Water Research 97 (2016) 55–68

Contents lists available at ScienceDirect

Water Research

journal homepage: www.elsevier.com/locate/watres

Phytoplankton community responses in a shallow lake following lanthanum-bentonite application

P. Lang [a,*], S. Meis [b,1], L. Procházková [c], L. Carvalho [b], E.B. Mackay [d], H.J. Woods [b], J. Pottie [e], I. Milne [f], C. Taylor [a], S.C. Maberly [d], B.M. Spears [b]

[a] Ecology Assessment Unit, Scottish Environment Protection Agency, 6 Parklands Avenue, Maxim Business Park, Eurocentral, North Lanarkshire ML1 4WQ, Scotland, UK
[b] Freshwater Ecology Group, Centre for Ecology & Hydrology, Bush Estate, Penicuik, Midlothian EH26 0QB, Scotland, UK
[c] Department of Ecology, Faculty of Science, Charles University in Prague, Viničná 7, CZ-128 44 Prague, Czech Republic
[d] Lake Ecosystems Group, Centre for Ecology & Hydrology, Lancaster Environment Centre, Library Avenue, Bailrigg, Lancaster LA1 4AP, England, UK
[e] Broombank, Loch Flemington, Inverness IV2 7QR, Scotland, UK
[f] Ecology Partnership Development Unit, Scottish Environment Protection Agency, Graesser House, Fodderty Way, Dingwall Business Park, Dingwall IV15 9XB, Scotland, UK

ARTICLE INFO

Article history:
Received 2 May 2015
Received in revised form
19 February 2016
Accepted 7 March 2016
Available online 15 March 2016

Keywords:
Lanthanum-modified bentonite
Eutrophication
Recovery
Lake restoration
Cyanobacteria

ABSTRACT

The release of phosphorus (P) from bed sediments to the overlying water can delay the recovery of lakes for decades following reductions in catchment contributions, preventing water quality targets being met within timeframes set out by environmental legislation (e.g. EU Water Framework Directive: WFD). Therefore supplementary solutions for restoring lakes have been explored, including the capping of sediment P sources using a lanthanum (La)-modified bentonite clay to reduce internal P loading and enhance the recovery process. Here we present results from Loch Flemington where the first long-term field trial documenting responses of phytoplankton community structure and abundance, and the UK WFD phytoplankton metric to a La-bentonite application was performed. A Before-After-Control-Impact (BACI) analysis was used to distinguish natural variability from treatment effect and confirmed significant reductions in the magnitude of summer cyanobacterial blooms in Loch Flemington, relative to the control site, following La-bentonite application. However this initial cyanobacterial response was not sustained beyond two years after application, which implied that the reduction in internal P loading was short-lived; several possible explanations for this are discussed. One reason is that this ecological quality indicator is sensitive to inter-annual variability in weather patterns, particularly summer rainfall and water temperature. Over the monitoring period, the phytoplankton community structure of Loch Flemington became less dominated by cyanobacteria and more functionally diverse. This resulted in continual improvements in the phytoplankton compositional and abundance metrics, which were not observed at the control site, and may suggest an ecological response to the sustained reduction in filterable reactive phosphorus (FRP) concentration following La-bentonite application. Overall, phytoplankton classification indicated that the lake moved from poor to moderate ecological status but did not reach the proxy water quality target (i.e. WFD Good Ecological Status) within four years of the application. As for many other shallow lakes, the effective control of internal P loading in Loch Flemington will require further implementation of both in-lake and catchment-based measures. Our work emphasizes the need for appropriate experimental design and long-term monitoring programmes, to ascertain the efficacy of intervention measures in delivering environmental improvements at the field scale.

1. Introduction

Shallow lakes are among the most abundant freshwater habitats worldwide (Downing et al., 2006; Verpoorter et al., 2014). They offer a valuable source of biodiversity (Williams et al., 2004;

* Corresponding author.
E-mail address: pauline.lang@sepa.org.uk (P. Lang).
[1] Current address: lanaplan GbR, Lobbericher Straβe 5, 41334 Nettetal, Germany.

http://dx.doi.org/10.1016/j.watres.2016.03.018

Scheffer et al., 2006), and provide important ecosystem services to humans (Postel and Carpenter, 1997; Millennium Ecosystem Assessment, 2005). Yet, with catchments often located in heavily-populated areas and surrounded by intense agriculture, shallow lakes are vulnerable to the detrimental effects of nutrient loading (Phillips, 2005; Smith and Schindler, 2009). An increase in the frequency and magnitude of potentially harmful cyanobacterial blooms is a common symptom of nutrient enrichment (Brookes and Carey, 2011; Downing et al., 2001).

Cyanobacterial blooms interfere with the ecological structure and function of lakes and can produce toxins with the potential to affect human and animal health (Codd et al., 1999, 2005). They therefore convey an important message regarding ecosystem health, and often trigger water quality managers to take action to resolve the core underlying environmental issues driving their excessive growth. The risk of occurrence of blooms of cyanobacteria generally increases at water column total phosphorus (TP) concentrations in excess of 10–20 μg L^{-1} (Carvalho et al., 2011, 2013a), and phytoplankton biomass decreases linearly with TP below about 100 μg L^{-1} in strongly phosphorus (P) limited lakes (Spears et al., 2013). Interventions to reduce cyanobacteria and phytoplankton biomass, normally attempt to reduce external P loads to lakes from their catchments. However, recent studies have highlighted a considerable temporal 'lag' in expected water quality improvements following successful catchment management (Søndergaard et al., 2003; Carvalho et al., 2012; Spears et al., 2012; Sharpley et al., 2014). The release of P from bed sediments (hereafter referred to as internal P loading) can delay the recovery of shallow lakes for decades following external P load reductions, depending on the pollution history, lake flushing rate, bed sediment surface redox conditions and its P-binding capacity (Sas, 1989; Søndergaard et al., 2001; Jeppesen et al., 2005a; Smolders et al., 2006; Spears et al., 2007). This temporal lag is also mirrored in phytoplankton community recovery, characterised by an increase in the biovolume of diatoms, cryptophytes and chrysophytes, and a decrease or no change in cyanobacteria relative to total phytoplankton community biovolume (Jeppesen et al., 1991, 2005b).

