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Lake restoration: successes, failures and long-term effects

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Summary

1. Eutrophication constitutes a serious threat to many European lakes and many approaches have been used during the past 20–30 years to improve lake water quality. Results from the various lake restoration initiatives are diverse and the long-term effects are not well described.

2. In this study we evaluated data from more than 70 restoration projects conducted mainly in shallow, eutrophic lakes in Denmark and the Netherlands. Special focus was given to the removal of zooplanktivorous and benthivorous fish, by far the most common internal lake measure.

3. In more than half of the biomanipulation projects, Secchi depth increased and chlorophyll *a* decreased to less than 50% within the first few years. In some of the shallow lakes, total phosphorus and total nitrogen levels decreased considerably, indicating an increased retention or loss by denitrification. The strongest effects seemed to be obtained 4–6 years after the start of fish removal.

4. The long-term effect of restoration initiatives can only be described for a few lakes, but data from biomanipulated lakes indicate a return to a turbid state within 10 years or less in most cases. One of reasons for the lack of long-term effects may be internal phosphorus loading from a mobile pool accumulated in the sediment.

5. *Synthesis and applications*. Lake restoration, and in particular fish removal in shallow eutrophic lakes, has been widely used in Denmark and the Netherlands, where it has had marked effects on lake water quality in many lakes. Long-term effects (> 8–10 years) are less obvious and a return to turbid conditions is often seen unless fish removal is repeated. Insufficient external loading reduction, internal phosphorus loading and absence of stable submerged macrophyte communities to stabilize the clear-water state are the most probable causes for this relapse to earlier conditions.

Key-words: biomanipulation, eutrophication, internal loading, macrophytes, phosphorus, shallow lakes, stocking of pisci, Water Framework Directive

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Introduction

For several decades eutrophication has constituted the most serious problem facing water managers in densely populated areas (Smith 2003). Turbid water, cyanobacteria blooms and loss of biodiversity have afflicted many lakes all over the world because of increased external nutrient loading (Cooke, Welch & Newroth 1993). In Europe, eutrophication is a serious environmental problem and an important issue in the implementation of the European Water Framework Directive. This directive stipulates that good ecological quality, defined as a status deviating only slightly from undisturbed

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conditions and determined by the use of biological characteristics, should be achieved in all lakes by 2015 (European Union 2000). Billions of euros have been invested in improved wastewater treatment and other pollution-combating measures, which in western Europe has reduced phosphorus concentrations by more than 25% in half of the rivers (Kristensen & Hansen 1994). However, despite these reductions, eutrophication remains the major problem, either because external loading has not been reduced sufficiently or because internal lake mechanisms, chemical or biological, prevent or delay recovery (Sas 1989; Gulati & Van Donk 2002; Søndergaard, Jensen & Jeppesen 2003). Climate warming may also counteract the long-term efforts made to reduce lake eutrophication (Jankowski *et al*. 2006).

High internal loading of phosphorus from lake sediments is frequently reported as an important mechanism delaying lake recovery after a reduction of the external loading (Marsden 1989; Phillips *et al*. 2005; Søndergaard, Jensen & Jeppesen 2005; Welch & Cooke 2005). A recent survey of long-term data from 35 lakes in Europe and North America concluded that internal release of phosphorus typically endures for 10–15 years after the loading reduction (Jeppesen *et al*. 2005) but in some lakes internal release may last longer than 20 years (Søndergaard, Jensen & Jeppesen 2003). Another mechanism potentially delaying lake recovery is the development of a large biomass of zooplanktivorous and benthivorous fish in eutrophic lakes, which reduces the possible top-down control of zooplankton on the phytoplankton (Shapiro & Wright 1984; Meijer *et al*. 1999); however, a multilake study showed a relatively fast response of fish to nutrient loading reduction (Jeppesen *et al*. 2005). Delay in submerged macrophyte appearance after improved transparency (Lauridsen, Sandsten & Møller 2003) may also lead to biological resistance. This is of particular importance in shallow lakes, where submerged macrophytes are important for maintaining the clear water state (Jeppesen *et al.* 1997), and any mechanism, such as grazing by waterfowl or fish, preventing or delaying their recovery may reduce the chances of obtaining stable clear-water conditions (Mitchell & Wass 1996; Søndergaard *et al*. 1996).

Numerous lake restoration techniques have been developed and used during the past decades to combat eutrophication and to overcome the chemical or biological resistance (Cooke, Welch & Newroth 1993; Meijer *et al*. 1999; Gulati & Van Donk 2002; Lathrop *et al.* 2002). Success or not of restoration involves many factors; it is generally accepted that permanent effects of restoration can only be achieved if the external nutrient loading is reduced to sufficiently low levels (Sas 1989; Jeppesen *et al*. 1990; Benndorf *et al*. 2002; Jeppesen & Sammalkorpi 2002; Mehner *et al*. 2002). Many restoration projects were carried out in the 1980s and 1990s, and the results of these have been repeatedly reported (Hansson *et al*. 1998; Søndergaard *et al*. 2000; Gulati & Van Donk 2002); there is a risk, however, that successful restoration projects have been more often described than failures. Moreover, in most cases only the effects observed in the first few years after the intervention are described and therefore little is known about the long-term perspective.

