EUTROPHICATION:

RESEARCH AND APPLICATION TO WATER SUPPLY

Edited by

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Published by the Freshwater Biological Association

Invited papers from a specialised conference held in London

on 10-11 December 1991 by the

Freshwater Biological Association,

The Ferry House, Far Sawrey, Ambleside, Cumbria LA22 0LP

and

International Water Supply Association,

1 Queen Anne's Gate, London SW1H 9BT

ISBN 0-900386-52-5

The scope for biomanipulation for improving water quality

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Biomanipulation is a form of biological engineering in which organisms are selectively removed or encouraged to alleviate the symptoms of eutrophication. Most examples involve fish and grazer zooplankton though mussels have also been used. The technique involves continuous management in many deeper lakes and is not a substitute for nutrient control. In some lakes, alterations to the lake environment have given longer-term positive effects. And in some shallow lakes, biomanipulation may be essential, alongside nutrient control, in re-establishing former aquatic-plant-dominated ecosystems which have been lost through severe eutrophication.

The emergence of biomanipulation techniques emphasises that lake systems are not simply chemical reactors which respond simply to engineered chemical changes, but very complex and still very imperfectly understood ecosystems which require a yet profounder understanding before they can be restored with certainty.

Introduction

In the summer of 1990, my postgraduate student, Laurence Carvalho and I were puzzled by events in a small and shallow lake, Little Mere in Cheshire. The water was extremely clear and there was a large development of aquatic plants, yet the algal growth potential of the water was huge. Effluent from a small sewage treatment works entered the lake, which had concentrations of available inorganic phosphate-phosphorus and ammonium-nitrogen each of the order of several milligrams per litre. The only algae of any consequence in the water were a few large colonies of *Volvox*. The resolution of this paradox came when we noticed large populations of a large-bodied grazer, *Daphnia magna*, in the zooplankton. The animals were unusually bright red with haemoglobin and the water, even in the middle of the day, had very low oxygen saturation values and concentrations less than $1 mgl^{-1}$. Subsequently we established that there were almost no fish in the lake despite normal coarse fish communities in Mere Mere, a larger lake which lies immediately upstream of Little Mere, and the stocking of Little Mere with fish by residents whose houses border the lake. The quality of the sewage effluent was such as to deoxygenate the water sufficiently to kill fish and hence remove major predation pressure on the *Daphnia*. Grazing was then sufficient to prevent the development of the large algal crops the water was otherwise capable of supporting. It was a further challenge to the idea that algal crop size is determined largely by "bottom–up" (in the foodchain) mechanisms and predictable simply from nutrient supply. This is undoubtedly true where prediction of the potential crop is concerned (Cranfield & Bachmann 1981; Dillon & Rigler 1974) but subject to modification by other biological processes when it is the actual crop that is of interest (Shapiro *et al.* 1975).

The concept of biomanipulation

There is now a variety of examples demonstrating the importance of grazing by the larger-bodied species of water-fleas (Cladocera) in determining algal crop sizes in fresh waters (e.g.

Pace 1984) and by mussels and other bivalve molluscs in saline lagoons (Officer *et al.* 1982). This has led to the concept of biomanipulation (Shapiro *et al.* 1975; Shapiro 1990; Gophen 1990) which is definable as the manipulation of the food webs of aquatic ecosystems in such a way as to increase the numbers of grazers on algae. At present this largely concerns the phytoplankton but conceivably could include the periphyton which covers aquatic plants and other surfaces also. Biomanipulation might be used in concert with nutrient control as an additional measure or possibly as a sole technique in the improvement of water quality from the point of view of its algal content. Techniques used so far have involved the complete removal of fish and maintenance of near zero fish stocks (van Donk *et al.* 1989); removal and then restocking with a fish community which gives greater precedence to the zooplanktivorous fishes' own predators (Shapiro & Wright 1984); direct stocking of grazers (examples include only molluscs) (Reeders & Bij de Vaate 1990); and major inadvertent restructuring of the ecosystem through changes at the tops of the food webs. The latter favour grazing without the need for continuous management by readjustment of fish communities, which inevitably otherwise drift back towards some sort of natural equilibrium which may be greatly different from that desired by the lake manager to minimise algal growth. A particularly good example is that of Lake Washington, which is described below.

