Their feeding eliminates the large filter-feeding cladocerans allowing the phytoplankton to flourish. For certain periods during the year, these species can alternatively be benthivorous or detritivorous, which can be also detrimental for water quality (see 11). Phytoplankton growth is additionally supported by nutrient import or recycling as a consequence of excretion by planktivores and benthivores (Horppila, Peltonen, Malinen, Luokkanen & Kairesalo 1998). Therefore, removal of planktivorous/benthivorous fish is one of the central targets of biomanipulations.

→ 13

13. Is manual removal of fish technically possible?

Continuous seining and trawling can efficiently remove unwanted planktivorous and benthivorous fish (roach, small perch, bream) (Perrow *et al.* 1997; Horppila *et al.* 1998; Hamrin 1999; Meijer, de Boois, Scheffer, Portielje & Hosper 1999; Mehner *et al.* 2001). To catch a sufficient proportion of juvenile fish, cod-end mesh size should not exceed 15 mm. Despite progress in the development of fishing gears, the features pointed out above restrict application of active fisheries to lakes with appropriate morphology. Catching efficiency depends on lake size. An optimal catching efficacy for a 750-m seine net was found in lakes up to 50 ha area, whereas efficacy was below 40% if lake area increased to more than 200 ha (Barthelmes 1994). Temporarily reducing the water level, where possible, might improve the efficacy considerably. In particular, in urban lakes or lakes in forested areas this action would also bring fishing out of the debris infested zone and reduce damage to fishing gear. In large lakes, it is recommended to involve professional, experienced fishermen as they possess the necessary skills for handling fishing and often are in possession of the necessary seines or trawls and equipment for transport (Jeppesen & Sammalkorpi 2002).

If intensive control is possible, angling for planktivorous and benthivorous fish should be allowed. Angling tournaments or matches could be organised regularly. Coarse fishing for bream and roach is sometimes popular, e.g. for match anglers (Welcomme 2001), and thus may contribute to fish removal if the catch is not released. Carp is highly valued by many European recreational fisheries (e.g. Linfield 1980; Vacha 1998). However, carp anglers tend to prefer large specimens to a high catch rate (Arlinghaus & Mehner 2003), therefore biomass reduction of carp may be required to prevent density-dependent growth

(Lorenzen 1996). A well managed carp fishery can also become attractive for other fisheries-related stakeholders, since specialised carp anglers spend large amounts of money for their hobby (Arlinghaus & Mehner 2003). It must be ensured, however, that anglers remove most of the smaller fish caught instead of practising catch-and-release fishing. A certain size limit above which fish should be released after catch can be negotiated to favour carp trophy fisheries.

A problem of all removal measures is to find appropriate ways of disposing of the catch in an economic and ethically acceptable way (Hamrin 1999). In some countries, the fish which are caught by manipulations can be sold as stocking material to support recreational fisheries, e.g. bream in The Netherlands (Lammens, Van Nes & Mooij 2002), although this raises problems like spread of disease and genetic contamination (Cowx 1994). Bream are of commercial value as food fish in some Eastern European countries, and some local areas of Germany. In some regions, coarse fish are also eaten by anglers, e.g. roach in the state of Berlin (Wolter, Arlinghaus, Grosch & Vilcinskas 2003). More often, however, there is no market for this species to support continuous commercial fisheries. Some frozen bream and roach could be sold to zoological gardens, e.g. as food for pelicans (Hamrin 1999). If the quantities are large enough it may be possible to sell the fish to a fishmeal producer or deliver them to a biogas facility.

Yes → 14
No → 15

14. Remove biomass of planktivorous fish to below 50 kg ha^{-1}, and/or biomass of benthivorous fish to below 25 kg ha^{-1}, within 1–2 seasons

Many papers recommend removal of a certain proportion of fish biomass from a lake. For example, a 75% removal of fish biomass was found to be effective for water quality improvement in biomanipulation actions (Perrow *et al.* 1999b; Hansson *et al.* 1998; Meijer *et al.* 1999). Considering the absolute thresholds given above, Jeppesen & Sammalkorpi (2002) determined the annual amount of fish removal required in shallow lakes to be:

$$\text{Catch-required} = 16.9\ \text{TP}^{0.52}$$

with catch in kg ha^{-1}, TP in μg L^{-1}.

