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Palaeoecological study of two lochs:
Butterstone Loch and Lindores Loch

Final Report to SNH

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COMMISSIONED REPORT

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(*iBids and Project n°,* if applicable)

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COMMISSIONED REPORT
Summary

Palaeoecological study of two lochs: Butterstone Loch and Lindores Loch

Background

Butterstone Loch (SSSI, SPA) and Lindores Loch (SSSI) are both designated sites that are utilised as sports fisheries, and have, historically, been stocked with fish. There are proposals to re-stock the lochs during autumn 2009. The aim of this research project was to supply data to assist Scottish Natural Heritage in its role of advising on the impacts of the proposed fish introductions to the open water interests of the two sites.

The report details the findings of a multi-proxy palaeoecological study of sediment cores collected from the lochs in 2009 and includes analyses of diatoms, Cladocera and plant macrofossils. The study aimed to determine the baseline floral and faunal assemblages and assess ecological change over the last few hundred years. Where possible, any relationship between the observed shifts and historic fish stocking of the lochs was explored.

Main findings

- Butterstone Loch is naturally nutrient-poor, formerly supporting an oligo-mesotrophic macrophyte flora, a non-planktonic dominated diatom community and a diverse zooplankton community. Lindores Loch is naturally more alkaline and productive, formerly supporting a diverse mesotrophic macrophyte flora, a non-planktonic diatom community and a diverse zooplankton community dominated by plant-associated taxa.

- Both lochs have experienced major ecological shifts over the period represented by the cores with increased planktonic production, a relative increase in diatom taxa associated with nutrient-rich waters, a reduction in the diversity and compositional shifts in the zooplankton communities, and a decline in the diversity and conservation interest of the aquatic plant communities.

- In both lochs the most marked and recent changes in the sediment records are coincident with the start of fish stocking operations, although the first notable shifts in the biological assemblages pre-date these by several decades in Butterstone Loch and by over a century in Lindores Loch, and provide evidence of long term, progressive enrichment.

- There is little substantive evidence of changes in fish predation in the palaeoecological record of Butterstone Loch but, in contrast, changes in the zooplankton record since

~1970 of Lindores Loch would be consistent with increased fish predation pressure and a degree of top-down control on the system. Nevertheless it is difficult to separate the effects of fish from those of nutrients.

- A reduction in nutrient concentrations and frequent monitoring of water quality is suggested as a priority for future management and, given the degraded status of both lochs, further fish stocking is not recommended, albeit on a precautionary basis at Butterstone Loch.

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1 INTRODUCTION AND OBJECTIVES

1.1 Background

The purpose of this research was to supply data to assist Scottish Natural Heritage (SNH) in its role of advising on the impacts of proposed fish introductions to the open water interests of two designated sites: Butterstone Loch (Loch of Butterstone, Craiglush and Lowes SSSI and Dunkeld Lochs SPA) and Lindores Loch (SSSI). The two lochs are utilised as sports fisheries and have, historically, been stocked with fish.

Butterstone Loch is a small (43.5 ha), relatively shallow (9 m max depth), lowland (97 m a.s.l.) naturally meso/oligotrophic loch, with a diverse aquatic flora. The site is also notable for the extensive area of fen. It is one of the few sites in Britain where ospreys have returned to breed, and there is also a good range of other breeding birds and wintering wildfowl. The condition of the oligo-mesotrophic loch SSSI feature is currently classed as unfavourable recovering. The annual mean total phosphorus (TP) concentration reported by SEPA, based on regular samples from 2006 to 2009, was ~20 µg L^{-1} compared with annual mean values of ~30 µg L^{-1} from 1999 to 2003. The measured mean orthophosphate (SRP) and chlorophyll a values recorded by SEPA in 2005 were 4 and 21 µg L^{-1}, respectively. The chemical data therefore indicate relatively nutrient-rich conditions and reasonably high algal biomass. Butterstone Loch has been stocked with fish in the past, and there are proposals to re-stock the loch during autumn 2009.

Palaeolimnological research, principally diatom analysis, by Bennion *et al.* (2001b) indicated that Butterstone Loch may have experienced significant ecological changes during the 20th century. It was suggested that possible agricultural activity or forest plantations led to enhanced in-wash of soils in the mid-twentieth century. It was also suggested that the site has undergone nutrient enrichment since ~1960. The most likely cause of nutrient enrichment was thought to be intensification of agriculture in the catchment, with a further source of nutrients being the fish farm that was established in the loch in 1981.

Lindores Loch is a small (40.5 ha), shallow (3.5 m max depth), lowland (68 m a.s.l.) mesotrophic loch, with extensive Charophyte (Stonewort) beds, and the largest number of *Potamageton* species of any open water site in Fife. The loch formerly supported the biodiversity priority species *Najas flexilis* (slender naiad), and therefore the history of this species in the loch as determined by the plant macrofossil record is of interest. The freshwater transition mire is the most extensive and least disturbed example of this habitat type in the District and, together with adjoining rich-fen and alder-willow carr, supports a diverse vascular plant flora which includes a number of local rarities. There is a diverse breeding bird community which includes several regionally uncommon waterfowl species and one national rarity. The condition of the mesotrophic loch feature of the SSSI is currently classed as unfavourable no change. SEPA water chemistry data for the period 2005 to 2009 revealed annual mean concentrations of TP, SRP and chlorophyll a of 93, 30 and 46 µg L^{-1}, respectively, indicating nutrient-rich conditions and high algal biomass. This site has been previously stocked with rainbow and brown trout. There is a proposal to re-stock the site with rainbow trout during autumn 2009.

1.2 Objectives

The project aimed to collect one open water core from each loch for analysis of diatoms and Cladocera to assess shifts in the floral and faunal assemblages. Additionally, the project aimed to collect one littoral core from each loch for analysis of plant macrofossil remains to assess changes in the aquatic plant communities. It was anticipated that the sediment records would cover at least the last few hundred years so that the nature of the baseline

biological assemblages can be determined. The project aims to apply an existing diatom-phosphorus (P) transfer function to the diatom data in order to infer the trophic histories of the lochs.

The project built on the previous palaeoecological study of Butterstone Loch (Bennion *et al.,* 2001b) by adding information on changes in the Cladocera and aquatic plant communities. The diatom record of the new core was compared with that produced by Bennion *et al.* (2001b) to determine the degree of reproducibility. There have been no previous palaeoecological studies of Lindores Loch so this project provided the first such data for this site. For both lochs the project aimed to assess ecological change and, where possible, explored any relationship between the observed shifts and historic fish stocking of the lochs.

2   METHODS

2.1   Core collection

A total of four sediment cores, approximately 1-1.5 m long, were collected on 17 and 18 February 2009 using a piston coring device. Cores were taken from two locations in each loch; one from the open water and one from the marginal/littoral zone, and locations were recorded by GPS.

Water depth, secchi depth, water temperature and pH were measured at each loch, and site details were noted. Summary details of the cores are given in Table 1 and additional notes are presented in Table 2.

2.2   Extrusion and core description

The cores were extruded in the field at 1 cm intervals and any visible stratigraphic changes were noted. The percentage dry weight (%DW) which gives a measure of the water content of the sediment, percentage loss on ignition (%LOI) which gives a measure of the organic matter content, and percentage carbonate were determined in the laboratory on alternate samples from each core by standard techniques (Dean, 1974). The pair of cores from each site was not sufficiently similar in their %DW or %LOI profiles to enable correlation by this method. Therefore, the results of X-Ray Fluorescence (XRF) analyses were used for core correlation purposes where possible (see section 2.4).

2.3   Radiometric dating

A reliable method of establishing a chronology for sediment cores is to use radiometric dating techniques (Appleby, 2001). ^{210}Pb occurs naturally in lake sediments as one of the radioisotopes in the ^{238}U decay series. It has a half-life of 22.26 years, making it suitable for dating sediments laid down over the past 100-150 years. The total ^{210}Pb activity in sediments comprises supported and unsupported ^{210}Pb. In most samples the supported ^{210}Pb can be assumed to be in radioactive equilibrium with ^{226}Ra and the unsupported activity at any level of a core is obtained by subtracting the ^{226}Ra activity from the total ^{210}Pb (Appleby *et al.*, 1986).

^{210}Pb dates for sediment cores can be calculated using both the constant rate of ^{210}Pb supply (CRS) model and the constant initial ^{210}Pb concentration (CIC) model (Appleby & Oldfield, 1978). The CRS model is most widely accepted; it assumes that the ^{210}Pb supply is dominated by direct atmospheric fallout, resulting in a constant rate of supply of ^{210}Pb from the lake waters to the sediments irrespective of net dry mass accumulation rate changes. If there are interruptions to the ^{210}Pb supply, for example sediment focusing, dates are calculated either by the CIC model or by using a composite of both models. The factors controlling the choice of model are described in full in Appleby & Oldfield (1983).

^{137}Cs (half-life 30 years) and ^{241}Am are artificially produced radionuclides, introduced to the study area by atmospheric fallout from nuclear weapons testing and nuclear reactor accidents. ^{137}Cs activity in sediments prior to the 1986 Chernobyl nuclear accident derives mainly from nuclear weapons testing fallout. Where this isotope is strongly adsorbed on to sediments, the activity versus depth profile is presumed to reflect varying fallout rate and useful chronological markers are provided by the onset of ^{137}Cs fallout in 1954, and peak fallout in 1963.

Sediment samples from each of the open water cores were analysed for ^{210}Pb, ^{226}Ra, ^{137}Cs and ^{241}Am by direct gamma assay in the Bloomsbury Environment Institute at University College London using either an ORTEC HPGe GWL series well-type, or an ORTEC HPGe

LOAX series planar-type, coaxial low background intrinsic germanium detector. ^{210}Pb was determined via its gamma emissions at 46.5keV, and ^{226}Ra by the 295keV and 352keV gamma rays emitted by its daughter isotope ^{214}Pb following three weeks storage in sealed containers to allow radioactive equilibration. ^{137}Cs and ^{241}Am were measured by their emissions at 662kev and 59.5kev. The absolute efficiencies of the detector were determined using calibrated sources and sediment samples of known activity. Corrections were made for the effect of self absorption of low energy gamma rays within the sample (Appleby *et al.*, 1992). The raw data are presented in Appendix 1 and the chronologies are described below.

2.4   XRF analyses and core correlation

XRF analysis is a method that measures the abundance of chemical elements in a material in order to determine its composition. Here, XRF analyses were carried out to track downcore changes in chemical composition as a potential means of correlating the pairs of cores from each site. High sensitivity energy dispersive X-ray fluorescence analysis was performed using a Spectro X-Lab 2000 instrument in the Department of Geography at UCL which covers all elements from Na-U. Sub-samples (every 3rd cm) from each core were run under helium, as a fine powder, using an internal calibration. Standards were run alongside the samples to check for accuracy and precision. Core correlation was based on the observation of common features in the XRF profiles of the open and littoral cores, such as peaks in concentrations or relative abundances of the major elements. All data were normalised by dividing by %LOI prior to correlation to ensure that changes in elemental composition were not simply a function of changes in percentage organic matter.

2.5   Diatom analysis

Diatom slides were prepared from 12 sub-samples of the open water cores using standard techniques (Battarbee, 1986). Analysis was carried out using a Leitz research microscope with a 100x oil immersion objective and phase contrast. Principal floras used in identification were Krammer & Lange-Bertalot (1986-1991). A minimum of 300 valves were identified in each sample. All diatom data are expressed as percentage relative abundance.

An existing diatom transfer function was applied to the diatom data for each core, following taxonomic harmonisation between the training set and the fossil data. Reconstructions of diatom-inferred total phosphorus (DI-TP) were produced using a Northwest European training set of 152 relatively small, shallow lakes (< 10 m maximum depth) with annual mean TP concentrations ranging from 5-1200 µg TP L^{-1} and a median value for the dataset of 104 µg TP L^{-1} (Bennion *et al.*, 1996). The model performs well and has a low root mean squared error of prediction (RMSEP) of 0.21 log$_{10}$ µg TP L^{-1} for the weighted averaging partial least squares two-component (WA-PLS2) model (ter Braak & Juggins, 1993; Bennion *et al.*, 1996). All reconstructions were implemented using C2 (Juggins, 2003). The accuracy of the reconstructions was assessed by comparison of the DI-TP value for the surface sample with current measured mean TP concentrations from the SEPA database. However it should be noted that this acts only as a guide and that, owing to high variability in TP concentrations, particularly in nutrient rich waters, the measured range of TP values is considerable at some lochs.

2.6   Cladocera analysis

Cladocera are microscopic crustaceans (zooplankton) and are represented in lake sediments by a variety of body parts. They can be used to infer changes in fish population density and shifts in habitat structure (i.e. macrophytes), particularly in shallow lakes (e.g. Jeppesen *et al.*, 1996, 2001). For the cladocera analysis 12 levels from the open water cores were examined. The selected sub-samples were prepared using an adaptation of the standard sub-fossil Cladocera preparation technique (Korhola & Rautio, 2001). This method is based

on that currently employed by colleagues working on Danish lakes (Jeppesen *et al.*, 1996; Jeppesen, 1998). For each sample at least 5 cm^3 of sediment was heated in a deflocculating agent (10% potassium hydroxide, KOH) and sieved at 150 µm and 50 µm. The retents of the two sieves were then washed into separate pots and safranin stain was added. A sub-sample (of known volume) was screened with a compound microscope and the chitinous remains of the Cladocera were identified with reference to Flössner (1972), Frey (1958, 1959) and Alonso (1996). Carapaces, head-shields and post-abdomens were recorded separately. All Cladocera data are expressed as percentage relative abundance.

2.7   Plant macrofossil and zooplankton ephippia analysis

For the macrofossil analysis 12 levels from the littoral cores were examined. A measured volume of sediment ($\sim$ 30 cm^3, the exact volume was assessed using water displacement) was analysed for each level. Samples were sieved at 350 and 125 microns and the residues from each were transferred using distilled water to plastic vials for storage. The entire residue from the 350 micron sieve was examined under a stereomicroscope at magnifications of x10-40 and plant and animal macrofossils (mostly zooplankton ephippia) were identified and enumerated. A quantitative sub-sample, approximately one fifth of the sample, from the 125 micron sieve sample was analysed for smaller remains such as leaf spines. All material was identified by comparison with herbarium documented reference material.

It was not always possible to ascribe remains to species level, thus in some cases an aggregate group of species corresponding to the highest possible taxonomic resolution was used. For example, *Potamogeton pusillus* agg. included remains of *P. pusillus* and *P. berchtoldii*. Distinct morphotypes of *Chara* oospores were also identified and presented as *Chara* oospores A, B or C. The data are presented as numbers of remains per 100 cm^3 of wet sediment.

2.8   Data analysis

Summary statistics of the biological data (diatoms, Cladocera, plant macrofossils) were calculated for each sample in the cores including the number of taxa observed and the Hill's N2 diversity score (Hill & Gauch, 1980). The results of the biological analyses were plotted as stratigraphic diagrams using C2 (Juggins, 2003). Cluster analysis was performed on the core data to identify the major zones in the biological records using CONISS (Grimm, 1987), implemented by TGView version 2.0.2 (Grimm, 2004) or ZONE v.1.2 (Juggins, 1991). CONISS is a program for stratigraphically constrained cluster analysis by the method of incremental sum of squares and ZONE is an MS-DOS program which employs a variety of constrained clustering techniques. Zones are illustrated on the stratigraphic plots for each biological group in order to facilitate description of the major compositional changes.

The degree of floristic change in the diatom assemblages and faunistic change in the Cladocera asssemblages between the bottom sample and every other sample in each core was assessed using the squared chord distance (SCD) dissimilarity coefficient (Overpeck *et al.*, 1985) implemented in C2 (Juggins, 2003). This is preferred to other dissimilarity measures as it maximises the signal to noise ratio, it performs well with percentage data and has sound mathematical properties (Overpeck *et al.*, 1985). The scores range from 0 to 2 whereby 0 indicates that two samples are exactly the same and 2 that they are completely different. Scores less than 0.29, 0.39, 0.48 and 0.58 indicate insignificant change at the 1st, 2.5th, 5th and 10th percentile, respectively (Simpson, 2005). It is advised that the 2.5th percentile (score <0.39) is used here to define sites with low change between the bottom and every other sample. This is more stringent than the 5th percentile (score <0.48) used in previous similar studies (e.g. Bennion *et al.*, 2004b) and reflects revised thinking on the use of the chord distance statistic. This revision follows closer examination of sediment sample diatom data from over 200 UK lake cores held in the ECRCs in-house AMPHORA database

whereby unimpacted sites typically have chord distance values of <0.4 (in many cases <0.3) between core top and bottom samples (e.g. Bennion, 2004). The original selection of the 5th percentile to indicate low change was developed based on between site comparisons where one has to account for natural variability (background noise) in the dataset – the result of natural differences between sites - and to reflect that no two sites will ever be perfectly similar in practise (Simpson, 2005; Simpson *et al.*, 2005). The SCD scores were not calculated for the macrofossil assemblages owing to the difficulty of applying this technique to abundance data, especially where the amount of the identifiable remains varies between plant taxa.

Indirect ordination techniques (principal components analysis – PCA) (ter Braak & Prentice, 1988) were used to analyse the variance downcore within the diatom, Cladocera and plant macrofossil assemblages, respectively, using CANOCO version 4.5 (ter Braak & Smilauer, 2002). The technique summarises the main changes in the data and helps to identify zones of change within complex species-rich data sets. The sample scores for PCA axis 1 are given. Where scores between two neighbouring samples in the core differ markedly this indicates that the assemblages have undergone substantial change between these two points in the core. The scores are also plotted in the stratigraphic diagrams to illustrate the timing of any shifts and whether these were gradual or abrupt.

Table 1 Details of the sediment cores collected from the two study sites

Site name	WBID	Lake NGR	Alt (m)	Area (ha)	Max depth (m)	Core code	Sampleid	Coring date	Core type	Coring location	Core length (cm)	Coring water depth (m)	Approx distance from shore (m)	Secchi depth-Feb09 (m)	pH	Water temp (°C)
Butterstone Loch	23531	NO 059 449	97	43.5	9.4	BUTT4	509929	17-Feb-09	Fat piston	NO 05971 44896	108	6.9	central	4.2	7.46	2
						BUTT5	509930	17-Feb-09	Fat piston	NO 05805 45172	102	2.1	50			
Lindores Loch	24422	NO 266 163	68	40.5	4.2	LIND1	509931	18-Feb-09	Fat piston	NO 26676 16408	120	3.5	central	0.9	9.54	4.6
						LIND2	509932	18-Feb-09	Fat piston	NO 26502 16372	145	2.7	80			

Table 2 Site and extrusion notes for the two study sites

Site name	Core code	Site notes	Extrusion notes	Further notes
Butterstone Loch	BUTT4	*Phragmites* in margins (narrow band along N, E, W shores). Other plants seen: *Elodea canadensis, Eleocharis acicularis, Elatine (hexandra?), Myriophyllum alterniflorum, Littorella uniflora, Potamogeton crispus.* Core taken in middle of loch but deepest point avoided as this is the site of the now removed fish cages (bottom likely to be disturbed).	Good top with chironomid tubes. No abrupt changes, colour change gradual; 0-26 dark brown; > 26 stiffer with grey-green streaking/marbling; > 30 lighter brown to base; > 97 more consolidated.	Fish cages removed in Dec 03/Jan 04 by present owner. No plans to reintroduce cages. Algal blooms have reduced since cage removal.
	BUTT5	Core taken off north shore. *Phragmites*, willow and alder in margins. *Elodea* beds and *Nitella* seen at coring site.	Top ok. 0-10 dark brown; 10-26 noticeably greenish-grey; 26-35 dark brownish grey with greenish streaks gradually changing to > 35 mid-brown.	
Lindores Loch	LIND1	Plants seen: *Ranunculus aquatilus* agg, *Lemna trisulca, Elodea canadensis, Eleocharis* spp., *Littorella uniflora.* Core taken in middle of loch.	Visible colour change at ~52 cm from dark brown to mid brown but gradual. Organic material with plant remains.	
	LIND2	Core taken in SW end offshore of *Phragmites*.	Similar sediment composition to the open water core with gradual colour change from dark to mid brown	Marginal core attempted at NO 26919 16439 in NE end near beds of *Persicaria (?)* but no sediment found

3 BUTTERSTONE LOCH

3.1 Core description

A piston core, BUTT4, 1.08 m in length, was collected from Butterstone Loch on 17 February 2009 in the deep water basin in a water depth of 6.9 m. A second core, BUTT5, 1.02 m in length, was collected on the same day, approximately 50 m from the northern shore in a water depth of 2.1 m.

The upper 26 cm of the open water core, BUTT4, was dark brown in colour, after which the sediment became more consolidated and greyish-green streaking was evident. Below 30 cm the sediment was lighter brown in colour although the colour change was gradual rather than abrupt (Figure 1a). BUTT4 was relatively organic throughout most of the core with %LOI values of ~25%, with the exception of the section from 15-45 cm where values decreased to ~15% (Figure 2). Carbonate values were very low throughout the core at 2-4%.

