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# Assessing the responses of aquatic macrophytes to the application of a lanthanum modified bentonite clay, at Loch Flemington, Scotland, UK

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## ABSTRACT

Loch Flemington is a shallow lake of international conservation and scientific importance. In recent decades its status has declined as a result of eutrophication and the establishment of non-native invasive aquatic macrophytes. As previous research had identified the lake bed sediments as an important source of phosphorus (P), the P-capping material Phoslock® was applied to improve water quality. This paper documents the responses of the aquatic macrophyte community by comparing data collected between 1988 and 2011. Summer water-column total P concentrations decreased significantly and water clarity increased following treatment.

Aquatic plant colonisation depth increased and plant coverage of the lake bed extended. However, the submerged vegetation remained dominated by the non-native *Elodea canadensis* Michx. Aquatic macrophyte community metrics indicated no significant change in trophic status. Species richness and the number of 'natural' eutrophic characteristic species remained broadly similar with no records of rare species of conservation interest. Loch Flemington is still classified as being in 'unfavourable no change' condition based on its aquatic macrophytes despite the water quality improvements. The implications of these results are discussed in relation to the future management of Loch Flemington and in the wider context of trying to improve our understanding of lake restoration processes.

**KEYWORDS**: Eutrophication, Loch Flemington, lake restoration, P-capping material, aquatic macrophytes, lake management

## INTRODUCTION

Eutrophication is regarded as being one of the most important factors causing degradation of lakes throughout Europe (Withers & Haygarth, 2007) and the rest of the world (Bennett *et al*., 2001; Schindler, 2006). In shallow (< 3 m depth) freshwater lakes, elevated nutrient inputs from the catchment, resulting from agricultural, cultural and industrial activity, are the primary cause of this eutrophication (Scheffer, 2004). Increased loadings of phosphorus (P) commonly result in a shift from macrophyte to planktonic production, with associated phytoplankton blooms (particularly cyanobacterial), leading to deterioration in water quality and associated changes in the biological communities. European legislation has led in the UK to the setting of P targets for high alkalinity, shallow lakes to achieve 'favourable condition' (JNCC, 2005) under the Habitats Directive (Council of the European Communities, 1992) and 'good' and 'high' ecological status (UKTAG, 2008) under the Water Framework Directive (WFD) (Council of the European Communities, 2000). However, many shallow lakes in Europe, because of a legacy of eutrophication, already have nutrient concentrations which exceed these targets (EEA, 2012). For shallow lakes, designated to be of conservation importance, this deterioration in condition is also indicated by the decline or disappearance of rare and scarce vascular plants and/or assemblages of notable vascular plants and charophytes (JNCC, 2005).

On a global scale, research on eutrophication in relation to lake management has received considerable attention (Jeppesen *et al*., 2003). Successful lake restoration depends on a good understanding of the site-specific drivers of eutrophication and using targeted management strategies which are based on good scientific evidence. In many lakes the main factor limiting phytoplankton abundance is P availability, so it is this nutrient which is usually targeted for control by most lake restoration strategies, although nitrogen (N) limitation in the summer months can also be important (Fisher *et al.*, 2009; May *et al.*, 2010). Reducing the external P load from a lake catchment is often the preferred remedial option where P is the limiting factor. However, its effectiveness is often reduced or delayed by internal recycling of P from the lake sediments (Søndergaard *et al*., 2007). In such cases, alternative approaches to lake recovery must be used, coupled with reducing the external P load, such as bio-manipulation, biomass harvesting, lake flushing, sediment removal, vertical mixing, and P inactivation (Cooke *et al*., 2005). The latter technique has in the past relied on adding iron, aluminium or similar salts to bind and precipitate available dissolved P from the water-column to the lake sediments. This prevents internal loading by maintaining, for example, a layer of iron over the sediments, but, often, after short-term success, pre-treatment levels of P release return within a few years (e.g. Foy, 1985). There have also been concerns that such techniques may have adverse effects on lake ecosystems (Randall *et al.*, 1999; Spears *et al.*, 2013a). A range of P-capping materials have been proposed for use in the UK (Spears *et al*., 2013b). Phoslock® is a lanthanum (La) modified bentonite clay designed to enhance the capacity of lake sediments to adsorb dissolved (i.e. bio-available) P and significantly reduce its subsequent release (manufacturers reported binding capacity of 100g Phoslock®: 1 g of P). $La^{3+}$ ions that are strongly bound within the clay matrix react with dissolved P to form the mineral rhabdophane ($LaPO_4$), a compound that is expected to be stable in the environment (i.e. beyond the pH range 4 – 9; Ross *et al*., 2008).

The expected general responses of the aquatic macrophyte community, following eutrophication management, have recently been summarised in a literature review which incorporated long-term data from oligotrophication case studies (Jeppesen *et al.*, 2005; Verdonschot *et al*., 2011). Typical macrophyte community responses included increases in colonisation depth, species richness (including relative characean abundance), the number of nutrient intolerant species and species distribution as TP concentrations decreased. Submerged macrophyte vegetation becomes increasingly restricted to shallower waters in response to decreasing light levels at the sediment surface as phytoplankton population levels increase. One simple measure of macrophyte abundance in lakes is maximum macrophyte growing depth (MMGD). MMGD is sensitive to eutrophication (Jupp & Spence, 1977; May & Carvalho, 2010; Søndergaard *et a*l., 2005; Spears *et al*., 2009) and can provide a direct measure of the success of lake management measures to shift primary production in lakes from a phytoplankton-dominated to a more macrophyte-dominated state (Sas, 1989).

