EC LIFE Project - Restoration of the Norfolk Broads:
(LIFE 92-3/UK/031 & NRA Project 475)

The Development of Biomanipulation Techniques
& Control of Phosphorus Release from Sediments.

National Rivers Authority and The Broads Authority
Progress Report Overview April 1994

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Dissemination Status

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Statement of Use

This project was commissioned to develop novel techniques to assist in the restoration of shallow lakes. The report provides an overview of progress made since April 1993 on several critical aspects including control of phosphorus release from sediments, biomanipulation and the growth of macrophytes.

Research Partners

This document was produced by the National Rivers Authority Broads Research Team, the Broads Authority and ECON (University of East Anglia).

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EC LIFE PROJECT - RESTORATION OF THE NORFOLK BROADS

The Development of Biomanipulation Techniques & Control of Phosphorus Release from Sediments.

An Overview

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OVERVIEW

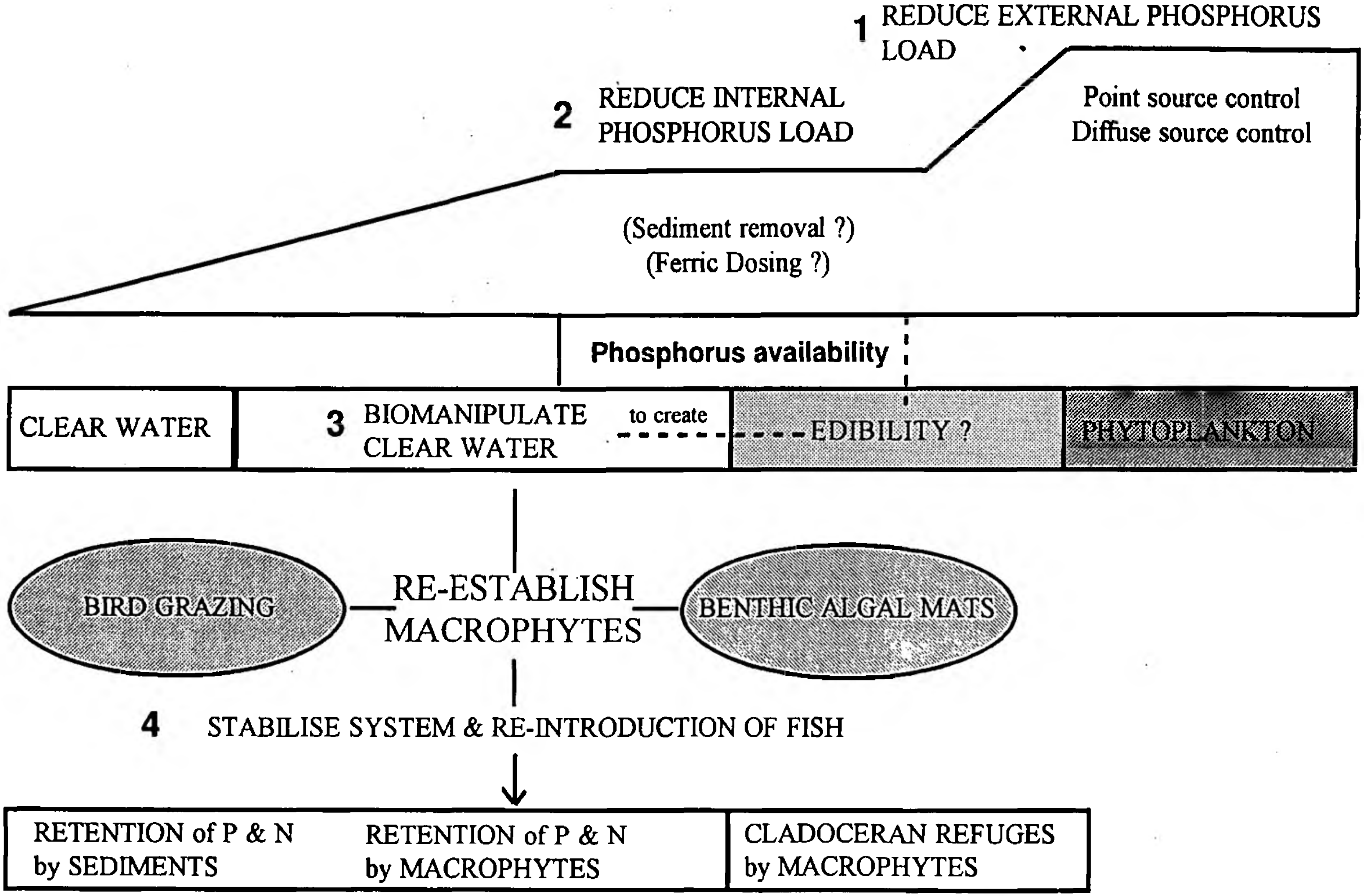
1.1 Background

The Broads Authority (BA) and the National Rivers Authority (NRA), together with their predecessor Anglian Water Authority (AWA) have been carrying out a programme of research with the aim of restoring the shallow eutrophic lakes that form the Broads. The overall aim is to control phytoplankton growth, creating clear water conditions that will allow submerged aquatic vegetation to grow in the lakes, providing habitat for a diverse bird, fish and invertebrate fauna. Initially work concentrated on reducing the input of phosphorus from sewage treatment and industrial discharges, but it has now become clear that restoration requires additional steps to be successful.