Five key questions

The key questions for water supply management are as follows: (i), Does biomanipulation really reduce algal crops significantly in the sorts of lakes and reservoirs used for water supply? (ii), Can biomanipulation be used as a technique on its own or only as an adjunct to nutrient control? (iii), Of the available approaches, which are likely to be most valuable and what are their limitations in terms of practicality? (iv), Are there circumstances where biomanipulation may be essential in reducing algal crops? (v), Notwithstanding the possibilities of its use in water-supply management, are there other roles for biomanipulation?

Question (i): Does biomanipulation work?

The case of Lake Washington in the USA, itself the classic instance of algal reduction by nutrient control, is also an excellent example of the positive benefits of biomanipulation in a very large and deep lake, and an answer to question (i). Lake Washington (Edmondson 1991) became eutrophic by the 1950s as a result of sewage effluent discharge. It had substantial growths of *Oscillatoria rubescens*, one of the blue-green algae, and its transparency was much reduced from that in previous decades. A programme of diversion of sewage effluent to the nearby sea was begun and during the 1960s the clarity of the lake steadily improved until, with complete diversion, it was believed that the algal crops could be reduced no further. However, the clarity of the water continued to increase and this was correlated with an increase in the populations of several *Daphnia* species in the zooplankton (Edmondson & Litt 1982). No measures to reduce fish stocks had been taken and fish were plentiful in the lake. Numbers of an invertebrate predator on the *Daphnia*, a mysid shrimp (*Neomysis mercedis*) had, however, concurrently declined (Murtaugh 1981). Why this should have happened is less clear but investigations showed that the main predator on the mysid was a fish, the long-fin smelt (*Sprinichus thaleichthys*); this had built up its population following inadvertent improvement to its spawning habitat by engineering works in one of the main inflow rivers to the lake.

A change three steps remote from the algae had thus resulted in reduction of their numbers very significantly. This was in a lake that had been much improved previously by nutrient control. Are such dramatic effects possible in lakes without such control?

Question (ii): can biomanipulation be used as a substitute for nutrient control?

An example is that of Brundall Broad in Norfolk (Leah, Moss & Forrest 1978) which, though much shallower than most British reservoirs, is not dissimilar from those used in the Netherlands. Brundall Broad was divided into two by dams and one part of it was isolated from inflow from the nutrient-rich River Yare, which carries effluent from the Norwich sewage treatment works immediately upstream. The other part of the lake was left open to the river. In the first year of investigation both parts developed large diatom crops in the phytoplankton and it was found that leaks had developed in the dams which, on the high tide, allowed river water to enter the supposedly isolated section. It was not possible to repair the leaks so we were surprised when, in the subsequent year, the water in the "isolated" part cleared and lost most of its algae, whilst the control section, open to the river, remained turbid with algae. A large population of *Daphnia longispina* had developed in the "isolated" part and fish were nearly absent. There were large stocks of zooplanktivorous fish in the control section. But why had the "isolated" part lost its fish? A fish-eating cormorant (*Phalacrocorax carbo*) with a damaged wing had been permanently confined to the "isolated" broad during the previous winter and had attracted other cormorants. They fished out the "isolated" broad and fish had been unable to move in from the river to replace the stock. It was a good example of inadvertent biomanipulation and improvement of water quality in a shallow lake in the absence of any nutrient control.