This paper examines how the aquatic macrophyte community in Loch Flemington responded following the application of the P-capping material Phoslock® to the lake bed sediments and, on the assumption that growing conditions will improve as a result of better water quality, tested the following hypotheses:

- There will be no negative impacts of the Phoslock® application on aquatic macrophyte community
- Macrophyte maximum growing depth and coverage of lake bed will increase
- Species diversity will increase and species of conservation interest will re-appear
- Aquatic macrophyte community attributes and metrics will indicate a change towards improvement in Loch Flemington's condition and trophic status
- Mechanical control of non-native aquatic species *Elodea canadensis* Michx. may encourage the recovery of native aquatic macrophyte species when used in combination with Phoslock®

## METHODS

### Study site

Loch Flemington (N 57$^0$ 32.570$^{'}$, W 3$^0$ 59.399$^{'}$) is a shallow (mean and maximum depths of 0.75 m and 2.9 m), lowland (altitude 46 m), high alkalinity (1240 μeql$^{-1}$), eutrophic lake, of glacial origin situated near Inverness in Scotland, UK (Figure 1). It has a surface area of 15 ha, a maximum fetch of 0.75 km and a perimeter of 2.7 km (UKLakes Database). The lake is situated in an area consisting of glaciofluvial sand and gravel within the Kildrummie Kames esker system (Gordon & Auton, 1993). Significant hydrological modifications were made to the lake in the 19th century by blocking the natural surface-water outflow and significantly increasing the surface area and depth of the loch (May *et al.*, 2001). Today, the lake has no natural surface water outflow and the Croy Burn is the only surface water inflow. Water leaves the lake by evaporation and by percolating through permeable gravels along the northwest shore, leading to an estimated water retention time of around 40 days (May *et al.*, 2001).

Loch Flemington lies within the Kildrummie Kames Site of Special Scientific Interest (SSSI) which was notified in 1974, in part, for Loch Flemington's eutrophic lake habitat and for supporting populations of aquatic macrophyte species of conservation interest:  the Nationally Rare *Potamogeton rutilus* Wolfg. and the Nationally Scarce *Potamogeton filiformis* Pers. In addition, macrofossils of the Nationally Scarce and European Protected Species *Najas flexilis* (Willd.) Rostk. & W. L. E. Schmidt (listed in Annexes II and IV of the Habitats Directive (Council of the European Communities, 1992)) have recently been recorded in Loch Flemington (Bennion *et al.*, 2008). From the 1960s onwards Loch Flemington had become increasingly eutrophic due to nutrient-laden waste entering from the catchment  resulting in a lake flora dominated by three submerged species *E. canadensis*, *Myriophyllum spicatum* L. and *Potamogeton crispus* L. (May *et al.*, 2001). Palaeolimnological records indicated that the aquatic macrophyte community had actually changed from a rich macrophyte flora characteristic of mesotrophic conditions before 1850 towards a more species poor community indicative of nutrient enrichment (Bennion *et al*., 2008). This resulted in a build up of P within the lake which caused, by the mid 1970s, troublesome algal blooms to develop and fish kills to occur. Nuisance algal blooms, particularly those dominated by cyanobacteria, continued throughout the 1980s and 1990s with increasing frequency, threatening the conservation status of the lake. By 2003/04 the SSSI eutrophic lake habitat feature was found to be in 'unfavourable condition'. The main reasons for this negative classification were the lake's continuing poor water quality and the domination of the submerged vegetation by the non-native *E. canadensis* plus the disappearance of all the aquatic macrophyte species of national conservation interest. Restoration efforts at Loch Flemington up to this point had been focussed solely on improving water quality by reducing catchment point sources of nutrients. An assessment of total P (TP) loads to the lake indicated that, by 2001, diffuse (mainly agricultural) sources, represented ~ 80% and septic tanks ~ 18% of the external TP load, respectively  (May *et al*., 2001). However, the same study also found that the internal, sediment-driven load to the water-column (680 kg TP yr$^{-1}$) was probably far greater than the external load from the catchment (120 kg TP yr$^{-1}$).

## Phoslock® application

Phoslock® was applied to Loch Flemington by Phoslock® Europe GmbH over a three day period, March 13th – 15th 2010. A pilot study had estimated that the dosage of Phoslock® required to be applied to Loch Flemington was 25 tonnes in order to control a maximum of ~ 22 kg total phosphorus (TP) in the water column and ~ 210 kg TP in the upper 3 cm of lake sediment, on the basis that 100 g of Phoslock® binds 1 g of phosphorus (Meis *et al*., 2012).

## Pre- and post-application water quality and ecological (non-aquatic macrophyte) monitoring

A range of water quality and ecological (non-aquatic macrophyte) parameters were monitored at Loch Flemington on a monthly basis, pre- and post-application of Phoslock®, at five open water sampling sites between May 2009 and March 2011, and at three of these sites from April 2011 to November 2011, with the exception of July 2011 when all five sites were sampled. Field water quality measurements included surface water pH, conductivity, temperature and dissolved oxygen concentrations while water clarity was assessed using a Secchi disc. Water samples were collected for later analysis. Parameters measured included soluble reactive P (SRP), TP, total lanthanum (TLa), soluble lanthanum, chlorophyll *a* and phytoplankton abundance, community composition and bioassessment of biovolume. Crustacean zooplankton and macroinvertebrates were also collected for later analysis at the open water sample sites. For further details of sampling processing and analyses see Spears *et al.* (2012). In this paper only the mean annual surface water TP and chlorophyll *a* concentration results are reported on.

