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Using novel palaeolimnological techniques to define lake conservation objectives

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Introduction

Natural England commission a range of reports from external contractors to provide evidence and advice to assist us in delivering our duties. The views in this report are those of the authors and do not necessarily represent those of Natural England.

Background

Natural England commissioned this research:

- To help define conservation objectives for a suite of lakes designated as Sites of Special Scientific Interest.
- To investigate the value of relatively novel techniques in doing this.

Palaeolimnology reconstructs the history of lake environments through the study of sediments and remains of plants and animals. Where conditions allow, it is possible to reconstruct the environmental history of a lake and identify major changes which can then be linked to known events in the surrounding catchment (e.g. major land use change).

It is also possible to determine the character of the lake prior to major human impact. This is known as the 'reference' condition. Defining reference conditions for a given lake is an important part of defining future conservation objectives (though the two may not necessarily be the same).

Diatom remains have traditionally been the focus of most palaeolimnology work and good relationships exist between diatoms and lake water chemistry, allowing past nutrient conditions to be inferred. However, in some lake sediments diatoms are poorly preserved and therefore other remains may be better indicators. This is particularly true for shallow lakes and marl lakes.

The work described in this report uses a range of indicators (plant remains, zooplankton remains and diatoms) to reconstruct the history of selected lakes. In particular the research investigated a recently developed method to identify preserved stonewort 'oospores' which are particularly abundant in the sediments of marl lakes.

The results of this work will be used to help define conservation objectives for the sites studied and will provide clues as to the cause of changes and deterioration.

The research has shown the value of new palaeolimnological techniques, particularly in lakes where more established methods are unreliable. The marl lakes aspect of this work is being continued through a join University College London and Natural England PhD project.

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Further information
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Environmental Change Research Centre

Using novel palaeolimnological techniques to define lake conservation objectives

Final Report to Natural England

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Executive summary

This is the final report to Natural England on the project 'Using novel palaeolimnological techniques to define lake conservation objectives' (SAE03/02/054). The aim is to use existing and recently developed palaeoecological techniques to define reference conditions and assess the condition of selected SSSIs in England, and thereby assist in the setting of conservation objectives and management goals. The eight sites are Aqualate Mere, Hawes Water (Silverdale), Cunswick Tarn, Over Water, Sunbiggin Tarn, Malham Tarn, Semer Water and Hornsea Mere. Task 1 involved the collection, processing and dating of cores. A single sediment core, approximately 1 m in length, was collected from each site during the period 14-21 January 2008. Dating of the cores was carried out using spheroidal carbonaceous particle (SCP) analyses. Cores from Cunswick Tarn, Over Water, Sunbiggin Tarn, Malham Tarn and Hornsea Mere exhibited typical features of SCP profiles for UK. At Aqualate Mere, the SCP record was somewhat irregular and appeared to be truncated but nonetheless several dates could be derived. The SCP profiles for Hawes Water and Semer Water were highly irregular and therefore a reliable chronology could not be obtained for these two sites.

Tasks 2 and 3 involved macrofossil analyses of cores from five sites: Aqualate Mere, Over Water, Hornsea Mere, Cunswick Tarn and Sunbiggin Tarn. For the latter two marl lakes, a new method for identifying the charophyte oospores was applied. For Over Water, diatom analysis was also undertaken and a diatom-phosphorus transfer function was applied to assess changes in water quality. Given the difficulties with dating the cores from Hawes Water and Semer Water, no further work was undertaken on these sites, and work on Malham Tarn will be taken forward via a PhD project. At Aqualate Mere, the data suggest that the present day plant community has few taxa in common with those observed in the reference assemblages, having experienced a reduction in stoneworts (charophytes), with fine-leaved pondweeds, particularly *Zannichellia palustris*, becoming the dominant component of the aquatic vegetation. The aquatic plant community of Hornsea Mere has undergone a gradual but marked shift from charophyte to fine-leaved pondweed dominance over the last century, probably associated with enrichment of the lake. Over Water has experienced a loss of isoetids and replacement by elodeids over the period represented by the core. This is most likely associated with gradual eutrophication but alterations in water level and the introduction of *Elodea nuttallii* may also be contributing factors. The aquatic plant community of Cunswick Tarn has shifted from a charophyte dominated flora typical of a mesotrophic, calcareous (marl) lake, to one dominated by *Nymphaeaceae* (water lillies) and elodeids, most probably caused by eutrophication. The changes in the macrofossil record of Sunbiggin Tarn are rather difficult to interpret owing to the high variability in abundance of remains. Nevertheless, the shifts indicate a possible decline in species richness, particularly in the charophyte community, and dominance of *Zannichellia palustris* since the 1980s.