Of course, in a subsequent year when the resident bird died the system would naturally revert to its former state, as indeed it did, but the example does show that biomanipulation can be effective without nutrient control (question ii). Two factors probably were crucial to its success in this instance. First, there was a high replacement rate of the water in the broad because of the twice-daily tidal-flushing, and secondly this maintained a diatom-dominated flora in the phytoplankton. In the particular riverine lake system of the Norfolk Broadland there is a strong relationship between diatom populations and conversely high flushing, and blue-green algal populations and reduced flushing, given high nutrient concentrations (Moss & Balls 1989). Diatoms are eminently edible by daphnids, blue-green algae are not. Experiments in netting enclosures in Broadland lakes have demonstrated that *Daphnia* populations cannot be sustained when filamentous blue-green algae come to dominate the phytoplankton, but do not preclude the daphnids if the algal community is otherwise dominated by diatoms (Moss *et al.* 1991; Irvine *et al.* 1992).

Question (iii): what are the most useful approaches to biomanipulation and what are their limitations?

Of the available approaches to deliberate biomanipulations, some are more usable than others. It is not feasible to grow a culture of suitable *Daphnia* and release it into a lake. The animals will very rapidly be eaten by any normal fish stock, and the levels of concentrations needed to give immediate high grazing impact in the lake (some tens to hundreds of animals per litre) are not much below those in which the animals could be cultured and viably transported. For even a small reservoir of (say) 250 000m^3, enormous numbers of tankerloads of culture would be needed. *Daphnia* is not the new copper sulphate!

Mussels have been deliberately stocked and the zebra mussel (*Dreissena polymorpha*) has been studied in freshwater lakes in the Netherlands (Reeders *et al.* 1989). Large numbers are needed and they must have a hard substratum or be placed in racks which are costly on a large scale and clutter the water-body. Marine mussels (*Mytilus edulis*) have the happy habit of colonising suspended vertical ropes and even natural settlements on the dock walls have successfully cleared enclosed docks in the Mersey Estuary (Allen & Hawkins in press). Unfortunately they die in fresh water.

Daphnia is a ubiquitous genus in temperate fresh waters and if fish predation is decreased, the *Daphnia* populations rapidly increase to effective sizes through their own very fecund parthenogenic reproduction. Doubling times are only a few days at summer temperatures. Ways of decreasing fish predation include total removal, partial removal or stocking of fish predators and, potentially, modification of the fishes' behaviour.

Of course not all fish species eat zooplankters. But of the British fish fauna a great many species at some time in their growth and development do depend on the zooplankton. Predominant among these are the cyprinid fish like roach (*Rutilus rutilus*) and bream (*Abramis brama*), and percids such as *Perca fluviatilis*, which are associated with fertile lowland waters where algae are likely to pose problems for water suppliers. Their young feed on the smallest zooplankters, the rotifers, soon after hatching but rapidly move to the cladocerans and other Crustacea when they are a few centimetres long. After their first year, or second year if growth is slow and they remain small, the fish need to take larger food particles, generally derived from the invertebrates of the bottom or plant beds, or, in some species, other fish. However, because almost all British fish have a reproductive strategy which involves production of large numbers of young, each with a low probability of survival in the long term, a huge number of small zooplanktivorous fish is present in the water from late spring and throughout the summer. Where growth is slow this cohort may be joined by successive ones to give continuous heavy impact on the zooplankton. It is not easy to remove these fish efficiently and selectively by known fishing techniques. Small fish are difficult to net out and respond least well to electrofishing. The complete fish stock can be removed from a small lake but only by very intensive fishing over a long period using staff with an intimate knowledge of the water-body and the habits and movements of the fish within it. This is very expensive in labour. It is very doubtful if all the fish can be taken from a large water-body using manual methods. It might be possible to remove many but if only a few adults are left these will ensure a heavy recruitment the following year, when the reduced stock will present reduced competition for, and greater early survival of, the young-of-the-year. A compromise is the use of nets to remove as many fish as possible and then to use a fish poison like rotenone to kill the remainder. Although this is an acceptable technique in some countries it is unlikely to be welcomed in Great Britain on a large scale.

Even the most intensive fish-removal operation is not complete. Some fish will always escape and will very quickly build up the population again. Fishing has to be repeated at least annually to maintain the stocks low enough to have a major impact on cladoceran survival. Where it can be done the effects are dramatic, as at Cockshoot Broad in Norfolk, where this technique has been used to create clear water for aquatic plant recolonisation (B. Moss, unpublished data).