## Aquatic macrophyte community monitoring

Assessment of the aquatic macrophyte communities at Loch Flemington, pre - and post - application of Phoslock®, involved three separate but related sampling monitoring programmes: Site Condition Monitoring (SCM) surveys, monthly qualitative assessments of the submerged vegetation and monitoring of the maximum macrophyte growing depths. Aquatic macrophyte data from a comprehensive 1988 survey of Loch Flemington, carried out by the Nature Conservancy Council Scottish Loch Survey team (NCC, 1988), were used to help draw historical comparisons.

### *Site Condition Monitoring (SCM) surveys*

The Site Condition Monitoring (SCM) survey method followed the Common Standards Monitoring (CSM) protocols produced by the UK Joint Nature Conservation Committee (JNCC) for assessing the aquatic macrophyte communities of standing waters of conservation importance (JNCC, 2005; JNCC, 2009). Pre-Phoslock® application SCM surveys were carried out in 2003/04 and 2009 and post-Phoslock® application aquatic macrophyte surveys were carried out in 2010 and 2011 (Table 1). Although the sampling effort differed slightly between these different SCM-style surveys, the resultant data are considered to be broadly comparable.

The SCM aquatic macrophyte survey techniques employed at Loch Flemington involved three main elements and are described in detail by (Gunn *et al.*, 2010; JNCC, 2005; JNCC, 2009). These were as follows: (1) perimeter strandline searches; (2) shore-wader depth transect surveys; and (3) boat-based depth transect surveys.

All three methods were based on representative 100 m sections or sectors selected around the perimeter of the lake in areas thought to be suitable for sustaining good aquatic macrophyte populations. Both the shore-wader and boat-based depth transects involved 20 sampling points per survey sector. These SCM methods were designed to produce data which are statistically robust (Gunn *et al*., 2010).

### ***Qualitative assessments of aquatic macrophyte vegetation***

Seven monthly pre-application and thirteen monthly post-application qualitative assessments of the aquatic macrophyte community composition and abundance were carried out at Loch Flemington between May 2009 and July 2011. These assessments involved random searches, by boat, for a fixed period of two hours. These searches were standardised by starting at a fixed point and going back and forth across the lake in straight transect lines sampling the submerged vegetation en route using a double-headed rake and/or using a bathyscope.

### ***Macrophyte maximum growing depth (MMGD) monitoring***

The MMGD of submerged macrophytes at Loch Flemington were assessed using a boat along five fixed transects that were evenly spaced around the deepest, north-eastern bay of the lake. Pre-application monitoring of the MMGD was carried out on a monthly basis from July 2009 to November 2009 and just before the Phoslock® application on the 11th March 2010. Post-application monitoring of MMGD was also carried out on a monthly basis from April 2010 through to March 2011 with an additional monitoring occasion in July 2011 using methods as described by Jupp *et al*. (1974). Water depth and plant occurrence were measured at about 2 m horizontal intervals along each transect until a point was reached at which no plants were collected. MMGD was corrected for changes in water level by measuring water level at a common datum and subtracting water level height from the measured MMGD. The common datum was fixed at an average water depth of 0.38 m (range 0.14 to 0.69 m). The methodology followed Spears *et al*. (2009). Data sets were arranged into seasons consisting of three months in line with the standard meteorological definition (Trenberth, 1983) resulting in four seasons: summer (June – August), autumn (September – November), winter (December – February) and spring (March – May). Statistical analyses were conducted using the software package Minitab 16 (Minitab® 16.1.1, Minitab

Ltd., Coventry, UK). Data sets of MMGD were not normally distributed (Anderson-Darling test, $\alpha < 0.05$) even after a range of transformations (including $x' = \log(x)$, $x' = \ln(x)$, $x' = \text{sqrt}(x)$, $x' = x^2$). Therefore a non-parametric Mann-Whitney U-test (MWU) was used to test for significant variation in MMGD between years for a given season, for seasons consisting of at least two out of three possible months as it is assumed that at least two months are required to represent a season. This procedure resulted in the following statistical comparisons: summer 2009 vs. summer 2010 and autumn 2009 vs. autumn 2010.

### Clear-cutting experiment to mechanically control *E. canadensis*

To assess the response of native macrophytes species in the absence of the non-native *E. canadensis* in Loch Flemington, a replicated clear-cutting experiment was carried out (summer 2010) following the application of Phoslock®. A diver manually cleared five 4 $m^2$ plots of *E. canadensis* and marked a further five plots as controls. The percentage volume inhabited (PVI) and the aquatic plant community composition were tracked in each plot over the growing season (May till October) using visual underwater inspection. Statistical analyses were conducted using Minitab 16 (Minitab® 16.1.1, Minitab Ltd., Coventry, UK). Data sets were normally distributed (Anderson-Darling test, $\alpha > 0.05$) but failed of a test for equal variance (Levene's test, $\alpha < 0.05$) even after a range of transformations (including $x' = \log(x)$, $x' = \ln(x)$, $x' = \text{sqrt}(x)$, $x' = x^2$). Therefore, a non-parametric MWU test was used to test for significant variation in PVI between clear cut plots and controls (both $n = 5$) in a given month.

### Condition assessment of Loch Flemington based on aquatic macrophyte monitoring, pre- and post-Phoslock® application

Loch Flemington was judged against the targets set for each of the attributes listed for natural lakes with *Magnopotamion* or *Hydrocharition*-type vegetation in the UK CSM Guidance for Standing Waters (JNCC 2005; JNCC, 2009). To be classified as being in 'favourable condition' Loch Flemington should have an aquatic macrophyte community with species characteristic of a natural eutrophic lake and comply with the specific aquatic macrophyte community composition and structure targets for that type of standing water (JNCC 2005; JNCC, 2009).