The littoral core, BUTT5, was dark brown in colour in the upper 10 cm, similar to the material in the upper part of BUTT4 (Figure 1b). From 10-26 cm there were notable greyish-green streaks (Figure 1c) and from 26-35 cm the sediment was a dark brownish grey with greenish streaks. The colour gradually changed to a mid-brown from 35 cm downwards. The section below 35 cm was relatively organic with %LOI values of 25%, as seen in BUTT4. However, the section from 5-35 cm was more minerogenic with low %LOI values of ~5-10% (Figure 3). The uppermost 5 cm were organic again with %LOI values of ~20%. Similarly to BUTT4, carbonate values were very low throughout the core at 3-4%.

Figure 1 Photographs of the cores from Butterstone Loch

a) BUTT4- open water core

b) BUTT5 – littoral core

c) BUTT5- greyish-green streaking

Figure 2 Percentage dry weight (DW), organic matter (LOI) and carbonate (CO3) profiles of BUTT4
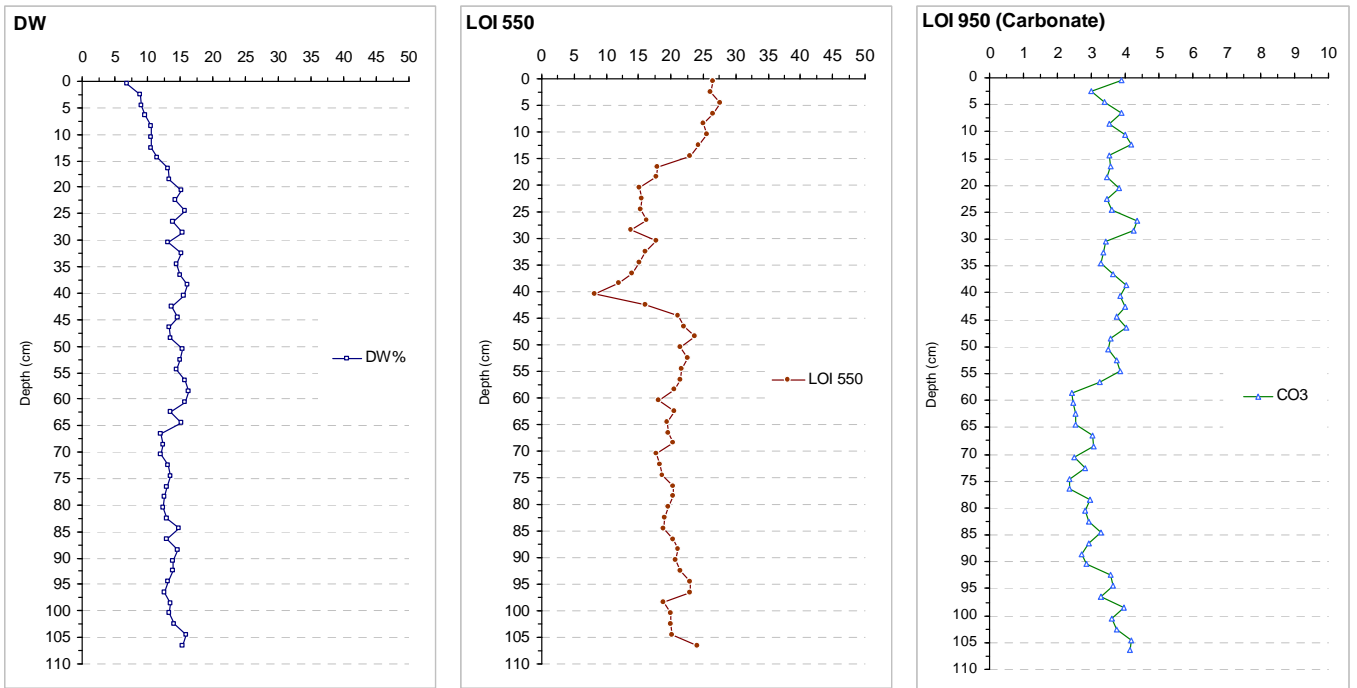
Figure 3 Percentage dry weight (DW), organic matter (LOI) and carbonate (CO3) profiles of BUTT5

10
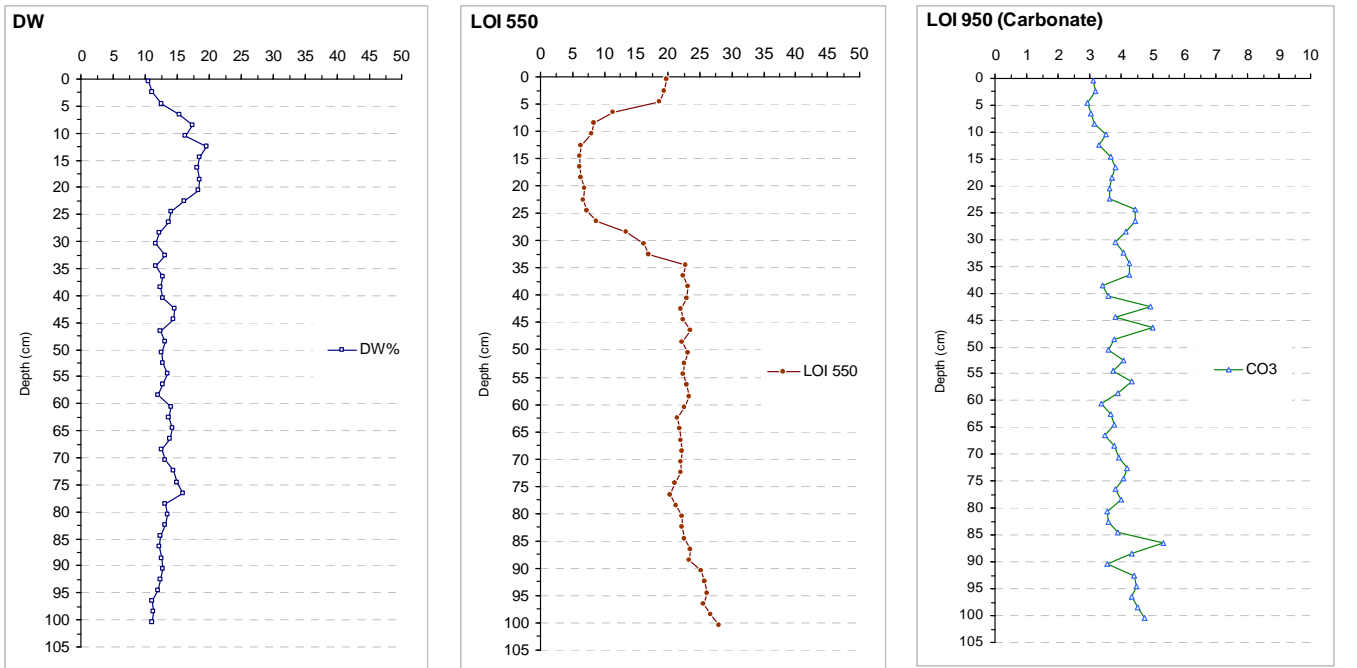
3.2 Radiometric dating

Equilibrium of total ^{210}Pb activity with the supporting ^{210}Pb, measured as ^{226}Ra activity, appeared to occur at ~17 cm of the core (Figure 4a). Unsupported ^{210}Pb activities, calculated by subtracting ^{226}Ra activity from total ^{210}Pb activity, declined irregularly with depth (Figure 4b). The top 6 cm showed little net decline, and below 7 cm the decline in unsupported ^{210}Pb activities was not exponential, suggesting that sediment accumulation rates are unstable. There appeared to be an increase in sediment accumulation rates towards the surface.

The ^{137}Cs activity versus depth profile (Figure 4c) had a well-resolved peak at 10.5 cm. This coincided with the detection of ^{241}Am in the core, thereby confirming that this represents 1963, the period of fallout maximum from the atmospheric testing of nuclear weapons.

Use of the CIC model was precluded by the non-monotonic nature of the ^{210}Pb data. Hence, ^{210}Pb chronologies were calculated using the CRS dating model (Appleby & Oldfield, 1978). The CRS dating model placed the 1963 layer at 10.5 cm which is in excellent agreement with the ^{137}Cs and ^{241}Am records, suggesting the CRS dates are reliable. Sedimentation rates calculated by unsupported ^{210}Pb data show an increase from the 1870s at 0.0046 g cm^{-2} yr^{-1} to present day values of 0.033 g cm^{-2} yr^{-1} (Table 3, Figure 5).

Table 3 ^{210}Pb chronology of core BUTT4

Depth	Drymass	Chronology			Sedimentation Rate		
		Date	Age				
cm	g cm^{-2}	AD	yr	±	g cm^{-2} yr^{-1}	cm yr^{-1}	± %
0.5	0.0413	2009	0	1	0.0332	0.397	7.9
1.5	0.1239	2005	4	2	0.0312	0.367	8
3.5	0.2976	2000	9	2	0.0306	0.334	7.2
5.5	0.4913	1992	17	2	0.0218	0.214	7.2
7.5	0.7051	1981	28	2	0.0186	0.169	9
10.5	1.0423	1962	47	3	0.0161	0.142	12.3
12.5	1.2726	1945	64	4	0.0109	0.088	17.2
13.5	1.4022	1929	80	7	0.009	0.072	25.1
14.5	1.5318	1913	96	9	0.0071	0.056	32.9
15.5	1.6614	1897	112	11	0.0051	0.04	40.8
16.5	1.791	1870	139	21	0.0046	0.032	45.1

Figure 4 Fallout radionuclide concentrations in BUTT4 showing (a) total ^{210}Pb, (b) unsupported ^{210}Pb, and (c) ^{137}Cs (solid line) and ^{241}Am concentrations (dotted line) versus depth.
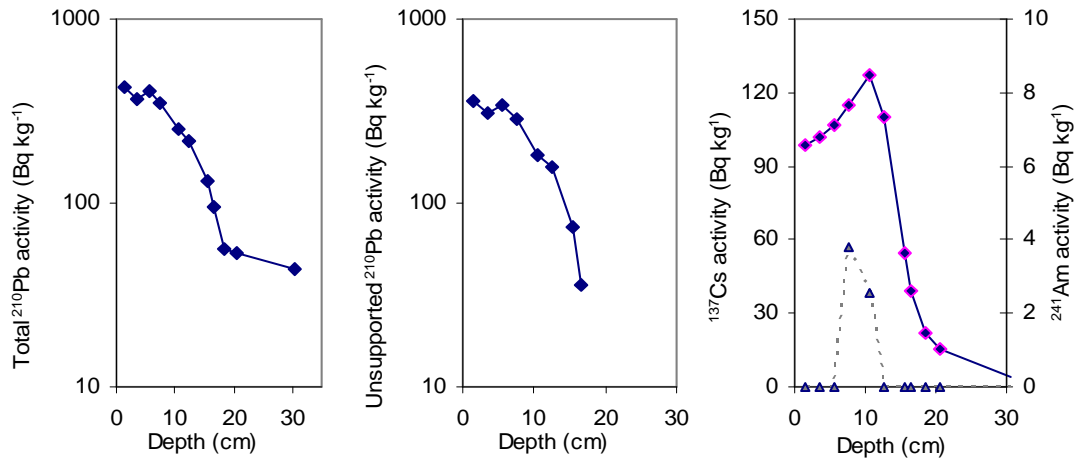
Figure 5 Radiometric chronology of BUTT4 showing the CRS model ^{210}Pb dates and sedimentation rates
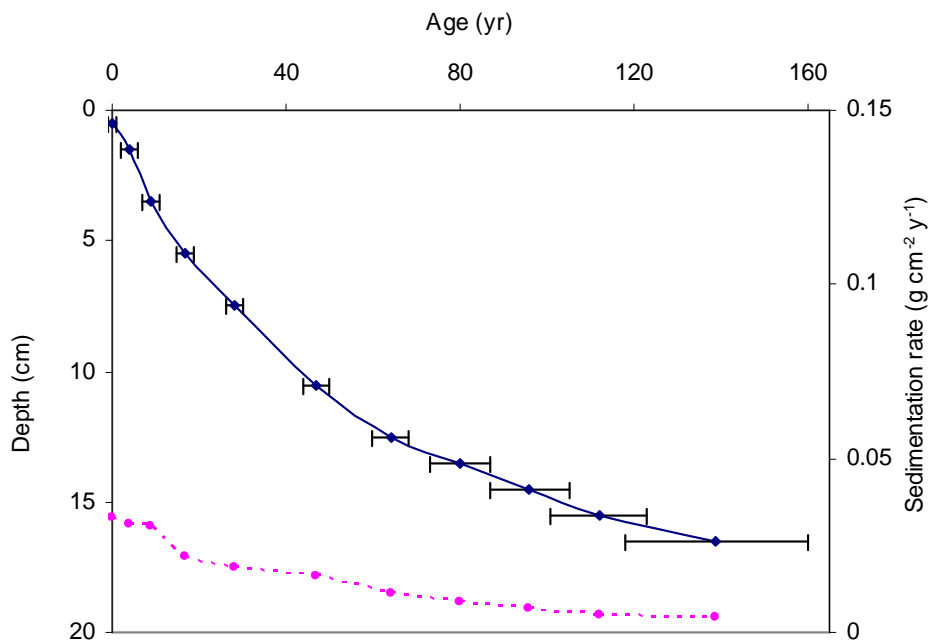
3.3   XRF analyses and core correlation

The XRF profiles of the major elements did not yield sufficient features common to both the BUTT4 and BUTT5 cores to allow core correlation to be undertaken (Figure 6). The sharp peak at ~20 cm in several elements including Mg, Al, Si, P, K, Ca and Ti in BUTT5 was not observed in BUTT4. In BUTT4, a peak was evident at ~40 cm in Si, Cr, Fe and Cu but these features could not be reliably matched against those in BUTT5. Nevertheless, the presence of the peaks is interesting and, although beyond the scope of this project, could represent historical inputs of mine waste. The large differences between the chemical composition of the open and littoral cores is most likely due to the more minerogenic nature of the littoral core and particle size differences between the two cores. The minerogenic layer in BUTT5 from ~5-35 cm could represent major in-wash, possibly arising from a period when the water level was lower (see evidence from the plant macrofossil record), and notably concentrations of all the major elements were at their highest in this section. On the basis of these results, no attempt was made to assign a chronology to BUTT5.

Figure 6 Selected chemical profiles of Butterstone Loch cores based on XRF analysis

a) Major elements (% data, normalised by dividing by %LOI)
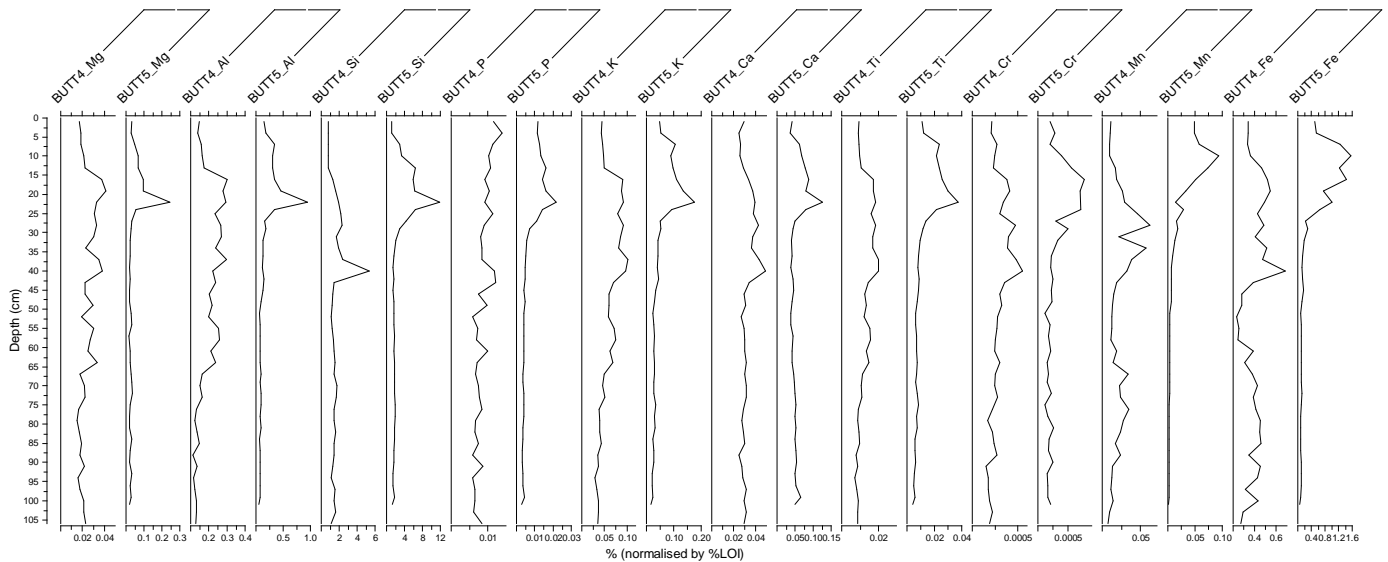
b) Major elements (µg g^{-1}, normalised by dividing by %LOI)
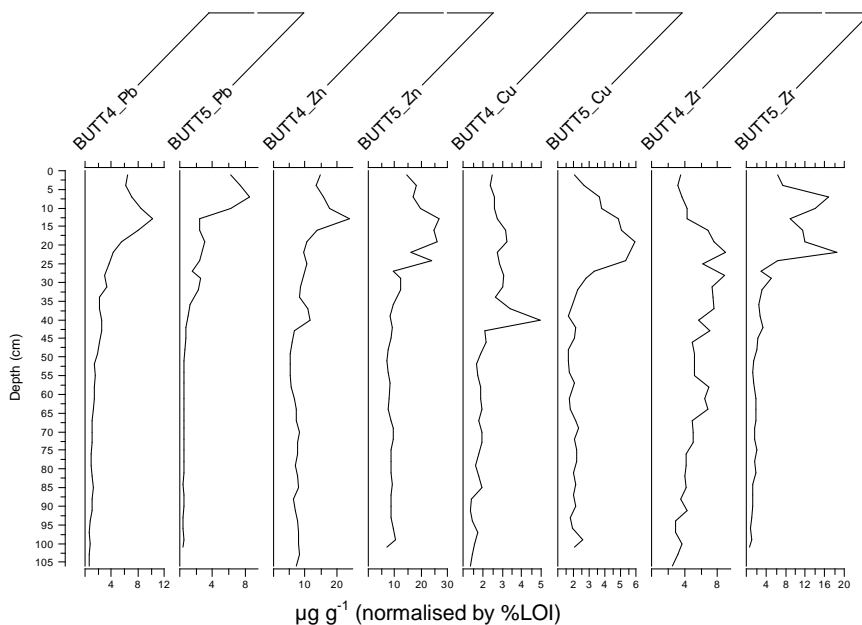
3.4 Diatom analysis

Twelve samples were analysed for diatoms in the BUTT4 core (Table 4). Diatom preservation was satisfactory for counting but valves were often fragmented and dissolved. A total of 166 diatom taxa were observed in the core with between ~50-70 taxa per sample (Appendix 2), and the results for the major taxa are shown in Figure 7.

There were marked changes in the assemblages during the period represented by the core with three zones identified by cluster analysis: Zone 1 from the core base to ~35 cm (pre-1900, date unknown), Zone 2 from ~35 to 9 cm (pre-1900 to ~1970) and Zone 3 from 9 cm to the surface (~1970 to present). Zone 1 (pre-~1900) was comprised largely of non-planktonic taxa (90% of the total assemblage) associated with relatively unproductive waters, particularly *Achnanthes minutissima* and *Achnanthes linearis*. These taxa decline in Zone 2 whilst several planktonic taxa typical of more productive conditions increase in relative abundance towards the upper part of this zone (from ~1900), namely *Aulacoseira subarctica, Aulacoseira ambigua, Stephanodiscus parvus* and *Fragilaria crotonesis*. Hence the planktonic component of the assemblage starts to increase from this time. These four taxa notably expand further in Zone 3 (from ~1970) along with *Asterionella formosa*, a planktonic diatom typically observed in the spring bloom of mesotrophic to eutrophic lakes. Consequently the percentage of planktonic taxa increases still further reaching 40% in the surface sample.

The diatom record indicates a stable period in the early part of the loch's history with only subtle species shifts prior to 1900. The first phase of enrichment starts at ~1900, followed by a second phase from ~1970 to more meso-eutrophic conditions which appear to have prevailed for the last few decades. The gradual but progressive change in the diatom assemblages throughout the sediment core are recorded by the PCA axis 1 scores which steadily decrease towards the surface with a slightly more abrupt change at ~9 cm marking the Zone 2/3 boundary. The SCD scores are low (<0.5) in the core section below 15 cm and then gradually increase to values of 0.85, reflecting the progressive deviation of the diatom assemblages from reference conditions (i.e. those at the bottom of the core).

