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RESTORATION OF EUTROPHIED SHALLOW SOFTWATER LAKES BASED UPON CARBON AND PHOSPHORUS LIMITATION

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KEYWORDS: restoration, softwater lakes, carbon limitation, phosphate.

ABSTRACT

Plant communities from oligotrophic, poorly buffered waters are seriously threatened by both, acidification and eutrophication/alkalinization. Acidification is mainly caused by atmospheric deposition of acidifying substances while eutrophication is often the result of inlet of nutrient enriched, calcareous brook- or groundwater. The plant production in very soft waters is often limited by low levels of inorganic carbon, nitrogen and/or phosphorus. This paper deals with the possibilities for restoration of formerly oligotrophic but now eutrophied and alkalinized softwater systems. Restoration based upon nitrogen limitation is not likely to be successful as the atmospheric deposition of nitrogen in The Netherlands is very high. Phosphorus limitation can also be a problem. One can stop the input of phosphorus and remove the mud layer, but the problem remains that also the deeper mineral sandy sediments are saturated with phosphate. A possible remedy, however, is a combination of carbon- and phosphorus limitation. Many plants from eutrophic environments never occur in very soft waters, probably as a result of carbon limitation. In addition, mobilisation of phosphate is much lower in waters with very low bicarbonate levels. Restoration of a former oligotrophic softwater lake by reducing the inlet of calcareous surface water, in combination with removal of the organic sediment layer, appeared to be very successful. Many endangered plant species such as *Isoetes echinospora, Luronium natans, Deschampsia setacea* and *Echinodorus repens* developed spontaneously from the still viable seedbank.

INTRODUCTION

In oligotrophic softwater lakes and pools in western Europe, a vegetation type commonly occurs belonging to the *Littorelletea* (SCHAMINÉE *et al.*, 1992, 1995). These *Littorelletea* communities are often characterised by the presence of isoetid plant species such as *Littorella uniflora, Lobelia dortmanna* and *Isoetes* spec. (DEN HARTOG and SEGAL, 1964; SCHOOF-VAN PELT, 1973; WITTIG, 1982). The fact that these plant species can often only survive in stagnant, extremely weakly buffered oligotrophic waters, is related to the carbon budgets in those ecosystems. The carbon dioxide levels of the water layer in these systems are generally below 40 µmol l^{-1} and many species that depend on CO_2 uptake by the leaves are unable to take up enough CO_2 for net photosynthesis, as the diffusion rate of CO_2 in stagnant water is 10^4 lower compared to the diffusion in air (MADSEN *et al.*, 1993). In the sediment pore water of soft water bodies however, the CO_2 level is 10-100 times higher compared to the water layer and can reach values up to 4000 µmol l^{-1} (ROELOFS, 1983). Isoetid plant species have several physiological and morphological adaptations to survive under those conditions such as root uptake of CO_2 (WIUM-ANDERSON, 1971, SAND-JENSEN and SØNDERGAARD, 1979), recapture of photorespired CO_2 in the lacunal system (SØNDERGAARD, 1979), dark fixation (KEELEY, 1982) and a high oxygen release by the roots (SAND-JENSEN *et al.*, 1982; ROELOFS *et al.*, 1984, ROELOFS *et al.*, 1994). Besides carbon dioxide, the availability of other nutrients, such as phosphorus and nitrogen, is often also very low in these systems. As a result, a very stable ecosystem, with low productivity, can exist and be sustained for many years. Through pollen analyses of the sediments from a Danish lake, it is clear that there have been hardly any changes in the abundance of isoetid species between 6000 and 100 years ago. In the last century, however, the isoetids decreased and the abundance of more eutrophic species increased (B. VAN GEEL, personal communication). In The Netherlands and Germany, there are also many observations of eutrophication and the decline of isoetid species during the last century (SCHOOF-VAN PELT, 1973; WESTHOFF, 1979; WITTIG, 1982; ARTS, 1990).