In order to evaluate if there has been any change in the trophic status in Loch Flemington, following the application of Phoslock®, the whole lake macrophyte assemblages recorded in the pre-and post-application surveys were assessed using two indices: the Trophic Ranking Score (TRS) (Palmer, 1992; Palmer *et al.*, 1992) and the Plant Lake Ecotype Index (PLEX) (Duigan *et al.*, 2006; Duigan *et al.*, 2007). Both scoring systems are based around assigning a score to species based on their affiliation to particular trophic conditions. Scores of qualifying species can be summed for a site, and an average score per taxon can be calculated to give a site TRS/PLEX score.

## RESULTS

### Summary of key water quality findings from pre- and post-Phoslock® application monitoring

The application of Phoslock® led to a significant decrease in annual mean TP concentrations to levels below the WFD target for the lake (Table 2). This led, in turn, to a significant reduction in algal levels in Loch Flemington, as indicated by decreases in annual mean chlorophyll *a* concentrations (to below the WFD target (Table 2)) and by 77% ($P < 0.001$) and 95% ($P < 0.001$) reductions in summer chlorophyll *a* concentrations in 2010 and 2011, respectively. There was also an increase in Secchi disc water clarity (from <0.5 m in summer 2009 to *c.* 1.4 m in summer 2011) (Spears *et al*., 2012).

Monthly estimates of MMGD between 2009 and 2011 showed that the aquatic macrophyte colonisation depth had significantly increased following the application of Phoslock®. An increase in MMGD was observed in summer (57% deeper; $W = 55$; $p < 0.001$; $n_1 = 10$, $n_2 = 15$) and autumn 2010 (15% deeper; $W = 162$; $p < 0.01$; $n_1 = n_2 = 15$) when compared to 2009, indicating an overall improvement in water quality corresponding with the increase in water clarity (Figure 2). With the lowering of the seasonal and annual mean chlorophyll *a* concentrations (Table 2), following the Phoslock® application, it is estimated that the depth limits of the dominant elodeid plant functional group (i.e. *E. canadensis*) increased (depending on the background light attenuation) from *c.* 1.4 - 1.6 m in 2009 to *c.* 2.3 - 2.9 m in 2011. Linked to this increase in MMGD, the coverage of aquatic macrophytes was estimated to also have increased by between 30 and 40% to c. 80% of the lake bed, after the application of Phoslock®.

### Condition assessment of Loch Flemington based on aquatic macrophyte monitoring, pre- and post-Phoslock® application

The number and abundance of ‘natural eutrophic’ characteristic species recorded in the post-application 2010 and 2011 SCM surveys marginally increased. Although three characteristic eutrophic species were recorded in these surveys, occurring in 28% and 36% of sampling points, respectively (Table 3), this was well below the target of six characteristic species occurring in at least 60% of sampling points. Nevertheless, this was an improvement on the situation in 1988 and 2003 (at a frequency of occurrence of 13% of sampling points), when only one characteristic species, *Potamogeton obtusifolius* Mert. & W. D. J. Koch was recorded and two in 2009 (at a frequency of occurrence of 16% of sampling points) (Table 3). Two other characteristic species, *Potamogeton perfoliatus* L. and *P. x zizii* W. D. J. Koch ex Roth were recorded on the monthly qualitative assessments in 2009 and assessed as "rare" (Table 3). Overall, the aquatic macrophyte community, as indicated by the 2010 and 2011 post-Phoslock® application surveys, remained broadly similar in terms of species composition and richness to the 2009 pre-application surveys and improved compared with the 1988 and the 2003/04 surveys (Table 3). There were no obvious negative impacts of the Phoslock® application on the aquatic vegetation. However, the submerged vegetation of Loch Flemington remained dominated by the non-native *E. canadensis,* which occurred at a frequency well above the 25% target threshold in the SCM survey sampling points (Table 3).

Analysis of the monthly qualitative assessments of the aquatic macrophyte vegetation indicated that the relative abundance of *E. canadensis* and another invasive non-native *Crassula helmsii* (Kirk) Cockayn had increased following the Phoslock® application, although this was not statistically significant. *C. helmsii* was first recorded as having colonised areas of shallows and margins along the northern shore Loch Flemington in 2009, prior to the Phoslock® application. In addition, none of the three species of national conservation value *N. flexilis, P. filiformis* and *P. rutilus* were re-recorded during any of the post-application aquatic macrophyte surveys including the extensive targeted searches carried out as part of the 2010 SCM survey. Overall, on the basis of the above assessments, measured against the set targets for a naturally eutrophic lake, Loch Flemington would still be classified as being in 'unfavourable no change' condition, post-Phoslock® application.