This target catch per year may be higher than the estimates of fish biomass based on TP-concentrations for stratified lakes (see 10, Jeppesen & Sammalkorpi 2002). According to an assumed range of TP up to about 500 μg L^{-1} in lakes where biomanipulation can be effective, fish biomass normally does not exceed 400 kg ha^{-1}. A residual fish biomass of 70 kg ha^{-1} was considered the critical level for Czech stratified reservoirs by Seda, Hejzlar & Kubecka (2000). Benndorf (1990) proposed critical figures such as 120 kg ha^{-1} for small-sized planktivores such as sunbleak, *Leuciscus delineatus* (Heckel), and almost 200 kg ha^{-1} for roach and bream. In summary, to be on the safe side, only 50 kg ha^{-1} or less planktivorous fish should remain in the lake (Barthelmes 1988; Kasprzak *et al.* 2000; Jeppesen & Sammalkorpi 2002). Backx & Grimm (1994) and Meijer & Hosper (1997) considered the target biomass for benthivores to be achieved by fish removal was 20–25 kg ha^{-1}.

According to practical tests in lakes over many years, seining can eliminate only bream stocks, whereas roach stocks may increase because of heavy fishing (Barthelmes 1994). Long-term seining or trawling, but at low intensity, does not result in fish biomass reductions needed for biomanipulation purposes (Mehner *et al.* 2001). The most sustainable removals are achieved if heavy manipulations are completed within one (Hamrin 1999) or 2 years maximum (Meijer *et al.* 1999). However, the application of more than one method to remove the fish is recommended. A combination of active (seine net, trawls, purse seines, electric fishing) and passive gears (gill nets, fyke nets, traps) may achieve the highest efficacy of fish removal (Jeppesen & Sammalkorpi 2002), and this could be accompanied by intensive angling. It may be useful to concentrate on places where fish aggregate at a specific time (e.g. overwintering areas, spawning places, migration routes).

If the lake is connected with other waters, there is a risk of continuous immigration of fish, thus counteracting manual removal. Therefore, connections have to be blocked mechanically. For constructions in navigable waterways, see for example Moss *et al.* (1996).

→ 15

15. Is there natural reproduction and recruitment of piscivores?

Enhancing the stocks of piscivores is another strategy to suppress the numerous planktivorous and benthivorous fish (Benndorf 1995; Berg, Jeppesen & Søndergaard 1997). Unwanted species can thus be transformed into locally more valuable species, mainly piscivores. This is also a pre-requisite for support of biomanipulation by fishery stakeholders interested in piscivores. However, natural reproduction or first-year recruitment are often the limiting factors in establishing piscivore populations (Skov & Berg 1999; Wysujack, Laude, Kasprzak & Mehner 2002). Both processes are linked with the availability of suitable habitats (e.g. macrophytes, see below). Young-of-the year recruitment is best determined by bongo net catches or push-net systems in late spring (Wanzenböck, Matena & Kubecka 1997; Tischler, Gassner & Wanzenböck 2000) and/or electric fishing in the littoral zone during summer (Copp & Peňaz 1988), whereas recruitment into older age groups can be evaluated using netting, hydroacoustics (Mehner & Schulz 2002), or electric fishing in the littoral areas.

Yes → 16
No → 17

16. Perform maintenance or compensatory stocking, if necessary

If piscivores reproduce naturally, supplementary stocking may be required only after drastic population crashes or in response to heavy exploitation rates (Cowx 1994; Salonen, Helminen & Sarvala 1996). In these cases, stocking with adult fish (for example pike) is recommended. However, even in these cases stocking may be of little benefit if sufficient recruits are naturally available (e.g. Grimm & Klinge 1996; Parsons & Pereira 2001). There are also possibilities for suppressing 0+ planktivores by excessive stocking 0+ pike, *Esox lucius* L., even where sufficient natural reproduction occurs in the lake. Long-term success of these measures is currently under evaluation but → *19* if prove successful, otherwise → *23*

17. Is the lake stratified with an extended pelagic zone?

If the lake basin is dominated by deep pelagic areas, pelagic piscivores will most likely have the strongest impact on planktivorous fish. Normally, in stratified lakes the dominant biomass of planktivores is concentrated in the pelagic area (see for example Horppila *et al.* 1998), although juvenile fish may sometimes prefer the littoral zone.