ROELOFS (1983) found that in 12 out of 53 waters from which isoetid species had disappeared since 1950, the water was now more or less turbid and covered by more eutrophic species like *Lemna minor* and *Riccia fluitans* in combination with more mesotrophic species like *Myriophyllum alterniflorum* and *Ranunculus peltatus*. The alkalinity was higher compared to waters where isoetid species were still abundant. Also the nitrogen and phosphorus concentrations of the water layer and/or sediment pore water were much higher. KOK and VAN DE LAAR (1990) found that increased alkalinity leads to increased mineralisation rates in the sediments of softwater ecosystems which can effect the phosphorus load to the water layer. Therefore, the effects of alkaline water on both organic and mineral softwater sediments (Lake Beuven) were studied in glass columns. From the results of this experiment, it is clear, that the phosphorus levels in the water layer are lowest at a very low alkalinity (ROELOFS *et al.*, 1996).

In this paper, the effect of bicarbonate level in the waterlayer on phosphate concentrations, as studied by means of enclosure experiments in a small moorland pool (Padvindersven) is reported. Furthermore, this paper discusses water quality and vegetation development of a eutrofied shallow, formerly soft water lake (Beuven) from which, in 1986, the mudlayer had been removed and the alkalinity was reduced by inlet of controlled, limited amounts of calcareous brook water.

MATERIAL AND METHODS

Enclosure experiment

For the distribution of soft water macrophytes in relation to bicarbonate alkalinity and nutrients data were obtained from DE LYON and ROELOFS (1986). Enclosure experiments were carried out in Padvindersven, a moorland pool near Etten-Leur in the southern part of The Netherlands (51°32' N; 4°40' E). This pool is partly fed by nutrient rich groundwater originating from heavily fertilized agricultural land. As a result the pool has become eutrophicated and species from oligotrophic conditions like *Littorella uniflora* have almost completely disappeared. In order to get insight in the relation between bicarbonate alkalinity and phosphorus level of the waterlayer, 6 enclosures were placed in the pool. These enclosures, in fact round polycarbonate cylinders with a depth of 2 m and a diameter of 1 m, were used to isolate the water and top layer of the sediment from the surrounding water and sediment by pushing them 20 cm into the sediment. The water in the pool has a bicarbonate-alkalinity of about zero as a result of atmospheric input of acidifying substances. In the two control cylinders water quality developed with a bicarbonate-alkalinity of about 50 $\mu mol\ l^{-1}$. In two cylinders the bicarbonate level was adjusted to 250 $\mu mol\ l^{-1}$ and in two other cylinders to 500 $\mu mol\ l^{-1}$ by adding sodium-bicarbonate. The experiment started on July 23, 1987 and three times a month water samples were collected in 200 ml iodated polyethylene bottles till the end of the experiment on October 20, 1987. Bicarbonate levels of unfiltered water samples were measured within 24 hours. From the remaining water 100 ml water was passed through a Whatman GF/C filter and stored at –28°C until analysis.

Chemical analyses

Alkalinity was determined by titrating 50 ml of water with 0.01M HCl down to pH 4.2 and bicarbonate was calculated from alkalinity after correction for pH. The following substances were determined colorimetrically using a Technicon AAII system: nitrate according to KAMPHAKE *et al.* (1977), ammonium according to GRASSHOFF and JOHANNSEN (1977) and ortho-phosphate according to HENRIKSEN (1965).

Statistics

Data obtained from the enclosure experiments were statistically analyzed using SAS for one-way analysis of variance with repeated measurements. Multiple comparisons among pairs of means were made with the Tukey-test.

Restoration of Lake Beuven.