Table 3 summarises all the species and their abundances as recorded in the various different aquatic macrophyte surveys in Loch Flemington over the period of 1988-2011 plus their associated TRS and PLEX scores. Overall, there had been a decline in both the TRS and PLEX average score per taxon values between 1988 and 2011, reflected in the re-appearance of *Apium inundatum* (L.) Rchb, f., *Chara virgata* Kütz. and *Myriophyllum alterniflorum* DC., species characteristic of more mesotrophic conditions (Preston & Croft, 1997; Stewart, 2004) although *M. alterniflorum* was recorded in the lake before the Phoslock® application. Pre- and post application the mesotrophic characteristic species *Potamogeton gramineus* L. has also regularly been recorded. Recordings of these more mesotrophic species are consistent with the palaeoecological results which indicated the lake supported mesotrophic species in the past (Bennion *et al*., 2008). However, Loch Flemington on the basis of its current aquatic plant community would still be classified as a Type 10 eutrophic standing water body (Palmer, 1992; Palmer *et al*., 1992) and as a species-poor example of a Group G Central and Eastern, above neutral, lowland lake with *Lemna minor*, *Elodea. canadensis*, *Potamogeton natans* and *Persicaria amphibia* (Duigan *et al.*, 2006; Duigan *et al*., 2007).

### Clear-cutting experiment to mechanically control *E. canadensis*

The result of the replicated clear-cutting experiment on *E. canadensis* indicated that although the PVI was reduced significantly ($W = 5$; $p < 0.05$; $n_1 = n_2 = 5$) in the cleared plots the presence of *E. canadensis* was not reduced and no desirable macrophyte species began to colonise the cleared patches (Figure 3).

## DISCUSSION

The application of Phoslock® to Loch Flemington led to a reduction in water column P concentrations and summer algal blooms, resulting in increased water clarity which potentially improved the light climate for aquatic macrophytes. As expected, the treatment appeared to have had no negative effect on the aquatic macrophyte community. However, although the light climate had significantly improved the only evidence of changes in the diversity of the aquatic macrophyte community were several new records of mesotrophic species (reflected in a slight decline in the average TRS/PLEX metric scores). Analysis of plant macrofossils taken from a sediment core, collected from the littoral zone of Loch Flemington in 2006, indicated a greater diversity of species characteristic of meso-eutrophic conditions in the years post-1850 than in more recent times (Bennion *et al.*, 2008). These findings suggest that a recovering Loch Flemington should exhibit greater species diversity with more species present which are indicative of meso-eutrophic lakes, including *Chara* species, *Isoetes lacustris* L. *N. flexilis, Nitella* species and *Potamogeton praelongus* Wulfen. Overall, Loch Flemington, post-Phoslock® application, remains classified as a eutrophic lake in ‘unfavourable’ condition on the basis of its failure to achieve a number of its set conservation targets. These included the continued absence of species of conservation interest, *N. flexilis*, *P. filiformis* and *P. rutilus* and the continued dominance of the aquatic vegetation by the non-native *E. canadensis* and the recent colonisation by the invasive *C. helmsii*.

Although in the short-term the Loch Flemington aquatic macrophyte community has yet to show the response to the Phoslock® treatment that are consistent with community shifts reported in other re-oligotrophication studies (e.g. Jeppesen *et al*., 2005), this is perhaps not surprising. Verdonschot *et al.* (2011), in their literature review on the ecological recovery of macrophyte communities from eutrophication, indicated that full recovery of species composition was rarely recorded, often as a result of physical barriers to distribution and/or the loss of nutrient intolerant seed banks in cases where eutrophic conditions had been prevalent for many years. At a structural level, macrophyte colonisation responses are generally observed relatively quickly (i.e. less than five years) after reductions in TP load, as was the case in this study. However, at a community composition level, the recovery timescales for macrophytes to shift from eutrophic to more mesotrophic conditions were generally reported to take place on a longer time-scale from 2 to 40+ years than reported here for Loch Flemington. Verdonschot *et al*. (2011) highlighted a number of factors which could explain such delayed responses in shallow lakes including the following: the suppression of native aquatic macrophyte species by the invasion of more competitive species; constant disturbance of lake sediments, e.g. by wind, linked to changes in climatic conditions (Spears & Jones, 2010), leading to a turbid state predominating (e.g. Lake Apopka, USA; Havens *et al*., 2001); recovery of macrophyte community being, in part, dictated by the presence of individual species seed banks, growth traits, distribution networks and pathways with species characterised by being slower growing, having higher root: shoot ratios, and being longer lived becoming increasingly prevalent as nutrient concentrations reduce (Riis & Biggs, 2011).

In the case of Loch Flemington the recovery of the aquatic macrophyte community may have been hampered by the presence of the invasive species *E. canadensis* and *C. helmsii*. *E. canadensis* holds a competitive advantage over many native species because it can maintain some above-sediment plant growth in the winter (Simpson, 1984) enabling it to outcompete other non-evergreen species that have to regenerate totally from turions or seeds. *E. canadensis* can also utilise bicarbonate rather than carbon dioxide for photosynthesis (Bowmer *et al.*, 1995; Maberly, 1983), which may give it a competitive advantage over species such as *N. flexilis,* which is reliant on carbon dioxide (Wingfield, *et al*., 2005). *N. flexilis* is an annual plant which spreads by underwater pollination and cannot reproduce vegetatively, relying instead on seed production to survive (Wingfield *et al*., 2004). Whilst it is possible that some seeds may survive in the seed bank for more than one year, their longevity is not well understood (Wingfield *et al.*, 2004). However, although no survey of contemporary aquatic macrophyte communities have ever recorded *N. flexilis* in Loch Flemington, a recent palaeoecological study found macrofossils of the species in the lake sediments indicating that it had been present for a minimum of 100 years (Bennion *et al.,* 2008). This suggests that there would be a readily available seed bank for *N. flexilis,* depending on seed longevity, to extend its coverage in the lake should suitable areas of the lake bed be opened up from *E. canadensis* dominance. Like *N. flexilis, P. rutilus* is typically found in unpolluted mesotrophic lakes in northern Scotland (Preston, 1995) and as such it might be expected to re-establish itself naturally in Loch Flemington if there were any local sources from which the plant could re-colonise. Partly because it is rare and partly because it grows often in deeper water where it is difficult to locate (Preston & Croft, 1997), little is known about the long-term survival of *P. rutilus* turions in the sediment. However, it is apparent from the clear-cutting experiment carried out at Loch Flemington, following the Phoslock® application, that local scale mechanical control methods did not help the process of re-establishing the native aquatic macrophyte community, at least in the short term.