The DI-TP reconstruction suggests that TP concentrations were relatively stable prior to 9 cm at ~20 µg L^{-1}. Values increased to maximum of ~40 µg L^{-1} in the 5 cm sample (1992) and, whilst there has been some fluctuation, have remained above baseline concentrations with a value for the surface sample of 35 µg L^{-1}. As for several other Scottish lochs, the Northwest European transfer function employed here appears to over-estimate TP concentrations for Butterstone Loch (Bennion *et al.*, 2004b). The annual mean total phosphorus (TP) concentration reported by SEPA, based on regular samples from 2006 to 2009, was ~20 µg L^{-1}. The over-estimation arises because the Northwest European training set contains many lakes with very high TP concentrations and it is in these sites that several of the abundant diatoms in the Butterstone Loch core are found. Hence, these taxa have high TP optima in the model, resulting in high DI-TP values for samples in which these species are abundant. Nevertheless, whilst the actual values appear to be over-estimated, there is no reason to believe that the inferred trend is unreliable.

The diatom record of BUTT4 is very similar to that of an earlier core, BUTT3, collected from the loch in 1998 (Bennion *et al.*, 2001b). The nature and timing of shifts in the major taxa are the same in both cores although the slower sediment accumulation rate in BUTT4 provides a longer record, potentially dating back four or five centuries. In summary, the diatom assemblages of BUTT4 exhibited an initial change at around 1900 with the arrival of planktonic, nutrient-tolerant taxa, followed by a further expansion of these taxa since ~1970 indicative of enrichment of the loch.

Table 4 Results of the diatom analysis on BUTT4

Depth (cm)	No. of taxa	N2	DI-TP µg L^{-1}	SCD	PCA axis 1 scores
1	64	18.85	35	0.85	-0.98
2	58	19.29	29	0.82	-1.01
5	58	14.80	39	0.83	-1.30
7	66	16.42	33	0.75	-1.06
10	62	13.85	23	0.50	0.07
15	61	17.42	23	0.38	0.29
20	62	16.79	23	0.35	0.42
30	70	14.29	21	0.35	0.57
40	52	6.23	14	0.40	1.44
50	69	17.63	25	0.42	0.33
70	61	14.42	19	0.30	0.61
90	68	14.66	20	0.00	0.62

3.5   Cladocera analysis

Twelve samples were analysed for chitinous cladoceran remains in the BUTT4 core (Table 5). A total of 28 taxa were observed in the core with between 18-24 taxa per sample (Appendix 3) and a summary diagram for the major taxa is presented in Figure 8.

Two zones were identified by cluster analysis: Zone 1 from the core base to ~7.5 cm (pre-1900 to ~1980) and Zone 2 from ~7.5 cm to the surface (~1980 to present). The assemblages were diverse throughout the core. In Zone 1 the open-water species, *Bosmina coregoni,* was the most abundant taxon (~20-30%) with *Chydorus piger* and the littoral and plant-associated taxa, *Alonella excisa* and *Alonella nana,* also frequent. There was an increase in the relative abundance of *Bosmina coregoni* to ~50% in the uppermost sample of Zone 1. Zone 2 was very similar to Zone 1 in terms of species composition with the exception that *Bosmina longirostris*, not previously seen in the core, was present in the upper two samples (from ~1990). This is a smaller-bodied species than *B. coregoni* and is, therefore, less vulnerable to fish predation. The relative abundance of *Bosmina coregoni* remained high in Zone 2 whilst several other taxa disappeared, thereby reducing diversity of the Cladocera assemblage in the upper zone (Table 5).

Given the relative stability of the species composition, the PCA axis 1 scores largely mirror the shifts in the abundance of the dominant species *Bosmina coregoni*, with the most marked changes occurring in the upper 10 cm of the core when this taxon increases. The SCD scores are low (<0.4) in the core section below 10 cm, reflecting the similarity of the Cladocera assemblages to those at the bottom of the core. The SCD scores increase slightly in the upper 10 cm to a maximum of 0.56 in the 5 cm sample, as a result of the expansion of *B. coregoni* and the arrival of *B. longirostris*.

Table 5 Results of the Cladocera analysis on BUTT4

Depth (cm)	No taxa	N2	SCD	PCA axis 1 scores
2	18	4.60	0.46	0.78
5	18	3.01	0.56	1.73
10	20	3.44	0.40	1.35
20	20	8.49	0.14	-0.50
30	21	8.35	0.30	-0.70
40	21	9.69	0.30	-0.65
50	23	9.19	0.16	-0.61
60	21	6.89	0.25	-0.36
70	22	5.43	0.25	0.39
80	22	6.48	0.32	0.16
90	20	9.00	0.18	-0.66
100	24	10.38	0.00	-0.94

3.6   Macrofossil analysis

3.6.1   Plant macrofossils

Plant macrofossil remains were enumerated from 12 levels in the BUTT5 core (Table 6). The remains were relatively species poor, however, with only seven aquatic plant species identified (Figure 9, Appendix 4). Three zones were apparent: Zone 1 from the core bottom to 30 cm, Zone 2 from 30 to 12 cm and Zone 3 from 12 cm to the surface of the core. These zones broadly correlate with the changes in organic material in the core (Figure 3 above).

Zone 1 was only slightly more species rich than the upper two zones, with *Najas flexilis* and *Nitella* oospores present in all levels. *Isoetes lacustris* megaspores were recorded in low numbers as well as *Isoetes echinospora* megaspores in the bottom and top levels of the zone. Towards the top of Zone 1 (45-30 cm) there were numerous fragments of unidentifiable plant leaf material, thought to be of reed origin.

Zone 2 was very species poor but had higher numbers of *Isoetes lacustris* megaspores present, as well as low numbers of *Nitella* and *Chara* oospores. No other aquatic plant remains were recorded in Zone 2, but the unidentified plant material seen at the top of Zone 1 was replaced in Zone 2 by large numbers of root fragments; again these were not identifiable. This Zone corresponds with the more mineral-rich section of the sediment core and sieving retained a significant amount of brown, iron-rich, particles.

The top two levels (Zone 3) were typified by higher numbers of *Nitella* oospores and low numbers of *Isoetes lacustris* megaspores. A fragment of *Potamogeton crispus* turion was the only evidence of pondweeds found in the sediment record. *Potamogeton crispus* was observed in the strandline during the coring in 2009.

A recent survey of Butterstone Loch (Darwell *et al.,* 2003) has shown the site to have a relatively diverse aquatic flora which includes *Nitella* spp., *Isoetes lacustris, I. echinospora* and *Najas flexilis,* the remains of which were identified in the sediments, although not all in the uppermost layer as would be expected if currently present. Other species that often leave remains in the sediment record were recorded in a survey carried out in 2003 (e.g. *Elatine hexandra, Myriophyllum alterniflorum, Potamogeton perfoliatus, P. berchtoldii, Eleocharis acicularis, Littorella uniflora, Nuphar lutea* and *N. pumila*) but these were not observed in the core. The recent arrival of *Elodea canadensis* was reported by Darwell *et al.* (2003) but this plant does not preserve in the fossil record. The reasons why the sediment record was so species poor and apparently under-representative of the wider lake flora are unclear. The core was taken in 2.1 m of water which is well within the photic zone for this site (Secchi depth 4.2 m), and close to shallow areas where plant productivity would be expected to be highest. The presence of only the most robust plant material and absence of vegetative remains from aquatic plants suggests that there may be preservation problems rather than lack of supply of material to the sediments. The analysis does,

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however, show a persistent presence at Butterstone Loch of the Schedule 8 species *Najas flexilis* and the nationally scarce species *Isoetes echinospora,* thus promoting the site's conservation importance.

The presence of large numbers of fragments of plant root tissue in Zone 2 and other degraded vegetation fragments at the top of Zone 1 is also unexplained. The root fragments coincide with levels of higher mineral content in the sediments which would suggest a period of increased in-wash and (if the fragments are from reeds) perhaps lower water levels in the past resulting in the coring area being reed bed for a period of time. The testing of these hypotheses is beyond the scope of this project.

Table 6 Results of the plant macrofossil analysis on BUTT5

Depth (cm)	No taxa	N2	PCA axis 1 scores
4	5	2.30	-0.65
10	3	2.67	-0.32
15	2	1.6	-0.08
20	3	1.27	2.13
25	3	1.36	1.21
30	6	3.33	0.22
35	4	2.44	-0.44
40	2	1.77	-0.53
50	4	2.08	-0.35
60	3	2.18	-0.49
70	5	3.13	-0.42
80	5	3.69	-0.29

3.6.2 *Zooplankton ephippia*

Zooplankton ephippial remains were enumerated from 12 levels in the BUTT5. With the exception of the uppermost sample, very few ephippial remains were recorded and all were of the *Daphnia hyalina* type (Figure 10). The very low numbers possibly reflect the relatively low productivity of Butterstone Loch in the past with an increase in the upper level indicative of a degree of enrichment.

Figure 7 Summary diatom diagram of Butterstone Loch core, BUTT4

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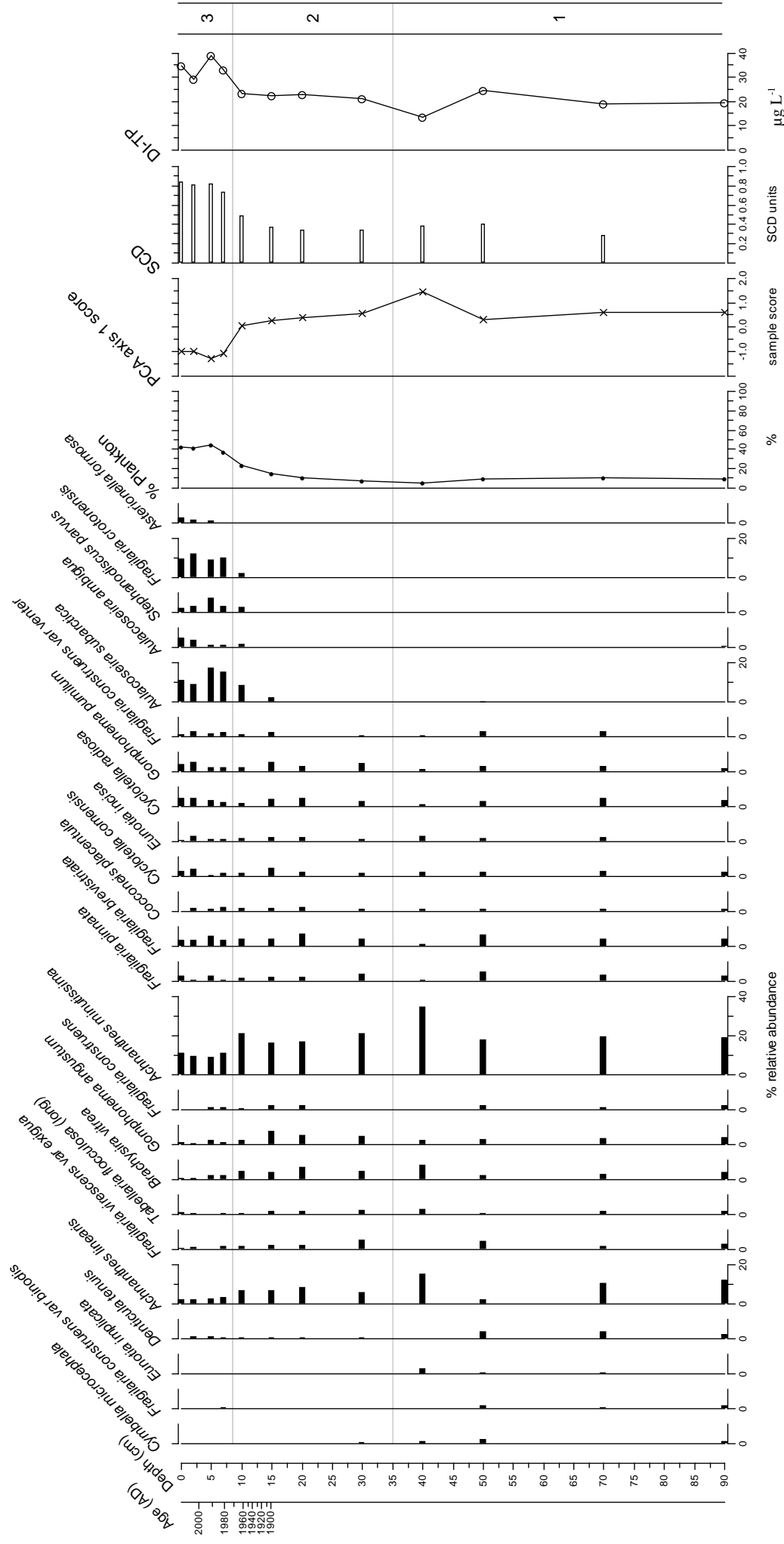
Figure 8 Summary Cladocera diagram of Butterstone Loch core, BUTT4

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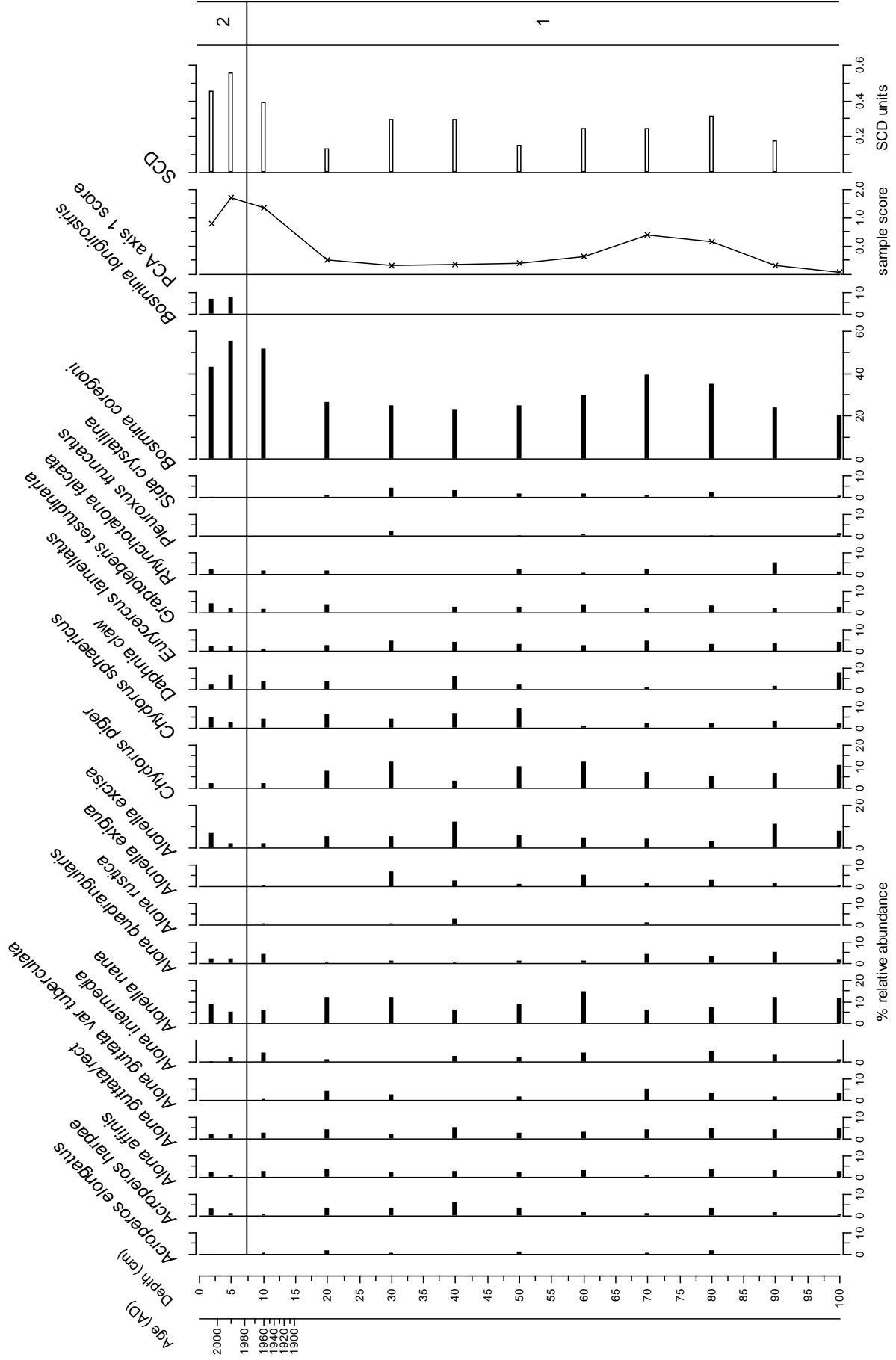
Figure 9 Summary plant macrofossil diagram of Butterstone Loch core, BUTT5
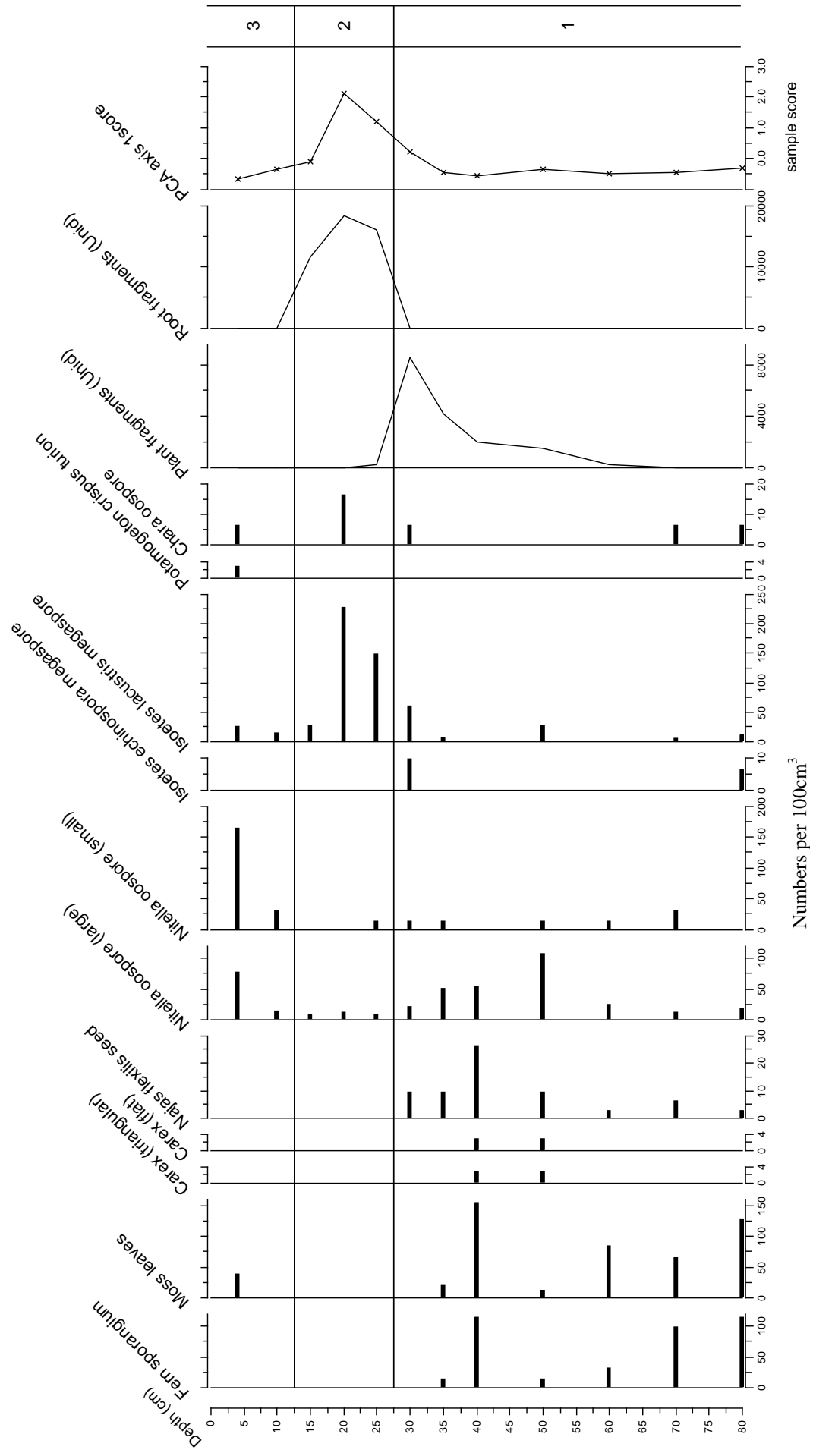
Figure 10 Summary zooplankton ephippia diagram of Butterstone Loch core, BUTT5
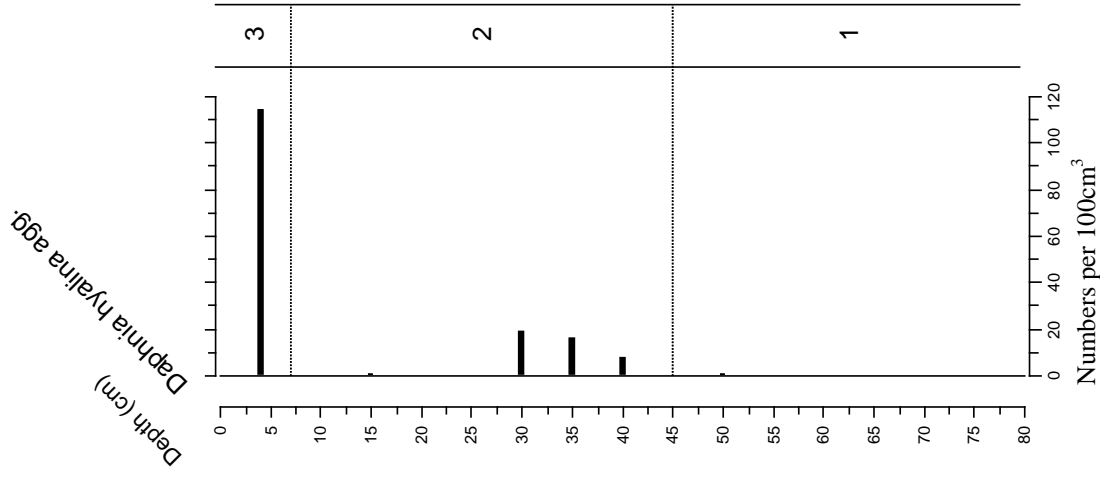
3.7   Discussion

The palaeoecological data indicate that Butterstone Loch is a naturally nutrient-poor loch, formerly supporting an oligo-mesotrophic macrophyte community including *Nitella, Chara, Isoetes,* and *Najas flexilis*, a non-planktonic dominated diatom community and a diverse zooplankton community. There is evidence of enrichment over the period represented by the cores starting at ~1900 and followed by a second phase from ~1970. This takes the form of a shift towards diatoms associated with more productive waters, an increase in the relative importance of planktonic relative to non-planktonic diatoms, a slight reduction in the diversity of the zooplankton community, and shifts in community composition of the Cladocera. The increase in *Bosmina coregoni* since ~1900 is indicative of greater planktonic production as this species feeds on planktonic algae. The record of chitinous cladoceran remains is enhanced by the ephippia data as the increase in pelagic *Daphnia* indicates greater availability of planktonic algae as a food source. Hence, the palaeoecological data suggest an increase in pelagic productivity reflecting more eutrophic conditions (Vadeboncoeur *et al.,* 2003).