The difficulties posed by fishing-out large bodies of water have been avoided in some lakes by the addition of fish predators (Benndorf *et al.* 1984, 1988; Scavia *et al.* 1986) or alteration of the ratio of existing predators and their prey. The latter requires continuous management as the fish community will drift back to whatever ratio represents a natural equilibrium, and the former poses problems of what fish to use and what undesirable side effects might be created. The literature is replete with the disasters caused by the introductions of exotic species, some of them fish (Zaret & Paine 1973; Barel *et al.* 1985).

In the USA, the fish fauna is rich enough to allow a degree of experimentation using native species, for example the large-mouthed bass (*Micropterus salmoides*), walleye (*Stizostedion vitreum*), and the several Pacific salmon species. However, it may be just as undesirable to transfer a species from one side of a continent to another as from continent to continent. Good results were obtained by Shapiro & Wright (1984) by adjusting the predator–prey ratio in a

Minnesotan lake. Stocking with predators seems also to have had impacts on the alewife (*Alosa pseudoharengus*, a zooplanktivorous fish even when adult) population of some of the St Lawrence Great Lakes, with consequent increases in zooplankton and reductions in algae (Scavia *et al.* 1986).

In Britain there are problems, however. The British fish fauna is singularly lacking in predators that thrive in eutrophic conditions and those that do, like pike (*Esox lucius*), do not hunt among the open-water shoals of young coarse fish. Pike are marginal-lurking predators, and stocking with additional pike is likely to lead only to pike mortality. Brown trout (*Salmo trutta*) are unlikely to survive under the sorts of conditions that are created by large algal growths and there might be dangers in extending the range of the exotic rainbow trout (*Salmo gairdneri = Oncorhynchus mykis*) any further. It is already regarded as an undesirable species among native communities. The perchpike or zander (*Stizostedion luciopercum*) is not now a native British fish though it may have been, prior to the glaciation, and has already been introduced to one part of eastern England. It is an open-water feeder on small fish and might merit further attention. It is unlikely, however, that a more extensive introduction of it would be countenanced by English Nature and other informed conservation opinion. The options for predator introduction are thus not great, and for natural lakes used for drinking-water supply there would be considerable opposition to complete fish removal or even selective removal, for almost all are of conservation importance.

For artificial drinking-water reservoirs, however, which are already severely managed water-bodies, biomanipulation could offer a reasonably cheap way of reducing algal growths. Fish removal would have to be near complete and continually attended to and the reservoir conditions would probably need to favour development of algae other than blue-green algae. There is much controversy about whether or not *Daphnia* can eat particular species of blue-green algae (de Bernardi & Giussani 1990; Gliwicz 1990). In general these algae seem to be poor food unable to sustain *Daphnia* (Arnold 1971) or not ingestible (Gliwicz 1980) or perhaps chemically inhibitory (Infante & Abella 1985). The genus *Oscillatoria* seems to be particularly unavailable (Moss *et al.* 1991) though even this is disputed (Dawidowicz 1990). Smaller blue-green algae may be eaten or at least they are not inhibitory if alternative edible algae are available. It is possible also that in a reservoir which develops blue-green algae under present conditions the development of *Daphnia* early in the season, under biomanipulated conditions, could influence the seasonal periodicity of the algae in favour of other groups.

The reason why fish removal needs to be near complete is that at present no absolute stocking density can be given which corresponds with a particular desired reduction in phytoplankton crop (Benndorf 1990). Doubtless, with the continued accumulation of data, equations will be developed for guidance. However, coarse fish recruitment is often so vigorous that the population will rapidly be replaced even if only a very small stock is left. Any improvement in the year following a partial removal will thus probably be confined to that year or not be seen at all (van Donk *et al.* 1990).

