Extremely Acidic Mine Lake Ecosystems in Lusatia (Germany): Characterisation and development of sustainable, biology-based acidity removal technologies

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Abstract

The extremely acidic mining lakes of Lusatia (north-eastern Germany) were formed by the infilling of open-cast lignite pits following mine closure. These lakes typically have pH values of 2.4 to 3.4 and high concentrations of dissolved iron (and occasionally other metals) and sulphate. There is considerable political and socio-economic pressure to neutralise the lakes and develop their considerable recreational potential. In a multidisciplinary project funded by the BMBF (Bundesministerium für Bildung und Forschung) and LMBV (Lausitzer und Mitteldeutsche Bergbau- Verwaltungsgesellschaft mbH), the living conditions of these lakes have been documented and methodology is being developed to use controlled eutrophication (increased nutrient supply) to increase lake productivity and sustainably remove acidity through sediment bound and water column biologically-mediated processes. The merits of such an approach are discussed in relation to other approaches such as infilling with river water. This multidisciplinary project involves scientists from various universities and institutes in a coordinated approach.

Introduction

In Germany, there are some 500 flooded, open-cast lignite mines (Tagebauseen). The morphometry, history and chemistry of these lakes is described in (Nixdorf et al., 2001a). Many of these lakes are extremely acidic due to high concentrations of dissolved metals (mostly iron and aluminium) in addition to protons (low pH) and also have high sulphate concentrations. During mining operations, water was pumped from the open cast pits. Following closure, many pits filled with groundwater and acidified to pH around 3 through exposure and oxidation of marcasite and pyrite within the mining wastes and overburden material. In the Lausitz region of north eastern Germany, there are some 175 Tagebauseen documented of which approximately half are extremely acidic (pH 2.4 – 3.4) (Nixdorf et al., 2001a). The chemistry of some of these waters is summarised in Table 1.

Table 1. Summary of some chemical parameters for acidic mining lakes (pH 2.4-3.4) in the Lausitz region. Data are from Nixdorf et al. (2001a).

Parameter	Units	Mean	Range
pH		2.9	2.4-3.4
Acidity ($KB_{4,3}$)	mmol l^{-1}	4.9	0.1-26.6
Fe	mg l^{-1}	95	0.2-800.0
Sulphate	mg l^{-1}	1448	460-4636
TOC	mg l^{-1}	3.4	0.8-10.9
Total-N	mg l^{-1}	3.5	0.9-5.3
Total-P	µg l^{-1}	14.3	4-26
chl a	µg l^{-1}	2	0.5-5.0

Economically and environmentally acceptable methods are being sought to sustainably remove the acidity of these lakes to assist in their development, mainly for recreational use. Some of the larger lakes are being subject to flooding through diversion of neutral, nutrient-rich river water. This method is attractive and early data indicates that it can be successful. However, there is insufficient water for all lakes and for many smaller and already filled lakes, this method is impractical. Another method is to enhance *in-situ* alkalinity generating processes through addition of nutrients/or wastes and/or the sustainable enhancement of productivity to feed such processes. This controlled eutrophication is the basis of this project

In this multidisciplinary project funded by BMBF and LMBV, the chemistry and ecology of these lakes are being researched in relation to the use of controlled eutrophication to increase lake productivity and sustainably remove acidity through sediment bound and water column biologically mediated processes. This project involves researchers from several universities and institutes in the region with considerable experience and expertise in handling these acidic waters. It includes basic research on particle transport in streams and lakes, pelagic food web interactions and submerged macrophyte metabolism as well as investigations on the roles of wetlands, bacterial interactions at the water-sediment interface (Wendt-Potthoff and Koschorrek, 2002) and modelling (Nixdorf and Uhlmann, 2002; Uhlmann and Nixdorf, 2002). This contribution focuses on the project "Controlled eutrophication and primary production".

Materials and Methods

Mesocosm experiments were carried out with clear PVC columns 2 m high and with an internal diameter of 0.2 m. These were filled with 60 l of lake water from ML117 (pH 3.0, Fe 15 $mg.l^{-1}$, total phosphorus (TP) 5-7 $\mu g.l^{-1}$) and with or without a 20 cm layer of sediment from the lake. These mesocosms were incubated at room temperature (18-22 °C) under artificial lighting (True Lite fluorescent tubes) with a near to sunlight light spectrum. Phosphorus (200 $\mu g.l^{-1}$) and/or acetic acid (0.1 mM) were added to the mesocosms at the start of the experiment. Each treatment was carried out in triplicate. Chemical parameters were determined according to standard German methods (DEV) modified according to Zwirnmann et al.(1999). Primary production was determined by the ^{14}C method as modified by Kapfer et al. (1997).

