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A meta-analysis of water quality and aquatic macrophyte responses in 18 lakes treated with lanthanum modified bentonite (Phoslock®)

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ABSTRACT

Lanthanum (La) modified bentonite is being increasingly used as a geo-engineering tool for the control of phosphorus (P) release from lake bed sediments to overlying waters. However, little is known about its effectiveness in controlling P across a wide range of lake conditions or of its potential to promote rapid ecological recovery. We combined data from 18 treated lakes to examine the lake population responses in the 24 months following La-bentonite application (range of La-bentonite loads: 1.4–6.7 tonnes ha^{-1}) in concentrations of surface water total phosphorus (TP; data available from 15 lakes), soluble reactive phosphorus (SRP; 14 lakes), and chlorophyll *a* (15 lakes), and in Secchi disk depths (15 lakes), aquatic macrophyte species numbers (6 lakes) and aquatic macrophyte maximum colonisation depths (4 lakes) across the treated lakes. Data availability varied across the lakes and variables, and in general monitoring was more frequent closer to the application dates. Median annual TP concentrations decreased significantly across the lakes, following the La-bentonite applications (from 0.08 mg L^{-1} in the 24 months pre-application to 0.03 mg L^{-1} in the 24 months post-application), particularly in autumn (0.08 mg L^{-1} to 0.03 mg L^{-1}) and winter (0.08 mg L^{-1} to 0.02 mg L^{-1}). Significant decreases in SRP concentrations over annual (0.019 mg L^{-1} to 0.005 mg L^{-1}), summer (0.018 mg L^{-1} to 0.004 mg L^{-1}), autumn (0.019 mg L^{-1} to 0.005 mg L^{-1}) and winter (0.033 mg L^{-1} to 0.005 mg L^{-1}) periods were also reported. P concentrations following La-bentonite application varied across the lakes and were correlated positively with dissolved organic carbon concentrations. Relatively weak, but significant responses were reported for summer chlorophyll *a* concentrations and Secchi disk depths following La-bentonite applications, the 75th percentile values decreasing from 119 μg L^{-1} to 74 μg L^{-1} and increasing from 398 cm to 506 cm, respectively. Aquatic macrophyte species numbers and maximum colonisation depths increased following La-bentonite application from a median of 5.5 species to 7.0 species and a median of 1.8 m to 2.5 m, respectively. The aquatic macrophyte responses varied significantly between lakes. La-bentonite

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application resulted in a general improvement in water quality leading to an improvement in the aquatic macrophyte community within 24 months. However, because, the responses were highly site-specific, we stress the need for comprehensive pre- and post-application assessments of processes driving ecological structure and function in candidate lakes to inform future use of this and similar products.

1. Introduction

Nutrient (i.e. mainly phosphorus (P) and nitrogen (N)) pollution has resulted in widespread degradation of ecological structure and function of freshwater lakes at a global scale (Smith, 2003). To address this issue, environmental policies have been implemented to reduce nutrient loads to lakes. Such policies often require management actions to improve water quality to support ecological recovery within a given timeframe (e.g. by 2027 in the case of the EU Water Framework Directive; European Commission, 2000). In many catchments large-scale reductions in P loading to fresh waters have been achieved (Withers and Haygarth, 2007). However, after P loading from the catchment is reduced, lake recovery can take several decades (Jeppesen et al., 2005; Sharpley et al., 2013). This is because P, accumulated in lake bed sediments when catchment inputs were high, continues to be released during the recovery process ("internal loading"), maintaining poor water quality conditions (Søndergaard et al., 2012; Spears et al., 2012). The effective control of internal loading may accelerate ecological recovery once external inputs have been reduced (Mehner et al., 2008).