The restoration strategy is set out in Figure 1.1 in the form of a number of steps. The first of these is the reduction of phosphorus inputs to the lake by the control of phosphorus discharges in the catchment. The second is the control of phosphorus released from the lake sediment to the overlying water. These two steps should result in a reduced lake phosphorus concentration and lower phytoplankton populations. However, background diffuse phosphorus inputs from the catchment, together with the inherent resilience of the lake's ecosystem to change appear to prevent the creation of clear water and plant growth. The third step is designed to overcome this problem through the "biomanipulation" of the planktonic community by the temporary removal of fish. This allows large grazing zooplankton populations to develop and create clear water conditions. The extent to which lake phosphorus concentration needs to be reduced before biomanipulation can result in a stable restructuring of the lake community is not known. However, available evidence suggests that the greater the reduction of lake phosphorus the more likely the change. Once clear water and plant growth have been established this community needs to be stabilised and an appropriate fish community returned to the lake This stabilisation and re-stocking forms the final stage of the restoration strategy.

There are several uncertainties relating to the implementation of this strategy and to create clear working guidelines this project is investigating the details and relationships between each of these steps. The first step (control of external phosphorus sources) is being carried out by the NRA as part of an ongoing investigation (Operational Investigation 540), but the remainder of the issues are being tackled within this project.

Figure 1.1 Diagram showing the steps in the restoration strategy for the Broads and the problems associated with re-establishing aquatic macrophytes in a stable lake community



Three main areas of investigation have been identified:

- The importance and control of phosphorus released from the lake sediment.
- The use of "biomanipulation" to overcome internal stabilising mechanisms that appear to be of critical importance in shallow lakes.
- The subsequent growth of submerged aquatic vegetation in the lakes and the potential stability that this provides to the lake ecosystem and hence its response to nutrient loading.

1.1.1 Approach

It is clear that while lake management needs to be founded on an understanding of lake ecology, derived from carefully designed and replicated experiments, ecosystem effects cannot be adequately reproduced in small scale experiments. This is due to size and time scale constraints. This project was designed to overcome this by taking existing knowledge and applying it on a practical management scale through the use of whole lake manipulations. However, unlike a purely practical conservation management exercise this project includes a wide range of experimental observations and monitoring designed to assess progress and increase understanding of the system. Although the management is aimed particularly at the restoration of the Broads, the information gained will have a wider use in other shallow lakes; one of the final project outputs will be a simple working guide to lake restoration.

Similar work has been conducted on a number of lakes in Europe, particularly in the Netherlands and in Denmark, and links have been established with researchers from both RIZA (Netherlands) and Danish National Environmental Research Institute. It is hoped that both these organisations will contribute to the ideas developed within the project and to the final working guide.

The project is primarily funded by the Broads Authority and National Rivers Authority with a 50% contribution from the EC LIFE Fund. Additional contributions come from the Soap and Detergent Industry Association and in 1993 from English Nature.

1.1.2 Project Structure and management

The overall project has a number of specific objectives (identified below) and has several integrated lines of investigation. The practical management is largely carried out by conservation staff at the Broads Authority while most of the monitoring and experimental work is undertaken by staff at the NRA. Additional work, particularly in relation to bird grazing and fish ecology, has been carried out by ECON at the University of East Anglia. Lastly a research assistant from RIZA has started a specific investigation on aquatic vegetation in both the Broads and the Netherlands. During 1993 the opportunity to incorporate student projects into the work enabled some additional short investigations on the role of macrophytic vegetation to be undertaken.

The large number of individuals and organisations involved requires careful management. The direction of the project is steered by a group consisting of the NRA and BA project managers (G Phillips, J Madgwick), E Lammens from RIZA and J Wortley, Fisheries Recreation and Conservation Manager for the NRA Eastern Area. Both project managers additionally report to their respective organisations. The Broads Authority via Broads Research Advisory Panel to the Environment Committee and the NRA via the R & D Commissioners representing water quality, conservation, recreation and fisheries.

1.1.3 Function of this report

This report details work carried out between April 1993 and September 1993. It is made up of two components:

- An overview, which seeks to provide a summary of the work, its context and future direction.
- A detailed report setting out progress in a number of topic areas, grouped according to specific research. This part of the report is detailed and in many cases poses unresolved issues. Its function is to provide a record of work undertaken and to keep the large number of project team members and other collaborating scientists informed of data, views and ideas. At this stage in the project it provides a medium for discussion and as a consequence only minimal conclusions are drawn.