A yet underdeveloped aspect of biomanipulation is that of altering the fish behaviour within a lake without removing the fish. Thus if zooplanktivorous fish can be confined to the edges of the lake, and kept out of the middle, predation on the zooplankton might be greatly reduced. Alarmed fish produce substances that scare away others. A synthetic source of such a substance held in the middle of a lake might be effective (M. Gliwicz, *pers. comm.*) but how effective it might be in ultimately reducing algal crops is not known.

Problems are always best solved by attending to their causes rather than by alleviating their symptoms, and the proper solution to that of large algal growths is nutrient control. Biomanipulation is a symptom treatment in most cases which might be used when the possibilities for reduction of nutrient loading from the catchment have been exhausted. It involves continuous management and this is not an alien concept in the management of artificial reservoirs. Where natural lakes are being used for water supply it is just as undesirable as the managed water levels which leave an unsightly and sterile zone at the lake edge. There are however instances where biomanipulation is not only useful but essential in restoring water quality (question iv) and environmental quality (question v) to a lake. These cases are of shallow lakes, formerly dominated by the aquatic plants of their extensive littoral zones, but in which eutrophication has led to replacement of the plants by dense phytoplankton crops. Such lakes may be used for water supply and are often of considerable fisheries, conservation and amenity importance (de Nie 1988).

Question (iv) & (v):– where biomanipulation may be essential for restoration of water quality or environmental quality

The process by which aquatic plants are lost during eutrophication is a complex one involving much more than the simple shading-out by the algae that is usually invoked as a mechanism. The change does not take place linearly as nutrient loadings increase. In the early stages there is a replacement of short-growing plant species by taller ranker-growing ones (Moss 1988, 1989) but these latter are then able to withstand considerable further increases in nutrient loading without being replaced by phytoplankton (Balls *et al.* 1989). The plant-dominated system appears to be buffered against such change by a number of mechanisms (Irvine *et al.* 1989; Moss 1990). These include the secretion of substances which inhibit algal growth, and the luxury uptake of nutrients. The most effective mechanism, however, is the harbouring of large communities of grazer Cladocera within the plant beds. These animals drift out at night and graze in the adjacent open water. In daylight they are taken by fish but their numbers can easily be replaced from the reserves held in the plant beds. With such a system of refuges, a stable coexistence of zooplankton, fish and plants can be maintained with clear water and very low phytoplankton crops (Timms & Moss 1984).

Plants probably disappear from such systems when something happens to disturb these buffer mechanisms. This might be the removal of the plants themselves by manual clearing, drawdown of the water level, herbicides, or grazing by an introduced herbivore like pinioned geese, muskrat or coypu (Moss 1991). Alternatively it might be destruction of the cladoceran grazer community by pesticide run-off (Stansfield *et al.* 1989). The disturbance need only be short-term, for at increased nutrient loadings it allows the system to switch to phytoplankton dominance, when a new set of buffer mechanisms comes into play which prevents a switch back to the former state. Thus the phytoplankters begin their growth earlier and can shade-out the young plant propagules at the bottom of the water column early in the summer; the open-water environment lacks refuges for the cladocerans, and fish can rapidly remove the larger species and individuals that are the most effective potential grazers. There thus exist two alternative states over a band of nutrient loadings, and nutrient control alone is unlikely to shift the system from one state to another (Irvine *et al.* 1989; Scheffer 1990). Biomanipulation, on the other hand, may be necessary to do so.

In the Norfolk Broadland (Moss 1983), many lakes have lost their plants and, together with them, their roles as habitat for invertebrates like dragonflies, as food for birds, and as stabilizers of sediment and protectors against bank erosion by tides, waves and boats, as well as their intrinsic and conservation importance. It is thus highly desirable to restore the plant communities. Nutrient control, by phosphorus-stripping at the sewage treatment works, has proved ineffective alone. It has led to a significant reduction in the total algal crop (Phillips & Chilvers 1991) but not to a clearing of the water sufficient to allow aquatic plants to grow. This has been because of the operation of the buffers mentioned above and to the still high availability of nutrients from agriculture and release from sediments within the lake.