The aim of this study was to give an overview of the different types of restoration projects carried out in Denmark and the Netherlands since the 1980s, and to evaluate the results in the context of international restoration projects. In both Denmark and the Netherlands, lake restoration has been widely used as a management tool to improve lake water quality. Biomanipulation has been the primary method and results from this method will be the main focus.

Methods and study sites

Summer means of total phosphorus (TP), total nitrogen (TN), chlorophyll *a* (chla), Secchi depth and sometimes suspended solids (SS) were used as key variables to evaluate the restoration projects. Surface samples were taken from a central location once or twice a month and analysed according to standard methods (Meijer *et al*. 1999; Kronvang *et al*. 2005). For some of the Danish lakes, data on fish, macrophytes and zooplankton were also available. Fish abundance and composition were sampled using multimesh-sized gill nets (6–75 mm) in August–September, submerged macrophytes by estimating coverage and plant height at > 100 locations in August, and zooplankton by bimonthly surface samplings during summer followed by enumeration and biomass calculation (further details are given in Søndergaard, Jeppesen & Jensen 2005).

Most of the restored lakes in both Denmark and the Netherlands were shallow, eutrophic and relatively small. However, Dutch lakes tended to be slightly larger (mean 239 ha compared with 116 ha in Denmark) and more eutrophic (mean TP of 0·37 mg P L^{-1} compared with 0·18 mg P L^{-1} in Denmark; Table 1). The variability among the restored lakes was, however, considerable, with TP ranging from 0·05 to 1·40 mg P L^{-1} and chla from 21 to 300 μg L^{-1}. The nutrient loading history of

Table 1. Summary description of lakes in Denmark and the Netherlands undergoing lake restoration. Minimum, mean and maximum values are given. SD of mean is given in parentheses

		Area (ha)			Mean depth (m)			Mean TP (mg P L^{-1})			Mean chla (μg L^{-1})		
Country	No. lakes	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.
Denmark	39–41	2	116 (204)	941	0·8	2·6 (2·7)	13·5	0·05	0·18 (0·19)	1·25	21	80 (49)	208
the Netherlands	28	1·5	239 (739)	3022	0·5	1·5 (0·4)	2·2	0·10	0·37 (0·28)	1·40	35	116 (63)	300

Table 2. Internal restoration measures and number of lakes (> 10 ha) to which they have been applied to combat eutrophication in Denmark and the Netherlands

	Denmark	the Netherlands
Fish removal (zoo- and benthivores)	42	14
Stocking of piscivores	34	4
Hypolimnetic oxygenation	6	3
Alum treatment	2	0
Sediment dredging	1	7

the lakes prior to the 1970s was generally undocumented but presumably loading increased steadily, particularly during the last part of 20th century, peaking around 1970 (Gulati & Van Donk 2002; Søndergaard, Jensen & Jeppesen 2003). Thereafter external loading to many of the lakes was reduced via chemical treatment of the waste water by connecting many isolated households to sewerage systems or by diversion of point source pollution from, for example, waste water treatment plants to almost all lakes. Consequently, mean TP concentrations in rivers, which represent the external loading of many lakes, decreased in Denmark by 73% from 1978 to 1993 (Jeppesen *et al*. 1999). During the period 1989–2002, the discharges of TN and TP from point sources to the Danish aquatic environment declined by 69% (N) and 82% (P) (Kronvang *et al*. 2005). Since the early or mid-1990s, most treatment plants have been fully developed and further reductions in the external phosphorus loading have been modest (Søndergaard, Jensen & Jeppesen 2005).

Results

DENMARK

Lake restoration has been conducted in more than 50 lakes in Denmark. Biomanipulation, by removing zooplanktivorous and benthivorous fish, mainly roach *Rutilus rutilus* and bream *Abramis brama*, often supplemented by piscivore stocking, has been the most frequently used method (Table 2).

The fish removal varied from less than 10% to more than 80% of the estimated total fish stock, corresponding to 100–870 kg ha^{-1} ($n = 21$ lakes, mean 321 kg ha^{-1}). The duration of the fish manipulation initiatives varied from 1 year to more than 10 years. For many lakes, marked improvements were recorded immediately upon fish removal (Table 3). Secchi depth increased by more than 50% in 14 of 20 lakes and chla decreased in eight of 21 lakes. TN and TP remained unchanged in most lakes, but decreased in five of the 21 lakes. Despite the improved transparency, coverage of submerged macrophytes only increased in a few lakes.

For three of the biomanipulated lakes, where a large proportion of the fish stock was removed within a few years, yearly data covering 12 years or more were available (Fig. 1). Generally, marked changes were seen shortly after the restoration in turbidity, chla, TN and TP. The most marked changes were seen after 5–6 years, when Secchi depth was more than doubled and TP, TN and chla were reduced to 20–50% of the pre-restoration levels. However, after 6–8 years all three lakes approached the turbid state again. Secchi depth tended to remain high in two of the lakes.