Yes → 18
No → 19

18. Stock pikeperch intensively

Pikeperch, *Sander lucioperca* (L.) [and walleye, *Stizostedion vitreum* (Mitchell), in North America] is the pelagic piscivore most often used for biomanipulation (see Hansson *et al.* 1998; Drenner & Hambright 1999). It feeds efficiently on small planktivores (Willemsen 1977; van Densen & Grimm 1988; Dörner, Wagner & Benndorf 1999; Wysujack & Mehner 2002) but bigger planktivores or benthivores (bream, carp) will soon reach a size refuge (Lammens 1999). The persistence of large adult cyprinids of a number of species always provides a source of recruits, explaining the potential for rapid community switches and recovery (Perrow *et al.* 1999b). Initial stocking with pikeperch fingerlings (up to 200 fish ha^{-1}) in summer may be useful. In ongoing projects, age-0 juveniles are a better alternative (up to 20 fish ha^{-1}), but since they are stocked in late autumn, a minimum fish length of 15 cm is required to prevent high overwinter mortality (Santucci & Wahl 1993; Lappalainen, Erm, Kjellmann & Lehtonen 2000). Experiences with walleye stocking suggest that overwinter mortality rates were 1.2–16 times higher in fingerlings stocked in autumn than with fingerlings originating from natural reproduction or fry stocking (McWilliams & Larscheid 1992; Mitzner 1992). Therefore, if available, age-1 fingerlings (juveniles) should be stocked in spring after having overwintered in hatcheries (Wysujack 2002).

→ 19

19. Does the lake have extended areas with submerged macrophytes?

Macrophytes play a central role in recovery of shallow lakes due to several self-stabilising effects that improve transparency within macrophyte stands (Jeppesen, Søndergaard, Søndergaard & Christoffersen 1997; Scheffer 1998). However, macrophyte-dominated littoral zones are also essential for reproduction and recruitment of phytophilic fish in stratified lakes. Increase in pike biomass is associated with increasing macrophyte cover in shallow lakes; and a similar response was found for perch, rudd, *Scardinius erythrophthalmus* (L.), and tench, *Tinca tinca* (L.) biomass (Perrow *et al.* 1999b). In contrast, zooplanktivorous roach stocks decrease with increasing macrophyte cover (Perrow *et al.* 1999b). Emergent reed (*Phragmites* spp.) belts may serve both as protection and feeding areas for young fish.

Yes → 21
No → 20

20. Introduce artificial structures in shallow areas

Pike often strike from moderately dense plant cover towards open water (Bean & Winfield 1995). Age structure of pike populations differs between vegetated and unvegetated lakes (Grimm & Backx 1990). Structural complexity allows provision of refuges against cannibalism from larger pike specimens (Grimm 1994) and gives cover for the young pike to lie in wait for prey (Casselman & Lewis 1996; Skov, Berg, Jacobsen & Jepsen 2002a). In unvegetated zones, spruce trees can be introduced to provide shelter for young stocked piscivores, enhancing recruitment to older life stages (McCarraher & Thomas 1972; Skov & Berg 1999).

→ *21*

21. Stock 0+ pike intensively

Stocking of pike is most effective in shallow lakes with extended areas of macrophytes, but predation by pike on juvenile fish also works in littoral areas of stratified lakes. Pike are associated with habitats with structural complexity (Grimm 1994) and if 30–50% of the surface area of a shallow lake is covered by macrophytes, production of age-0 cyprinids may be controlled by pike (Grimm & Backx 1990; Prejs, Martyniak, Boron, Hliwa & Koperski 1994; Berg *et al.* 1997). Negative correlation between stocking density of age-0 pike in May or June, and juvenile planktivorous fish density in the littoral zone in August have been found (Berg *et al.* 1997). At least 75 kg ha^{-1} biomass of juvenile pike are necessary to control planktivorous cyprinid populations in highly productive lakes (Grimm 1989). Even if there is little negative correlation between 0+ pike density and their 0+ prey, densities of adult pike can be negatively correlated with those of adult planktivorous fish (Skov, Perrow, Berg & Skovgaard 2002b).