The study has successfully determined the reference communities and the degree of ecological change for the five sites, and at Aqualate Mere and Hornsea Mere macrofossil analysis has proved more informative than diatoms. The application of the new charophyte oospore identification system to Cunswick Tarn and Sunbiggin Tarn illustrates its potential for inferring submerged vegetation histories in marl systems where stoneworts are typically abundant. Finally, the study highlights the difficulty of interpreting changes based on a small number of samples owing to high variability in abundance of macrofossil remains. Hence, the addition of five further samples for macrofossil analysis is recommended to assess changes in the aquatic plant community more fully and to provide a sounder interpretation of the palaeoecological record.

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Cover photograph: Hawes Water, Silverdale (January 2008).

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SPECIFICATION

Statement of understanding, purpose and aims of project

The primary objective of this project is to use existing and recently developed palaeoecological techniques to define reference conditions and assess the condition of selected SSSIs in England, and thereby assist in the setting of conservation objectives and management goals. The eight selected sites are Aqualate Mere, Hawes Water (Silverdale), Cunswick Tarn, Over Water, Sunbiggin Tarn, Malham Tarn, Semer Water and Hornsea Mere.

The project is divided into three main tasks. Task 1 involved the collection, processing and dating of cores from the study sites, Task 2 focused on three lakes where new palaeolimnological studies were required to help define conservation objectives and Task 3 employed macrofossil studies at two marl systems to determine reference conditions and ecological change. Further details of each task are given below.

Task 1: Collection and dating of cores

This task involved:

1. Collection of a long (~1 m) sediment core from each of eight selected sites
2. Sub-sampling and standard sediment analysis (% dry weight, % organic matter)
3. Spheroidal carbonaceous particle analyses to provide a chronology for approximately the last 150 years for each core.

Task 2: Preliminary palaeolimnology for SSSI lakes

This task focuses on three lakes, Aqualate Mere, Hornsea Mere and Over Water. Sediment cores have been collected by ENSIS-ECRC from the former two sites on previous occasions and diatom analysis was attempted. However, in Aqualate Mere, diatoms were preserved only in the surface sediments (Bennion, 2004) and in Hornsea Mere diatoms could be analysed in only the upper 40 cm owing to increasing preservation problems downcore (Johnes *et al*., 1998). A recent core from Aqualate Mere has been dated using radiometric dating and the SCP method, and both techniques produced a reliable chronology (Hutchinson *et al*., in prep). In contrast, a previous core from Hornsea Mere could not be well dated using radiometric methods (Johnes *et al*., 1998). There have been no previous palaeolimnological studies on Over Water to our knowledge.

Over the last ten years ENSIS-ECRC has been developing the technique of plant macrofossil analysis. This involves the study of sediment core samples for macro-remains of water plants including various propagules (seeds, fruits, oospores, turions) and vegetative fragments (leaves, stems, cells and spines) that are visible with a standard dissecting microscope up to 40x magnification (Lowe & Walker, 1997; Birks, 2001). We have undertaken a number of studies with a view to assessing the effectiveness and potential of this technique (e.g. Davidson *et al*., 2005; Zhao *et al*., 2006) although applications to lakes of conservation interest are relatively few (e.g. Bennion *et al.,* 2008).

A knowledge of past vegetation and its influence upon wider lake ecology is important for guiding lake management and restoration under a number of drivers. For example, the European Council (EC) Water Framework Directive (WFD) requires ‘reference conditions’ (i.e. prior to anthropogenic impact) to be determined for a range of biological elements, and macrophytes are one of the elements that must be defined for lakes. The focus for this project is on those lakes designated for nature conservation reasons; Natural England is responsible for overseeing the management of Sites of Special Scientific Interest (SSSIs). There is a government public service agreement (PSA) target for 95% of SSSIs to be in favourable or unfavourable recovering condition by the end of 2010 and consequently Natural England is currently engaged in defining and implementing the necessary management. One of the sites, Sunbiggin Tarn, is also designated as a Special Area of Conservation (SAC) under the EC Habitats and Species Directive which brings further obligations for monitoring and reporting on condition.