Lake Væng, for which post-restoration data covered 18 years, showed substantial changes in fish and macrophyte composition and abundance during approximately the first 10-year period following restoration; thereafter a steady return to the turbid state took place (Fig. 2). Following fish removal, chla and turbidity decreased. Two years after the improved Secchi depth, submerged macrophytes colonized (*Potamogeton crispus* followed by *Elodea canadensis*) and within a further 1–2 years completely covered the lake. After a period with low coverage in 1993, the macrophytes recovered again until 1996. Since 1998 macrophytes have been completely absent or appear only in low densities. Simultaneous with the changes in macrophytes, nitrogen and phosphorus concentrations have fluctuated, indicating a high impact of clear-water conditions on the nutrient retention. Since the late 1990s roach biomass has increased steadily. The number of perch has also increased but the stock is dominated by individuals

Table 3. Changes recorded after biomanipulation by fish removal. Decrease or increase is defined as a more than 50% change in summer means from before to after. Before is the mean of 1–3 years before biomanipulation, and after is the mean of 1–3 years after. Zoo:phyto, the ratio between zooplankton and phytoplankton biomass. *n*, number of lakes; nc, no changes, incr., increase; decr., decrease

	Denmark				the Netherlands			
Variable	*n*	nc	incr.	decr.	*n*	nc	incr.	decr.
Secchi depth	20	6	14	0	14	8	6	0
Chla	21	13	0	8	14	6	1	7
TP	21	15	1	5	14	9	0	5
TN	21	16	0	5	13	9	0	4
Suspended solids	17	13	0	4	–	–	–	–
Daphnia/cladocerans, number	14	7	7	0	–	–	–	–
Mean weight cladocerans, µg dry wt ind.$^{-1}$	13	9	4	0	–	–	–	–
Zoo:phyto, dw:dw	12	7	5	0	–	–	–	–
Submerged macrophytes, coverage	12	10	2	0	13	8	5	0

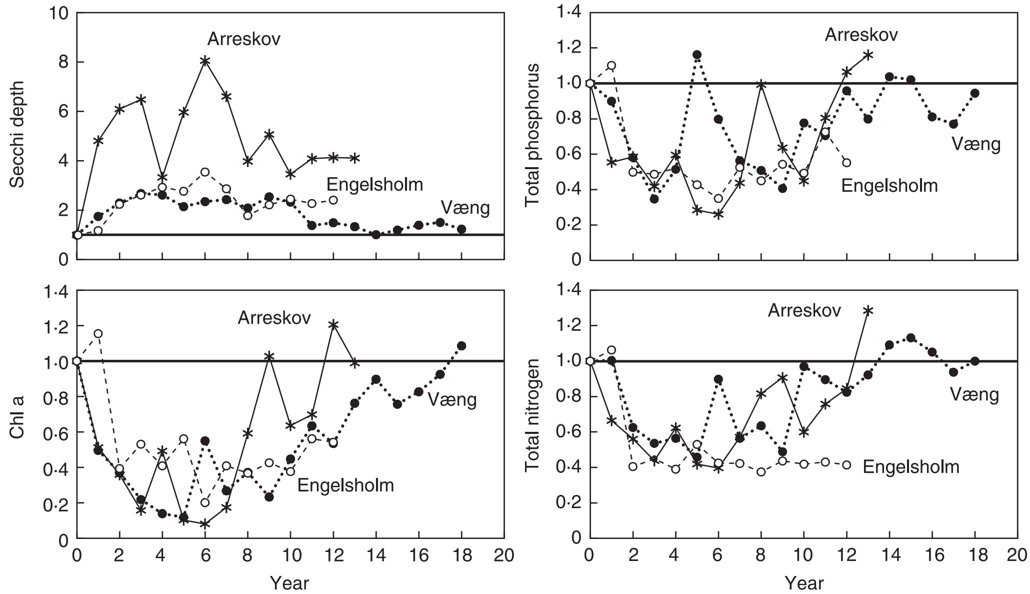

Fig. 1. Long-term changes in Secchi depth, chla, TP and TN in three shallow Danish lakes, where at least 50% of the zooplanktivorous fish stock was removed within 1–3 years. The changes are relative and shown as the ratio of the value the current year to the pre-manipulation value. The pre-manipulation value is the mean of 1–4 years before the fish removal (= year 0) and based on summer means. The lakes are: Lake Arreskov (mean depth 1·9 m, area 317 ha, TP (year 0) 0·235 mg P L^{-1}, year 1 = 1992, submerged macrophytes reached a maximum of 60% in year 6); Lake Engelsholm (mean depth 2·6 m, area 44 ha, TP (year 0) 0·197 mg P L^{-1}, year 1 = 1993, submerged macrophytes largely absent throughout the period); Lake Væng (mean depth 1·2 m, area 16 ha, TP (year 0) 0·124 mg P L^{-1}, year 1 = 1987, for macrophytes see Fig. 2).

smaller than 10 cm. Today the lake has almost returned to the conditions prevailing some 20 years earlier.

Immediately upon the fish removal, seasonal TP in Lake Væng changed considerably (Fig. 3). When submerged macrophytes were abundant and chla low, TP remained relatively stable and ranged between 0·05 and 0·1 mg P L^{-1} throughout the season, although large fluctuations were seen in February–March. Later, when macrophytes had disappeared and the water turned turbid, a steady increase in TP was seen from about April until maximum concentrations of 0·15 mg P L^{-1} were reached in August. The mean summer TP increased from 0·07 to 0·12 mg P L^{-1}, when the lake changed from clear (1989–95) to turbid (1997–2004) conditions.