Results and Discussion

Living conditions in the extremely acidic mining lakes

The pH of the extremely acidic mining lakes is buffered by high concentrations of dissolved Fe(III) (see Totsche et al., this volume). Increasing pH enhances the hydrolysis and precipitation of the iron as Fe(III) oxyhydroxides, which releases protons, thus decreasing pH. Increasing pH to neutral conditions can be achieved by direct addition of alkali, which is expensive and not self-sustaining, or through biologically mediated alkalinity generating processes such as sulphate and iron (III) reduction. These processes can lead to the sequestration of the iron in sediments as stable, poorly soluble sulphides. Sulphate reduction can be enhanced through increasing the supply of organic substrates through addition of wastes or from dead organisms produced within the water body. Increasing autochthonous primary production through controlled eutrophication (enhanced production through enhancement of nutrient supply) is therefore an attractive strategy for the long-term neutralisation of these lakes. These mining lakes are characterised by extremely low phosphorus and dissolved inorganic carbon concentrations on account of the high iron (III) concentrations and low pH respectively. The iron (III) precipitates as iron(III) oxyhydroxides with the coprecipitation of phosphorus. Subsequent reduction of these precipitates in anoxic conditions can re-releases the phosphorus.

Increasing the available P and C through nutrient additions and/or stimulation of phosphorus cycling is being tested experimentally as a means of enhancing production and providing a sustained supply of organic C to fuel the sediment processes.

Biodiversity is clearly lower in these waters in comparison to neutral lakes in the region, indicating that many organisms are unable to survive or compete in this chemical milieu. On the other hand, biomass may be high when high concentrations of nutrients and carbon are present (Fyson and Rücker, 1998). The utilisation of biological acidity removal technologies requires the enhancement of nutrient availability. This in turn requires the removal of dissolved Fe(III) and hence the elimination of the P co-precipitation process.

The food web of acidic mining lakes

An understanding of the overall functioning of these ecosystems is essential for the development of ecotechnological remediation measures that optimise the role of biological alkalinity-generating processes for sustainable, environmentally acceptable acidity removal. Food webs in these lakes are relatively simple (e.g. top predators are water bugs (corixids); Wollmann et al., 2000). A small number of rotifer species occur (Deneke, 2000) and heliozoans are sometimes abundant (Packroff, 2000). Diverse planktonic algae are found, even in the most acidic lakes, with Chlorophyta (*Chlamydomonas* spp.) and Chrysophyta (*Ochromonas* spp.) usually dominant (Nixdorf et al., 1998; Lessmann et al., 2000). The benthos and littoral of some lakes are colonised by filamentous algae (*Zygogonium* spp., Chlorophyta), which may contribute substantial primary production, as well as *Euglena mutabalis* (Euglenophyta) and diatoms, notably *Eunotia exigua*. Macrophytes are found on the shorelines of all lakes (Fyson, 2000; Nixdorf et al, 2001b). *Phragmites australis* is by far the most abundant. *Juncus bulbosus* grows as a submerged macrophyte in all but the most acidic lakes and may form extensive mats, contributing significantly to primary production and strongly influencing exchange processes between the sediment and water column. The physiological ecology of this species is being studied in this project (Chabbi et al., 2001). The potential for establishment of constructed wetlands is also being investigated within this project. High rates of primary productivity can occur in the water column in the presence of high phosphorus and DIC concentrations, either of which may be limiting (Krumbeck et al., 1998). Primary production is generally not limited directly by low pH although biodiversity is.

The role of pelagic bacteria is also being investigated. Rates of secondary (bacterial) production may be higher than those of primary production and will have an important role in controlling the carbon and nutrients available to algae. Other studies (Wendt-Potthoff and Koschorreck, 2002) are investigating sediment processes (chemical gradients and distribution of alkalinity generating processes).

These relatively simple ecosystems provide model system for studies of trophic interactions and with the acquisition of further knowledge, both of ecosystem functioning and the geohydrological situation, integrated development strategies, incorporating long-term, self-sustaining acidity removal may be developed.