It is proposed that the Overview has a limited distribution within the Public Domain, but that until the end of the project the detailed report will be restricted to collaborating and funding organisations. An additional data appendix will be produced and made available to project team members. (Data regarding monitoring of the Aquatic Environment is of course available from the NRA through the Water Resources Act 1991 public register)

1.2 Biomanipulation - an essential element of shallow lake restoration

1.2.1 Why is it important?

It has become clear that internal stabilising mechanisms operating primarily through the planktonic system delay the recovery of lakes following the reduction of external nutrient supply. This issue has recently been reviewed by Phillips & Moss (1994) and is particularly pronounced in shallow lakes. Essentially the lack of habitat structure in the open water of a productive phytoplankton dominated lake provides ideal conditions for the production of large numbers of small planktivorous fish. Feeding by these fish prevents the development of significant populations of large bodied grazing zooplankton (e.g. *Daphnia* spp.) which can graze phytoplankton, effectively reinforcing the turbid phytoplankton dominated state. This contrasts with the unenriched shallow lake, where the clear water enables submerged aquatic vegetation to develop, providing habitat diversity and leading to a more diverse fish population with a smaller proportion of planktivorous individuals. The reduced fish predation and habitat diversity enables large populations of grazing zooplankton to develop which helps maintain the clear water conditions. In addition the vegetation acts as a temporary nutrient sink, further restricting growth of phytoplankton during the summer period.

Although phosphorus availability is a critical factor in determining which of these two conditions exist there is growing evidence that, for a relatively wide range of phosphorus concentrations, either plant or phytoplankton dominated states can exist (Scheffer *et al* 1993). As a result of these interactions the reduction in phosphorus supply during restoration does not result in rapid or stable changes to the lake ecosystem. However, the temporary removal of planktivorous fish can overcome the ecosystem's resilience and create clear water conditions allowing vegetation to colonise. In the Broads temporary fish removal has been undertaken at several sites where nutrient supply has been reduced (Table 1.1). The effect on the relationship between phytoplankton (chlorophyll *a*) and phosphorus (total phosphorus) is shown in Figure 1.2.

Contrasting Upton Broad, a plant dominated and relatively pristine broad, with Barton Broad, a site where phosphorus control at point discharges has been undertaken since 1980 (but not biomanipulated), demonstrates that while the slope of the relationship is similar the relative amounts of phytoplankton produced for any given phosphorus concentration are quite distinct. The biomanipulated sites Cockshoot, Hoveton Great Broad fish exclosure and Pound End fall between the two lines, depending on the relative success of the fish removal techniques applied. Alderfen Broad, a lake where anoxia has created naturally low fish populations, falls to the far extreme apparently demonstrating that grazing can overcome very high phosphorus concentrations. Jeppesen *et al* (1990) has noted similar situations in Denmark, but points out that these lakes are very unstable and long term records for Alderfen (Moss 1990; Perrow *et al* 1994) confirm this.

1.2.2 Progress at biomanipulated sites (1993)

Biomanipulated broads are listed in Table 1.1. Routine sampling of zooplankton, phytoplankton and a variety of chemical determinands including chlorophyll a and total phosphorus were collected from all sites every two weeks (March - October) and monthly in the winter.

Fish removal was continued at both Cockshoot Broad and Pound End and as a result clear water conditions were maintained at both sites (Chlorophyll 10.3, 12.0 $\mu g\ l^{-1}$ respectively April - September mean). The problem of predation of *Daphnia* spp. in Cockshoot by the brackish shrimp *Neomysis* sp. that occurred following a saline intrusion in 1992 (Stansfield *et al* 1993) did not reoccur in Cockshoot during 1993 despite the presence of *Neomysis* sp.. This may be due to slightly higher Perch (*Perca fluviatilis*) predation in Cockshoot during 1993 or the lower chloride concentrations (438 $mg\ l^{-1}$ April - September mean).

Unfortunately at Hoveton Great Broad underyearling fish could not be removed during the critical early summer period and the water within the exclosure remained turbid with only slightly lower chlorophyll levels than the open water of the lake (exclosure chlorophyll 61.4, open water 93.6 $\mu g\ l^{-1}$ April - September mean).