While *E. canadensis* is well established at the site and is the dominant submerged macrophyte species, *C. helmsii* appears to be in the early stages of colonisation having first been recorded in Loch Flemington in 2009, prior to the Phoslock® application. Therefore, the options for management of these two species are very different. In the case of *E. canadensis,* although P concentrations in Loch Flemington have significantly dropped following the Phoslock® application, they are still too high to cause a decline in the population, as the species is known to exist in a wide range of nutrient concentrations in the UK (Preston & Croft, 1997). Although mechanical control methods such as clear-cutting may be used to contain the spread of *E. canadensis* it requires implementation on a regular basis, is often labour intensive and even then success in achieving long-term control is unlikely (Howard-Williams *et al.,* 1996). Wade (1990) showed that the recovery of pre-existing submerged vegetation is often rapid after being cut, particularly by species such as *E. canadensis*, which can re-colonise and spread quickly from undifferentiated plant fragments left behind and which is even less susceptible to control by cutting compared to other competitive disturbance-tolerant species such as *Myriophyllum spicatum* (Abernethy *et al.,* 1996). As well as clear cutting a number of other measures have been proposed for the control of dense stands of *E. canadensis*, including the use of jute mats (Caffrey *et al.,* 2010), and in extreme cases, draw-down followed by the application of a herbicide (Cooke *et al.*, 2005) but as far as the authors are aware, there have been no examples of the successful complete eradication of *E. canadensis* from lakes similar to Loch Flemington. In contrast to *E. canadensis*, an opportunity to eradicate *C. helmsii* from the lake exists as it is not abundant or widespread. In 2011, colonies of *C. helmsii* were restricted to shoreline areas and had not yet reached the open water areas of the lake. Control measures of *C. helmsii*, so far, have focused on the use of shading. This has involved identification and mapping existing colonies of *C. helmsii* prior to laying plastic sheeting in an attempt to shade out some of the colonies but this work is extremely time consuming and labour intensive but important, particularly as it may aid the potential re-colonisation by the Nationally Scarce *P. filiformis*, which typically grows in shallow open water areas such as where the *C. helmsii* populations are currently concentrated. Future efforts to manage the *C. helmsii* population, during these early stages of colonisation, are likely to focus on the continued use of plastic sheeting supplemented by the possible use of selective herbicides.

The sediment treatment work in Loch Flemington has, so far, been shown to be successful in reducing P concentrations and summer algal blooms, and improving macrophytes growing conditions without any noticeable negative impacts on the ecology of the aquatic macrophyte community. However, it is also clear that the biological community, as exemplified by the aquatic macrophytes, will take longer than the water chemistry to recover. This study shows that reducing P loading is not sufficient in itself to rapidly restore the aquatic macrophyte species diversity of a lake, including the desirable re-colonisation of species of conservation value, if there is a pre-existing problem with invasive, non-native species or if there is a lack of plant propagules. In the case of Loch Flemington, while *C. helmsii* can be hopefully eradicated before becoming fully established, management *of E. canadensis* will need to focus on control and containment, with the aim of facilitating the recovery of some of the former aquatic macrophyte species diversity, for which the site was renowned. It is also important to emphasise that without reducing nutrient loads from the catchment, the water quality improvements so far brought about by the application of a P-capping agent such as Phoslock®, may not persist. Therefore, it is crucial that catchment nutrient sources continue to be monitored and managed where necessary.

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**Loch Flemington bathymetric map**