Stocking of piscivores has also been widely used as a restoration tool in Denmark for the past 15 years (Jacobsen, Berg & Skov 2004), most frequently involving stocking of pike *Esox lucius* fingerlings (2–4 cm) during spring in densities ranging from 50 to 4000 individuals ha^{-1} $year^{-1}$. Thus in the past 10 years 0·4–0·8 million pike fry have been stocked yearly in Danish lakes (Jacobsen, Berg & Skov 2004). In most cases the ensuing reduction of small cyprinids has not been sufficient. Clear effects were seen in only one out of 34 lakes larger than 10 ha, and effects were traceable in only three lakes (Skov *et al.* 2006).

Other restoration measures applied to Danish lakes included hypolimnetic oxygenation, alum treatment and sediment dredging (Table 2). The first oxygenation project started in 1985 in Lake Hald (340 ha, maximum depth 31 m) and was conducted each summer for 20 years until 2005. However, it is difficult to determine whether the positive results obtained were caused by the oxygenation or by a simultaneous reduction of the external loading. The first alum treatment was conducted in 2001 in the 8-ha Lake Sønderby (Reitzel *et al*. 2003). During 2001–03, TP and Secchi depth improved significantly, but during 2004–05 Secchi depth decreased and TP increased again (K. Reitzel, unpublished data). Recently, alum was applied to Frederiksborg Castle Lake (20 ha, maximum depth 9 m) and treatments are planned for several other lakes in the near future. Sediment dredging has been carried out in one large lake (Lake Brabrand, 150 ha, maximum depth 2 m) by removing approximately 0·5 million m^3 phosphorus-rich sediment, but despite reduced internal loading the effects on lake water quality were very limited because of continuously high external nutrient loading (mean inlet TP > 0·2 mg P L^{-1}).

Overall, only about half of the biomanipulation projects were successful in reducing the chla concentrations and increasing the Secchi depth (Table 3) and if data from more than the first few years after the restoration are included the success rate is even lower. Generally, it is difficult to draw firm conclusions about the reasons for unsuccessful restorations but, apart from insufficient reduction of the external phosphorus loading, a number of different internal mechanisms have been suggested to contribute to the limited sustainability of the effects (Table 4).

THE NETHERLANDS

Lake restoration has been carried out in about 30 Dutch lakes (Table 2). The internal measures have included