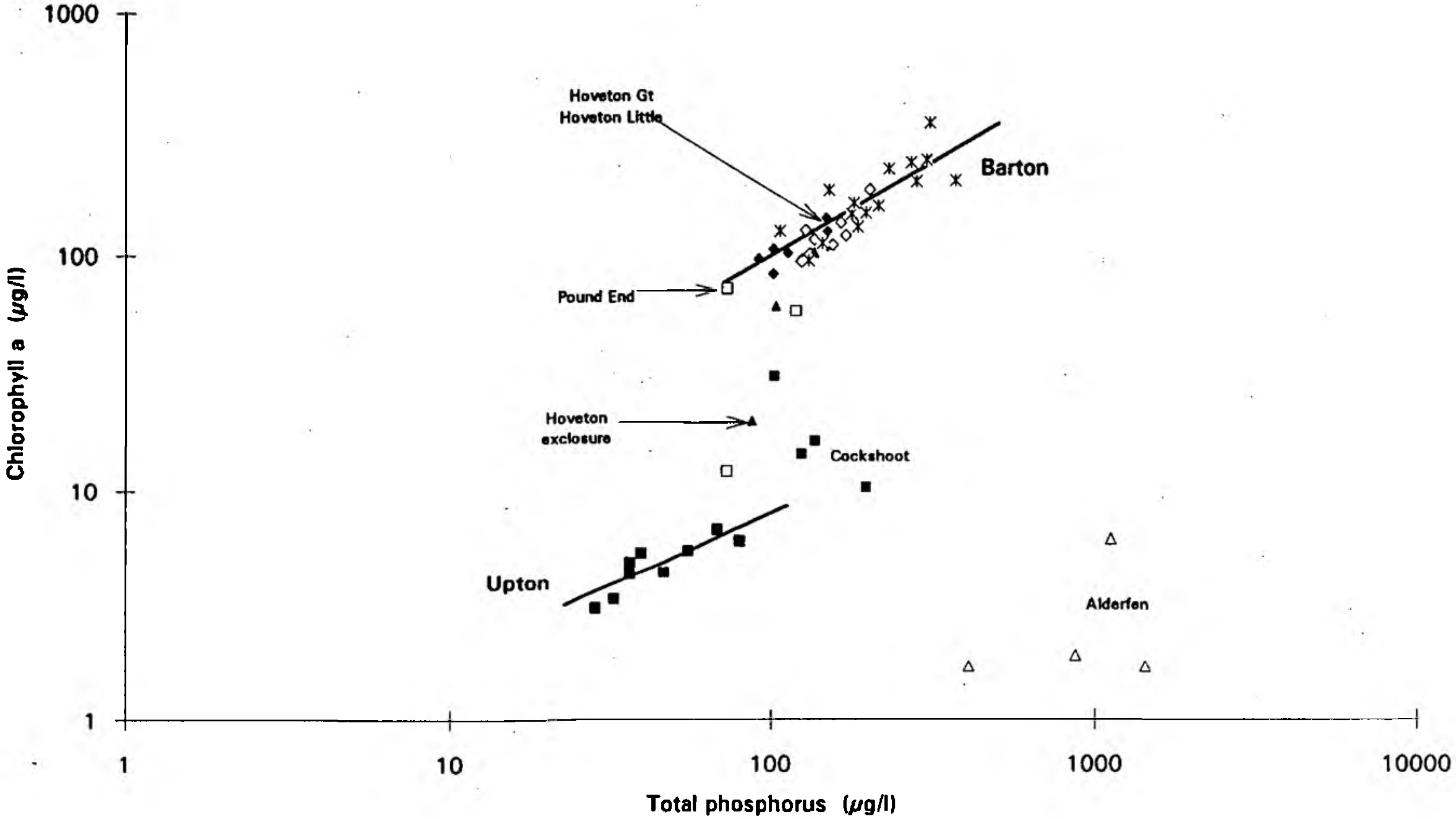


Figure 1.2 The relationship between chlorophyll a and total phosphorus

The mud pumping at Alderfen Broad was completed in 1993 together with the construction of the experimental barriers. Despite this water turbidity did not increase and phytoplankton populations remained very low at Alderfen Broad (chlorophyll 6.2 $\mu g\ l^{-1}$ April - September mean) due to the continued existence of large bodied *Daphnia* spp.

Table 1.1 Details of biomanipulated experimental broads

Cockshoot Broad	Isolated from river & suction dredged 1982. Saline intrusion 1992 allowed *Neomysis* sp. to develop	Regular fish removal since 1989 continued through 1993.
Pound End	Suction dredged & isolated by water permeable fish barrier 1991/92. Barrier breached, repaired 1992	Fish removed since 1991, continued during 1993
Hoveton Gt Broad Fish exclosure	Water permeable fish barrier constructed early 1990. Breached in 1991. Reinstated 1992.	Fish removed early 1992, partial removal during 1993.
Alderfen	Broad isolated from inflow 1979. Suction dredged 1993 and fish barrier installed.	Fish mortalities 1989-1992 Variable, then low fish numbers since 1990. Fish removal during 1993 followed by low density stocking with Tench (*Tinca tinca*) late 1993.

1.3 Development of submerged vegetation

The primary objective of the restoration strategy for the Broads is to enable a diverse submerged aquatic flora to re-develop. Apart from the intrinsic value provided by species restricted to the Broads (e.g. *Najas marina*) this vegetation provides habitat for a variety of invertebrates and food for both invertebrates and birds. This increased diversity not only contributes to the conservation value of these lakes but is vital for their stability.

It is clear from the observations of the experimental broads that a "fish free" lake is unstable, expensive to maintain and in the long run undesirable. While biomanipulation can clearly provide the clear water conditions thought to be necessary to enable submerged vegetation to grow it is important that this develops as rapidly as possible. Cockshoot Broad was the first broad to be biomanipulated. Aquatic vegetation had already developed in the narrow neck of the broad which originally connected the lake to the river and with improved water clarity plants began to colonise the lake (Stansfield *et al* 1993) and in 1993 a substantial growth was observed in the broad. Although still well below the standing crop expected from a mature macrophyte community this was a very encouraging development.