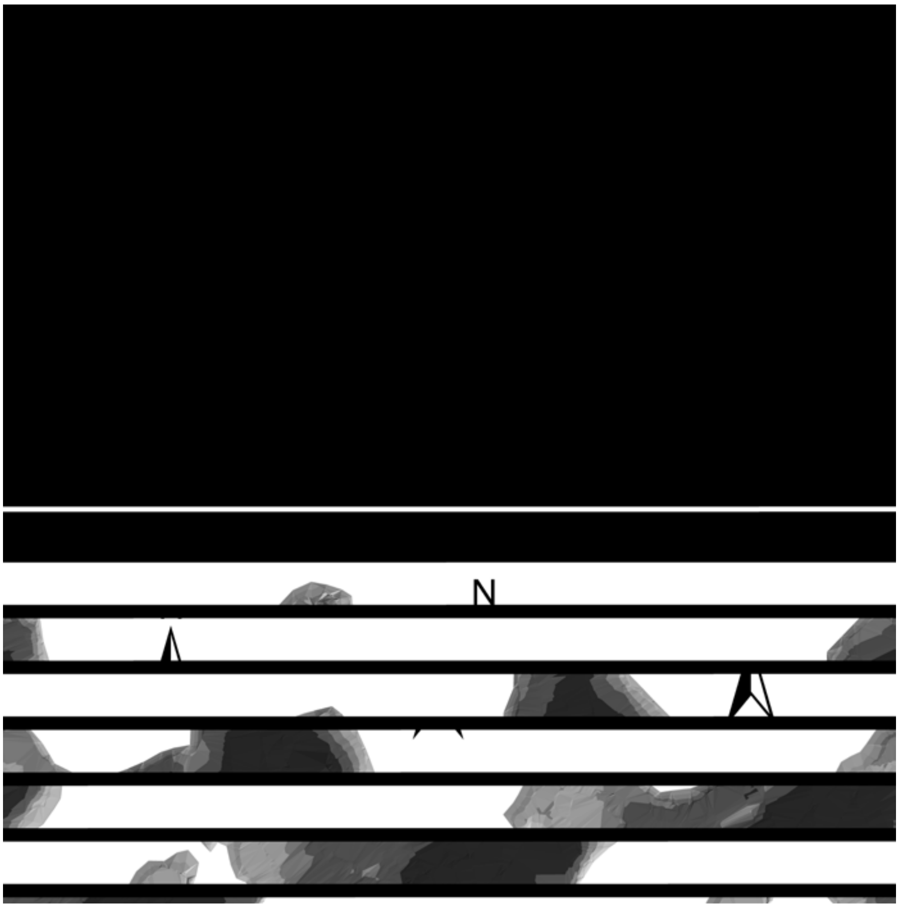

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**Fig. 1.** Bathymetric Map of Loch Flemington

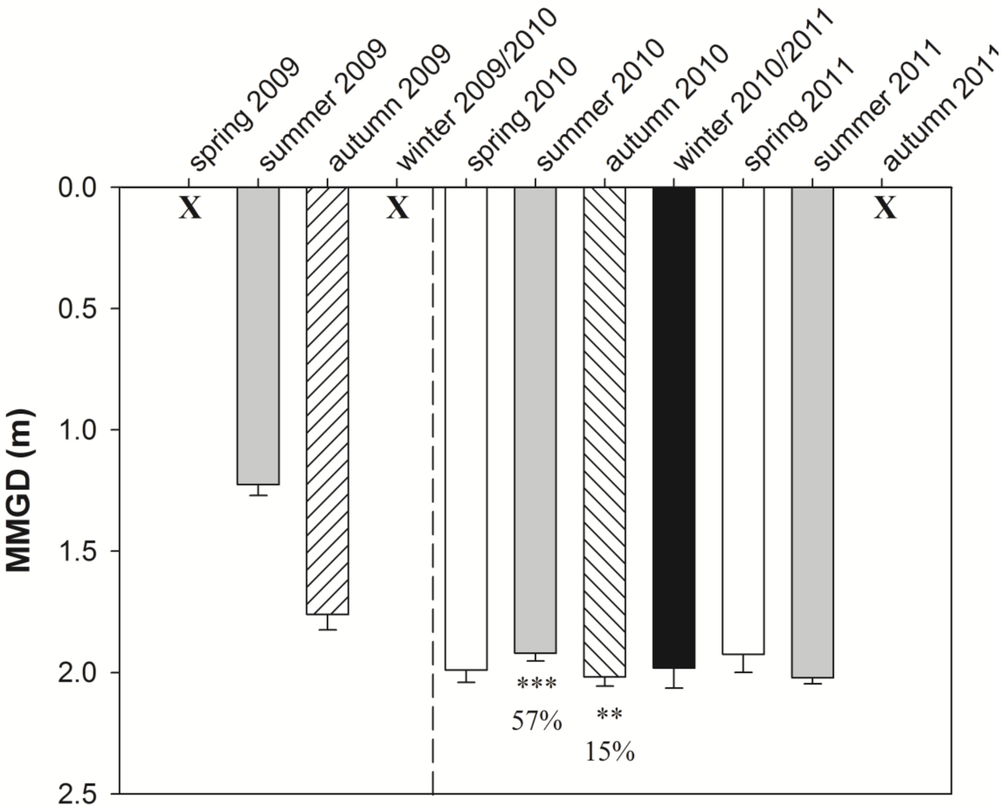

**Fig. 2.** Seasonal variation in macrophyte maximum growing depth (MMGD) in Loch Flemington. Dashed vertical line indicates timing of the Phoslock® application, error bars represent standard error of the mean (n = variable) and seasons in which no sampling occurred are marked with ‘X’. Significant differences (**, $p < 0.01$; ***, $p < 0.001$) in a season between pre- and post-application years and percent change are indicated