Together with modelling of the chemical processes in relation to lake morphometry, the results of these studies will be combined to provide a picture of the ecological functioning of these lakes and assist in the development of biologically based remediation strategies. The potential role of sulphate reduction and primary production/respiration in relation to lake morphometry and ecotechnological water quality control are discussed in Nixdorf and Uhlmann (2002) and Uhlmann and Nixdorf (2002) respectively.

Mesocosm experiments

Microcosm experiments (20 – 60 l) have been carried out to investigate the effect of phosphorus and organic carbon additions on the water chemistry and biology of acidic lake water in the presence or absence of sediment. In the study described here, chemical and biological changes have been studied in 60 l mesocosms with water from ML117 with or without sediment (Figure 1) to determine the effects of added nutrients on primary production and water chemistry. In the absence of sediment, addition of P and organic C (acetic acid) together resulted in higher primary production rates than in controls or with addition of phosphorus alone throughout the duration of the experiment (about 230 days) (Figure 1a). However, phosphorus concentrations (Figure 1b) declined rapidly coupled to removal of Fe (Figure 1c) indicating that high P concentrations *per se* are not indicative of high primary production rates. In this treatment, pH was only slightly elevated and overall acidity only slightly reduced (data not shown). It is unlikely that assimilation alone can substantially reduce water acidity. The primary role of algal growth in the water column is to maintain a supply of organic carbon and nutrients to fuel the growth and activity of sediment bound alkalinity generating bacteria (sulphate and iron reducers).

In a similar experiment but with sediment from ML117 (20 cm depth), an additional treatment with potatoes (120 g fresh weight per mesocosm) was included. The presence of sediment alone resulted in a small increase in water pH over time (Figure 2a). As with water alone, added phosphorus disappeared rapidly (Figure 2b) through co-precipitation with Fe(III) oxyhydroxides and biological uptake. However, in the presence of potatoes, TP concentration increased to fairly steady values of about 100 $\mu g.l^{-1}$ for the duration of the observations. This was coupled to decomposition, the generation of anoxic conditions and the increase in pH to neutral values through sulphate and iron reduction. This confirms earlier observations made in 20 l mesocosm experiments with lake water and sediment from Lake Koschen (pH 3.1, Fe 21 $mg.l^{-1}$) another lake in the area. In this previous study, anoxic conditions were temporary but neutral conditions with enhanced P concentrations were maintained until the end of the observation period (2 years after set-up) (Fyson et al., 1998; Fyson and Steinberg, 1999). Biological acidity removal clearly works in laboratory mesocosms and enhanced P and C supply can greatly enhance primary production and support enhanced algal growth. Ongoing mesocosm and future field enclosure studies will further investigate the optimisation of primary production in ML117 and assess the role of water-sediment transfer processes in generation and maintenance of neutral conditions.

Summary

A multidisciplinary project is investigating living conditions and developing treatment strategies employing controlled eutrophication to enhance natural, self-sustaining processes for acidity removal from the extremely acidic mining lakes in the Lausitz region. It has been demonstrated that supplementary supply of phosphorus and carbon to the water column can enhance primary production. Ongoing studies will develop treatment strategies that are environmentally acceptable and provide a viable alternative to expensive chemical treatments for neutralisation of these waters.

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References

Chabbi A., Hines, M.E., Rumpel C. (2001). The role of organic carbon excretion by bulbous rush roots and its turnover and utilization by bacteria under iron plaques in extremely acid sediment. Environmental and Experimental Botany 87, 237-246.

Deneke R. (2000). Review of rotifers and crustaceans in highly acidic environments of pH values ≤ 3. Hydrobiologia 433, 167-172.

DEV Deutsche Einheitsverfahren zur Wasser-, Abwasser-, und Schlammuntersuchung, Fachgruppe Wasserchemie i. d. GDCh in Gemeinschaft mit dem NAW im DIN (Eds.). VCH Verlagsges., Weinheim, 1976-1998.

Fyson A. (2000). Angiosperms in acidic waters at pH 3 and below. Hydrobiologia 433, 129-135.

Fyson A., Nixdorf, B., Kalin M., Steinberg, C.E.W. (1998). Mesocosm studies to assess acidity removal from acidic mining lakes through controlled eutrophication. Ecological Engineering, 10, 229-245.