However the growth of vegetation in the other sites remains poor or unstable. *Ceratophyllum demersum* development in Alderfen Broad during 1993 was very poor. This may be a short - term side effect of mud pumping, although the data fit with an apparent long term cycle of plant biomass fluctuation with a periodicity of 7-8 years. The cause of this is unclear, but might be related to changes in sediment chemistry (Perrow *et al* 1994). Very little higher plant vegetation developed in Pound End, except where plants were protected from bird grazing, although both this broad and Alderfen had extensive cover of benthic macro algae during the summer. The fish exclosure at Hoveton Great Broad yielded only small amounts of *C. demersum*, which was perhaps not unexpected given the poor water clarity during 1993.

The conclusions that can be drawn from the last few years' observations are that re-colonisation by submerged vegetation is slow and unreliable and therefore the maintenance of clear water through artificial management of the fish community needs to be continuous for several seasons. The failure of rapid growth of vegetation in apparently favourable conditions is a major problem and has been identified as one of the most important areas for investigation.

1.3.1 Factors influencing plant recovery

A number of issues have been identified as potential causes of the failure of aquatic vegetation to take advantage of improved water clarity:

- Lack of viable propagules (seeds or turions).
- Loss of seedlings/germinating turions due to unstable sediment.
- Coot (*Fulica atra*) grazing.
- Chemical environment of sediment or water not suitable for growth
- Competition with benthic macro-algae.

Many of these causes have not been adequately investigated and a literature review on this issue is currently being completed by Hans Schutten from RIZA in the Netherlands prior to the start of a joint BA/NRA/RIZA investigation addressing this issue.

Some preliminary work germinating seeds from sediment collected from both the unpumped and pumped area of Alderfen Broad demonstrated that similar numbers of viable seeds of *C. demersum* (26 ind. m^{-2}) and *Chara* spp. (19 ind. m^{-2}) were found from both areas, but significantly more *Zanichellia palustris* seedlings grew from the unpumped sediment (4 & 0.5 ind. m^{-2}). Although these are preliminary experiments, casual observations of sediment returned to the laboratory for use in tanks and inspections of broads where clear water has occurred (e.g. Belaugh Broad) confirm that significant numbers of seedlings do germinate in clear water conditions, suggesting that the problem is not viable seed availability.

Field germination may be a problem but no specific work on this or the effects of sediment stability on seedling survival have been undertaken. It is possible that following suction dredging the physical nature of the sediment is changed, due perhaps to the deposition of very fine particles and this and other aspects of the sediment will be investigated in 1994. Similarly the chemical nature of the sediment, redox potential, ammonium and ferrous iron concentrations in relation to plant growth have not been adequately investigated.

Coot grazing has however received some attention in the past. In 1990 bird exclosures (8m diameter) were set up in Belaugh, Hoveton Great open water and fish exclosure, Pound End and Ranworth Broads. A detailed description of the set-up of this experiment is contained in Stansfield *et al* 1993, but in each site paired carousels (+ & - bird grazing) allowed the comparison of the effects of grazing. In addition smaller, but replicated experiments using *Elodea canadensis* in crates were set up in 1991 in Hoveton Great Broad (fish exclosure and open water) and at Cockshoot Broad. These experiments clearly demonstrate that without protection small patches of vegetation are very heavily grazed and are easily eliminated. The only species to survive without protection from grazing was the white water lily (*Nymphaea alba*).

Vegetation also developed in large bird exclosures constructed in the littoral fringe of Pound End. These contained a diversity of vegetation, including *Potamogeton crispus* which formed 25% cover in June and July before disappearing in August. A substantial cover of the macro-alga *Enteromorpha* sp. was also present until August and although its effects on plant growth are unknown the impact of grazing is clear, as no significant higher plant growth occurred outside of the enclosures.

Given the potential importance of grazing a more detailed study of coot feeding behaviour was carried out from July 1993 by ECON (University of East Anglia)

1.4 Macrophyte grazing by coot (*Fulica atra*)

Coots are found throughout the UK and judging from shooting records very large numbers existed in the Broads in the past. In this investigation flocks of up to 250 birds were recorded on the larger broads such as Hickling. They are highly omnivorous, feeding on a variety of aquatic and aerial insects, detritus, fishermens' ground bait and other offerings from the public in addition to submerged and emergent plants.

The objectives of this investigation were to determine their diet and to identify how seasonal variations in foraging behaviour, their numbers and distribution might influence the growth of re-colonising aquatic vegetation. Ten sites (Alderfen, Pound End, Cockshoot Hoveton Great, Upton Hickling, Martham North, Belaugh, Cromes and Ormesby) were visited monthly to determine numbers of coot, their feeding activity and food items. The weight of macrophyte material removed was estimated using a scale calibrated against bill length. These sites included all the biomanipulated areas, broads with established plant communities and those with some sporadic macrophytes.

This work confirms that coot feed on a wide range of food items including a significant amount of macrophytic vegetation. This is important because it enables populations to exist in broads prior to their colonisation by vegetation and allows them to exploit any new macrophyte resources if they become available. In general the birds feed in an opportunistic way and their diet reflects what is available at the site. However during the few weeks after eggs hatch they appear to actively seek high protein food items such as insect material for the young birds.