Crucially, internal P loading is often the mechanism restricting immediate improvements in shallow lakes following reductions in catchment contributions, preventing water quality targets being met within timeframes set out by environmental legislation (e.g. EU Water Framework Directive: EC, 2000). Therefore to enhance the recovery process, supplementary solutions for the control of internal loading such as sediment dredging, hypolimnetic aeration, and applying materials to 'cap' bed sediment P release have been explored (Hupfer and Hilt, 2008; Hickey and Gibbs, 2009; Lewandowski et al., 2013; Spears et al., 2013). This includes use of a lanthanum (La)-modified bentonite clay to manage eutrophication impacts by capping sediment P release (Douglas patent; Douglas et al., 2004, 2008) and its application at the field scale (Robb et al., 2003; Lürling and Faassen, 2012; Meis, 2012; Meis et al., 2013; van Oosterhout and Lürling, 2013; Douglas et al., 2016). Although some *in situ* studies have indicated that La-bentonite is effective at controlling internal P loading, in turn reducing water column TP, filterable reactive phosphorus (FRP) and chlorophyll *a* concentrations (Robb et al., 2003; Meis, 2012; Gunn et al., 2014; Douglas et al., 2016) and the occurrence of cyanobacteria (Lürling and van Oosterhout, 2013; Bishop et al., 2014), there is currently no comprehensive assessment on phytoplankton community responses following La-bentonite application from a long-term field trial.

To determine the efficacy of any restoration measure, it is vital that the results of field scale trials are analysed rigorously using appropriate statistical approaches. This is especially important for short lived organisms with turnover rates of days to weeks, as is the case for phytoplankton, where natural seasonal and inter-annual variation can be mistaken for treatment responses when inappropriately analysed. In this context, the Before-After-Control-Impact (BACI) approach has been applied successfully within environmental impact assessments in other systems (Schroeter et al., 1993; Conquest, 2000). We employed this approach to distinguish natural variability from treatment effects in phytoplankton composition and abundance, following La-bentonite application to a shallow lake. Where the control of internal P loading is successful, one would expect a rapid (i.e. within a few years) and sustained response in phytoplankton community structure and biovolume (e.g. decline in cyanobacterial blooms).

In Europe, Annex V of the EU Water Framework Directive (WFD: 2000/60/EC) outlines three features of the phytoplankton community to be considered in the ecological status assessment for lakes: (1) phytoplankton biomass or abundance, (2) phytoplankton composition and (3) bloom frequency and intensity (EC, 2000). Here we examine the responses of a range of the most robust phytoplankton metrics developed in Europe (Carvalho et al., 2013b) and evaluate their responsiveness to restoration actions using the phytoplankton classification methods routinely employed by UK environment agencies. This provides important evidence for environmental regulators and water resource managers on the effectiveness of intervention measures and their capacity to restore 'failing' lakes to acceptable water quality standards, over relevant regulatory timescales (e.g. to have achieved Good Ecological Status for the WFD, or at least have the appropriate measures in place, by 2027) and, more generally, for the control of cyanobacterial blooms in shallow lakes.

We report on a long-term field trial (i.e. one year pre- and four years post-treatment monitoring) designed to quantify responses in the phytoplankton community following La-bentonite application to a shallow lake, placed into context of the WFD as a proxy target of ecological improvement. The specific objectives of the study were to: (*i*) quantify the seasonal and annual responses in phytoplankton community structure and biovolume following La-bentonite application, (*ii*) evaluate the responses in relevant phytoplankton community metrics in line with proxy WFD ecological quality targets, and (*iii*) discuss implications of the results in the context of eutrophication management and ecological recovery in lakes.

2. Material and methods

2.1. Description of treatment (T) site and sampling design

Loch Flemington (57° 32′ N, 3° 59′ W) is located around 20 km east of Inverness, Scotland, UK (Fig. 1). It is a small, high alkalinity (>50 mg L^{-1} as $CaCO_3$), shallow lake (Table 1), with no natural outflow (groundwater flows to north-east) and a water retention time of around 2 months (May et al., 2001). The international conservation importance of the site is summarised elsewhere (e.g. Gunn et al., 2014). Located in a largely agricultural lowland catchment, Loch Flemington has suffered a long-standing history of cyanobacterial blooms associated with high catchment P loading resulting in a fish kill in the 1990s (May et al., 2001). Initially, catchment management activities were undertaken to reduce external P loading: treated effluent from a nearby wastewater treatment works (WwTW) was re-directed away from its inlet in 1989, and the WwTW was upgraded during 1993 because sporadic effluent spillages continued to enter the Croy Burn (the primary feeder stream for the lake) during periods of overload (May et al., 2001). A recent assessment of TP loads to Loch Flemington indicated that the dominant external sources were now diffuse (mainly agricultural) and from septic tanks, and was estimated at