Beuven is a late glacial shallow lake (70 ha;

Table 1. The distribution of aquatic macrophyte species which are able to grow in very soft waters or moderately soft waters, in relation to the bicarbonate alkalinity, ortho-phosphate and mineral nitrogen level of the waterlayer in Dutch surface waters. n = number of sampling sites, min. = minimum level, w.a. = weighed average, med. = median level and max. = maximum level (µmol l^{-1}). Data obtained from DE LYON and ROELOFS (1986).

	n	HCO_3^-		$P\text{-}PO_4$		Min. N
		min.	w.a.	med.	max.	med.
Very soft waters						
Littorella uniflora	17	0.0	0.4	0.2	0.8	32
Luronium natans	32	0.0	0.4	0.2	1.9	150
Elatine hexandra	7	0.0	0.4	0.2	0.2	7
Pilularia globulifera	10	0.0	0.6	0.2	0.7	126
Lythrum portula	23	0.0	0.4	0.2	2.2	52
Panunculus ololeucos	5	0.0	0.3	0.2	0.9	69
Moderately soft waters						
Myriophyllum alterniflorum	18	0.2	0.7	0.7	5.6	170
Ranunculus peltatus	28	0.2	0.7	0.7	2.7	136
Lemna trisulca	131	0.2	1.2	2.2	26.0	21
Lemna minor	178	0.2	2.5	4.4	20.6	9
Riccia fluitans	37	0.2	1.2	1.1	10.8	27

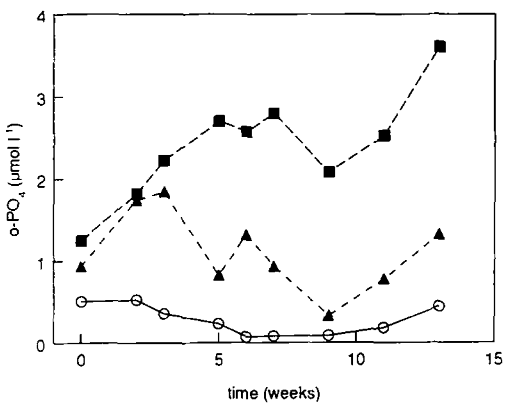

Fig. 1. The ortho-phosphate level of the water layer in enclosures in Padvindersven in relation to the bicarbonate alkalinity of the water layer. Open circles: HCO_3^- = 0.05 mmol l^{-1}, closed triangles: HCO_3^- = 0.25 mmol l^{-1}, closed squares: HCO_3^- = 0.50 mmol l^{-1}. The differences between the treatments are significant (p=0.05, n=2).

max. depth 1.5 m), situated east of Eindhoven in the south-eastern part of The Netherlands (51°24'N; 5°39'E). It belongs to a 2300 ha sandy heathland area. In the past, Lake Beuven was mainly fed by rainwater and some water from its small catchment. The water is hydrologically isolated from deeper groundwater by thin loam layers in the subsoil. Until the 1960s, the water layer was dominated by submerged aquatic plants belonging to the *Littorelletea* (SCHAMINÉE *et al.*, 1995), like *Littorella uniflora, Isoetes echinospora, Lobelia dortmanna, Elatine hexandra, Echinodorus repens* and *Luronium natans*. Since the late sixties the water has become very eutrophic, turbid and relatively alkaline as a result of the inlet of nutrient-rich, relatively calcareous streamwater (Peelrijt) which, in fact, originates from the run-off of higher situated, heavily fertilised agricultural land. All submerged aquatic macrophytes disappeared within a few years. Only small populations in very shallow water in the littoral zone could survive. In 1986 most of the dense *Phragmites* vegetation and the complete mudlayer had been removed. A small part of the lake was isolated from the rest by means of a dam (BUSKENS and ZINGSTRA, 1988). When necessary, water from the stream can be let into the small part of the lake decreasing the nitrogen and phosphorus load by 80-90% within two weeks. This relatively calcareous, nutrient-poor water can be let into the large part of the lake to prevent acidification as a result of atmospheric deposition and to maintain the inorganic carbon in the water layer at low levels. In this way a water layer with a bicarbonate alkalinity of about 100 µeq l^{-1}, which results in a pH of *c.* 6.0, and a CO_2 level of about 50 µmol l^{-1}, is created.