The amount of vegetation removed is extremely variable, depending on availability, coot population, territory size etc. Values ranged from 78 kg wet weight ha^{-1} d^{-1} in August at Martham North (a site with a well developed macrophyte population close to its peak biomass) to 0.1 kg wet weight ha^{-1} d^{-1} in July at Upton where the late germinating *N. marina* would be at maximum growth rate. The maximum recorded rate a single bird could remove, 1.7 kg wet weight d^{-1}, is equivalent to approximately 170 g dry wt. d^{-1}. Typical growth rates for *C. demersum* and *N. marina* range from 0.7 - 4.0 g dry wt. $m^{-2} d^{-1}$ depending on the time of year (Phillips 1976). From these values it is clear that a single bird could remove plant material covering at least 200 m^2 early in the growing season, when productivity is low, or 50 m^2 at peak growth rates. It is therefore not surprising that small scale experimental plantings are affected, and quite possible that during recolonisation growth is severely restricted. What may be of critical importance is the relative timing of plant growth, coot breeding and density together with the optimum conditions of water clarity, temperature and other factors. In sites where vegetation is well established the much greater density of propagules is likely to make the vegetation more resilient, although grazing during the winter may also have significant effects.

It is very unlikely that any attempt to control coot numbers could or would be made. However more information on factors influencing coot feeding together with the density and growth rate of macrophytes will be needed to determine optimum plant densities for re-establishment. With this knowledge it may be possible to decide if natural regeneration is possible or if planting is a practical alternative.

1.5 Stabilising role of aquatic plants

The potential importance of aquatic vegetation in stabilising clear water conditions is now widely recognised (Hosper & Jagtman 1990), but the mechanism by which this takes place is less clear. Macrophytes may influence phytoplankton directly through the production of allelopathic substances (Wium-Anderson *et al* 1982) or they may compete for nutrients, particularly nitrogen (Van Donk *et al* 1993). Alternatively they may provide shelter for large-bodied cladoceran grazers, protecting them from fish predation (Hosper 1989), or provide habitat for piscivorous fish such as Pike (*Esox lucius*).

Timms & Moss (1984) working in a bay connected to Hoveton Great Broad suggested that the dominant effect of aquatic vegetation was to provide *Daphnia* spp. with a refuge from fish predation. They showed that *Daphnia* spp. moved out from the weed bed during the night and grazed in the open water thus reducing the phytoplankton crop. It is important to determine if this is a dominant mechanism and in what types of plant bed (density, size, structure etc) it is most effective, in order to develop appropriate management strategies which will stabilise biomanipulated lakes. Closely linked to this issue is the composition of the fish community and its distribution within the lake.

Two student projects assisted in these investigations, both under the close supervision of members of the project team at ECON (UEA) and in the NRA. One project investigated the distribution of fish, macrophytes and zooplankton on a single day in August at Cromes Broad where a natural re-colonisation of *C. demersum* took place during 1993. Fish abundance was assessed in four habitat types using a point electro fishing technique. Fish were significantly less abundant in dense beds of *C. demersum* than in the open water, sparse macrophyte beds or the edge of the broad. While roach (*Rutilus rutilus*) dominated the catch in all habitats, the edge contained a more diverse community with increased representation of eel, pike and perch. Gut analysis was used to assess diet and to derive predation pressure on the zooplankton. As expected predation pressure was most intense in the open water, but it was only in the dense macrophyte beds that pressure was significantly reduced.

A second project investigated the potential refuge effect of water lilies which are one of the more resilient species. Samples of zooplankton were collected from lily beds (mainly *Nuphar lutea*, but including one *Nymphaea alba* site) and the surrounding open water at four sites on 1 or 2 occasions in July/August. The results showed considerable variability and may be linked to variable levels of fish predation and the size and distribution of the lily beds. Where cladoceran abundance in the open water was low, suggesting significant fish predation, some refuge effect was observed at one site, Salhouse Little Broad, where the density of lilies was very high. Chlorophyll content of water within the bed was not significantly less than the surrounding water, but the lake is directly connected to the River Bure which had a higher chlorophyll content, suggesting a significant effect, probably due to grazing. Sampling at night and during the day did not reveal any evidence for migration of cladoceran species into the open water at night. These observations together with other data collected in previous unpublished investigations do not confirm the observations of Timms & Moss. It seems more likely that in the Broads tidal or wind action circulates water through macrophyte beds where phytoplankton may be removed by grazing.

1.6 The nature of fish communities in broads dominated by macrophytes

As stated earlier the goal of the restoration programme is to re-establish stable lake communities including fish. Very little information about the nature of the fish community of a stable macrophyte dominated broad is available. Techniques such as seine netting, developed in the non-macrophyte dominated lakes to assess fish stock, cannot be used where plants are abundant and only one freshwater site (Upton Broad) is available as a model. Two surveys (July & October 1993) were carried out at Upton Broad by ECON. The littoral zone was sampled by free electrofishing, including an area within stop nets to assess biomass. The open water was sampled by electrofishing ten replicate rings created by a 60m net set in a circle. Macrophyte beds were sampled by electrofishing along transects for a fixed time enabling abundance estimates to be compared on a catch per unit effort (CPUE) basis.