A further notable shift in the chitinous Cladocera assemblages is the arrival of *Bosmina longirostris* since ~1980. This is a smaller-bodied species than *Bosmina coregoni* and tends to live mostly in the littoral zone rather than in the open water and is, therefore, less vulnerable to fish predation than *B. coregoni*. The arrival of *B. longirostris* in the sediment record is coincident with the installation of the fish cages in 1981 and hence could potentially signal an increase in fish predation. However, *Daphnia hyalina* increases in the upper core whereas a decline in abundance would be expected if fish predation pressure was the sole cause (see Lindores Loch results below). Given that the main planktonic Cladocera species increase in numbers and/or relative abundance in the upper core it seems more likely that an increase in food availability (as a result of greater planktonic production), rather than any alteration in fish predation pressure, was responsible for the observed changes. Between 1981 and 2004 there were six fish cages in the loch, stocked with 5.1 tonnes of rainbow trout. The caged fish were fed with a low phosphate fish feed, suggesting that predation on the natural zooplankton community would be minimal, and were essentially confined to a small area of the loch, hence top-down effects of fish predation on the wider ecology of the loch are unlikely to be detected. Information on the fish community and stocking practices outside the fish cages was not available at the time of reporting and the fishery website mentions only trout and pike. Nevertheless if it is assumed that fish were released into the loch they would likely exert some grazing pressure on the zooplankton. Whilst large trout tend to be less zooplanktivorous than their smaller counterparts, there would possibly be an indirect impact on the food web, although any such effect was not detectable in the palaeoecological record.

The plant macrofossil data suggest that there have been modest changes in the aquatic vegetation, with a decline in the abundance of the Schedule 8 species *Najas flexilis* and the nationally scarce species *Isoetes echinospora,* and the arrival of *Potamogeton crispus*. Whilst the timing of these changes has not been established, these findings are broadly in accordance with the Site Condition Monitoring report (Scottish Natural Heritage, 2005) which classified the loch as unfavourable and reported a decline in *Najas flexilis* from several thousand plants in 1997 to only one colony of 12 plants in 2004. Murphy & Hall (2005) reported that in 2004 the *Najas* colony was smothered by dense stands of *Elodea canadensis*, which was extremely abundant in the loch. Subsequently, a report to SNH by Benthic Solutions Ltd (2007) based on a survey carried out in September 2007 states that "No *Najas* plants were recorded during the snorkel survey of Loch of Butterstone, even though much time was spent, especially in the vicinity of the previous record of *Najas*". The palaeoecological data suggest that enrichment of the loch has most likely contributed to these changes. Nevertheless, currently Butterstone Loch has a relatively species-rich plant

community of *Isoetes lacustris*, *Littorella uniflora*, fine-leaved *Potamogeton* spp., *Nitella*, *Elatine hexandra* and *Myriophyllum alterniflorum* as well as *Elodea canadensis*.

Whilst there is evidence of ecological change in the sediment record since the installation of the fish cages in 1981, the diatom data indicate that changes have occurred over longer timescales. Indeed the first marked shifts in the diatom assemblages towards taxa typically associated with nutrient-rich waters pre-date the arrival of the fish cages by around 20 years, suggesting that there are several drivers of ecological change operating at Butterstone Loch. The most likely cause of the earlier enrichment is intensification of agriculture in the catchment. Nevertheless the additional pressure of fish stocking in recent decades may have played a role in maintaining the relatively high productivity of the site via bottom-up effects (e.g. Moss *et al.*, 1994), principally addition of phosphate into the water in the form of fish food, as well as excrement. An annual input of 70 kg of phosphate from fish feed was reported in 1997. Prior to February 2000, the discharge consent allowed for an input of 110 kg but this was reduced to 80 kg before being revoked, and the cages removed, in 2004. The current consent, issued in 2004, allows for the release of between 150 and 600 rainbow, brown, blue and gold trout per week, which is a significant number of fish and, therefore, top-down effects on grazing cannot be ruled out (e.g. Zambrano *et al.*, 2006). The latest Site Condition Monitoring report (2005) states that 'Since removal of fish rearing cages the water quality shows early signs of recovery'. The removal of the fish cages in 2004 is too recent for any effect to be observed in the sediment record as the resolution of the data is insufficient.

In previous palaeoecological studies that have examined the impacts of fish stocking on lochs in the North-west Highlands and Islands, the focus has been on lochs in relatively unimpacted, unproductive catchments with extensive sheep grazing (e.g. Bennion *et al.*, 2004a; Clarke *et al.*, 2007). In these cases, the observed ecological shifts in the sediment records could be more readily attributed to the installation of the fish cages. The marked and abrupt changes in the diatom assemblages, indicative of nutrient enrichment, following long periods of stability were coincident with the start of fish farming operations and there were no other pressures in the catchment that could explain the observed shifts (e.g. Bennion *et al.*, 2004a; Clarke *et al.*, 2007). In lowland, more productive catchments such as Butterstone Loch, however, there are multiple pressures and thus, in the absence of detailed historical catchment and fish stocking data and nutrient budget studies, it is difficult to ascertain the degree to which each nutrient source has contributed to eutrophication of the loch.

In summary, the palaeoecological data indicate that whilst Butterstone Loch still retains the flora and fauna of a mesotrophic system, it has experienced enrichment leading to an increase in planktonic production, most notably since ~1970, and a decline in the aquatic plant community. Shifts in all the biological elements examined in this study indicate that there is deviation from the pre-enrichment reference communities and that the loch has undergone a moderate degree of ecological change. The extent to which fish stocking has contributed to the observed degradation cannot be established with any certainty but there is evidence of ecological change since the installation of the fish cages in 1981 and this, and the subsequent stocking, may have played a key role in eutrophying and degrading the site. The reduction of nutrient concentrations is an obvious priority for future management and, whilst a decline in TP concentrations has already been observed since the introduction of the Lunan Lochs Natural Care Scheme in 2004, the effect on water quality of the fish cage removal in 2004 should be closely monitored. In light of the findings of the palaeoecological study, on a precautionary basis, further fish stocking of the loch is not recommended.

4   LINDORES LOCH

4.1   Core description

A piston core, LIND1, 1.2 m in length, was collected from Lindores Loch on 18 February 2009 in a water depth of 3.5 m from the central, open water zone. A second core, LIND2, 1.45 m in length, was collected on the same day, approximately 80 m from the south-western shore in a water depth of 2.7 m.

The upper 52 cm of the open water core, LIND1, was dark brown in colour. There was a visible, although gradual, colour change at ~ 52 cm to mid-brown (Figure 11a). LIND1 was highly organic throughout much of the core with %LOI values of 35-40%, with the exception of a slightly less organic section from 20-60 cm when %LOI values decreased to ~25% (Figure 12). Plant remains were abundant throughout. Carbonate values were low at <7%.

The littoral core, LIND2, had a similar sediment composition and colour to the open water core with a gradual colour change from dark to mid-brown at ~50 cm (Figure 11b). The percentage organic matter was similar to that of LIND1 with values of ~30-40%. Whilst %LOI values were slightly lower in the section 20-50 cm of LIND2 the less organic horizon was not as pronounced as that seen in the open water core (Figure 13). Carbonate values were low at <5%.

Figure 11 Photographs of the cores from Lindores Loch

a) LIND1- open water core   *b) LIND2 – littoral core*

Figure 12 Percentage dry weight (DW), organic matter (LOI) and carbonate (CO3) profiles of LIND1
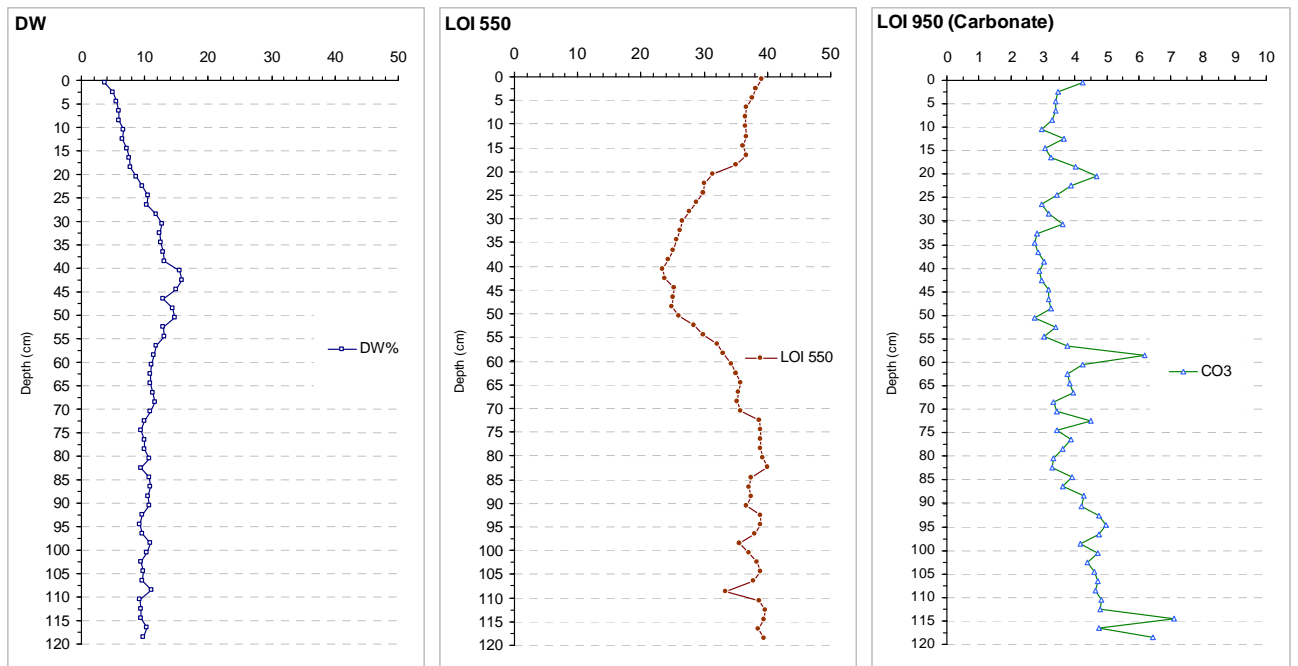
Figure 13 Percentage dry weight (DW), organic matter (LOI) and carbonate (CO3) profiles of LIND2
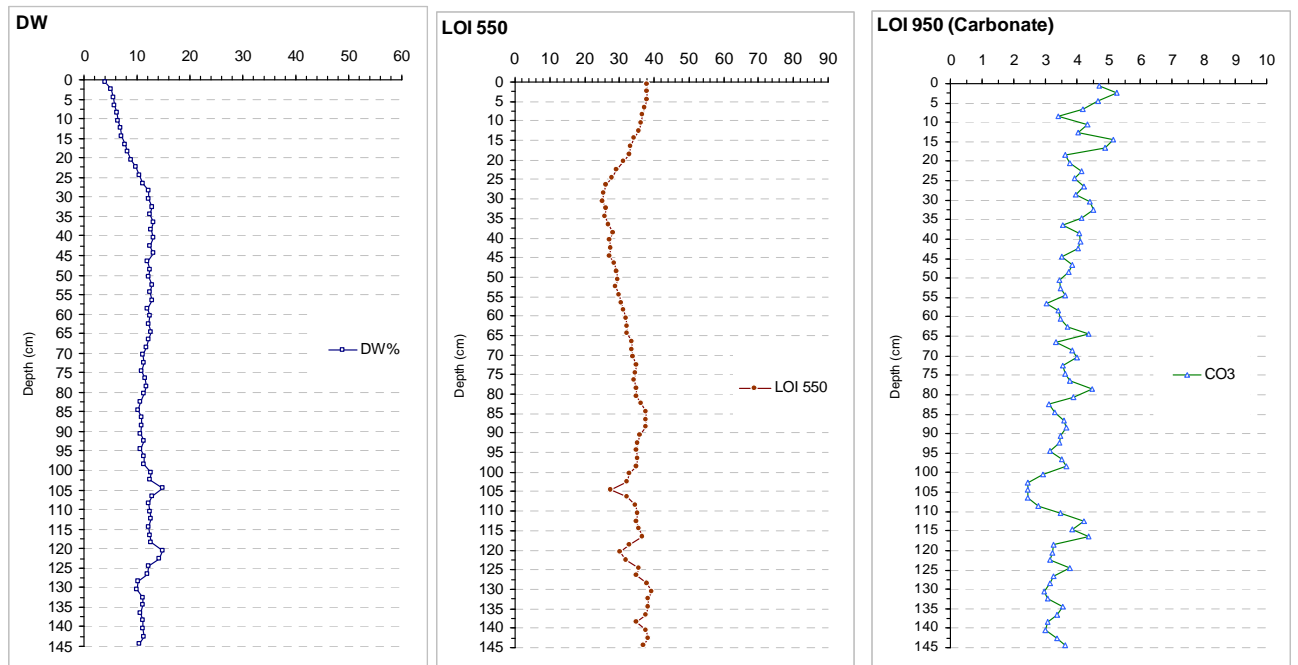
4.2 Radiometric dating

Total ^{210}Pb activity reached equilibrium depth with the supporting ^{210}Pb at ~36 cm of the core (Figure 14a). Unsupported ^{210}Pb activities declined more or less exponentially with depth in the top ~30 cm (Figure 14b), suggesting that sediment accumulation rates are relatively uniform in this part of the core.

The ^{137}Cs activity versus depth profile (Figure 14c) showed a relatively well-resolved peak at a depth of 10.5 cm. The inventory of ^{137}Cs against the inventory of ^{210}Pb activity was 1400 Bq m^{-2} / 2600 Bq m^{-2} for LIND1, which is similar to the inventory ratio of ^{137}Cs/^{210}Pb (2100 Bq m^{-2} /4000 Bq m^{-2}) in the core BUTT4. The peak in the ^{137}Cs record of BUTT4 was attributed to the fallout maximum from atmospheric atomic bomb testing in 1963. The relatively low ^{137}Cs inventory in LIND1 and the similarity of the ^{137}Cs/^{210}Pb ratio with that of BUTT4 suggest that the peak in the LIND1 ^{137}Cs record can also be attributed to this source and therefore represents 1963.

Raw ^{210}Pb chronologies calculated using the CRS and CIC dating models (Appleby, 2001) placed the 1963 layer at ~20.5 cm and 25 cm, respectively. As the depth of the 1963 layer calculated by the CRS model is closer to that suggested by the ^{137}Cs record, the CRS dating model was used in combination with the ^{137}Cs record to derive a chronology for the core (Table 7, Figure 15). Prior to 1963, the data suggest that the mean sediment accumulation rate was 0.028 g cm^{-2} yr^{-1}, and that after 1963 the rate decreased to 0.0148 g cm^{-2} yr^{-1}.

Table 7 ^{210}Pb chronology of core LIND1

Depth	Drymass	Chronology			Sedimentation Rate		
		Date	Age				
cm	g cm^{-2}	AD	yr	±	g cm^{-2} yr^{-1}	cm yr^{-1}	± %
0	0	2009	0				
1.5	0.068	2005	4	2	0.0187	0.372	15.6
5.5	0.2761	1992	17	2	0.0135	0.244	17.7
7.5	0.3993	1983	26	4	0.0135	0.214	20.8
10.5	0.5923	1963	46	7	0.0135	0.208	30.4
12.5	0.7237	1959	50	8	0.0323	0.4545	35.3
15.5	0.9475	1952	57	9	0.0282	0.3478	34.8
20.5	1.3733	1936	73	12	0.026	0.270	46.1
25.5	1.9088	1915	94	20	0.0255	0.2381	70.8

Figure 14 Fallout radionuclide concentrations in core LIND1 showing (a) total ^{210}Pb, (b) unsupported ^{210}Pb, and (c) ^{137}Cs concentrations versus depth
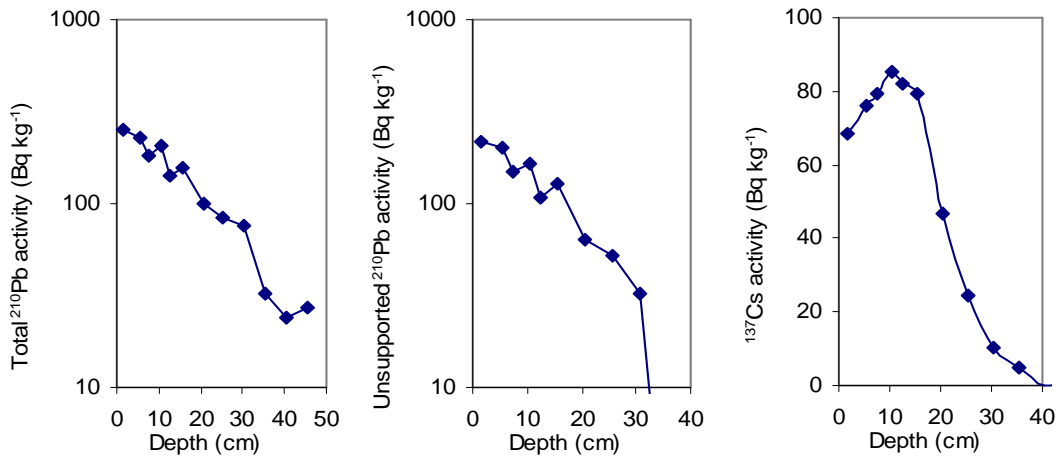
Figure 15 Radiometric chronology of core LIND1 showing the CRS model ^{210}Pb dates and sedimentation rates
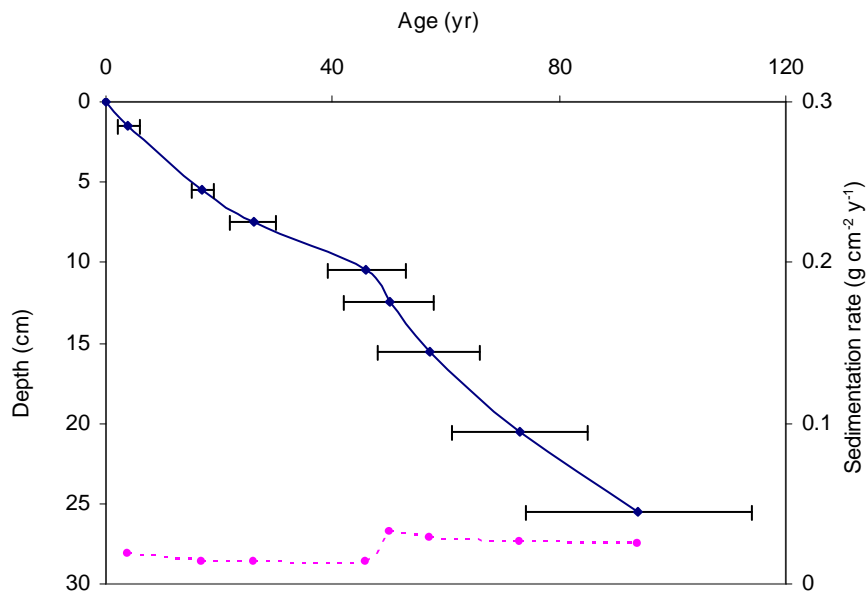
4.3   XRF analyses and core correlation

The XRF profiles for the major elements exhibited several features that are common to both the LIND1 and LIND2 cores (Figure 16): i) a peak in Mg, Al, Si, K, Ca, Ti, Fe and Zr at 40 cm in LIND1 was evident at 30 cm in LIND2, and ii) a peak in Pb and Zn at 25 cm in LIND1 was apparent at ~20 cm in LIND2. Core correlation was based on these features and approximate dates from the LIND1 core were allocated to the corresponding depth in the LIND2 core. The results suggested that the littoral core LIND2 had a slightly slower sediment accumulation rate than the open water core LIND1. The start of an increase in P and Mn at 15 cm in LIND1 which occurred at ~5 cm in LIND2 was not used for core correlation purposes as this may be a function of upward mobility of P and Mn in the sediments.