In one instance, Cockshoot Broad, isolation of the lake from the river did give a marked improvement at first (Moss *et al.* 1986) and plants recolonised a sheltered section of the lake known as Cockshoot Dyke. There they have formed a permanent community. In the more exposed open Broad, plants colonised more slowly and then declined again as phytoplankton crops built up from 1985 onwards (B. Moss, unpublished data). A progressive decline in the size of both the *Daphnia* population and in the body-sizes of its constituent animals suggested that the early restoration had involved both nutrient control and biomanipulation. The fish stock in the lake had not been high previously, for the lake was then very shallow. Pumping out of sediment had probably scared what fish there were back to the river and damming had prevented the return of most of them. In the early years there was thus only a small fish stock, *Daphnia* populations were very high and the water cleared. In the dyke, plants were quick to colonise and the stabilising buffer mechanisms were early re-established. Wave disturbance and bird grazing slowed the colonisation of the main Broad so that when, by 1984-85, fish stocks had built up again from the small inoculum left in the Broad and *Daphnia* populations were decimated, there was not enough plant structure available to allow establishment of the refuge mechanism and the plants succumbed to the increasing algal competition. Since 1988 the fish have been removed each winter, the water has cleared again and the plants are slowly returning. Biomanipulation has thus proved essential in this system.

Despite the success of biomanipulation in Cockshoot Broad and the eventual intention to allow the fish community to re-establish once a sufficiency of plant refugia have re-established, there is still local opposition to even temporary fish removal, largely from anglers. Though this arises from misconception and ignorance and can be dealt with, there are still problems in the use of temporary total fish removal in the Broadland system. The riverine and tidal nature of the area mean that it is not possible to isolate areas once the fish have been removed. This is because there are rights of navigation on tidal waters which prevent connections with the river from being blocked. Our solution to this has been to experiment with artificial refuges designed to build up the *Daphnia* population in the presence of fish so that the water may clear and thus the natural plant refuges return.

None of a series of refuges based on polypropylene rope, suspended fruit-cage netting, or bundles of alder twigs, proved satisfactory for either cost or operational reasons or both (Irvine *et al.* 1990). Our current design (Moss 1990) involves isolation of a 1-ha area by a fence permeable to water and algae but not to fish or their larvae. Fish have been removed from within the fenced area in which it is expected that plants will be able to establish in the clear water. Once a vigorous plant bed has been formed, the refuge enclosure will be progressively extended until a substantial part of the lake is occupied by protected plant beds. We will then remove all the fences at a stage when the natural buffer mechanisms should be able to stabilise the system without further intervention. The water of the lake in question has had its phosphorus content reduced by precipitation at the upstream sewage treatment works and has a diatom-dominated phytoplankton. The refuge enclosures are permeable to water through mesh screens, to maintain a flushing regime which will continue to support edible diatoms and not the blue-green algae which the water chemistry would support in a less well flushed situation. Broads in the downstream part of Broadland which have low flushing rates and extensive crops of filamentous blue-green algae, particularly *Oscillatoria* spp. (Moss & Balls 1989), seem less likely to be restorable by these techniques without prior very severe nutrient control.

Conclusions

Biomanipulation is thus not a palliative to solve eutrophication problems at minimal expense. It is not recommended in large natural lakes but is a potentially useful tool in artificial reservoirs where there is already a high degree of intervention and where water retention times are low. It is most likely to succeed in the UK through total removal of fish and is thus not compatible with amenity fisheries on reservoirs. In these cases it could replace nutrient control or permit controls of low rigour so long as the nutrient and flushing regimes do not favour blue-green algae.

Biomanipulation is likely to be essential for the improvement of water quality in shallow lakes used for water supply where the nature of the usually very fertile catchment limits the degree to which nutrients can be controlled or where internal loading of phosphorus from the sediments cannot be stopped. It is similarly essential for the restoration of the conservation and amenity values of such shallow lakes where once extensive plant communities have been lost.

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