The seasonal timing of the 0+ pike stocking might influence the efficiency of pike controlling the 0+ cyprinids. The best result is probably achieved if the stocking coincides with the appearance of the newly hatched larvae of the dominant prey species (Prejs *et al.* 1994). Stocking the 0+ pike too late in season might cause increased post-stocking mortality due to cannibalism from larger-sized, native 0+ pike (Grimm & Klinge 1996; Skov 2002). To minimise post-stocking mortality due to intracohort cannibalism, the size heterogeneity among the stocked pike should be minimal (Skov 2002).

Pike for population enhancement can be stocked as advanced pike fry (2–6 cm length) at annual rates up to 200 fish ha^{-1} in spring; or larger age-0 juveniles (minimum length 20 cm) can be stocked in autumn (Wysujack *et al.* 2001). Higher stocking densities of pike fry in spring are preferred for the purpose of instantaneous predation on 0+ planktivores, and are recommended at densities of 500–1000 fish ha^{-1} (Raat 1988), or even 1000–4000 fish ha^{-1} (Prejs *et al.* 1994; Berg *et al.* 1997). This corresponds to even higher stocking densities if density is calculated on the basis of lake area covered with macrophytes or other submerged structures, where stocking typically takes place (instead of being based on total lake area). The maximum achievable pike biomass is about 110 kg ha^{-1} vegetated area (Grimm 1989; Grimm & Klinge 1996).

→ *22*

22. Prohibit angling and fishing for piscivores for at least 2 years

Due to the time lag in the response of piscivore populations to stocking events, and because of the huge overfishing potential of angling and fishing (Mosindy, Momot & Colby 1987), temporally limited restrictions to fisheries are a pre-requisite to build up a piscivore community (Mehner *et al.* 2001; Wysujack & Mehner 2002). A full closure of fishing for piscivores is recommended for the time span which the stocked fish need to come to first maturation and spawning. For zander and pike stocks, this is at least 2 years, but 3 or 4 years should improve efficacy of stocking measures.

→ *23*

23. Is proportion of piscivores >25% of adult fish biomass?

A sufficient proportion of piscivores is the only solution to control enhanced recruitment of age-0 cyprinids after biomanipulation, which occurs regularly after heavy planktivorous fish removal (Meijer, Jeppesen, van Donk, Moss, Scheffer, Lammens, van Nes, van Berkum, de Jong, Faafeng & Jensen 1994; Mehner, Schultz, Bauer, Herbst, Voigt & Benndorf 1996; Romare & Bergman 1999). Fish removal improves food availability for the remaining fish, and may increase growth rates and fecundity of adult cyprinids (Papageorgiou 1979). Therefore, the higher numbers of planktivorous juveniles after biomanipulation may outweigh the effect of removal of adults due to the high daily feeding rates of juveniles (Romare & Bergman 1999).

According to simple mass balance calculations, piscivores may control planktivorous fish stocks and their annual production at ratios of about 25% biomass piscivores to 75% biomass planktivores (Barthelmes 1981; Wysujack & Mehner 2002). In shallow Danish lakes, up to 30% piscivores were found where the TP concentration was between 70 and 100 $\mu g\ L^{-1}$ (Jeppesen, Jensen, Kristensen, Søndergaard, Mortensen, Sortkjaer & Olrik 1990). To optimise fisheries yield in terms of a proper balance between small-bodied cyprinids and larger piscivores, proportions of piscivores should range between 25 and 30%

(Bonar 1977; Barthelmes 1981). Higher proportions may work (for example, 30–40% piscivores were recommended by Benndorf & Kamjunke 1999), but force the piscivores into a greater degree of cannibalism or mutual piscivory, e.g. perch–zander-interaction (Mehner *et al.* 1996; Mehner, Dörner & Schultz 1998; Dörner *et al.* 1999; Dörner, Schultz, Mehner & Benndorf 2001). An overmanipulation with piscivore proportions above 40% may eventually lead to high densities of invertebrate planktivores such as *Chaoborus* and *Leptodora* (Benndorf, Wissel, Sell, Hornig, Ritter & Böing 2000).