Figure 16 Selected chemical profiles of Lindores Loch cores based on XRF analysis
(arrows indicate the position of common features)

a) Major elements (% data, normalised by dividing by %LOI)

b) Major elements (µg g^{-1}, normalised by dividing by %LOI)

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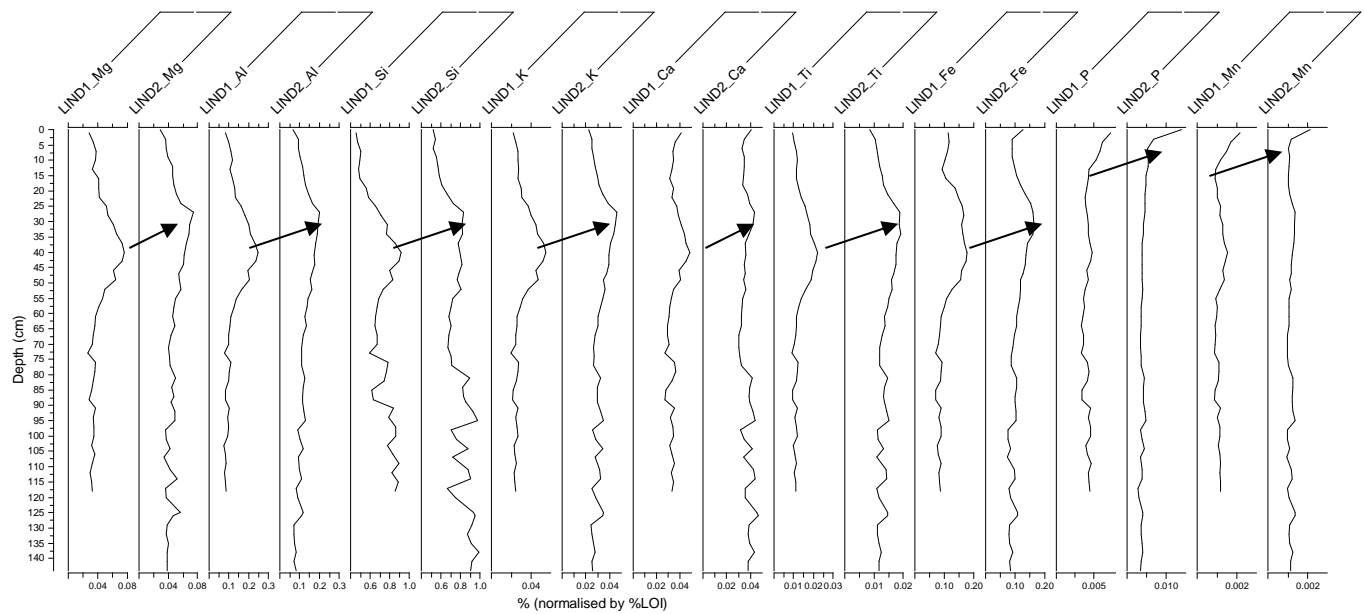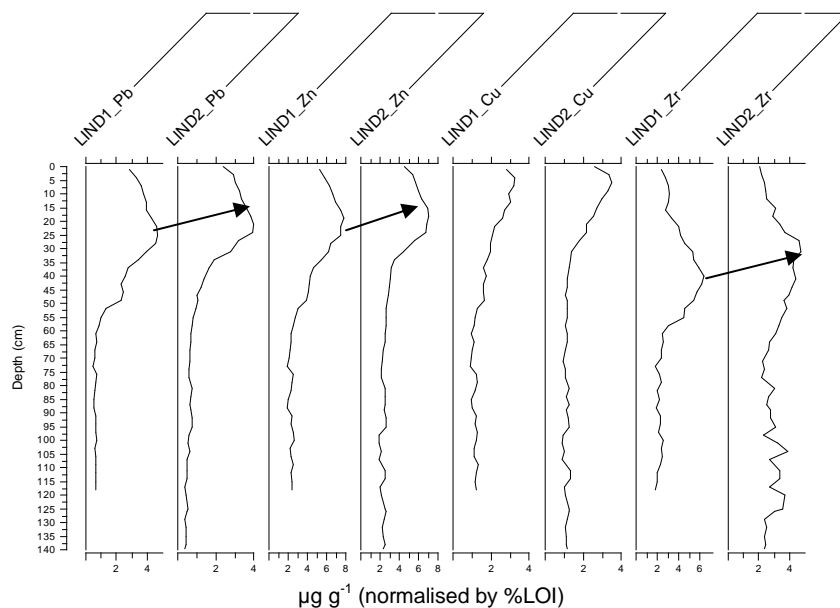
4.4 Diatom analysis

Twelve samples were analysed for diatoms in the LIND1 core (Table 8). Diatom preservation was good throughout the core. A total of 104 diatom taxa were observed in the core but samples were relatively undiverse with between 23-38 taxa per sample (Appendix 2). The results for the major taxa are shown in Figure 17.

There were marked changes in the assemblages during the period represented by the core with three major zones identified by cluster analysis: Zone 1 from the core base to ~45 cm (pre-1900, date unknown), Zone 2 from ~45 to 9 cm (pre-1900 to ~1970) with a sub-zone 2a from ~18 cm to 9 cm (~1945 to1970), and Zone 3 from 9 cm to the surface (~1970 to present). Zone 1 (pre-~1900) was comprised largely of non-planktonic forms (>90% of the total assemblage), notably *Fragilaria* taxa typically associated with alkaline, relatively productive waters (Bennion, 1995). These taxa are often observed as the dominant component of the diatom assemblages in the pre-enrichment period of sediment records of shallow lakes (Bennion *et al.*, 2001a). It is likely that under a favourable light climate, these taxa grow in abundance attached to the surfaces of sediments, stones and aquatic plants. The dominance of the non-planktonic *Fragilaria* spp. continued in the lower part of Zone 2, the only notable difference from Zone 1 being the increase of *F. construens* and *F. construens* var. *venter* relative to *F. pinnata* although this is unlikely to represent any major ecological change in the loch. However, in sub-zone 2a, dated to ~1945-1970, several planktonic taxa typical of more productive conditions increased in relative abundance, namely *Stephanodiscus parvus*, *Asterionella formosa* and *Cyclostephanos dubius*. Hence the planktonic component of the assemblage started to increase from this time. The planktonic taxa expanded still further in Zone 3 (from ~1970) with the addition of further centric diatoms associated with nutrient-rich waters including *Cyclostephanos tholiformis* and *Cyclostephanos invisitatus* and the araphid diatom *Synedra acus*. Consequently the percentage of planktonic taxa increased, reaching 58% in the surface sample. Nonetheless there is perhaps some evidence, albeit subtle, that the loch may be experiencing slight recovery in that the relative abundances of *Cyclostephanos dubius* and *C. tholiformis* both declined in the upper two samples. The high percentage of *Stephanodiscus parvus* in the top sample of the core is likely to be an artefact of the surface sediment rather than a real increase in abundance. The surface sediment sample appears to have captured a recent bloom of this planktonic species and has not yet fully integrated it into the sediment record.

The diatom record indicates a stable period in the early part of the loch's history with only subtle species shifts prior to the mid-1940s. The diatom assemblages in the lower core are typical of alkaline, relatively productive, clear water shallow lakes. The first phase of enrichment started at ~1945, followed by a second phase from ~1970 to more eutrophic conditions, plankton dominated conditions which appear to have prevailed for the last few decades. The compositional change is recorded by the PCA axis 1 scores which increased towards the surface with the most abrupt change occurring at the Zone 2a/3 boundary. The SCD scores were low (<0.4) in the core section below 10 cm and then increased to values of 0.85 at the surface, reflecting the deviation of the diatom assemblages from reference conditions (i.e. those at the bottom of the core) since ~1970.

The DI-TP reconstruction suggests that TP concentrations were relatively stable prior to 18 cm (~1945) at ~130 μg L^{-1}. Values increased from this time to ~180 μg L^{-1} in the 5 cm sample (1992) and have remained at approximately this value to the present day although there is a slight reversal in DI-TP values in the upper two samples. Similarly to shallow lakes elsewhere where *Fragilaria* taxa dominate the sedimentary assemblages, the Northwest European transfer function employed here appears to over-estimate TP concentrations for Lindores Loch (Bennion *et al.*, 2001a; Sayer, 2001). The measured mean TP, based on regular samples from 2006 to 2009, was 93 μg L^{-1} although summer values can exceed 200 μg L^{-1}. The over-estimation arises largely because the *Fragilaria* taxa have wide tolerances to

nutrient concentrations, making them poor indicators of lake trophic status. Nevertheless, while the actual values appear to be over-estimated, there is no reason to believe that the inferred trend is unreliable.

In summary, the diatom assemblages of LIND1 exhibited an initial change around the mid-1940s with the expansion of planktonic, nutrient-tolerant taxa. This was followed by a further increase in planktonic species since ~1970 and a relative decline in the non-planktonic *Fragilaria* spp. indicative of enrichment of the loch and a deteriorating light climate. The decline in relative abundance of some of the most nutrient-tolerant taxa in the upper two samples hints at possible, though slight, recovery. However, this cannot be concluded with any certainty on the basis of only two samples.

Table 8 Results of the diatom analysis on LIND1

Depth (cm)	No. of taxa	N2	DI-TP µg L^{-1}	SCD	PCA axis 1 scores
1	33	9.25	181	0.85	1.57
2	37	8.99	172	0.62	0.51
5	31	6.90	181	0.71	1.03
7	32	7.19	160	0.59	0.55
10	28	4.03	153	0.35	-0.70
15	28	5.51	145	0.37	-0.15
20	27	4.77	134	0.36	-0.59
30	33	5.41	131	0.36	-0.43
40	23	4.84	126	0.36	-0.34
50	34	4.22	132	0.28	-0.86
60	37	5.60	129	0.22	-0.44
80	38	6.44	136	0.00	-0.14

4.5   Cladocera analysis

Twelve samples were analysed for chitinous cladoceran remains in the LIND1 core (Table 9). A total of 28 taxa were observed in the core (Appendix 3) with between 11 and 23 taxa per sample and a summary diagram for the major taxa is presented in Figure 18.

There were marked changes in the sediment record with two zones identified by cluster analysis: Zone 1 from the core base to 55 cm (pre-1900, date unknown) and Zone 2 from 55 cm to the surface (pre-1900 to present). Zone 1 was more species rich than Zone 2 with > 16 taxa per sample, and was dominated by *Chydorus sphaericus,* a species most strongly associated with littoral and sub-pelagic zones (van Damme & Dumont, 2006)*,* with several plant-associated taxa such as *Alonella nana*, *Alonella excisa*, *Graptoleberis testudinaria*, *Pleuroxus uncinatus* and *Eurycercus lamellatus* also abundant. In Zone 2 the relative abundance of *Chydorus sphaericus* remained similar to that in Zone 1 at ~20-30% but the contribution of most of the other taxa that had been present in Zone 1 declined notably in Zone 2. In contrast, the abundance of the small-bodied pelagic cladoceran *Bosmina longirostris* increased markedly and abruptly at the boundary of Zones 1 and 2 from <5% to 40%, and continued to increase throughout Zone 2 reaching a maximum of 75% at the top of the core.

The compositional change is recorded by the PCA axis 1 scores which were stable in Zone 1 and then shifted at the Zone 1/2 boundary and subsequently increased towards the surface. Similarly, the SCD scores were low (<0.4) in Zone 1 and then increased to values of ~0.8 at the Zone 1/2 boundary. The SCD scores increased further to a maximum of 1.27 at the

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surface, reflecting the large deviation of the Cladocera assemblages from reference conditions (i.e. those at the bottom of the core) over the last 100 years or so.

Table 9 Results of the Cladocera analysis on LIND1

Depth (cm)	No taxa	N2	SCD	PCA axis 1 scores
2	12	1.68	1.27	1.40
5	11	2.01	1.16	1.10
10	11	2.56	0.90	0.64
20	16	2.34	1.01	0.92
30	15	2.76	0.92	0.61
40	14	3.79	0.88	0.40
50	18	4.42	0.77	0.27
60	17	4.85	0.22	-1.06
70	23	8.46	0.34	-0.98
80	20	7.77	0.35	-1.04
90	18	6.90	0.34	-1.07
100	16	4.10	0.00	-1.18

4.6   Macrofossil analysis

4.6.1   Plant macrofossils

Plant macrofossil remains were enumerated from 12 levels in the LIND2 core (Table 10, Appendix 4). The diverse remains demonstrated a transition of species through four zones, with remains of at least 13 species of submerged aquatic macrophyte identified (Figure 19). Remains of *Najas flexilis* were not found in any of the samples analysed. Zone 1 was between the core bottom and 95 cm, Zone 2 was from 95 to 65 cm, Zone 3 was from 65 to 15 cm and Zone 4 was from 15 cm to the surface of the core, the latter zone representing the period from approximately 1940 to present based on the core correlation data.

Zone 1 was diverse with particularly high abundances of *Nitella* oospores, *Chara* oospores, *Ceratophyllum* spines and *Nymphaeaceae* trichosclereids. The turions of *Potamogeton crispus* and *Ranunculus* sect. *Batrachium* seeds were also found in this zone, along with fragments of submerged broad-leaved *Potamogeton* spp. leaves. Unfortunately, leaf tips or other identifiable species characteristics of the latter were not apparent and therefore a firm species identification could not be made. However, historical plant records report the presence of the broad-leaved species *Potamogeton perfoliatus* and, therefore, it is possible that the fragments are from this taxon.

In Zone 2, the numbers of *Nitella* and *Chara* oospores, *Ceratophyllum* spines and *Nymphaeaceae* trichosclereids declined whilst fragments of submerged broad-leaved *Potamogeton* spp. leaves remained abundant. In Zone 3, *Ceratophyllum* spines disappeared but the abundance of *Ranunculus* sect. *Batrachium* seeds, *Callitriche* cf. *hermaphroditica.* and *Potamogeton crispus* (both seeds and turions) increased and charophyte oospores were still abundant. The seeds of several new taxa were found including *Myriophyllum alterniflorum*, *Potamogeton natans*, *Potamogeton berchtoldii* and *Potamogeton obtusifolius* and hence the assemblage remained diverse.

There was a notable decline in species richness in Zone 4 with a shift to more nutrient tolerant species, such as the fine-leaved *Potamogeton* taxa (e.g. *P. pusillus*) and *Callitriche* spp. The remains of *Chara* oospores and *Nymphaeaceae* trichosclereids were present in small numbers, but only five species of aquatic macrophyte were evident, as compared with 11 in Zone 2 and 13 in Zone 1. Filamentous algal cells were also present for the first time in this zone, providing further evidence of a shift towards more productive conditions, although

downcore deterioration in preservation may also influence the algal cell counts. The PCA axis 1 scores reflect the points of major compositional change with increases at the boundaries of Zones 1 and 2, and Zones 3 and 4.

In summary, the flora in the past was diverse and comprised charophytes and broad leaved *Potamogeton* taxa. As the lake became more productive, diversity initially increased and the record provides evidence of dynamics in the aquatic vegetation. In the uppermost section of the record, however, further enrichment has resulted in a loss of diversity and a shift in the relative dominance of broad- to fine-leaved *Potamogeton* species.

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Table 10 Results of the plant macrofossil analysis on LIND2

Depth (cm)	No taxa	N2	PCA axis 1 scores
2	4	1.28	1.40
10	4	1.39	1.63
20	6	3.34	-0.09
30	6	3.29	-0.11
40	8	5.65	-0.09
50	6	3.28	-0.16
60	6	3.06	-0.20
70	3	1.85	-0.08
80	6	4.60	-0.11
90	9	3.49	-0.15
100	9	2.72	-0.87
110	5	1.43	-1.18

4.6.2 Zooplankton ephippia

Zooplankton ephippial remains were enumerated from 12 levels in the LIND2 core and cluster analysis identified three major zones: Zone 1 from the core base to 55 cm, Zone 2 from 55 to 25 cm and Zone 3 from 25 cm to the core top (~1915 to present based on core correlation data) (Figure 20). Zone 1 was dominated by *Ceriodaphnia*, along with lower numbers of *Daphnia hyalina* and the plant-associated cladoceran *Simocephalus*. Zone 2 saw increased numbers of *Daphnia hyalina* ephippia, a decline in *Ceriodaphnia* and the disappearance of *Simocephalus*, suggesting a possible loss of macrophyte habitat within the lake. In Zone 3 *Daphnia hyalina* reached a peak at 20 cm but then the numbers of both this taxon and *Ceriodaphnia* declined in the upper 10 cm of the core, most likely associated with increased fish predation pressure.

Figure 17 Summary diatom diagram of Lindores Loch core, LIND1

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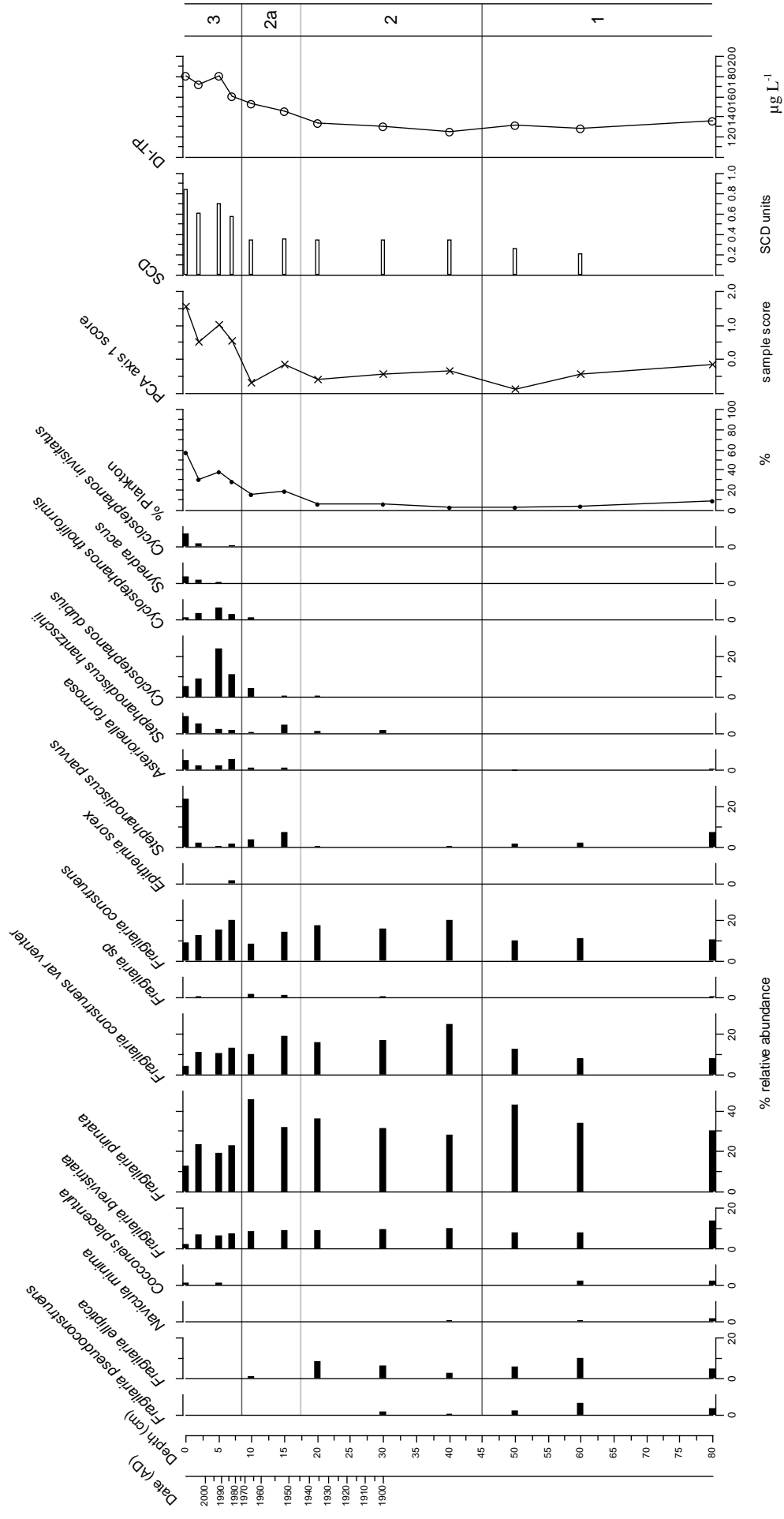
Figure 18 Summary Cladocera diagram of Lindores Loch core, LIND1