RESULTS

From the data presented in Table 1 it is clear that species from moderately soft waters hardly

Table 2. Water chemistry of the waterlayer of Lake Beuven before and after restoration. Mean and standard error (between parentheses) are given in µmol l^{-1} (except for pH).

	Before (N=32)		After (N=97)	
HCO_3^-	503	(44)	155	(28)
pH	7.4	(0.2)	5.9	(0.1)
NH_4^+	25	(4)	13	(1)
NO_3	38	(12)	27	(6)
o-PO_4	1.88	(0.31)	0.38	(0.04)

Table 3. The aquatic vegetation of Beuven (main lake) before and after the restoration measures in 1986. The abundance of the species is estimated by a subjective scale: 1: rare; 2: scattered; 3: frequent; 4: locally dominant; 5: dominant (dominating large parts of the lake); – : not present.

Species	1976-1985	1986-1995
Isoetids		
Littorella uniflora	2	5
Lobelia dortmanna	1	3
Isoetes echinospora	–	2
Echinodorus repens	1	3
Luronium natans	1	3
others		
Pilularia globulifera	–	2
Eleocharis acicularis	2	4
Eleocharis multicaulis	2	2
Juncus bulbosus	4	2
Elatine hexandra	2	4
Lythrum portula	1	3
Hypericum elodes	1	4
Potamogeton gramineus	–	3
Potamogeton obtusifolius	–	1
Potamogeton pusillus	1	1
Potamogeton natans	2	2
Sparganium minimum	2	2
Apium inundatum	–	2
Deschampsia setacea	–	1
Utricularia australis	–	2
Callitriche hamulata	2	2
Polygonum amphibium	2	2
Lemna minor	3	2
Lemna trisulca	–	2
Riccia fluitans	2	2
number of species	**17**	**25**

occur in very soft waters. In those moderately soft waters now often a plant community exists of highly productive submerged species, such as *Myriophyllum alterniflorum, Ranunculus peltatus* or floating species such as *Lemna minor.* Looking to some chemical properties of the waters it is clear that the latter species never occur in waters with bicarbonate levels below 200 µmol l^{-1}, while all investigated species from oligotrophic waters (category A) also occur in waters with bicarbonate levels below 200 µmol l^{-1}. Also the median and maximum ortho-phosphate levels are much lower in very soft waters. The median mineral nitrogen level is high in both types of water.

The enclosure experiments in Padvindersven showed that ortho-phosphate levels of the waterlayer where lowest when the bicarbonate level of the waterlayer was very low and significantly higher when the bicarbonate level was higher (Fig. 1). This correlation was also found (before restoration) in column experiments with sediments from Lake Beuven (ROELOFS *et al.*, 1996).

In Table 2 water quality data are presented from the period before restoration of Beuven in 1986 and afterwards until 1996. It is clear that the lake has become slightly acidic and poorly buffered again. The phosphate in the waterlayer decreased to very low levels and from that time on the water has been very clear (data not shown). The restoration measures had also a very clear effect on the vegetation. (Table 3). In the years before restoration Isoetid species were rare, while after restoration they were very abundant. *Littorella uniflora* is now dominant and other species belonging to the *Littorelletea* are very abundant now, like *Elatine hexandra, Eleocharis acicularis* and *Hypericum elodes.*