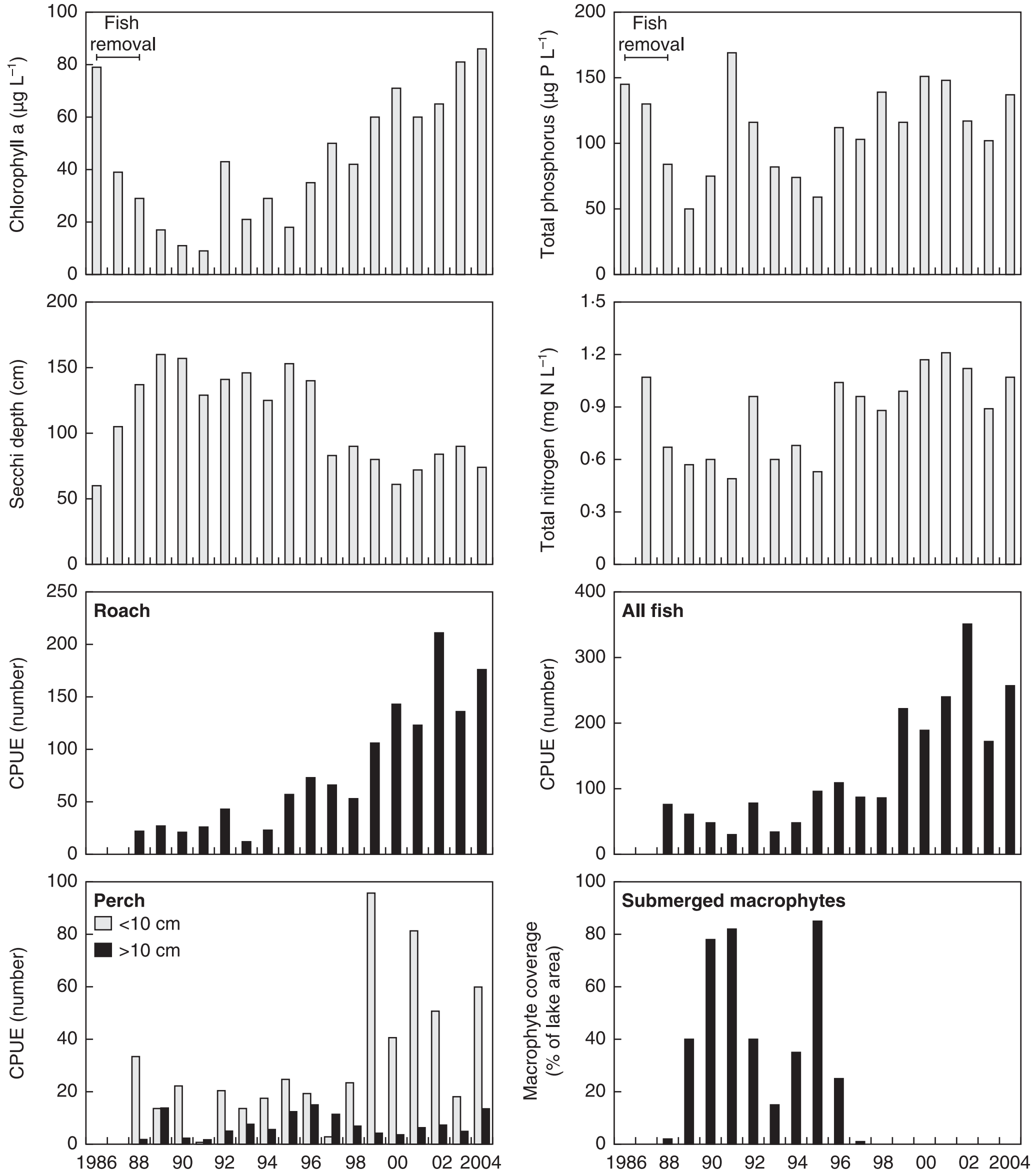

Fig. 2. Changes in Lake Væng (summer means), Denmark, following biomanipulation in 1986–88, when approximately 50% of the biomass of roach and bream was removed (Søndergaard *et al.* 1990). CPUE is late summer concentrations of fish in multimesh-sized gill nets per net per night.

Table 4. 'Internal' reasons for failure (excluding insufficient external nutrient loading reduction) of lake restoration in Denmark and the Netherlands

Method	Reasons
Fish removal	Insufficient number of fish removed
	Rapid return of strong cohorts of zooplanktivorous fish
	Invertebrate predators (*Neomysis*/*Leptodora*) reduce the zooplankton
	High resuspension rate of loose sediment
	Internal P loading because of formerly high external loading
	'Instability' because of low coverage of submerged macrophytes
Pike stocking	Low survival of stocked fish, for example because of predation and cannibalism
	Low pike consumption of young-of-the-year fish
	Bad timing of pike stocking relative to the hatching of young-of-the-year cyprinids
Sediment removal	Low P sorption capacity of new sediment surface
	Incomplete dredging
P-fixation	'Ageing' of alum and reduced P retention capacity
	Reduction/binding of ferric chloride by carbonate or sulphide
Oxygenation	No permanent effects achieved? Continued oxygenation
	Increased mobile phosphorus pool because of mineralization

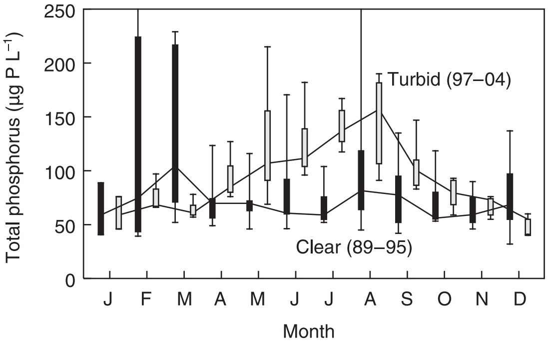

Fig. 3. Seasonal TP concentrations in Lake Væng after biomanipulation. Black boxes represent 5 years with dense macrophyte beds [coverage > 30% and low chla concentrations (< 20 µg L^{-1}) from 1989 to 1991, 1993 and 1995] (see also Fig. 2). Grey boxes represent 8 years with low macrophyte coverage (< 5%) and high chla (> 40 µg L^{-1}) from 1997 to 2004. Each box shows 25% and 75% quartiles and end of line 10% and 90% fractiles. Median values are connected by lines.

dredging (Van der Does *et al*. 1992), sediment fixation with iron or aluminium to decrease internal phosphorus release, hydrological measures such as flushing (Jagtman, Van der Molen & Vermij 1992), isolation (Naardermeer; Bootsma, Barendregt & van Alphen 1999) and biomanipulation (Van Donk *et al*. 1990). Biomanipulation experiments have involved not only fish removal and stocking (Meijer *et al*. 1999), but also stimulation of zebra mussels *Dreissena polymorpha*, as an aid to increase transparency by filtering seston particles (Reeders & Bij de Vaate 1990), and the planting of submerged macrophytes (Ozimek, Gulati & Van Donk 1990).

Unfortunately many of the measures have been implemented simultaneously or shortly after each other, making it difficult to discern the effects of the individual measures. Some of the restoration projects had an immediate effect and in seven out of 14 lakes from which fish were removed chla was reduced by more than 50% within the first 3 years (Table 3). Sediment dredging was also successful in most cases (Table 3). Of the three cases where phosphorus was chemically removed ($FeCl_3$) only one showed a positive effect (Boers *et al*. 1992). As in the Danish examples, the effects from the restorations tended to abate over time. Only two out of six biomanipulated lakes were still clear after more than 10 years (Fig. 4). In one lake (Lake IJzeren Man), TP, TN, chla and Secchi depth were still considerably improved after 15 years. In this lake, during the winter of 1989–90 all fish were removed and the lake was slightly deepened. During the following 2 years the lake was stocked again with pike, tench *Tinca tinca*, roach and rudd *Scardinius erythrophthalmus* (in total 120 kg ha^{-1}). The transparency of the lake improved immediately and the submerged vegetation flourished.