34
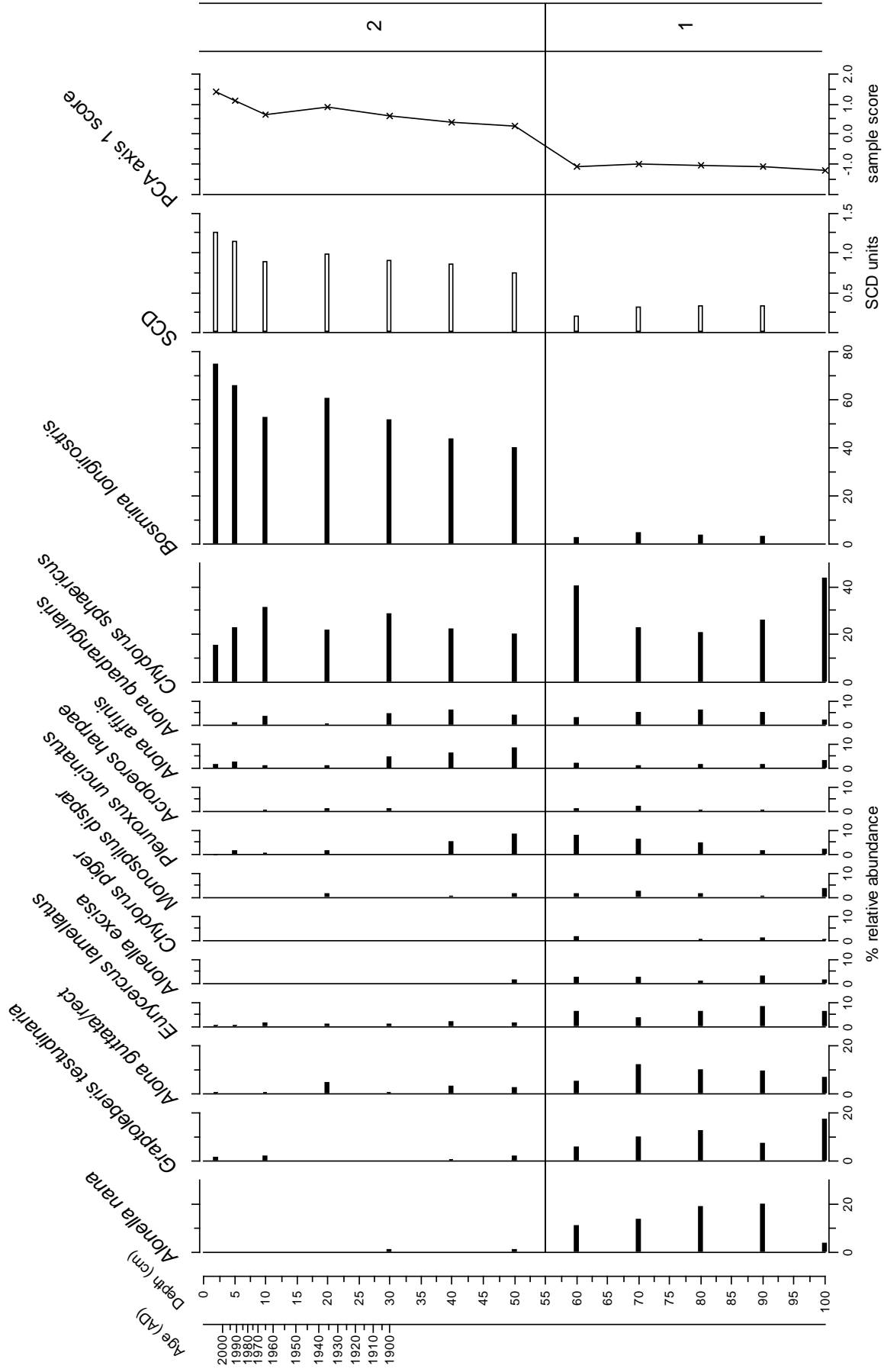
Figure 19 Summary plant macrofossil diagram of Lindores Loch core, LIND2
(Note variable scaling on the x axis; dates are estimated from core correlation with LIND1)

35
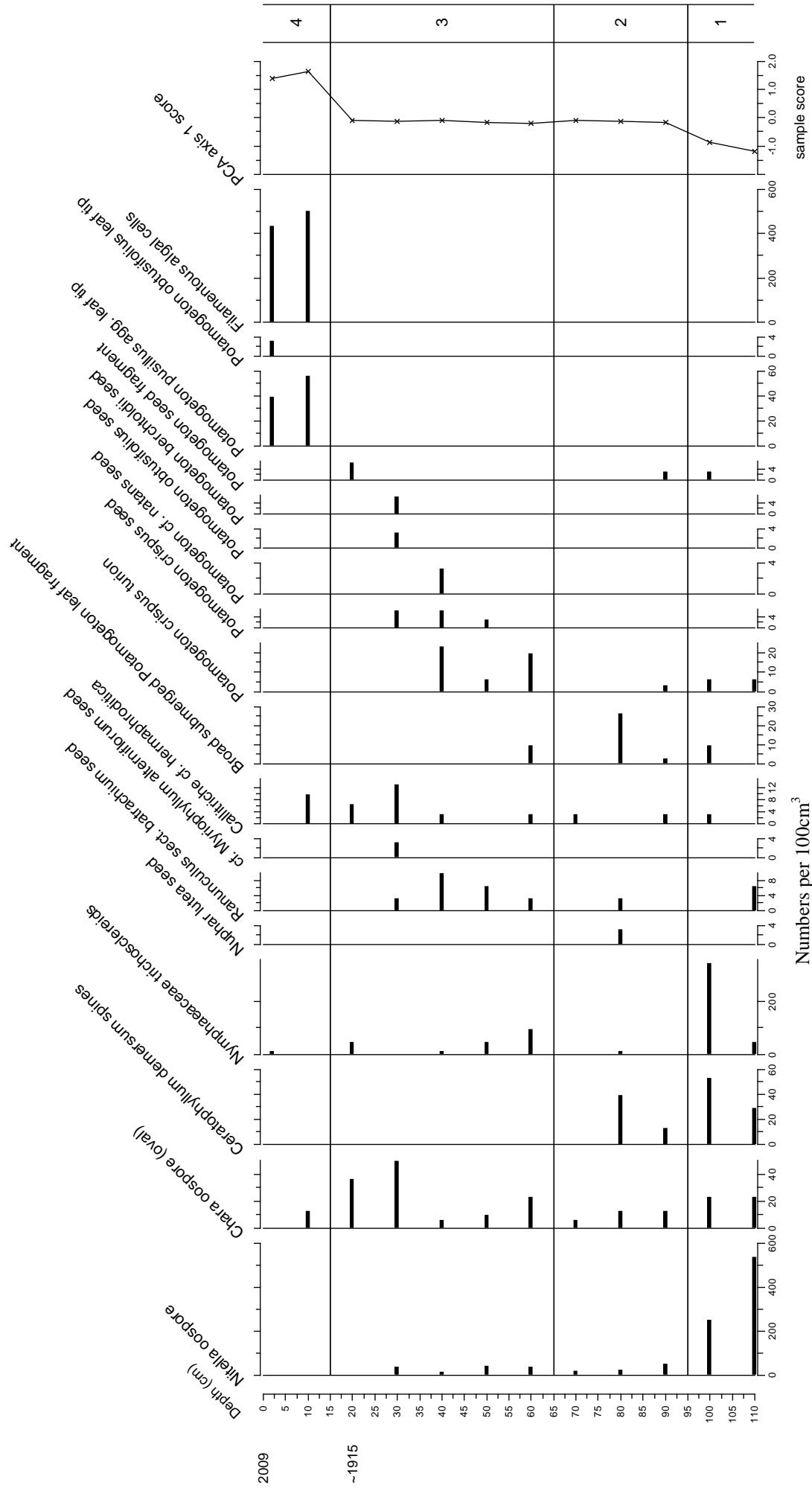
Figure 20 Summary zooplankton ephippia diagram of Lindores Loch core, LIND2
(Dates are estimated from core correlation with LIND1)

36
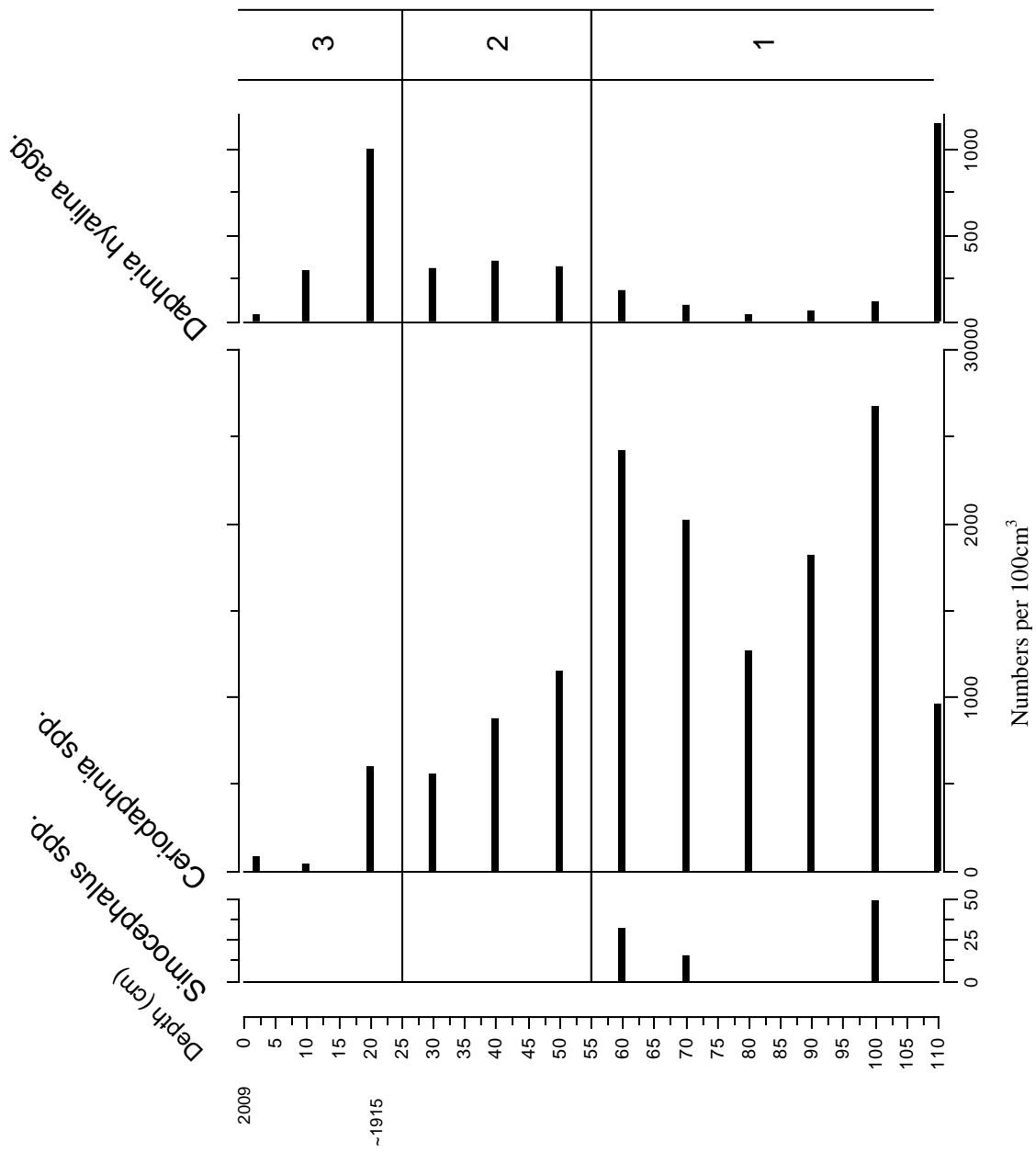
4.7   Discussion

The palaeoecological data indicate that Lindores Loch is a naturally mesotrophic loch, formerly supporting a diverse mesotrophic flora composed of *Nitella, Chara, Nymphaeaceae, Myriophyllum alterniflorum,* aquatic *Ranunculus* and an array of *Potamogeton* species including both broad- and fine-leaved taxa. The reference diatom community (pre-1900) was dominated by non-planktonic species typical of relatively alkaline, shallow lakes with clearwater conditions, and the zooplankton community was diverse and dominated by plant-associated taxa and those typically found in the littoral zone of shallow lakes. The palaeoecological data suggest that Lindores Loch is naturally more alkaline and more productive than Butterstone Loch.

There is evidence of ecological change at several points in time in the loch's history. The first major change is the increase in the pelagic taxa, *Bosmina longirostris* in LIND1 (pre-1900) and *Daphnia hyalina* in LIND2, at ~50 cm relative to the littoral and plant associated zooplankton taxa. This shift from benthic to pelagic dominance likely reflects the first stages of eutrophication (Vadeboncoeur *et al.,* 2003). However, there is little evidence of eutrophication at this point in the core in the diatom assemblages. It is possible that in shallow lakes the Cladocera are more sensitive indicators of the initial stages of enrichment than diatoms (Davidson *et al.*, in press b). By controlling the enhanced planktonic production through grazing, alterations to the light climate may be minimal, changes to the diatom community may be suppressed and the only observed impact is an increase in pelagic zooplankton species abundance.

The second change in the sediment record occurs at ~1945 when planktonic diatom taxa associated with more productive waters increase, signalling perhaps an acceleration of enrichment. However, the most marked shifts in all biological groups occur in the uppermost section of the cores, dated to ~1970 in LIND1. From this time, there is an increase in planktonic diatom representation, a further expansion of diatoms associated with eutrophic conditions, an increase in filamentous algal cells, and a reduction in the diversity of the aquatic plant community. These shifts are indicative of further eutrophication with a consequent increase in pelagic production and turbidity. The shifts seen in the plant macrofossil record from *Nitella* to broad-leaved *Potamogeton* taxa and finally to fine-leaved *Potamogeton* spp are typical of lakes that have undergone progressive enrichment (Bennion *et al.*, 2008). The latter are known to persist in nutrient-rich, turbid lakes (e.g. Sand-Jensen *et al.*, 2008) while the broader-leaved species are typically lost with enrichment. Macrophytes act as an underwater buffer against physical disturbance by wave action (Moss *et al.*, 1996) and the broad-leaved pondweeds are more vulnerable to physical damage caused by the increased water turbulence that arises as plant cover declines.

Historical macrophyte surveys of Lindores Loch, carried out as part of the Fife Loch Survey, have found up to 20 submerged or floating species in the loch over the last hundred years with 12 species observed by West in the period 1905 to 1909, 12 species by Young & Stewart in 1982, 5 species by Bell in 1991 and 10 species by Bell in 2005. More recently in a survey carried out in September 2007, 15 submerged or floating taxa were found in the loch. Many of the taxa recorded in the historical surveys were also evident in the submerged aquatic plant macrofossil record including *Callitriche hermaphroditica, Callitriche stagnalis, Chara* and *Nitella* oospores*, Myriophyllum alterniflorum, Nuphar lutea, Potamogeton natans, P. obtusifolius, P. pusillus/berchtoldii* agg and aquatic *Ranunculus* species. In addition, leaf fragments belonging to a submerged broad-leaved *Potamogeton* were prevalent in the core, and based on the contemporary survey data these are likely to be *P. perfoliatus*. Interestingly seeds of *Myriophyllum alterniflorum* were found at 30 cm depth in the core and were also recorded as present in the loch in the 1909 survey. The more recent plant surveys record only *Myriophyllum spicatum* which is consistent with the evidence for enrichment of the loch.

Overall, a similar loss of species diversity was recorded by both the historical plant surveys and the palaeoecological dataset with more nutrient tolerant species appearing in recent times. However, several taxa, namely *Elodea canadensis, Lemna trisulca* and *Lemna minor* were observed in the post-1980 surveys but were not present in the sediment record. Such plants are underrepresented in macrofossil records as their leaf remains do not readily preserve (Davidson *et al.*, 2005; Zhao *et al.*, 2006). Furthermore *Littorella uniflora* (observed in 1909, 1982 and 2005 surveys) is capable of producing viable seed banks, yet its seeds have rarely been found preserved in sediments. Conversely remains of several taxa were observed in the palaeo-record but were not represented in the historical surveys. For example, *Ceratophyllum demersum* leaf spines were abundant below a depth 80 cm and *Potamogeton crispus* seeds and turions were common below 30 cm but neither of these species was identified in any of the Fife Loch surveys, although the former was found in the most recent 2008 survey of the loch.

According to SEPA's Environmental Improvement Action Plan, the Biodiversity Action Plan priority species *Najas flexilis*, was present in Lindores Loch in the past. It was found during a macrophyte survey in 2000 but it was not found more recently in the 2005 and 2008 surveys. *Najas* is represented in sediment cores by seeds and leaf spines and in previous studies its remains have provided a faithful record of *Najas* occurence (e.g. Bennion *et al.*, 2008). It is possible that *Najas flexilis* has always been relatively rare in the loch and not particularly widespread and, therefore, the core may have been collected at a considerable distance from the *Najas* bed thereby resulting in an absence of remains.

Whilst the diatom and plant macrofossil data provide evidence of floristic changes, here associated with enrichment and a deteriorating light climate, the zooplankton data enable us to gain some insights into the effects of fish predation on the system. This is of interest given the history of fish stocking at Lindores Loch. In 1966 rotenone was applied to kill the fish, principally pike and perch, and the loch was then restocked with trout in 1967. This included 48,000 young rainbow trout, 4000 brown trout and 1500 American brook trout. Records state that the Fishing Association has consent to stock with up to 500 brown trout annually and up to 200 rainbow trout per week although a note dated February 1995 gives slightly different stocking figures of up to 150 brown and rainbow trout per week during season. In addition to the trout, the loch is known to support eel, pike, carp and perch. The Association has consent to occasionally control the pike population using pike nets and to net the coarse fish. For example, gill nets were used in 1991/1992 to help control pike numbers, resulting in a catch of ~80 pike between December 1991 and the end of January 1992. A report made in 1992 states that ~600-1000 pike are caught in the nets per year.

The removal of piscivorous fish (pike and perch) and restocking with trout in 1967, which tend to be more opportunistic feeders with a varied diet, would in theory lead to an increase in predation pressure on the zooplankton. The reduction in the piscivorous fish density would allow zooplanktivorous fish to increase and thereby would remove the top down grazing control on the phytoplankton. This is borne out by the fossil zooplankton assemblages. The increase in *Bosmina longirostris* towards the top of LIND1 (from ~1970) and the concomitant decline in *Daphnia hyalina* ephippia in the upper part of LIND2 may indicate increased fish predation. *Daphnia* spp are recognised as keystone species in the planktonic foodweb (Crowder *et al.*, 1988) and their numbers decline sharply at the top of the core. An assemblage dominated by *Bosmina longirostris* and *Chydorus sphaericus,* as observed in the upper zone of the Lindores Loch cores, is typical of a turbid site supporting a high density of fish (Davidson *et al.*, in press a). The spike in *Daphnia* numbers at 20 cm in LIND2 could possibly be the result of the rotenone application, as the fish kill would have allowed the zooplankton population numbers to expand. However, in the absence of a chronology for LIND2, this explanation is speculative. The evidence for top-down influences on the system needs to be balanced against the knowledge that the site is becoming more eutrophic over

the same timescale and, therefore, the observed changes could be attributed to enrichment or fish effects or indeed, most likely, a combination of the two.

The palaeoecological evidence for enrichment of the loch is supported by chemical and physical data. Algal blooms were reported in 1997/1998 following which barley straw was applied as a control measure. Consent was given in January 2004 for the use of a diffuse oxygen compressor during periods of low oxygen levels, clearly indicating that the loch experiences anoxic conditions in the hypolimnion, a feature typical of productive waters. Current annual mean TP, SRP and chlorophyll a values are high at Lindores Loch, concentrations being those associated with eutrophic rather than mesotrophic conditions. The annual mean chlorophyll a values are high relative to the TP concentrations, as can be seen when the chemical data for the loch are plotted alongside data from a set of 39 English and Danish shallow lakes distributed along a trophic gradient (Sayer *et al.*, in press) (Figure 21). The sample for Lindores Loch lies outside the general line of the relationship between TP and chlorophyll a, suggesting that top-down factors may be contributing to the higher than expected chlorophyll a concentrations, although the influence of nitrogen could also be important.

There are several drivers of ecological change operating at Lindores Loch including longer term nutrient enrichment and more recently the fishery. The early changes in the zooplankton record prior to 1900 and in the diatom record from the mid-1900s reflect the shift from benthic to pelagic dominance typically seen as lakes become increasingly productive (Vadeboncoeur *et al.,* 2003). Subsequent shifts in the diatom and Cladocera assemblages coincide with the start of fishery operations, in this case the main restocking event with trout in 1967. However there are several other potential causes of the observed ecological changes since this time including agricultural activities in the catchment, slurry from a nearby piggery which was reported to be dumped in fields adjacent to the loch until ~1982 and raw sewage discharge from Lindores House. As stated previously, it is difficult to unravel the effects of these sources because of the co-influences of nutrients and fish.