There are few methods available to control internal loading (Hickey and Gibbs, 2009). Sediment dredging has been demonstrated as an internal loading control measure (e.g. Van Wichelen et al., 2007) but may have limited application when habitat destruction, waste disposal and cost are taken into account. In addition, like other restoration measures, sediment dredging has not always been successful (Søndergaard et al., 2007). P-sorbing materials (e.g. modified clays, industrial by-products, flocculants and physical barriers; Hickey and Gibbs, 2009; Zamparas et al., 2012; Spears et al., 2013a) have also been used to strip P from the water column and, after settling, reduce P release from the sediments (Hickey and Gibbs, 2009; Meis et al., 2012). Lanthanum (La) modified bentonite, is being increasingly used in lakes for P control (Douglas et al., 2000; Robb et al., 2003; Haghseresht et al., 2009). However, there has been limited evaluation of its effectiveness in controlling P across diverse lake conditions, or of its potential to promote rapid ecological recovery.

When considering the effectiveness of any lake management approach it is important to consider responses across multiple lakes (Jeppesen et al., 2005; Spears et al., 2013b). Long-term catchment nutrient load reduction studies indicate that a range of responses characterise the recovery period in lakes. In temperate lakes, following catchment management, a rapid decline in winter P concentration occurs followed by a gradual decline in summer P concentrations as the intensity of internal P loading diminishes with time (Phillips et al., 2005; Søndergaard et al., 2012). Whereas winter P concentrations are generally driven more by catchment inputs, sediment P release is more prominent in the warmer summer months when redox conditions of bed sediments can become reducing (i.e. liberating soluble reactive phosphorus (SRP) from Fe–P sediment complexes) and high temperatures increase sediment-water SRP concentration gradients and diffusive fluxes from the sediment to the water column (Spears et al., 2007). The period over which these responses occur is lake-specific and regulated by various factors including hydraulic residence time, sediment P concentrations and depth (Sas, 1989). Where the phytoplankton community is primarily P limited, reductions in annual average total phosphorus (TP) concentrations should elicit a reduction in phytoplankton biomass (commonly measured as chlorophyll *a* concentration), an increase in water clarity, and an increase in the extent and diversity of aquatic macrophytes (Jeppesen et al., 2000). Where La-bentonite has been successful in controlling internal loading these responses should occur relatively quickly, at least within the recovery time scales known to occur following catchment nutrient load reduction alone (i.e. >5 years; Jeppesen et al., 2005; Sharpley et al., 2013).

We assessed these responses following La-bentonite application (two years post-application), relative to pre-application conditions (i.e. two years pre-application), in 18 lakes and addressed the following specific questions: (1) were the responses in water quality (i.e. concentrations of TP; SRP; and chlorophyll *a* and Secchi disk depth) statistically and ecologically significant and did these responses vary seasonally?; (2) were the responses in water column TP and SRP concentrations regulated by physico-chemical conditions of the receiving lake water?; (3) did aquatic macrophyte diversity and extent increase in treated lakes?; and (4) what are the implications of these results for the use of La-bentonite as an eutrophication management tool in other lakes?

2. Methods

2.1. Data collation, assessment and processing

The following analyses are based on collated information from 18 lake case studies where La-bentonite has been applied. Surface water TP, SRP, and chlorophyll *a* concentrations and Secchi disk depth data, in the years preceding and following an application of La-bentonite, were compiled to allow an assessment of general responses across the population of lakes. All available aquatic macrophyte community data, including species lists and maximum colonisation depth estimates, were compiled. The product application procedures for 14 of the study lakes are described by Spears et al. (2013b), with the exception of Mere Mere, Hatchmere, Cromes Broad and Swan Lake to which La-bentonite was added in the absence of a flocculant and as a slurry. In four of the lakes it was reported that repeat applications had been conducted but only data following the first application and prior to the second were included in this study. The number of lakes for which data were available for TP, SRP, chlorophyll *a* concentrations and Secchi disk depth, in the months preceding and following La-bentonite application, are reported. Supporting data for location, maximum fetch, mean depth, maximum depth, surface area, alkalinity, dissolved organic carbon (DOC) concentration, La-bentonite dosage and pH were requested for the pre- and post-application periods with which the general chemical and physical conditions of the treated lakes are described.