The other successfully restored lake was the peat bog Lake Nannewijd (Fig. 5). The lake became eutrophicated between 1960 and 1970, mainly because of the influx of nutrients from the surrounding agricultural areas. Several restoration initiatives were undertaken in the period 1993–95, such as hydrological isolation, leading the inlet water through a wetland to remove nutrients, dredging, P-fixation and reducing the fish stocks (83% was removed). Both TP and TN levels decreased, resulting in a lower algal biomass and increased transparency. Although aquatic vegetation cover somewhat improved, this has not yet resulted in a full recovery of the submerged vegetation (R. Veeningen, personal communication). In 2002 the bream population returned to the level before the fish stock manipulation.

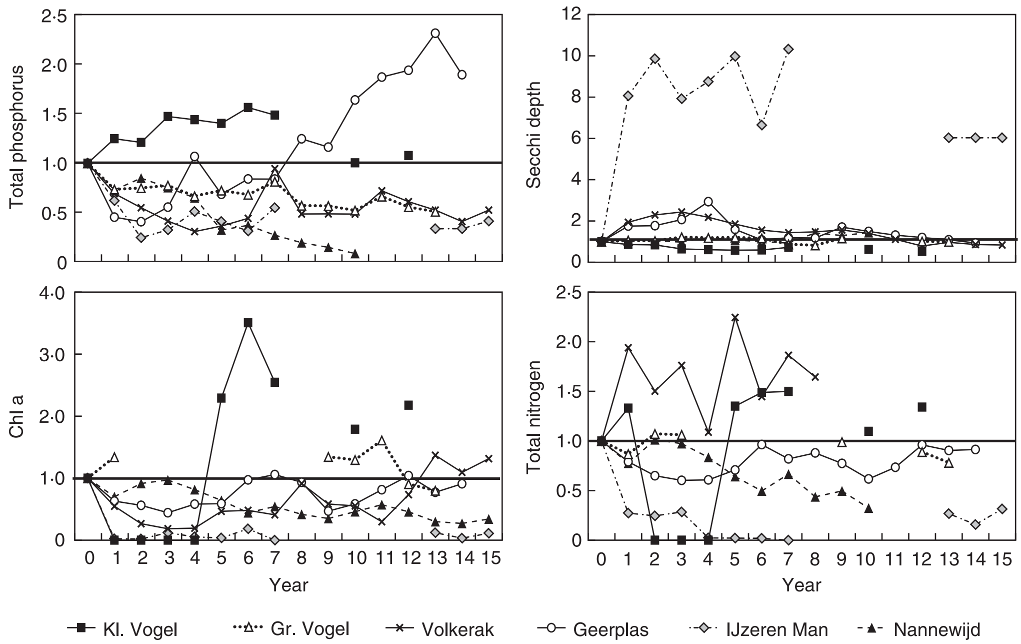

Fig. 4. Changes in chla, TP, TN and Secchi depth in six biomanipulated Dutch lakes > 10 ha. The changes are relative and shown as the value ratio of the current year to the pre-manipulation value. The pre-manipulation value is the mean of 1–4 years before the fish removal (= year 0) and based on summer means. See text for further explanation.

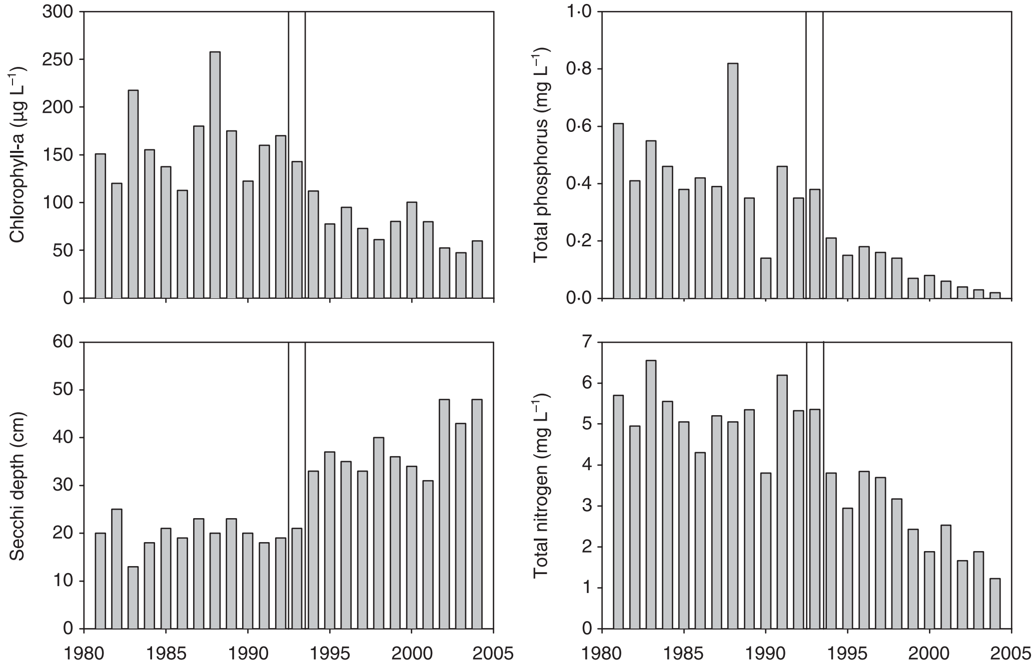

Fig. 5. Changes in Lake Nannewijd (area 100 ha, mean depth 1 m), the Netherlands, before and after its restoration (indicated by two vertical lines).