Fyson, A. and Ruecker (1998). Die Chemie und Ökologie des Lugteiches – eines extrem sauren, meromiktischen Tagebausees. In Schmitt M. and Nixdorf B. (Eds) Gewaesserreport (Nr. 4). BTUC-AR 5/98: 18-34. ISSN 1434-6834

Fyson A., Steinberg, C.E.W. (1999). Sustainable acidity removal from Lusatian mining lakes through temporary eutrophication. Berichte des IGB, Heft 8 Jahresforschungsbericht 1998. ISSN 1432 – 508X, 133-142.

Kapfer M., Mischke U., Wollmann K., Krumbeck H. (1997). Erste Ergebnisse zur Primärproduktion in extrem sauren Tagebauseen der Lausitz. In Deneke R. and Nixdorf B. (Eds). Gewässerreport Nr. 3. BTUC-AR 5/97, 31-40. ISSN 1434-6834

Krumbeck H., Nixdorf, B., Fyson, A. (1998). Ressourcen der Bioproduktion in extrem sauren Tagebauseen der Lausitz – Angebot, Verfügbarkeit und Umsetzung. In Schmidt M and Nixdorf B. (Eds). Gewässerreport (Nr. 4). BTUC-AR 5/98, 7-17. ISSN 1434-6834

Lessmann D., Fyson, A., Nixdorf, B. (2000). Phytoplankton of the extremely acidic mining lakes of Lusatia (Germany) with pH ≤ 3. Hydrobiologia 433, 123-128.

Nixdorf B., Mischke M., Lessmann, D. (1998). Chrysophytes and chlamydomonads: Pioneer colonists in extremely acidic mining lakes (pH<3) in Lusatia (Germany). Hydrobiologia 369-370, 315-327.

Nixdorf B., Hemm M., Schlundt A., Kapfer M., Krumbeck H. (2001a). Tagebauseen in Deutschland – ein Überblick. Umweltforschungsplan des Bundesministeriums für Umwelt, Naturschutz und Reaktorsicherheit Forschungsbericht 298 22 240 UBA-FB 000146.

Nixdorf B., Fyson A., Krumbeck H. (2001b) Review: plant life in extremely acidic waters. Environmental and Experimental Botany 46, 203-211.

Nixdorf B., Krumbeck H., Jander J., Beulker C. (2002). Comparison of bacterial and phytoplankton productivity in extremely acidic mining lakes and eutrophic hard water lakes. Acta Oecologica in press.

Nixdorf B., Uhlmann W. (2002). Ökotechnologische Steuerung der Gewässergüte in sauren Tagebauseen. Teil 1: Desulfurikation und Morphologie. Wasser und Boden 54, 16-21.

Packroff G. (2000). Protozooplankton in acidic mining lakes with special respect to ciliates. Hydrobiologia 433, 156-166.

Uhlmann W., Nixdorf B. (2002). Ökotechnologische Steuerung der Gewässergüte in sauren Tagebauseen. Teil 2: Primärproduktion und Respiration. Wasser und Boden 54, 22-26.

Wendt-Potthoff K., Koschorreck M. (2002). Mikrobiologie schwefelsaurer Tagebauseen. Wasser und Boden 54, 6-10.

Wollmann K., Deneke R., Nixdorf B., Packroff G. (2000). The dynamics of planktonic food webs in 3 mining lakes across a pH gradient (pH 2-4). Hydrobiologia 433, 3-14.

Zwirnmann E., Krüger, A., Gelbrecht, J. (1999). Analytik im Zentralen Chemielabor des IGB. Institut für Gewässerökologie und Binnenfischerei, Report 9. ISSN 1432 – 508X.