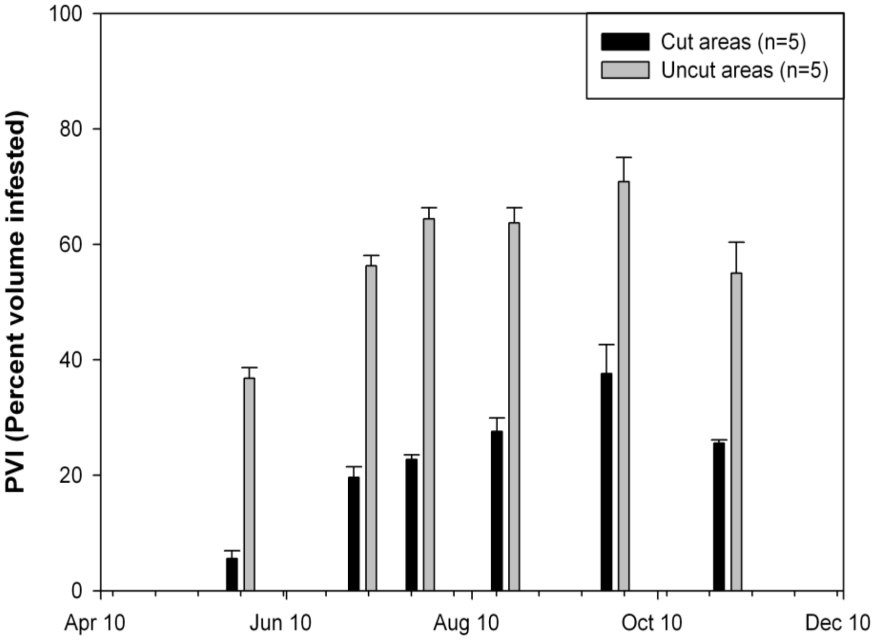

**Fig. 3.** Seasonal variation in percentage volume inhabited (PVI) of *Elodea canadensis* following clear-cutting in five 4 $m^2$ plots compared with five uncut 4 $m^2$ plots in Loch Flemington in 2010. Error bars represent the standard error of the mean.

**Table 1.** Summary of SCM aquatic macrophyte surveys carried out at Loch Flemington, pre- and post-Phoslock® application.

| | **SCM surveys pre-Phoslock® application** | | **SCM surveys post-Phoslock® application** | |
|---|---|---|---|---|
| | 3 July 2003 + 5 August 2004 | 12 August 2009 | 26/27 July + 2/3 August 2010 | 18/19th July 2011 |
| Number of perimeter strandline searches | 4 | 4 | 5 | 4 |
| Number of shore-wader depth transects | 4 | 4 | 3 | 3 |
| Number of boat-based depth transects | - | 1 | 2 | 2 |
| Other | Targeted search for rare species in open-water | - | Targeted search for rare species in open water | - |

**Table 2**. Summary table of annual mean surface water TP and chlorophyll *a* concentrations, pre - and post-Phoslock® application

| **Year** | **Mean TP concentrations (µg P $l^{-1}$) (n = variable)** | **Mean chlorophyll *a* concentrations (µg $l^{-1}$) (n = variable)** |
|---|---|---|
| WFD target | 32 | 16 |
| 2009 (Pre-application ) | 60 | 51 |
| 2010 (Post-application) | 31 | 25 |
| 2011 (post-application) | 27 | 12 |

**Table 3**. Summary of aquatic macrophyte species occurrence, species abundance (% of SCM survey sampling points), Trophic Ranking Scores (TRS) and Plant Lake Ecotype Complex (PLEX) scores for Loch Flemington from 1988 - 2011.

| | | | **Pre - Phoslock® application** | | | **Post – Phoslock® application** | |
|---|---|---|---|---|---|---|---|
| **Species** | **TRS** | **PLEX** | **1988[a]** | **2003/04** | **2009[c]** | **2010[c]** | **2011[c]** |
| *Apium inundatum* | 7.00 | 7,50 | - | - | - | 1% | present |
| *Chara virgata*[d] | 7.30 | 7.69 | - | - | - | present | - |
| *Crassula helmsii* | X | X | - | - | present | present | present |
| *Elodea canadensis* | 8.50 | 7.95 | LD | 56% | 62% | 52% | 51% |
| *Lemna minor*[d] | 9.00 | 8.85 | - | - | 3% | 5% | 28% |
| *Littorella uniflora* | 6.70 | 4.23 | O | 6% | 3% | 3% | present |
| *Myriophyllum alterniflorum* | 5.50 | 4.23 | - | - | 14% | 9% | 7% |
| *Myriophyllum spicatum* | 10.00 | 8.85 | - | 1% | 1% | present | - |
| *Persicaria amphibia* | 9.00 | 7.95 | LD | 28% | 33% | 16% | 22% |
| *Potamogeton gramineus* | 7.30 | 7.31 | - | present | 3% | present | 1% |
| *Potamogeton natans* | 6.70 | 4.23 | - | 7% | 17% | 8% | 6% |
| *Potamogeton obtusifolius*[d] | 7.30 | 6.54 | O-F | 13% | 13% | 27% | 9% |
| *Potamogeton perfoliatus*[d] | 7.30 | 7.69 | - | - | present | - | present |
| *Potamogeton* x *zizii*[d] | X[b] | 7.69 | - | - | present | - | - |
| *Ranunculus aquatilis* | 8.50 | 7.95 | R | - | - | - | - |
| **Total number of species** | | | 5 | 7 | 12 | 12 | 11 |
| **Mean number of species per SCM survey transect (wader & boat)** | | | N/A | 3.75 | 4.00 | 4.17 | 4.20 |
| **Total number of characteristic[d] species** | | | 1 | 1 | 4 | 3 | 3 |
| **% frequency of sampling points with characteristic[d] species** | | | N/A | 13 | 16 | 28 | 36 |
| **Total TRS** | | | 40 | 55.50 | 77.3 | 84.3 | 74.3 |
| **Total PLEX** | | | 34.62 | 47.07 | 75.52 | 75.33 | 66.48 |
| **Mean Score Per Taxon - TRS** | | | 8.00 | 7.93 | 7.73 | 7.66 | 7.43 |
| **Mean Score Per Taxon - PLEX** | | | 6.92 | 6.72 | 6.87 | 6.85 | 6.65 |

[a] in 1988 DAFOR (Dominance, Abundant, Frequent, Occasional, Rare) abundance scale used; LD = Locally Dominant

[b] X indicates no scores allocated to species

[c] species list includes data from monthly qualitative assessments in addition to SCM survey data – only SCM survey data used for abundances

[d] characteristic species of natural eutrophic lakes with *Magnopotamion* or *Hydrocharition*-type vegetation (JNCC 2005; JNCC, 2009)