The concept of favourable condition was derived from the EC Habitats and Species Directive which, in part, defines favourable conservation status as when ‘specific structure and functions which are necessary for its long-term maintenance exist’. The UK conservation agencies have developed ‘Common Standards for Monitoring’ guidance to help define favourable condition in detail for a range of habitats including lakes (JNCC, 2005). This is intended to guide status assessments and managment. Macrophyte community composition and structure are two key elements of the ‘structure’ component of favourable condition and are also indicators of the ‘functional’ components such as water quality. Consequently, a better understanding of historic plant communities and any changes that may have occurred is important in setting objectives for a particular lake, particularly where anthropogenic impacts may have resulted in changes to the character of a site and the ‘natural’ reference condition is in question. In addition to helping define lake type and set conservation objectives, macrofossil analysis may help in determining the presence and abundance of a rare plant species at a particular site.

This task involves macrofossil analysis of five samples per core from Aqualate Mere, Hornsea Mere and Over Water SSSIs, selected to cover the period of interest and to enable the pre-enrichment conditions to be determined. At Aqualate Mere and Hornsea Mere, it is expected that plant macrofossil analysis will provide an alternative and more informative method to diatoms for establishing reference conditions and ecological change.

Given that Over Water has not been the subject of previous palaeoecological studies, diatom analysis of five samples will be carried out in addition to the plant macrofossil analysis. If appropriate, an existing diatom-phosphorus (P) transfer function (Bennion *et al*., 1996) will be applied to the diatom data to reconstruct the nutrient history of the lake and define P targets (e.g. Bennion *et al*., 2004).

Task 3: Defining reference conditions for marl lakes

This task focuses on two SSSI marl lakes, Cunswick Tarn and Sunbiggin Tarn. Sunbiggin Tarn is also designated as an SAC as an example of habitat 3140 – ‘hard oligo-mesotrophic waters with benthic vegetation of *Chara* spp.’ and has been previously studied by ENSIS-ECRC. In contrast to most marl lakes, diatom preservation was good in a dated core from the tarn and 17 samples were analysed (Goldsmith *et al*., 2003). ENSIS-ECRC has not conducted any previous palaeolimnological studies on Cunswick Tarn.

This task aims to explore the potential of plant macrofossil analyses as an alternative and potentially more appropriate method than diatom analysis to define past conditions and to assess ecological change in marl lakes. The task involves macrofossil analysis of five samples per core from the two sites, selected to cover the period of interest and to enable the pre-enrichment conditions to be determined.

The methods employed will be the same as those in Task 2. Additionally, where charophyte oospores are abundant, we will apply the new identification system recently developed as part of a NERC funded project by ENSIS-ECRC that determines the provenance of the fossil oospores to species or sub-group level (Davidson *et al*., in prep.). This technique expands the potential of palaeolimnology for inferring submerged vegetation histories in lakes and is expected to be particularly valuable in lime-rich, marl waters where stoneworts (*Characeae*) often grow in profusion.

The results are presented for each site.

METHODS

Core collection

A single sediment core (~1 m in length) was collected from the sites during the period 14-21 January 2008 using a wide-diameter (~8 cm) Livingstone type piston coring device. The cores varied in length from 0.74 to 1.35 m and were expected to represent approximately the last 100-150 years, thereby allowing reference conditions to be defined and recent ecological change to be assessed. Expert judgement and any previous data on sediment distribution were used to decide on the optimal coring location that maximises the likelihood of obtaining a sound chronology and finding abundant remains of the fossil groups of interest, particularly plant macrofossils. All cores were taken from shallow water areas within 100 m distance from the shore and locations were recorded by GPS. Summary details of the cores are given in Table 1.