It is clear from the palaeoecological data that Lindores Loch is far removed from reference condition and has experienced enrichment leading to an increase in planktonic production, most notably since ~1970, and a decline in the aquatic plant community. While the contribution of each of the potential causal factors cannot be quantified there is evidence from the recent zooplankton record that top-down factors may have played a role in maintaining high productivity in the last four decades. Similarly to Butterstone Loch, the findings suggest that some of the resilience mechanisms have broken down but in the case of Lindores Loch the degree to which this has already happened seems to be somewhat greater as the shifts seen in the Lindores cores are more striking than those observed in Butterstone Loch. It is, therefore, crucial that any existing pressures on the loch are kept to a minimum and, ideally, are reduced. The reduction of nutrient concentrations is an obvious priority for future management and, in light of the findings of the palaeoecological study, further fish stocking of the loch is not recommended. The decline in relative abundance of some of the diatom taxa associated with eutrophic conditions in the upper two samples of LIND1 tentatively suggests that there may be signs of slight recovery although there is no similar evidence in the other proxies. Regular monitoring of water quality is required in order to assess whether there is any sign of sustained recovery.

Figure 21 The relationship between TP and chlorophyll a in a set of 40 lakes, showing the position of Lindores Loch
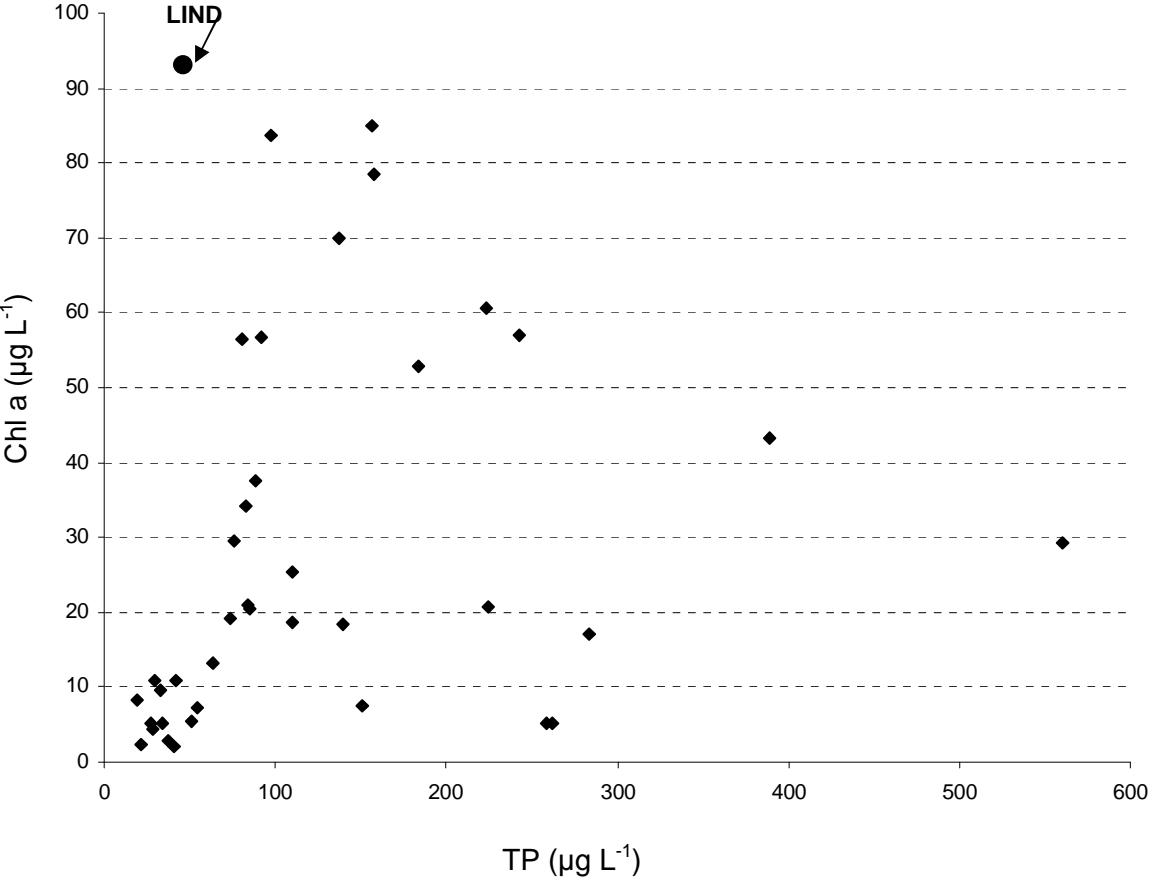
5   SUMMARY

The palaeoecological study has successfully determined the reference communities and the degree of ecological change for Butterstone Loch and Lindores Loch and has thereby demonstrated the value of multi-proxy palaeoecological studies for understanding lake dynamics. The data indicate that Butterstone Loch is a naturally nutrient-poor loch, formerly supporting an oligo-mesotrophic macrophyte community including *Nitella, Chara, Isoetes,* and *Najas flexilis*, a non-planktonic dominated diatom community and a diverse zooplankton community. Lindores Loch is naturally more alkaline and more productive than Butterstone Loch, formerly supporting a diverse mesotrophic flora of *Nitella, Chara, Nymphaeaceae, Myriophyllum alterniflorum,* aquatic *Ranunculus* and several *Potamogeton* species, a non-planktonic diatom community and a diverse zooplankton community dominated by plant-associated taxa and those typically found in the littoral zone of shallow lakes.

The study has shown that both lochs have experienced major ecological shifts over the period represented by the sediment cores. This shift has taken the form of increased planktonic production, a relative increase in diatom taxa associated with nutrient-rich waters, a reduction in the diversity and compositional shifts in the zooplankton communities and a decline in the diversity and conservation interest of the aquatic plant communities. In both lochs the most marked and recent changes in the sediment records are coincident with the start of fish stocking operations, i.e. the installation of fish cages in 1981 in Butterstone Loch and trout stocking in 1967 in Lindores Loch. However, the palaeoecological data indicate that changes have occurred over longer timescales. The first marked shifts in the diatom assemblages towards planktonic taxa typically associated with eutrophic conditions in Butterstone Loch pre-date the start of fish stocking by several decades and the shifts in the Cladocera assemblages towards dominance by pelagic taxa in Lindores Loch occurred over a century ago.

The study, therefore, concludes that there are several drivers of ecological change operating at both sites. The early shifts in the biological assemblages are indicative of enrichment, probably at least in part due to intensification of agriculture in these lowland catchments. There is little substantive evidence of changes in fish predation in the palaeoecological record of Butterstone Loch, possibly because much of the fish stocking activity was confined to cages. However, in Lindores Loch the recent changes in zooplankton composition since ~1970 are consistent with increased fish predation pressure and, therefore, top-down factors may be contributing to the high productivity of this loch. In productive, lowland catchments with multiple pressures, such as those studied here, it is difficult to disentangle the effects of fish from nutrients. Nevertheless, the study nicely illustrates the power of using a range of proxies. Here, the diatom records provide background information on the enrichment histories of the two sites whilst the additional proxies (Cladocera and macrophytes) provide important extra information that assist in testing theories about the relative role of nutrients and fish. The analysis of both chitinous and ephippial cladoceran remains is shown to be complementary, each informing us about the nature of different components of the zooplankton community.

For both Butterstone Loch and Lindores Loch, the findings suggest that some of the resilience mechanisms that buffer the lake ecosystems against fluctuating inputs and allow water quality to be maintained may have started to break down. It is, therefore, concluded that any existing pressures should be minimised. A reduction in nutrient concentrations and frequent monitoring of water quality is suggested as a priority for future management and, given the degraded status of both lochs, further fish stocking is not recommended, albeit on a precautionary basis at Butterstone Loch.

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APPENDIX 1 RADIOMETRIC DATING RESULTS

Table 1 ^{210}Pb concentrations in core BUTT4

Depth	Dry Mass	Total		Supported		Unsupp		Cum Unsupported Pb-210	
		Pb-210							
cm	g cm^{-2}	Bq kg^{-1}	±	Bq kg^{-1}	±	Bq kg^{-1}	±	Bq m^{-2}	±
1.5	0.1239	429.84	24.49	73.25	5.75	356.59	25.16	449.5	31.5
3.5	0.2976	367.71	17.39	63.05	3.73	304.66	17.79	1022.6	56.7
5.5	0.4913	405.22	16.71	65.76	3.71	339.46	17.12	1646	72.7
7.5	0.7051	353.6	18.33	67.32	4.29	286.28	18.83	2313.3	88.1
10.5	1.0423	255.15	14.12	74.33	3.47	180.82	14.54	3087.3	110.4
12.5	1.2726	216.44	17.32	60.86	4.19	155.58	17.82	3473.9	118.7
15.5	1.6614	133.35	17.29	59.77	4.7	73.58	17.92	3899.7	135.7
16.5	1.791	95.57	8.65	59.72	2.49	35.85	9	3967.7	139.3
18.5	2.0951	56.71	7.08	57.72	2.17	-1.01	7.41	4020.7	141
20.5	2.3992	53.01	9.91	62.19	2.86	-9.18	10.31		
30.5	4.1143	43.64	8.55	48.33	2.69	-4.69	8.96		

Table 2 Artificial fallout radionuclide concentrations in core BUTT4

Depth	Cs-137		Am-241	
cm	Bq kg^{-1}	±	Bq kg^{-1}	±
1.5	98.59	5.02	0	0
3.5	102	3.77	0	0
5.5	106.81	3.38	0	0
7.5	114.94	4.16	3.78	1.59
10.5	126.8	3.33	2.58	1.26
12.5	109.98	4.17	0	0
15.5	54.61	3.56	0	0
16.5	38.9	1.84	0	0
18.5	21.84	1.24	0	0
20.5	15.48	1.49	0	0
30.5	3.89	1.24	0	0

Table 3 ^{210}Pb concentrations in core LIND1

| Depth | Dry Mass | Pb-210 | | | | | | Cum Unsupported | |
| | | Total | | Supported | | Unsupp | | Pb-210 | |
cm	g cm^{-2}	Bq kg^{-1}	±	Bq kg^{-1}	±	Bq kg^{-1}	±	Bq m^{-2}	±
1.5	0.068	250.46	27.29	34.29	5.62	216.17	27.86	149.9	15.3
5.5	0.2761	231.07	25.14	31.76	5.23	199.31	25.68	582.1	53
7.5	0.3993	180.28	20.81	30.73	4.16	149.55	21.22	795.5	64.7
10.5	0.5923	205.99	21.85	39.68	4.69	166.31	22.35	1100.1	76.4
12.5	0.7237	142.75	19.99	35.92	4.54	106.83	20.5	1276.6	83.4
15.5	0.9475	155.68	18.44	28.02	3.59	127.66	18.79	1538.3	93.3
20.5	1.3733	100.32	11.92	36.27	2.6	64.05	12.2	1931	114.4
25.5	1.9088	83.94	13.57	32.1	3	51.84	13.9	2240.2	132.2
30.5	2.538	75.29	14.48	42.5	3.41	32.79	14.88	2501.9	158.1
35.5	3.2221	32.37	7.77	31.17	1.67	1.2	7.95	2567.2	182
40.5	3.9945	24	9	27.29	2.12	-3.29	9.25		
45.5	4.8388	27.08	10.3	27.11	2.29	-0.03	10.55		

Table 4 Artificial fallout radionuclide concentrations in core LIND1

| Depth | Cs-137 | |
cm	Bq kg^{-1}	±
1.5	68.38	4.5
5.5	76.23	4.41
7.5	79.59	4.15
10.5	85.32	3.99
12.5	81.81	4.29
15.5	79.32	3.39
20.5	46.96	1.99
25.5	24.71	1.98
30.5	10.4	1.61
35.5	4.68	0.85
40.5	0	0
45.5	2.41	1.1

APPENDIX 2 DIATOM DATA

Table 5 Diatom counts for core BUTT4

Name	Diatcode	Depth (cm)											
		0	2	5	7	10	15	20	30	40	50	70	90
Achnanthes calcar	AC005A	2	5	1	2	1	2						
Achnanthes clevei	AC006A	2	1	2	2	4	1						
Achnanthes didyma	AC039A											1	
Achnanthes flexella	AC025A									1	2		
Achnanthes laevis	AC083A	3			1		1	2		1	2	3	
Achnanthes lanceolata	AC001A	1	1		3	2	1						
Achnanthes levanderi	AC044A			1	1	3	1						2
Achnanthes linearis	AC002A	8	9	10	12	23	26	29	23	52	11	37	45
Achnanthes marginulata	AC022A									2		2	2
Achnanthes minutissima	AC013A	38	31	31	39	70	60	56	81	117	73	68	70
Achnanthes oestrupii	AC007A				2								
Achnanthes saccula	AC119A				2								
Achnanthes scotica	AC048A				2								
Achnanthes sp.	AC9999	2	3	1	2		1	1	2		5	1	
Achnanthes subatomoides	AC136A							1		2		1	
Achnanthes suchlandtii	AC034A							1			1		1
Amphipleura pellucida	AP001A			1	1		1	2	1		2		
Amphora coffaeformis	AM006A						1				1		
Amphora inariensis	AM013A				1	1		1		4	2		1
Amphora libyca	AM011A		3			1	2	1	3				
Amphora pediculus	AM012A	1	1	1		1			1				
Amphora sp.	AM9999											1	
Amphora thumensis	AM008A											1	
Anomoneis brachysira	AN008A								2	1		2	1
Asterionella formosa	AS001A	10	7	5	2	1	1		1				
Aulacoseira alpigena	AU031A	2					3				6	1	
Aulacoseira ambigua	AU002A	17	13	5	6	6			1				3
Aulacoseira distans	AU005A					4	6	3	5			3	4
Aulacoseira sp.	AU9999	2		2	2	5	1	1		1		4	1
Aulacoseira subarctica	AU020A	39	29	59	52	28	9	2	1		1		2
Brachysira vitrea	BR001A	4	4	9	8	15	15	22	18	27	11	11	16
Caloneis sp	CA9999										1		3
Cocconeis neodiminuta	CO066A				3								
Cocconeis neothumensis	CO067A	2	2							1		2	
Cocconeis pediculus	CO005A					2							
Cocconeis placentula	CO001A	2	6	6	8	6	7	8	6	5	6	5	5
Cyclotella comensis	CY010A	11	14	4	7	6	17	9	7	9	10	10	10
Cyclotella ocellata	CY009A										1		
Cyclotella pseudostelligera	CY002A	1	1	3		1			1		1		
Cyclotella radiosa	CY019A	16	15	12	8	7	14	16	12	5	13	16	13
Cyclotella sp.	CY9999							1		1	2	1	
Cymatopleura solea	CL001A		1										
Cymbella affinis	CM022A	1	1		2	2		2	2				
Cymbella amphicephala	CM016A								1				
Cymbella caespitosa	CM070A					1	3						
Cymbella cesatii	CM015A	1	1	2	1	3	6	4	2	1	2	4	2
Cymbella delicatula	CM038A								2	1	2		1
Cymbella descripta	CM052A								2				
Cymbella gracilis	CM018A		4		3	3			4		2	1	3
Cymbella hebridica	CM017A									1			2
Cymbella helvetica	CM013A												2
Cymbella leptoceros	CM086A											1	
Cymbella microcephala	CM004A		1		1	1	2		4	6	11	2	6
Cymbella minuta	CM031A	3	1	3		1	3	4	1		7	1	1

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Name	Diatcode	0	2	5	7	10	15	20	30	40	50	70	90
								Depth (cm)					
Cymbella lapponica	CM085A							1					
Cymbella reichardtii	CM113A		1								1		
Cymbella silesiaca	CM103A								4	1	1	1	2
Cymbella sinuata	CM003A						1	2			1		
Cymbella sp.	CM9999	4		1	1	4	5	1	4	2	2	2	2
Cymbellonitzschia diluviana	CN001A												
Denticula tenuis	DE001A		5	6	3	3	4	4	3	2	17	14	9
Diatoma elongatum / tenuis	DT001A	3											
Diatoma mesodon	DT021A	1											
Diploneis oblongella	DP007A							3					
Diploneis ovalis	DP001A	1				1	1	3	3	2			
Diploneis petersenii	DP002A	1			2						3	1	
Epithemia adnata	EP007A	1											1
Epithemia smithii	EP021A								1				
Epithemia sorex	EP001A			1			1		2				1
Epithemia sp.	EP9999	4	1	2									
Eunotia bilunaris	EU070A					1	1	2	5	1	3	2	5
Eunotia exigua	EU009A							1					
Eunotia implicata	EU107A	2	2			1		1	2	10	4	4	2
Eunotia incisa	EU047A	4	10	6	5	6	9	9	5	10	8	9	1
Eunotia pectinalis var minor	EU002B	2	4	2	2	2	4	3	4	1	1	2	2
Eunotia praerupta	EU003A								1				
Eunotia sp.	EU9999				1	1				1	1	1	2
Eunotia sudetica	EU021A					1							
Fragilaria brevistriata	FR006A	12	12	20	13	13	15	22	15	5	25	14	16
Fragilaria capucina	FR009A	4	2		3		3	1	4		2		2
Fragilaria capucina var. gracilis	FR009H	4		1	2	1			5		2		
Fragilaria capucina var. perminuta	FR009J	1											
Fragilaria construens	FR002A	1	2	6	6	3	9	8	2	1	10	6	9
Fragilaria construens var binodis	FR002B	1	1	1	4	1	1	2	2	1	8	3	7
Fragilaria construens var venter	FR002C	6	10	7	9	5	9	2	4	4	12	10	1
Fragilaria crotonensis	FR008A	34	39	32	35	8	1	2					
Fragilaria elliptica	FR018A	1	1										
Fragilaria lapponica	FR011A	3			1				1	1		1	
Fragilaria leptostauron	FR014A								1				
Fragilaria intermedia	FR019A		1	2		1	1		2	2	2	1	2
Fragilaria parasitica	FR045A	2						3	1		1	1	
Fragilaria parasitica var subconstricta	FR045E				1								
Fragilaria pinnata	FR001A	11	3	10	4	6	9	9	15	3	20	12	11
Fragilaria sp	FR9999	1		2	2		1		2	1	3	3	
Fragilaria virescens var exigua	FR005D	4	5	1	7	7	9	8	19	2	19	7	12
Frustulia rhomboides	FU002A									2			3
Gomphonema acuminatum	GO006A	1	2	1	1				1			4	
Gomphonema angustum	GO073A	5	3	9	6	8	26	18	17	9	13	13	16
Gomphonema dichotomum	GO036A	1											
Gomphonema gracile	GO004A	1		3		1	2	3	3	1		1	3
Gomphonema minutum	GO050A								7	2			1
Gomphonema olivaceum	GO001A					1	1					2	
Gomphonema olivaceum var calcareum	GO001B					1							
Gomphonema pumilum	GO080A	14	17	8	8	9	18	11	18	6	13	11	7
Gomphonema sp.	GO9999	1	1		1	1	2	1				1	1
Gomphonema truncatum	GO023A			1				2					
Gyrosigma attenuatum	GY001A			1			3	4	1				1
Navicula absoluta	NA161A				1								
Navicula agrestis	NA190A						1	3					
Navicula atomus	NA084A										3		
Navicula bacillum	NA071A												1
Navicula capitoradiata	NA745A					2	2		1		1	1	1

						Depth (cm)							
Name	Diatcode	0	2	5	7	10	15	20	30	40	50	70	90
Navicula cocconeiformis	NA032A					1							
Navicula costulata	NA299A				1								
Navicula cryptocephala	NA007A	1	1		1	1		2	2		1		
Navicula cryptotenella	NA751A		4		1			2		1	2		2
Navicula ignota var. palustris	NA433C				1								
Navicula jaernfeltii	NA002A	1	1	1	3	2	2	2			2	3	2
Navicula lanceolata	NA009A	1											
Navicula minima	NA042A	1	1		1					1	2	2	1
Navicula porifera	NA577A										1		
Navicula porifera var opportuna	NA577B				1								
Navicula pseudolanceolata	NA079A			1	1								
Navicula pseudoscutiiformis	NA013A											1	1
Navicula pseudoventralis	NA590A	2										1	2
Navicula pupula	NA014A			1	1				1		2	3	1
Navicula radiosa	NA003A	3	3	1	2	1	2	4	3	2	3	4	3
Navicula rhyncocephala	NA008A		1		1	2		1	2	1			1
Navicula schassmannii	NA133A											2	4
Navicula seminulum	NA005A	1	1	3					2	1	1		1
Navicula soehrensis	NA048A								2				
Navicula sp.	NA9999	3	2	3	3		3	2	3	3	1	3	5
Navicula subminuscula	NA134A		1										
Navicula submuralis	NA166A			2	2								
Navicula subrotundata	NA114A			1		1						1	
Navicula tripunctata	NA095A							1					
Navicula trivialis	NA063A												1
Navicula vitiosa	NA738A					6	3	3	1	2			4
Neidium alpinum	NE006A						1						
Neidium ampliatum	NE036A						1						
Neidium sp.	NE9999			1		6				1			
Nitzschia angustata	NI020A	1	3				3						1
Nitzschia dissipata	NI015A						2	1					
Nitzschia fonticola	NI002A		1	3	1			1		2	7	2	3
Nitzschia gracilis	NI017A			1									
Nitzschia lacuum	NI198A										2		
Nitzschia paleacea	NI033A										1		
Nitzschia perminuta	NI005A												1
Nitzschia sp.	NI9999		1	1				1	1		1		1
Pinnularia gibba	PI001A								4				
Pinnularia interrupta	PI004A										2		
Pinnularia sp.	PI9999		1	3	2				1		1		
Rhopalodia acuminata	RH008A								1				
Rhopalodia gibba	RH001A							1			1		
Rhopalodia sp.	RH9999					1							
Stauroneis anceps	SA001A						1		1				
Stauroneis phoenicentron	SA006A										1		
Stauroneis sp	SA9999	1											
Stephanodiscus medius	ST014A								1	1	2	1	
Stephanodiscus parvus	ST010A	9	11	26	13	10	2	1		1			
Surirella sp.	SU9999								1				
Synedra acus var angustissima	SY003C												2
Synedra nana/ Synedra tenera	SY009A	2		2	3		1	2	1		2		1
Synedra ulna	SY001A	1	2		1								
Tabellaria flocculosa (short)	TA9997	1	1	1		1					2	1	
Tabellaria flocculosa (long)	TA9998	5	3		3	3	8	7	10	10	5	7	7
Unknown centric	UN9995							1					
SUM		332	314	333	332	322	351	327	375	334	393	337	361