DISCUSSION

In laboratory experiments KOK and VAN DE LAAR (1990) found that increased alkalinity leads to increased mineralisation rates in sediments of softwater ecosystems. This increase can affect the nutrient status of the waterlayer. Indeed column experiments with both organic and mineral sediments of Lake Beuven revealed that the phosphorus level in the waterlayer was much higher at relatively high alkalinity of the waterlayer (ROELOFS *et al.*, 1996). Also the enclosure experiments carried out in Padvindersven proved that the phosphorus level in the water of softwater ecosystems is lowest when the alkalinity of the waterlayer is low (Fig 1). It is also striking that the alkalinity of eutrophicated softwater lakes is higher compared to the undisturbed ones (ROELOFS, 1983). Besides this eutrophying aspect it is also of interest that more eutrophic plant species never occur in waters with very low alkalinity probably as a result of carbon limitation (Table 1). So restoration measures based upon carbon and phosphorus limitation seem to be most promising. In Lake Beuven this was achieved by removal of the nutrient rich, alkalinity generating reductive organic layer and a strong reduction of the inlet of calcareous brookwater. That some buffered water was needed to protect the system from acidification appeared in the year after restoration (BUSKENS and ZINGSTRA, 1988). After replenishment of the water layer with rainwater in 1986, there was a rapid acidification of the water layer down to pH 4.5 after six months. From that time on, small quantities of calcareous water from the isolated part of the lake were allowed to create optimal conditions as described earlier. The water quality developed as expected. Before the restoration, the bicarbonate alkalinity was high and fluctuated in line with high or low precipitation rates. The phosphorus concentration in the water layer clearly correlated with its alkalinity (ROELOFS *et al.*, 1996). After the restoration measures, the alkalinity and phosphorus levels of the water layer were always very low and the water was very clear.

The development of the aquatic vegetation after the restoration was spectacular. Within one year the whole lake was colonised by *Littorelletea* species. Most abundant was *Littorella uniflora*, but many other species such as *Echinodorus repens, Luronium natans, Lobelia dortmanna, Hypericum elodes* and *Eleocharis acicularis* developed well (Table 3). Even *Isoetes echinospora*, a species which was last recorded in The Netherlands in 1972, established obviously from spores in the sediment. Such a quick recovery of the vegetation is only possible when there are many living seeds or spores present in the sediments, so it is likely that in sediments of eutrophied softwater lakes, seeds or spores of *Littorelletea* species can survive at least some decades. Seed-bank experiments of ARTS and VAN DER HEIJDEN (1990) revealed that *Littorelletea* species developed from sediments of lakes where those species had disappeared more than 30 years ago. Now, ten years after the restoration measures, the water quality is still very good and the aquatic vegetation is still in a good condition. Above the waterline however, there is, as could be expected, a robust development too of grasses. These grasses are mainly *Agrostis caninae* on the windy, mineral north-eastern shores and *Phragmites australis* on the more sheltered, slightly organic sediments along the south-western shores and most shallow parts of the lake. The growth of these emergent or terrestrial plants is not restricted by low CO_2 levels in the water layer. The atmospheric deposition of nitrogen is high in this region (20-40 kg N ha^{-1} y^{-1}) and it is known from several studies that nitrogen stimulates the growth of (semi-)aquatic grass species in those soft water lakes and their surroundings (*e.g.* SCHUURKES *et al.*, 1987; AERTS and BERENDSE, 1988).

After the successful restoration of Lake Beuven in 1986, Lake Banen has recently been restored. This lake was eutrophied and alkalinized by the inlet of brookwater originating from the river Meuse. In the winter 1992-1993 the organic mudlayer of this lake has been removed and since then brookwater has been excluded. To prevent acidification by atmospheric deposition, the alkalinity is controlled by inlet of calcareous groundwater at 50 µeq l^{-1}. The first results of the restoration of Lake Banen are promising. The waterlayer became oligotrophic and many *Littorelletea* species colonized large areas of the lake (ROELOFS *et al.*, 1996).

It is not yet known whether, by controlled inlet of calcareous groundwater only, restoration of acidified shallow softwater lakes will be successful. Only very recently, this approach has been applied in three acidified moorland pools or complexes of pools. At least the development of the waterquality is as expected (ROELOFS *et al.*, 1996). Until now, however, there is hardly any response of the vegetation.

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