In Lake Klein Vogelenzang the removal of fish was initially successful. However, the resuspension of settled peat particles after a few years reduced the transparency and increased TP levels, thus stimulating algal growth (Meijer *et al.* 1999). In Lake Groot Vogelenzang, phosphorus removal resulted in a lower phosphorus level in the lake but a reduction of chla and enhanced transparency did not follow. Failure was because of the still high external loading and the reduction or binding of the applied alum with carbonate or sulphide (Boers *et al.* 1992). In Lake Geerplas, sediment dredging resulted in increased transparency during the first 4 years because of a lower algal biomass. After about 3 years the phosphorus level and algal biomass increased and accumulation of organic matter continued (Van der Does *et al.* 1992).

The reason for the failure of some of the restoration measures in Dutch lakes could not always be determined. In the case of fish removal, for example, many factors came into play, such as resuspension by wind, a still too high background colour (by humic acids), the presence of the recently introduced planktonic predator *Neomysis integer* and insufficient removal of fish (Meijer *et al.* 1999; Table 4).

Discussion

Many difficulties arise when interpreting the results obtained from lake restoration projects, and fundamentally lake restoration still involves a large proportion of trial and error, where the mechanisms for a successful restoration remain largely unclarified. Carpenter *et al.* (2001) similarly found difficulty in predicting the conditions under which food web structure will control pelagic primary producers. Restorations are often conducted primarily to improve water quality and are not designed as a scientific experiment (Mehner *et al.* 2002). This implies that multiple restoration measures are often used more or less simultaneously, rendering it impossible to disentangle fully the impact of individual measures. A slowly reduced influence of internal phosphorus loading blurs the effects obtained from the restoration. Also, many restoration projects, particularly those involving biomanipulation, are often conducted repeatedly at different time intervals (1 to more than 10 years), which makes it difficult to define and compare pre- and post-conditions. Finally, the large interannual variations in macrophyte coverage, in particular in shallow, biomanipulated lakes (Lauridsen *et al.* 2003), demand long-term studies to elucidate the effects of the restoration measures, as the presence or absence of macrophytes fundamentally influences a number of lake parameters (Jeppesen *et al.* 1997).

Generally, both the Danish and Dutch results indicate that in most lakes marked effects do occur shortly after restoration, including changes in crucial ecological variables such as chla, Secchi depth and sometimes nutrient concentrations. Thus many of the biomanipulation projects clearly induced cascading effects on lower trophic levels and improvements in lake water quality. Only submerged macrophytes seem to respond slowly to restoration, which is in accordance with many other findings (Strand 1999; Jeppesen *et al.* 2005; Hilt *et al.* 2006), although a fast response of the plants has occurred in other case studies (Hansson *et al.* 1998).

Traditionally biomanipulation by fish removal aims to increase the top-down control on phytoplankton by cascading effects of increased zooplankton grazing

(Brooks & Dodson 1965; Persson *et al*. 1988; Bergman, Hansson & Andersson 1999). It has also been suggested that the effects of reduced fish stock are mediated through a decreased recycling of nutrients or storage of nutrients in a fast-growing fish biomass (Horppila *et al*. 1998; Kairesalo *et al*. 1999; Olin *et al*. 2006). The increased *Daphnia* and cladoceran number and the decreased chla in at least some of the lakes after restoration indicate that increased top-down control may be part of the explanation. Significantly reduced suspended solid concentrations, however, also suggest that other mechanisms, such as decreased resuspension of sediment with decreased benthivores (particularly bream), may be important factors.

The results of pike stocking vary (Prejs *et al*. 1994; Meijer & Hosper 1997; Søndergaard, Jeppesen & Berg 1997) and of a comprehensive analysis of 47 Danish examples of pike stocking documents only a few provided examples of positive effects (C. Skov, unpublished data). Drenner & Hambright (1999) similarly concluded that piscivore stocking had the lowest success rate among biomanipulation techniques, although marked effects were seen after repeated stocking of zander (*Sander Lucioperca*) in the German Bautzen Reservoir (Dorner, Wagner & Benndorf 1999). The reasons for the low effects of pike stocking might be that small pike (2–4 cm) in the weeks after stocking feed more on other food items than fish prey and that pike in most cases will not be able to consume the amounts of 0+ cyprinids required to improve water quality (Skov *et al*. 2003; C. Skov, unpublished data). Therefore, until more knowledge, particularly of 0+ cyprinid production regimes, is available, stocking of pike will not be a recommended measure in future Danish biomanipulation projects (Skov *et al*. 2006).

Physicochemical restoration techniques have been much less frequently used in Denmark and the Netherlands and general conclusions cannot be drawn. Use of alum for restoration purposes has shown noticeable short-term effects, while the long-term effects (> 2–3 years) seem less promising (Reitzel *et al*. 2003; Reitzel *et al*. 2005; K. Reitzel, unpublished data). The potential of this method remains to be elucidated in more detail under North European conditions, particularly regarding its longevity and the dose required to inactivate phosphorus (Rydin & Welch 1998; Welch & Cook 2005). Hypolimnetic oxygenation is a restoration measure that reduces the accumulation of phosphate in deep waters, but it needs to be conducted for a long period to avoid the return of anoxic conditions. Its potential has been debated because oxygenation will only lead to increased phosphorus retention if the sulphide production is lowered and more ferrous phosphate is deposited in the anoxic sediment (Gächter & Müller 2003).