Extrusion, core description and stratigraphic analyses

The cores were extruded in the field or the laboratory at 1 cm intervals to provide a resolution of approximately a few years per sample, and any visible stratigraphic changes were noted. The percentage dry weight (DW) which gives a measure of the water content of the sediment, the percentage loss on ignition (LOI 550) which gives a measure of the organic matter content, and the percentage carbonate content (LOI 950) was undertaken using standard techniques (Dean, 1974; Heiri *et al.,* 2001) on selected sub-samples from each core. Sub-samples at 2 cm intervals from each core have been frozen for potential future pigment analyses at University of Nottingham.

Dating

Dating of the cores from the eight sites was carried out using the well established technique of spheroidal carbonaceous particle (SCP) (Rose, 1994). Dried sediment was subjected to sequential chemical attack by mineral acids to remove unwanted fractions leaving a suspension of mainly carbonaceous material and a few persistent minerals in water. SCPs are composed mostly of elemental carbon and are chemically robust. The use of concentrated nitric acid (to remove organic material), hydrofluoric acid (siliceous material) and hydrochloric acid (carbonates and bicarbonates) therefore does them no damage. A known fraction of the resulting suspension was evaporated onto a coverslip and mounted onto a microscope slide. The number of SCPs on the coverslip was counted using a light microscope at x400 magnification and the sediment concentration calculated in units of ‘number of particles per gram dry mass of sediment’ (gDM^{-1}). The criteria for SCP identification under the light microscope followed Rose (2008). Analytical blanks and SCP reference material (Rose, 2008) were included in each batch of sample digestions. Reference concentrations agreed with the expected values while no SCPs were observed in the blanks. The detection limit for the technique is ~100 gDM^{-1} and concentrations have an accuracy of ~ ± 45 gDM^{-1}.

The analysis of the cores was completed in two stages. First, a ‘skeleton’ profile covering the length of the core was produced and then, after this initial analysis was completed, a second stage of ‘filling-in’ was undertaken. This approach allows a more targeted analysis and is able to focus on the area of the sediment cores containing the SCP profile.

The dating of the cores followed the method described in Rose *et al*. (1995) whereby three main features of the SCP profile are used to provide dates. A later approach using cumulative SCP inventory profiles (Rose & Appleby, 2005) is less applicable to littoral cores. This is because the method requires that a full record be present so that percentiles from the cumulative curve can each be ascribed a date. This is not possible where the record is incomplete. Sediment accumulation in littoral cores is not always as consistent as in deeper waters and hence application of the cumulative approach may lead to erroneous dates being applied. Hence in these cores the former method, although providing fewer dates for each core, was considered to be more reliable. The results have been used to ascribe the dates to the cores as shown in the stratigraphic diagrams in this report.

Diatom analysis

For Over Water, standard diatom analysis (Battarbee *et al*., 2001) of five samples was undertaken. At least 300 valves were counted from each sample using a research microscope with a 100x oil immersion objective and phase contrast. Krammer & Lange-Bertalot (1986-1991) was the principal flora used in identification. The diatom data were expressed as percentage relative abundances. The results were plotted as a stratigraphic diagram using C2 (Juggins, 2003). Cluster analysis was performed on the core data to identify the major zones in the diatom profile using ZONE v.1.2 (Juggins, 1991), an MS-DOS program for constrained clustering of palaeoecological (i.e. stratigraphic) data. This employs a suite of techniques including CONSLINK – constrained single link clustering, CONISS – constrained incremental sum of squares clustering, SPLITLSQ and SPLITINF – binary division using sum of squares and information statistic criteria. All clustering techniques have weaknesses and in certain circumstances provide misleading zones. Hence, in order to obviate this problem, the results of the various methods were compared and only the patterns which were consistent in a number of the techniques were employed. The zones are illustrated in the stratigraphic plots to facilitate description of the major compositional changes.

An existing diatom-phosphorus (P) transfer function (Bennion *et al*., 1996) was applied to the diatom data to reconstruct the nutrient history of the lake and define P targets (e.g. Bennion *et al*., 2004). This was based on a Northwest European training set of 152 relatively small, shallow lakes (< 10 m maximum depth) with a median value for the dataset of 104 µg TP L^{-1} and a root mean squared error of prediction (RMSEP) of 0.22 and 0.21 $\log_{10}$ µg TP L^{-1} for the weighted averaging partial least squares one-component (WA-PLS1) and two-component (WA-PLS2) models, respectively. The reconstruction was implemented using C2 (Juggins, 2003).