Table 6 Diatom counts for core LIND1

Name	Diatcode	Depth (cm)											
		0	2	5	7	10	15	20	30	40	50	60	80
Achnanthes clevei	AC006A									1			1
Achnanthes conspicua	AC023A						1						1
Achnanthes joursacense	AC170A		1									1	
Achnanthes lanceolata	AC001A				1			2	2		1		1
Achnanthes minutissima	AC013A			1		2					3	1	3
Achnanthes sp.	AC9999			1									
Amphora libyca	AM011A				1							1	
Amphora pediculus	AM012A	2	2	1		2		1	4	1	3	1	2
Asterionella formosa	AS001A	17	10	8	20	5	5	1		1	0.5	2	4
Aulacoseira ambigua	AU002A		6		1	4	2	3	1				1
Aulacoseira granulata	AU003A	3	4			3	1	1					
Cocconeis pseudothumensis	CO068A					1							
Cocconeis pediculus	CO005A		1										
Cocconeis placentula	CO001A	5	2	5	1	1	1	1	1	2	2	10	10
Cyclostephanos dubius	CC001A	20	33	80	40	15	4	4	1	1			
Cyclostephanos invisitatus	CC002A	23	8		3		1						
Cyclostephanos tholiformis	CC003A	6	13	21	10	5		1	1				
Cyclotella atomus	CY011A	2			1								
Cyclotella pseudostelligera	CY002A	3	2		1				2		1		
Cyclotella radiosa	CY019A			1	2	2	3	4	5	4	1	1	
Cymbella helvetica	CM013A			1									
Cymbella hustedtii	CM033A										1		
Cymbella microcephala	CM004A										1		1
Cymbella minuta	CM031A										1	1	1
Cymbella reichardtii	CM113A												1
Cymbella silesiaca	CM103A					1							2
Cymbella sp.	CM9999	1		1	1								
Cymbellonitzschia diluviana	CN001A				1								
Diatoma elongatum / tenuis	DT001A										1		
Epithemia sorex	EP001A			2	7	1			2	1		1	1
Epithemia sp.	EP9999				1								
Fragilaria brevistriata	FR006A	8	27	23	27	29	34	34	34	36	27	30	54
Fragilaria capucina	FR009A	6		1							1	1	
Fragilaria capucina var perminuta	FR009J								1				
Fragilaria capucina var mesolepta	FR009B						4						
Fragilaria capucina var. gracilis	FR009H												1
Fragilaria construens	FR002A	31	47	53	70	30	52	66	57	70	34	41	42
Fragilaria construens var binodis	FR002B									1	2	3	
Fragilaria construens var venter	FR002C	15	41	36	47	35	68	60	60	88	42	30	31
Fragilaria crotonensis	FR008A			1			1						
Fragilaria elliptica	FR018A					6	2	33	23	11	21	37	20
Fragilaria lapponica	FR011A		1	1	1								
Fragilaria intermedia	FR019A	1			1						1	2	1
Fragilaria parasitica	FR045A	1	1						1				
Fragilaria pinnata	FR001A	44	86	66	80	153	113	135	111	100	141	122	115
Fragilaria pseudoconstruens	FR056A								8	3	8	23	14
Fragilaria robusta	FR063A											2	
Fragilaria sp	FR9999		4		1	7	5	2	4	1	2		4
Fragilaria virescens var exigua	FR005D											1	
Gomphonema acuminatum	GO006A												2
Gomphonema minutum	GO050A				1		1			1	2	5	3
Gomphonema olivaceum	GO001A		1					1				1	1
Gomphonema parvulum	GO013A								1			2	4
Gomphonema sp.	GO9999		2	3					2		1	1	
Gomphonema truncatum	GO023A										1	1	

Name	Diatcode	0	2	5	7	10	15	20	30	40	50	60	80
						Depth (cm)							
Gyrosigma acuminatum	GY005A								2	4	1		
Gyrosigma sp.	GY9999		1			1		1					
Navicula absoluta	NA161A								1				
Navicula agrestis	NA190A		1										
Navicula atomus	NA084A					2							
Navicula bacillum	NA071A		1										
Navicula cari	NA051A											1	
Navicula clementioides	NA281A								1				
Navicula cryptocephala	NA007A					2							
Navicula gregaria	NA023A										2	1	
Navicula jaagii	NA101A								1				
Navicula menisculus	NA030A	1	5										
Navicula minima	NA042A	2	1		1		1		1	4	1	3	8
Navicula modica	NA123A												1
Navicula porifera	NA577A											1	1
Navicula pseudolanceolata	NA079A		3										
Navicula pupula	NA014A	1		1			1		1		3	2	
Navicula radiosa	NA003A			1			1		1		1	3	
Navicula rhyncocephala	NA008A	1									1		
Navicula scutelloides	NA028A		1	1			1	1	1				
Navicula seminulum	NA005A	1	2				1				5	7	
Navicula sp.	NA9999	1	4	1	1	1	1	1	1	3	2	2	1
Navicula subrotundata	NA114A			1	1	1	1					1	3
Navicula trivialis	NA063A		3	1									
Navicula vitabunda	NA168A							1					
Nitzschia amphibia	NI014A				1								
Nitzschia angustata	NI020A				1								
Nitzschia dissipata	NI015A			1			1						1
Nitzschia fonticola	NI002A	4	1										2
Nitzschia gracilis	NI017A	2											
Nitzschia linearis	NI031A		2										
Nitzschia paleacea	NI033A	1											
Nitzschia sp.	NI9999			1		1		1					1
Nitzschia subacicularis	NI171A											1	3
Pinnularia sp.	PI9999	1											
Rhoicosphenia curvata	RC001A								1				
Stephanodiscus hantzschii	ST001A	29	19	9	8	4	16	5	7		1		
Stephanodiscus tenuis	ST002A	6											
Stephanodiscus medius	ST014A	1			2		2						
Stephanodiscus minutulus	ST021A								3	1			
Stephanodiscus neoastraea	ST022A		1										
Stephanodiscus parvus	ST010A	80	9	4	8	14	27	4	1	4	7	10	30
Stephanodiscus sp.	ST9999							1		1	1		
Synedra acus	SY003A	12	7	3		1			1				1
Synedra nana/ Synedra tenera	SY009A							0.5	1	2		1	1
Synedra ulna	SY001A							0.5		2			1
Tabellaria flocculosa (short)	TA9997									2			
Tabellaria flocculosa (long)	TA9998										0.5		
Unknown centric	UN9995	2	3	3	3	1	4						
SUM		333	356	333	345	330	351	369	345	345	323	355	375

APPENDIX 3 CLADOCERA DATA

Table 7 Cladocera data (% relative abundance) for core BUTT4

Name	Code	2	5	10	20	30	40	50	60	70	80	90	100
							Depth (cm)						
Acroperos elongatus	CACEL	0.1	0.0	1.0	2.3	1.0	0.1	1.5	0.6	1.1	2.1	0.3	0.7
Acroperos harpae	CACHA	3.7	1.4	1.3	4.2	4.2	6.6	4.5	2.1	1.4	4.2	2.3	1.2
Alona affinis	CALAF	2.4	1.7	3.1	4.4	2.5	3.3	2.7	3.5	1.8	4.4	3.8	3.3
Alona costata	CALCO	0.0	0.1	0.3	0.0	0.3	0.0	1.4	0.9	0.2	0.3	0.5	0.4
Alona guttata/rectangula	CALGR	2.4	2.7	3.1	4.9	2.6	5.6	3.2	3.5	4.9	5.3	4.5	5.0
Alona guttata var. *tuberculata*	CALGT	0.0	0.0	0.9	4.7	3.4	0.7	2.2	0.0	5.7	3.5	1.9	3.7
Alona intermedia	CALIN	0.1	2.4	4.6	1.7	0.7	3.3	2.7	4.6	0.7	5.3	3.8	1.7
Alonella nana	CALNA	9.5	6.0	6.9	12.8	12.6	6.6	9.4	15.1	6.6	7.9	12.7	12.3
Alona quadrangularis	CALQU	2.4	2.4	4.5	1.2	1.4	1.0	1.6	1.6	4.9	3.6	5.7	2.0
Alona rustica	CALRU	0.0	0.0	1.0	0.0	1.2	3.3	0.0	0.0	1.4	0.0	0.0	0.0
Alonella exigua	CALXG	0.0	0.0	1.0	0.0	7.4	3.3	1.4	5.8	2.1	3.5	1.9	0.8
Alonella excisa	CALXS	7.1	2.4	2.7	6.0	5.9	12.4	6.5	5.0	4.6	3.5	11.4	8.4
Bosmina coregoni	CBOCO	43.3	55.8	52.2	26.9	25.6	23.5	25.4	30.3	39.6	35.5	24.4	20.7
Bosmina longirostris	CBOLO	7.1	8.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Camptocercus rectirostris	CCARE	0.0	0.0	0.0	0.8	0.3	0.4	1.4	0.6	0.4	0.1	0.9	2.9
Chydorus piger	CCHPI	2.4	0.3	2.5	8.2	12.8	3.4	10.7	12.7	8.0	5.7	7.2	11.2
Chydorus sphaericus	CCHSP	5.2	3.2	4.5	6.7	4.7	7.5	9.6	1.4	2.8	2.5	3.7	2.8
Daphnia claw	CDAPC	2.4	7.2	4.1	4.0	0.0	6.6	2.7	0.0	1.4	0.0	1.9	8.4
Eurycercus lamellatus	CEULA	2.5	2.7	1.8	3.4	5.3	4.6	3.6	3.0	5.1	3.8	4.4	4.9
Graptoleberis testudinaria	CGRTE	4.8	2.5	2.0	4.0	0.6	3.4	3.0	4.0	2.4	3.5	2.8	3.4
Leydigia leydigi	CLELI	0.0	0.1	0.0	0.0	0.0	0.1	1.4	0.0	0.1	1.8	0.2	0.2
Monospilus dispar	CMODI	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Phrixura rostrata	CPHIR	2.4	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0
Pleuroxus laevis	CPLLA	0.0	0.0	0.0	0.2	0.0	0.1	0.2	0.0	0.0	0.1	0.0	0.8
Pleuroxus truncatus	CPLTR	0.0	0.0	0.0	0.0	2.5	0.0	0.2	1.2	0.0	0.1	0.0	1.7
Pleuroxus uncinatus	CPLUN	0.0	0.1	0.5	0.0	0.0	0.0	0.0	1.2	0.0	0.9	0.0	0.8
Rhynchotalona falcata	CRHFA	2.4	0.0	2.0	2.0	0.0	0.0	2.7	1.2	2.8	0.0	5.7	1.7
Sida crystallina	CSICR	0.1	0.7	0.0	1.6	5.0	3.9	2.1	2.1	1.8	2.4	0.0	1.1

Table 8 Cladocera data (% relative abundance) for core LIND1

Name	Code	2	5	10	20	30	40	Depth (cm) 50	60	70	80	90	100
Acroperos elongatus	CACEL	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0
Acroperos harpae	CACHA	0.6	0.4	1.3	1.5	1.4	0.7	0.7	1.6	2.6	0.9	1.0	0.7
Alona affinis	CALAF	2.0	3.0	1.8	1.4	5.1	6.9	9.0	2.8	1.5	2.2	2.0	3.6
Alona costata	CALCO	0.0	0.8	0.0	0.1	0.2	0.4	0.8	0.2	0.2	1.0	0.4	0.0
Alona guttata/rectangula	CALGR	1.1	0.0	1.0	5.3	1.1	3.8	3.0	5.7	12.7	10.6	9.9	7.6
Alona guttata var. *tuberculata*	CALGT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.5	0.1	2.3	0.0
Alona intermedia	CALIN	0.3	0.0	0.0	0.2	0.0	1.9	0.0	0.5	1.7	0.3	0.4	0.0
Alonella nana	CALNA	0.0	0.0	0.0	0.0	1.6	0.0	1.3	11.7	14.3	19.7	20.5	4.2
Alona quadrangularis	CALQU	0.8	1.6	4.2	1.3	5.1	6.6	4.7	3.9	6.0	7.1	5.7	2.5
Alona rustica	CALRU	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.3	0.1	0.1	1.4	0.0
Alonella excisa	CALXS	0.0	0.0	0.0	0.0	0.0	0.0	2.2	3.0	3.0	1.6	3.8	2.0
Bosmina longirostris	CBOLO	75.4	66.4	53.3	61.1	51.9	44.3	40.3	3.3	5.3	4.4	3.7	0.0
Camptocercus rectirostris	CCARE	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Chydorus piger	CCHPI	0.0	0.0	0.0	0.0	0.0	0.0	0.4	2.3	0.7	0.9	1.7	0.9
Chydorus sphaericus	CCHSP	15.9	23.2	32.1	22.1	29.4	22.8	20.5	41.0	23.2	21.4	26.5	44.0
Daphnia claw	CDAPC	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	1.5	1.3	0.0	0.0
Eurycercus lamellatus	CEULA	1.3	1.3	2.3	1.8	1.8	2.7	2.3	6.6	4.1	6.8	9.0	7.0
Graptoleberis testudinaria	CGRTE	2.2	0.5	2.4	0.3	0.5	1.1	2.6	6.3	10.5	12.9	8.0	18.0
Leydigi leydigi	CLELI	0.2	0.5	0.0	0.2	0.5	0.3	0.0	0.0	0.1	0.0	0.0	0.2
Monospilus dispar	CMODI	0.0	0.0	0.0	2.2	0.5	0.9	2.2	2.0	3.3	2.1	1.2	4.1
Phiruxa rostrata	CPHIR	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pleuroxus aduncus	CPLAD	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0
Pleuroxus denticulatus	CPLDE	0.1	0.3	0.5	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0
Plevroxus laevis	CPLLA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.1	0.0	2.0
Plevroxus truncatus	CPLTR	0.0	0.0	0.1	0.2	0.0	1.9	0.2	0.0	0.0	0.0	0.0	0.4
Plevroxus uncinatus	CPLUN	0.2	1.9	1.0	2.3	0.6	5.7	8.9	8.7	7.0	5.3	2.3	2.6
Rhynchotalona falcata	CRHFA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3	0.0	0.0
Sida crystallina	CSICR	0.0	0.0	0.0	0.2	0.0	0.0	0.3	0.0	0.2	0.0	0.2	0.2

APPENDIX 4 MACROFOSSIL DATA

Table 9 Macrofossil data (Numbers per 100cm^3) for core BUTT5

Name	4	10	15	20	25	30	35	40	50	60	70	80
						Depth (cm)						
Potamogeton crispus turions (fragment)	3	0	0	0	0	0	0	0	0	0	0	0
Isoetes lacustris	27	17	30	230	150	63	10	0	30	0	7	13
I. lacustris fragment	50	33	97	1070	417	177	107	50	0	0	20	0
Isoetes echinospora	0	0	0	0	0	10	0	0	0	0	0	7
I. echinospora fragment	0	0	0	0	0	17	0	0	0	0	0	17
Chara A oospore	7	0	0	17	0	7	0	0	0	0	7	7
Nitella (large)	80	17	10	13	10	23	53	57	110	27	13	20
Nitella (small)	167	33	0	0	17	17	17	0	17	17	33	0
Najas flexilis seed	0	0	0	0	0	10	10	27	10	3	7	3
Najas flexilis seed fragment	0	0	0	0	0	3	10	0	3	20	13	23
Betula sp.	0	0	0	0	0	3	7	0	3	0	3	7
Carex (triangular)	0	0	0	0	0	0	0	3	3	0	0	0
Carex (flat)	0	0	0	0	0	0	0	3	3	0	0	0
Typha seed	0	17	0	0	0	0	0	0	0	0	0	0
Moss leaves	40	0	0	0	0	0	23	157	13	87	67	130
Gloeotrichia	117	0	0	0	3	0	0	3	0	0	3	0
Root fragments (Unidentified)	0	0	11663	18363	16043	10	0	0	3	0	0	0
Plant fragments (Reed? Unidentified)	0	0	0	0	257	8610	4217	2040	1537	283	0	0
Fern sporangium	0	0	0	0	0	0	17	117	17	33	100	117
Daphnia hyalina ephippia	115	0	2	0	0	20	17	8	2	0	0	0
Campocerus ephippia	0	0	0	0	0	0	0	8	0	0	0	0

Table 10 Macrofossil data (Numbers per 100cm^3) for core LIND2

						Depth (cm)						
Name	**2**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**	**110**
Chara fragment	0.0	0.0	10.0	0.0	0.0	0.0	0.0	0.0	6.7	0.0	0.0	0.0
Chara A	0.0	3.3	10.0	0.0	10.0	10.0	0.0	0.0	0.0	16.7	16.7	0.0
Chara B	0.0	13.3	36.7	50.0	6.7	10.0	23.3	6.7	13.3	13.3	23.3	23.3
Chara C	0.0	0.0	0.0	6.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.3
Nitella A (large)	0.0	0.0	6.7	40.0	20.0	43.3	40.0	23.3	26.7	56.7	256.7	540.0
Potamogeton seed fragment	0.0	0.0	6.7	0.0	0.0	0.0	0.0	0.0	0.0	3.3	3.3	0.0
Potamogeton berchtoldii seed	0.0	0.0	0.0	6.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Potamogeton obtusifolius seed	0.0	0.0	0.0	3.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Potamogeton crispus seed	0.0	0.0	0.0	6.7	6.7	3.3	0.0	0.0	0.0	0.0	0.0	0.0
Potamogeton cf. natans seed	0.0	0.0	0.0	0.0	3.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Potamogeton crispus turions	0.0	0.0	0.0	0.0	23.3	6.7	20.0	0.0	0.0	3.3	6.7	6.7
Callitriche shoot	0.0	6.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Callitriche cf. hermaphroditica	0.0	10.0	6.7	13.3	3.3	0.0	3.3	3.3	0.0	3.3	3.3	0.0
Potamogeton pusillus agg leaf tip	40.0	56.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Broad submerged *Potamogeton* leaf fragment	0.0	0.0	0.0	0.0	0.0	0.0	10.0	0.0	26.7	3.3	10.0	0.0
Potamogeton obtusifolius leaf tip	3.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ceratophyllum spines	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	40.0	13.3	53.3	30.0
Nuphar lutea seed	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.3	0.0	0.0	0.0
Myriophyllum alterniflorum seed	0.0	0.0	0.0	3.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ranunculus sect. Batrachium	0.0	0.0	0.0	3.3	10.0	6.7	3.3	0.0	3.3	0.0	0.0	6.7
Nymphaeaceae trichosclereids	16.7	0.0	50.0	0.0	16.7	50.0	100.0	0.0	16.7	0.0	350.0	50.0
Gloeotrichia	43.3	70.0	550.0	540.0	393.3	256.7	610.0	623.3	1356.7	1286.7	1066.7	166.7
Selaginella	0.0	0.0	0.0	0.0	0.0	0.0	6.7	0.0	0.0	0.0	3.3	3.3
Filamentous algae cells	436.7	503.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Moss leaf A	0.0	0.0	23.3	36.7	10.0	50.0	90.0	6.7	26.7	20.0	13.3	0.0
Moss leaf B	0.0	0.0	0.0	0.0	10.0	0.0	6.7	10.0	16.7	136.7	110.0	0.0
Moss leaf C	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	16.7	0.0	0.0	0.0
Moss leaf D	0.0	3.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Juncus (yellow)	0.0	0.0	0.0	16.7	100.0	16.7	16.7	0.0	83.3	33.3	16.7	16.7
Juncus (orange)	0.0	0.0	0.0	16.7	16.7	16.7	16.7	0.0	33.3	16.7	33.3	0.0
Fern sporangium	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0	50.0	0.0	16.7
Daphnia hyalina ephippia	56.7	308.3	1013.3	318.3	363.3	325.0	193.3	103.3	51.7	75.0	126.7	1158.3
Simocephalus ephippia	0.0	0.0	0.0	0.0	0.0	0.0	33.3	16.7	0.0	0.0	50.0	0.0
Ceriodaphnia ephippia	100.0	50.0	616.7	566.7	891.7	1166.7	2425.0	2033.3	1283.3	1825.0	2683.3	966.7