The survey revealed a fish community that contrasted markedly with other non-macrophyte dominated broads. Roach, normally the most abundant species, were not recorded and although large numbers of young bream (*Abramis brama*) were found in July these had largely disappeared by October. The open water of the broad in October was dominated numerically by perch and tench while pike were dominant in biomass on both sampling occasions. Compared to surveys of other broads Upton has a much greater Pike:Prey biomass ratio (1.5:1) than at other sites (Cromes 1:3.6, Horsey Mere 1:5, Alderfen 1:3.5) and, at 51.6 g ha^{-1}, has the highest recorded pike biomass in the Broads. The dominance of this species accounts for the very low planktivorous fish population and is consistent with the observation that in the Netherlands lakes dominated by vegetation have a pike biomass of at least 25 kg ha^{-1}. The only other lakes in the Broads that have a biomass greater than this value are Alderfen (36.7 kg ha^{-1}), Cockshoot (31.7 kg ha^{-1}) and Cromes (36.5 kg ha^{-1}) all of which have some macrophyte development.

1.7 The influence of benthivorous fish on benthic communities - indirect effects of biomanipulation

In considering the effects of biomanipulation attention is normally given to the planktonic community. However benthic fish also play an important role in the functioning of eutrophic lakes. There are several mechanisms through which this can operate. High densities of bream or carp (*Cyprinus carpio*) may create water turbidity by sediment disturbance or directly uproot aquatic plants. Such high populations of large bream are not common in the broads, but the foraging behaviour of these fish may increase the loss of phosphorus from the sediment pore water into the overlying water (Tatrai *et al* 1990). In addition the removal of fish such as roach and bream enables large biomasses of benthic invertebrates to develop in the sediment (Phillips *et al* 1994). There is evidence that under some circumstances chironomids can enhance the rate of phosphorus release by pumping phosphorus rich interstitial water into the water column (Phillips & Jackson 1990). Thus it is possible for biomanipulation to have the indirect effect of enhancing sediment phosphorus release rates and some evidence for this was obtained in the Hoveton Great Broad fish exclosure (Phillips *et al* 1994).

The lack of sediment disturbance by fish foraging may also enable filamentous macro-algae to develop. In a biomanipulated lake clear water is likely to exist as a result of the desired planktonic changes, and if nutrient release is enhanced the ideal conditions for benthic algal growth have been created. This could be as detrimental to higher plant development as phytoplankton (Phillips *et al* 1978) and hence it is essential that these indirect benthic interactions are examined.

This has been incorporated into the design of the experimental restoration at Alderfen Broad which was started in 1993. Following mud pumping to increase water depth, prevent periods of anoxia and minimise phosphorus release, a fish proof barrier was constructed to divide the lake into two halves. All the remaining fish were removed from the lake but tench were restocked into one half at a low density (35 kg ha^{-1}). It is hoped that these fish will disturb the sediment sufficiently to maintain aerobic conditions in the superficial layers, and reduce benthic chironomid populations, with the combined effect of reducing phosphorus release and minimising benthic algal growth. The experimental design at Alderfen also includes large bird exclosures positioned on both sides of the barrier and thus the effects of benthic fish on plant growth can also be established.

During 1993 preliminary monitoring of the benthic invertebrate population has taken place. As expected the open water fauna is extremely species poor with a much greater diversity around the littoral fringe. Following mud pumping the extremely low benthic oligochaete and chironomid populations have increased to moderate levels similar to other broads.

1.8 Phosphorus release from sediments

1.8.1 Background

It has always been clear that the release of phosphorus from the sediments could provide a substantial source of available phosphorus to the overlying water in these shallow lakes (Phillips 1977, Osborne & Phillips 1978). However, following the control of external phosphorus sources, either directly by removing it from effluents (Barton Broad), or indirectly by isolation (Cockshoot) or diversion of the inflow stream (Alderfen), sediment phosphorus becomes the most significant input and might be a critical factor preventing restoration.

High lake phosphorus concentration will enable substantial phytoplankton crops to occur and may result in their dominance by cyanobacteria. These filamentous algae are less likely to be controlled by grazing zooplankton. As a result, without reduced lake phosphorus concentration, biomanipulation may be less effective. There is also evidence that the long term stability of a biomanipulated lake may be dependent on nutrient levels and as a consequence the control or reduction of sediment phosphorus release was an objective for this project.

Sediment phosphorus contributions may be reduced by suction dredging through the removal of a large reservoir of potentially available phosphorus and this has been assumed to be a significant benefit where sediment has been removed to create greater water depth (e.g. Cockshoot Broad). However the benefits of sediment removal have not been specifically investigated and this is one aim of the current investigations at Alderfen Broad. Biomanipulation may indirectly influence phosphorus exchange across the sediment water interface and investigating this forms the second aim of the work at Alderfen Broad. Some initial observations on this aspect were undertaken in the Hoveton Great Broad exclosure as part of a previous project (Phillips *et al* 1994) and during 1993 this work was continued.