Macrofossil analysis and charophyte identification

For the macrofossil analysis five levels were examined in the core from each of the five study sites. A measured volume of sediment (~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 (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 plant 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*. The data are presented as numbers of remains per 100 cm^3 of wet sediment. It should be noted that five samples provides only a low resolution analysis and can, therefore, provide only limited information on the changes in aquatic vegetation. It is advised that the data presented here are treated as preliminary and analysis of additional samples is recommended to produce a fuller interpretation of ecological change.

The results of the macrofossil analyses were plotted as stratigraphic diagrams using C2 (Juggins, 2003) for the plant remains and the zooplankton ephippia. Cluster analysis was performed on both plant and animal macrofossil data to facilitate the description of zones for the core. A variety of constrained clustering techniques were employed using the program ZONE v.1.2 (Juggins, 1991), as described above for diatom analysis.

A new technique developed in an attempt to determine species or species group level identification of *Chara* from their oospores (Davidson *et al*., in prep) was applied to the oospores found in the cores from the two marl lakes, Cunswick and Sunbiggin Tarn. This model has been developed using the UK reference dataset of pressed charophyte specimens. Oospores taken from identified live reference material have been morphologically characterised and the features which best separate the oospores identified by a classification tree (Breiman *et al*., 1984) as shown in Figure 1. This model can then be used to identify the oospores from core material based on these characteristics. However, it was not always possible to identify the oospores to species level, and in these cases the taxonomic level of species group was used. For example, *Chara vulgaris* type includes *C. vulgaris* and *C. contraria*, whilst *Chara aspera* type includes *C. aspera, C. curta* and *C. virgata*. It should be noted that there is some error of prediction associated with the identifications as indicated by the percentage figure given in parentheses after each species in Figure 1. Therefore, a majority approach is employed rather than allocation of a species name based on a single oospore. For example, if 30 oospores in a given sample are identified as *Chara rudis*, then the confidence of a correct identification is high. However, if there was only one oospore in a sample that was identified as *Chara aculeolata*, there is much greater uncertainty associated with that identification.

Figure 1 Classification tree of *Chara* oospore types

(error of prediction for each species is indicated by the percentage figure given in parentheses). From Davidson *et al*. in prep.