In the long-term, a decline in trophic state of the manipulated lake favours stocks of pike and perch (Persson *et al.* 1991; Perrow *et al.* 1999b). The growth of perch to predatory sizes has been found to improve by removal of cyprinids (Søndergaard, Jensen, Jeppesen & Lauridsen 2000), or as an indirect result of 0+ pike stocking, which makes 0+ planktivores more available to perch in the pelagic zone (Berg *et al.* 1997). These effects are positive as perch is needed to suppress the age-0 cyprinids; and perch may become piscivorous early in its life (Mehner *et al.* 1996; Dörner *et al.* 2001). Efficacy could be reinforced by enhancing existing perch stocks by stocking. Perch stocking is, however, difficult, e.g. adult perch stocking was not successful in Feldberger Haussee, Germany (Mehner *et al.* 2001), and had only some effect in Lake Udbyover, Denmark (Skov *et al.* 2002b). Strong perch year classes can be achieved by reduction of zander stocks in manipulated lakes due to the heavy feeding of zander on age-0 perch (Dörner *et al.* 1999; Wysujack *et al.* 2002). Accordingly, perch stocking most likely induced a feeding impact on young roach in Lake Udbyover where zander was not a part of the natural fish community (Skov *et al.* 2002b). The role of other predatory species such as eel, *Anguilla anguilla* (L.), or wels, *Silurus glanis* L., is poorly understood (Perrow *et al.* 1999a; Wysujack 2002; Dörner & Benndorf 2003). The introduction of non-native predatory species (rainbow trout, *Oncorhynchus mykiss* (Walbaum); brown trout, *Salmo trutta* L., or lake trout, *Salvelinus namaycush* (Walbaum), (but note zander and pike are alien species in parts of Europe) is not recommended for nature conservation and biodiversity reasons.

Yes → 24
No → 15

24. Control fishing and/or angling for piscivorous species

If planktivorous and benthivorous fish biomass is below the thresholds, water quality improvement can be expected. However, the piscivorous fish in the lake can be eliminated by selective commercial and recreational fishing (Mosindy *et al.* 1987; O'Grady 1995; Salonen *et al.* 1996), as many anglers in Europe and North America target piscivores for capture and harvest (Johnson & Staggs 1992; Bogelius 1998; Jantzen 1998; Wolter *et al.* 2003). Therefore, specific regulations such as annual limits or quotas (Lathrop, Johnson, Johnson, Vogelsang, Carpenter, Hrabic, Kitchell, Magnuson, Rudstam & Stewart 2002) or access restrictions (numbers of licenses, see Welcomme 2001), or catch and release, may be useful to prevent overexploitation of piscivores. A broad length range of piscivores guarantees a feeding pressure directed to as many as possible length classes of unwanted fish (Benndorf 1990; Perrow *et al.* 1997). However, there is a risk that prey fish that are too large may escape predation by reaching a size refuge, e.g. bream in lakes dominated by zander as predators (Lammens 1999). Therefore, fishing for larger planktivores should be promoted.

if anglers dominate → 25
if commercial fisheries dominate → 26

25. Anglers dominate

Anglers often prefer catching few trophy-sized fish instead of many smaller fish (Pierce, Tomcko & Schupp 1995; Frank, Lejeune & Herman 1998; Paukert, Klammer, Pierce & Simonson 2001; Arlinghaus & Mehner 2003). The objective of enhancement of the percentage of specimen-sized fish is a difficult task, the success of which is dependent on, *inter alia*, compliance with regulations and harvest rates of anglers (Gigliotti & Taylor 1990; Pierce & Tomcko 1998), morphometry of lakes (more likely successful in larger and deeper lakes, Paukert *et al.* 2001), or the degree of natural recruitment and environmental influences on growth and recruitment (Paukert *et al.* 2001). Dependent on legal constraints, trophy sizes may be produced by full protection of predators larger than, for example, 70 cm long (catch-and-release with a maximum size limit). Alternatively, an inverse slot (or window) length limit might be favourable which allows harvest of predators caught within a certain size slot (for example, 50–70 cm long, combination of minimum and maximum size limit, see also Pierce & Tomcko 1998 for protected slot length limit). Since medium-sized predators contribute most strongly to annual reproduction of the population, this management strategy may require ongoing stocking. However, due to the low density of predators, cannibalism and mutual predation are low, and growth rates are high thus creating a strong predation pressure on the (unwanted) juvenile cyprinids. Both strategies necessitate the implementation of low daily bag limits (one or two predators per angler) and closed seasons during spawning to prevent (recruitment) overfishing. In addition, only artificial lures may be allowed to minimise mortality after release (Beukema 1970; Benndorf 1995). To protect smaller predators, an obligation to use lures larger than, for example, 20 cm may work. However, the frequency distribution of the catch among anglers is typically highly skewed to the left, which suggests that most anglers catch few or no fish, and that most of the fish are caught by only a few anglers (Baccante 1995). Thus, bag limits are often not effective in reducing harvest by anglers (Baccante 1995; Paukert *et al.* 2001). Alternatively, minimum size limits can be increased considerably up to 70 cm for zander and 90 cm for pike, and daily bag limits even reduced to one predatory fish per angler (Benndorf 1995; Mehner *et al.* 2001; Lathrop *et al.* 2002). In the case of heavy exploitation, only limited access and catch and release fishing can ultimately protect piscivorous fish from being overharvested. All measures may favour trophy sizes, but at the expense of harvest rates. In either case, regular creel surveys are recommended to evaluate the success of the regulations (Radomski, Grant, Jacobson & Cook 2001).