The findings from our study indicate that after 5–10 years the positive effects observed in many biomanipulated lakes immediately upon restoration abate, and after 10 years most lakes have returned to a turbid state, although the long-term effects of restoration are still not well documented. Thus biomanipulation, which comprises most of the restoration cases investigated here, may often need to be applied repeatedly to ensure clear water conditions (Van de Bund & Van Donk 2002). The reasons for this lack of long-term effect remain uncertain, but new results suggest that the return of a large roach biomass is a significant factor (M. Søndergaard *et al.*, unpublished results). Insufficient reduction of external loading probably applies to several of our study lakes, but this may not always be the sole explanation. In the case of Danish Lake Væng, external loading was diverted after which clear-water conditions with extensive growth of macrophytes appeared. However, after some years the lake returned to a turbid state and internal phosphorus release from the sediment raised the summer concentrations again. This case study illustrates how biomanipulation can induce profound changes at all trophic levels, including nutrient concentrations. A limited effect for about 10 years, however, raises the question whether biomanipulation should be conducted repeatedly or periodically to achieve stable clear-water conditions in the long term.

A probable criterion for successful restoration is that a shift occurs to a state characterized by a permanent positive nutrient retention capacity of the sediment (Carpenter, Ludwig & Brock 1999; Søndergaard, Jeppesen & Jensen 2003). As internal phosphorus loading will eventually abate, biomanipulation may potentially be most successfully applied when approaching equilibrium conditions. It is unknown what triggered the increased internal loading seen in Lake Væng after some years with clear water. Enhanced turbidity because of an increase in cyprinids cascading to phytoplankton could result in a diminished benthic primary production and thereby internal phosphorus release, but the turbid conditions could also reappear because of enhanced internal loading. However, it seems clear that a large pool of mobile phosphorus in the sediment increases the risk of a return of turbid conditions in successfully biomanipulated lakes.

Instability and oscillations of shallow lakes because of a cyclic pattern in the development of macrophytes may also increase the flux of phosphorus as decaying plant material accumulated over time is mineralized (Moss, Stansfield & Irvine 1990; Rip *et al*. 2005; Van Nes, Rip & Scheffer 2007). Furthermore, a delay in the recovery of submerged macrophytes may also contribute to the lack of stable positive effects. Submerged macrophytes are known to be important in stabilizing the clear-water state in shallow lakes (Scheffer *et al*. 1993; Jeppesen *et al*. 1997) and if recovery is prevented by, for instance, waterfowl grazing or unsuitable habitats (Søndergaard *et al*. 1996; Strand 1999), the lake may turn turbid. Exclosure experiments have shown that coot *Fulica atra* and mute swan *Cygnus olor* feeding and foraging have a strong negative impact on macrophytes (Lauridsen, Sandsten & Møller 2003), although the effect of waterfowl in Mediterranean lakes seems to be less important (Rodríguez-Villafañe *et al*. 2007).

In addition, the role of nitrogen in establishing clear-water conditions and high coverage of submerged macrophytes in shallow lakes might be more important than previously thought (Gonzales Sagrario *et al*. 2005; James *et al*. 2005; Jeppesen *et al*. 2007) and must be considered when discussing the need to reduce the external nutrient loading further.

A new challenge to future restoration projects is future climate changes and the extent to which increased temperature or changed precipitation patterns may influence the choices and plans for restoration. There are several indications that climatic changes will increase the risk of eutrophication and thereby counteract restoration measures and destabilize the macrophyte-dominated clear-water state in coastal north temperate lakes (Mooij *et al*. 2005; Jeppesen *et al*. 2007): higher precipitation will increase the external nutrient loading and higher temperatures might improve the conditions for zooplanktivorous fish species such as carp *Cyprius carpio* and other cyprinids, and in combination this may diminish the possibility of obtaining top-down control of phytoplankton.

In summary, two key findings emerge from this study. First, marked improvements in lake water quality can be achieved using different restoration techniques, here mainly by fish removal. Secondly, long-term effects (> 10 years) of lake restoration seem unlikely, at least with the present conditions in Denmark and the Netherlands. The reasons for the relatively short-term effects remain uncertain, but the need to reduce the external loading further as well as the internal loading capacity and the often delayed appearance of submerged macrophytes are probably important factors. It should be noted, however, that conclusions based on the Danish and Dutch experience may be skewed because of the very nutrient-rich conditions of the lakes and other conclusions might emerge when analysing less eutrophic lakes.

Lake restoration can be recommended to improve water quality of eutrophic, shallow lakes considerably. Long-term effects (more than 5–10 years) can, however, be difficult to achieve, and in many cases lake restoration may need to be conducted on a regular basis to maintain positive effects. Therefore lake restoration in relatively nutrient-rich lakes, such as those included in this study, should probably be perceived as a management tool rather than a 'once and for all' solution. Establishment of mechanisms stabilizing the clear-water state, which in shallow lakes could be a high and stable coverage of submerged macrophytes, may provide long-term and permanent effects of restoration. Fish removal in shallow lakes can establish clear water and have marked effects on the whole system, including nutrients and suspended solids. Pike stocking to improve lake water quality has yielded disappointing results and does not seem to be a way forward.

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