Previous work has identified the important role of iron in regulating phosphorus release (Jackson 1989) and laboratory experiments indicated that the addition of ferric chloride at low dose rates directly to the sediment could prevent phosphorus release. These observations suggested that direct dosing of ferric salts to the surface sediment might provide an alternative method of reducing phosphorus release. The addition of ferric chloride initially oxidises the sediment and increases the amount of soluble phosphorus bound to the surface of sediment particles, preventing its release to the overlying water. However as the sediment becomes more anaerobic as a result of decomposition, the ferric iron will be reduced making particulate bound phosphorus potentially available. Anaerobic conditions are a particular problem in the Broads where the proximity to brackish estuarine water encourages the production of sulphides and the loss of soluble iron to insoluble sulphides, enabling phosphorus to be released into the overlying water.

These processes could not be investigated in the laboratory due to the difficulty of establishing realistic organic loading rates to the experimental cores and as a consequence a trial iron dose to an area of sediment in Ranworth Broad was attempted in 1992. To avoid the effects of an enclosure which would change the planktonic and benthic systems due to the absence of fish, this dosing was carried out in the open water of Ranworth Broad. Unfortunately subsequent monitoring revealed that sediment disturbance quickly redistributed the dosed sediment and the long term effects of the dosing could not be determined (Pitt *et al* 1992).

Data accumulated since 1989 showed that the rate of release of phosphorus from the sediments of several of the broads was much more variable than had been previously realised. It was not clear if this was due to the technique used to assess release or that it reflected the actual situation. As a consequence it was decided that prior to any further dosing trials the techniques used should be re-evaluated and that other potential sites for a whole lake iron dosing should be investigated during 1993.

1.8.2 Technique development

Phosphorus release rates have been measured using a flow through technique. This is time consuming to set up and requires large volumes of water. "Artificial" broads water is both expensive to make up and its high calcium content is difficult to maintain in solution. Thus the use of batch experiments where undisturbed sediment cores are allowed to incubate with overlying filtered water in a culture cabinet was investigated during 1993.

Using batch experiments with filtered Alderfen Broad water produced low phosphorus release rates. This was due to the relatively high phosphate content of the water and the shallow concentration gradient between the pore water and the overlying water. To an extent these experiments reflect the "true" field phosphorus release rate, although in the field any uptake of phosphate by the biota might be replaced by phosphorus from the sediment. A more useful measurement might be the "potential" release rate measure by batch incubation with water from Ormesby Broad that had a much lower soluble phosphorus content. This rate was measured on one occasion and compared with the flow through system, also using Ormesby water, that had been used in the past. Both results showed much higher potential release rates as expected, but the flow through system was significantly greater than the batch. The explanation of this is not clear but may be related to the build up of a concentration gradient in the batch cores. Clearly the interpretation of rates derived from these experiments needs to be interpreted with care and both techniques have potential value.

1.8.3 Phosphorus release rates

Alderfen Broad

Observations of the monitoring data revealed very high phosphorus concentrations in Alderfen Broad (summer mean 1.0 mg l^{-1}) and it is clear from this and the measurements of "potential release" that a substantial input of phosphorus from the sediment occurred in Alderfen Broad. This is perhaps surprising given that the superficial sediment had been removed by mud pumping. However this may be due to the exposure of labile organic material and might be a transitory phase. Examination of total phosphorus confirms that the phosphorus content of the sediment was reduced from 1.5 - 2.6 mgP g^{-1} to 0.25 - 1.28 mgP g^{-1} sediment dry weight.

Hoveton Great Broad

In 1989 phosphorus release rates at this site were relatively high. Since 1991 they have decreased substantially and although some high rates were measured in 1992 only low release rates were recorded in 1993. This may be partly due to the use of the batch technique, but as the overlying water did not contain a high phosphate concentration this is unlikely to be the only explanation. Monitoring data does not suggest that there have been marked changes at the site, although the degree of tidal water exchange could easily mask this. Similar anomalies have been noted at other sites in the past and it is possible that the release of phosphorus at high rates is a spasmodic event. If this is the case this makes its measurement very difficult, but may throw new light on the mechanisms involved. Thus sediment disturbance by wind or benthic invertebrates may release phosphorus if it coincides with a high phosphate/iron(II) ratio.

1.8.4 The effect of chironomids on phosphorus release

A small number of experiments from a variety of sites were used to assess the degree to which chironomids could increase sediment release. The results were variable although a clear positive relationship between numbers and release rate was found using sediment from Barton Broad, confirming previous results (Phillips & Jackson 1990). Overall it seems likely that chironomids are capable of influencing release rates, but only under certain conditions - for example when a high concentration of phosphate has built up in the pore water.

1.8.5 Assessment of sites for whole lake iron dosing

Cromes Broad and Burnt Fen Broad were both monitored to assess there potential as sites for whole lake dosing. While some release was measured at Cromes Broad the rates were low which together with the low concentration in the pore water does not make it a very appropriate site. In addition the broad has become very shallow and would require mud pumping as part of its restoration plan.

It was not possible to gain access to Burnt Fen until later in the year, but it does appear that phosphorus release from the sediment was occurring. Thus this site may have potential, although additional data will be required to confirm this.

1.9 References

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