→ 27

26. Commercial fisheries dominate

Usually, commercial fisheries are interested in continuous harvest rates of medium-sized fish which can be better marketed than trophy-sized fish. Therefore, in this case maximum annual harvest rates (quotas) have to be defined, but minimum size limits can be low, only allowing for first maturation of predators (40–45 cm length for zander and pike). Due to the continuous removal of medium-sized fish, large predators are scarce and cannibalism is low, whereas growth and individual consumption rates are high. Normally, in many European countries one would expect full agreement of commercial fishermen with the interest of lake managers to keep the density of planktivorous fish low. However, the aim of the quota management needs to be communicated to the local fishermen by an educational outreach.

→ 27

27. The final stage: adaptive management

Fish biomass and fish community composition have to be controlled annually, and the management (stocking measures and harvest regulations) be adapted to the prevailing situation and the management targets. This kind of continuous evaluation and adaptation of management decisions is called 'adaptive management' (Walters & Hilborn 1976), and has been applied successfully in inland fisheries systems to enhance and stabilise fisheries' and angler's yields (Johnson & Staggs 1992; Garvey, Dingledine, Donovan & Stein 1998; Müller & Bia 1998).

According to ecosystem theory, strong and intense perturbations are required to shift a system into another stable state, whereas pulsed perturbations are of too little impact (Persson, Johansson, Andersson, Diehl & Hamrin 1993; Perrow *et al.* 1997). Therefore, to stabilise manipulated fish communities in the long term, ongoing maintenance and management may be required over many years (Mehner *et al.* 2002). However, since stocking and regulations are traditional inland fisheries management practices regularly performed in most (developed) inland fisheries systems of industrialised countries (Welcomme 2001; Arlinghaus *et al.* 2002), the ongoing measures are very likely to be successful, especially in recreational fisheries. A stable, self-sustaining fish community composition can be achieved only, if: (1) external and internal nutrient loading to the lake is below the effective thresholds to allow decline in trophic state towards mesotrophic or weakly eutrophic conditions during the manipulation; and (2) the piscivorous fish stocks are only moderately harvested and properly managed.

→ 28

28. Is water still turbid?

If after about 5 years of manipulation the water is still turbid, changes in structure of the food web may be not strong enough to compensate for the deteriorating impact of physical or chemical processes. Thus, physical or chemical in-lake rehabilitation techniques are required to improve water quality (see Mehner & Benndorf 1995).

Yes → 7

No → Goal achieved

Conclusions

There are links between biomanipulation as a lake rehabilitation tool and traditional inland fisheries management, mainly because the removal of small-sized planktivores and enhancement of piscivores complies with the interests of both lake and fisheries managers. The guidelines presented are based on experience from several long-term manipulation projects. However, details have to be verified in the light of frequent future applications. Not all relevant features may have been adequately considered since not enough is known about the role of habitat heterogeneity (e.g. the ratio of littoral to pelagic habitats) or proportions of species in the fish community for long-term stability of manipulated systems (Mehner *et al*. 2002).

A successful combination of biomanipulation and fisheries management is based on four main steps: (1) the definition of the main goals and a principal stakeholder analysis; (2) an analysis of the nutrient situation (external load and internal concentration); (3) planning and performing of the manipulation measures considering characteristics of the fish stock and management aspects (e.g. technical feasibility of mass removal, interests of fisheries, stocking measures, catch restrictions); and (4) maintenance (adaptive management). If the respective targets and thresholds in fish biomass can be achieved, then improvements of water quality and satisfaction of fisheries stakeholders are very likely.

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