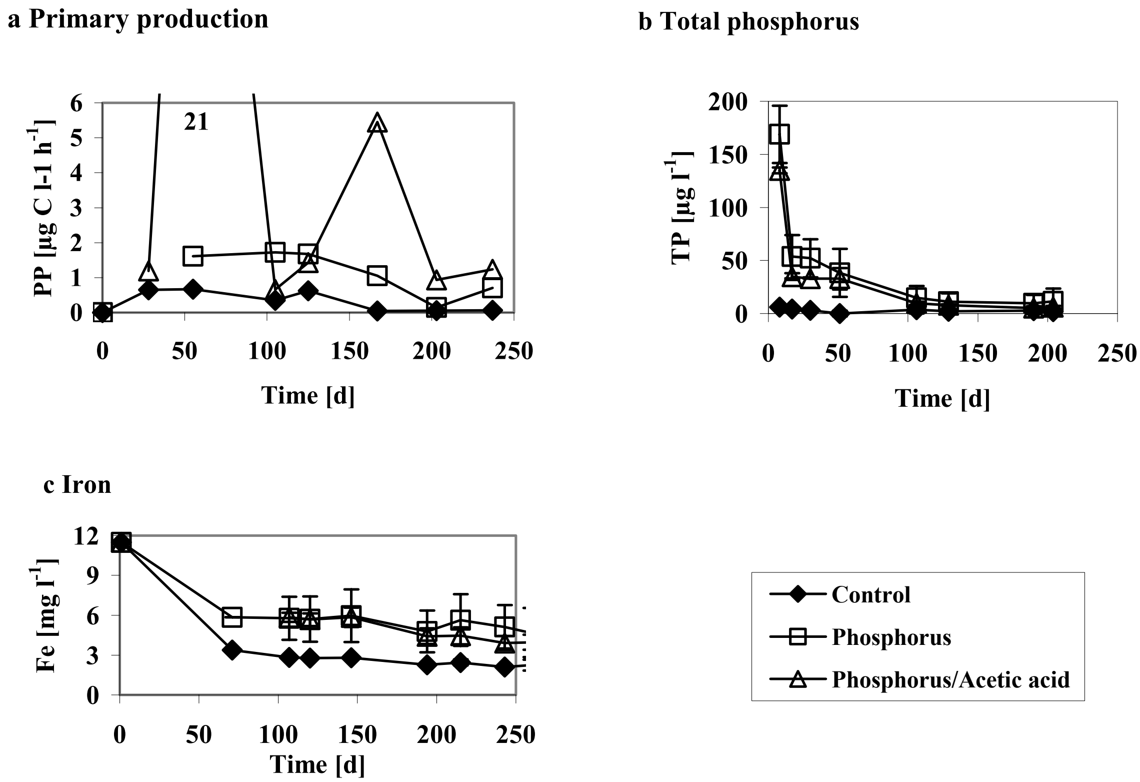

Figure 1. Changes in a) primary production, b) total phosphorus and c) iron concentrations in 60 l mesocosms filled with ML117 water with or without additions of phosphorus (200 µg.l^{-1}) or acetic acid (0.1 mM) as a source of carbon. Values for iron and phosphorus are means (± S.D.) of 3 mesocosms for samples from the middle of the column. The primary production data is for particular production and was measured at a light intensity of 500 µE.m^{-2}.s^{1}. Only one measurement per treatment per sampling date was possible.

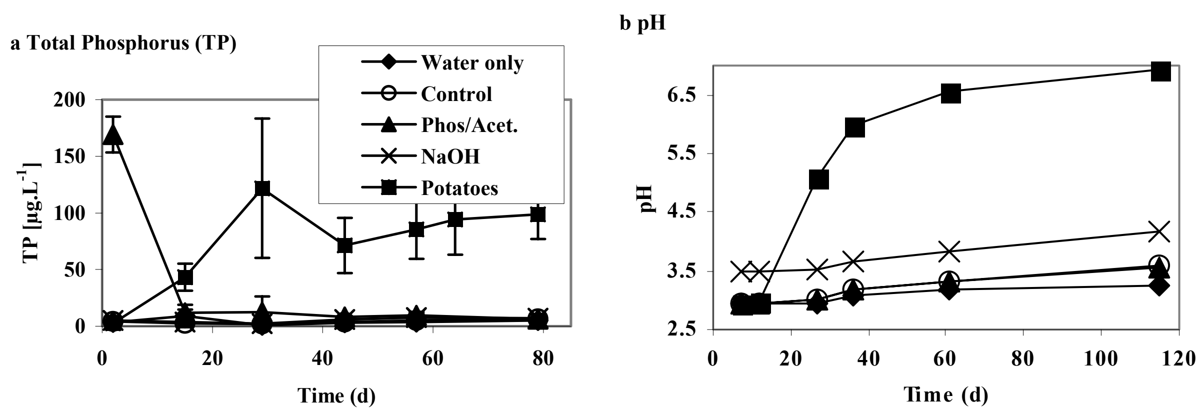

Figure 2. Changes in a) total phosphorus and b) pH in 60 l mesocosms filled with ML117 water with or without a 20 cm ML117 sediment layer and with or without additions of phosphorus (200 µg.l^{-1}), acetic acid (0.1 mM) or potatoes (120 g fresh weight per mesocosm). Means (± S.D.) of 3 mesocosms for samples from the middle of the column.