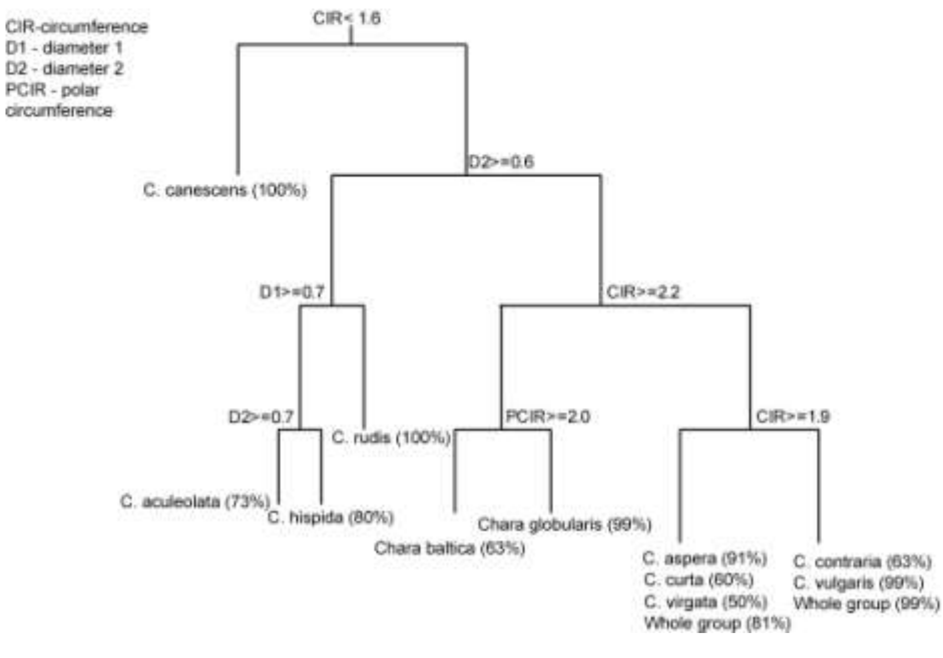


Table 1 Details of the sediment cores collected from the eight study sites

Site name	WBID	Lake NGR	Alt (m)	Area (ha)	Max depth (m)	Core code	Sampleid	Coring date	Core type	Coring location	Core length (m)	Coring water depth (m)	Approx distance from shore (m)	Secchi depth-Jan08 (m)
Aqualate Mere	35724	SJ 772 204	67	75.3	< 1	AQUA3	509367	14-Jan-08	Fat piston	SJ 77484 20188	0.86	1.3	40	0.3
Hawes Water	29647	SD 477 766	8	5.7	12	HAWE2	509361	15-Jan-08	Fat piston	SD 47872 76670	0.79	2.6	2	7.0
Cunswick Tarn	29394	SD 489 937	138	0.8	?	CUNS1	509086	16-Jan-08	Fat piston	SD 48943 93728	0.74	2.4	10	2.7
Over Water	28806	NY 251 350	188	19.7	8	OVER1	509362	17-Jan-08	Fat piston	NY 25069 34884	1.35	2.8	20	2.2
Sunbiggin Tarn	29178	NY 676 076	255	3.7	11	SUNB3	509363	19-Jan-08	Fat piston	NY 67566 07611	1.35	2.3	15	2.0
Semer Water	29479	SD 919 872	246	28.6	12	SEME3	509364	19-Jan-08	Fat piston	SD 91846 87326	0.91	2.95	20	0.45
Malham Tarn	29844	SD 893 667	375	60	4.4	MALH4	509365	20-Jan-08	Fat piston	SD 89145 67039	1.18	2	100	>2
Hornsea Mere	30244	TA 190 469	8	133.3	< 2	HORN3	509366	21-Jan-08	Fat piston	TA 19148 47477	1.32	1.75	20	0.5

AQUALATE MERE

Site description

Aqualate Mere (NGR: SJ772204) is the largest (75 ha.) of the West Midland meres, a group of waterbodies mostly of glacial/periglacial origin scattered across the counties of Shropshire, Cheshire and Staffordshire. The meres and the associated wetlands – 'mosses' are recognised as an important nature conservation area and many are designated as SSSI and included within the Midlands Meres and Mosses Ramsar site. Aqualate Mere SSSI occupies a shallow basin in glacial drift overlying Triassic sandstone and is relatively unique amongst the meres in having extensive reedswamp and willow and alder carr. The conservation interest of the open water has declined in recent years due to progressive nutrient enrichment and sedimentation which has reduced the water depth to around 1 m from an average of 2-3 m since the 1930s. Although diffuse sources of nutrients and sediments from agriculture in the surrounding area has played a part in this process the greatest contribution seems to be from the Shropshire Union canal which overflows into the Wood Brook which flows into the mere. In addition to silt the canal has brought nutrients from Barnhurst sewage treatment works into the mere. Although phosphorus stripping has now been applied to this discharge and hence external nutrient loads have been reduced there is still a large volume of nutrient-rich silt in the mere. At present the mere has an impoverished macrophyte community and has been subject to cyanobacterial blooms which have caused fish kills downstream of the mere. There are plans to undertake dredging to remove this accumulated silt as the first step in restoring the mere to favourable condition. Before these major works take place it was considered prudent to obtain a sediment core to enable further analysis and to try to reconstruct the past plant community to inform restoration goals.

Core description

A piston core, 0.86 m in length, was collected from Aqualate Mere on 14-Jan-08 in 1.3 m water depth, approximately 40 m from the southern shore. At the time of coring, the water level was high and the lake was turbid (secchi depth 0.3 m) and orange-brown in colour.

The core had two distinct horizons (Figure 2). The upper 28 cm of the core was mid-brown in colour and was comprised of an odourless, silt-clay which may be in-washed material from the canal. The section from 28 to 73 cm was a dark brown, fine lake material with odour. The section below 73 cm to the core base was also a dark brown, fine lake mud but was denser than the upper core with abundant fossil remains, especially molluscs. There was a general increase in the numbers of mollluscs downcore. The very bottom of the core was comprised of peat with abundant molluscs suggesting that the entire lacustrine sequence was recovered by the core.

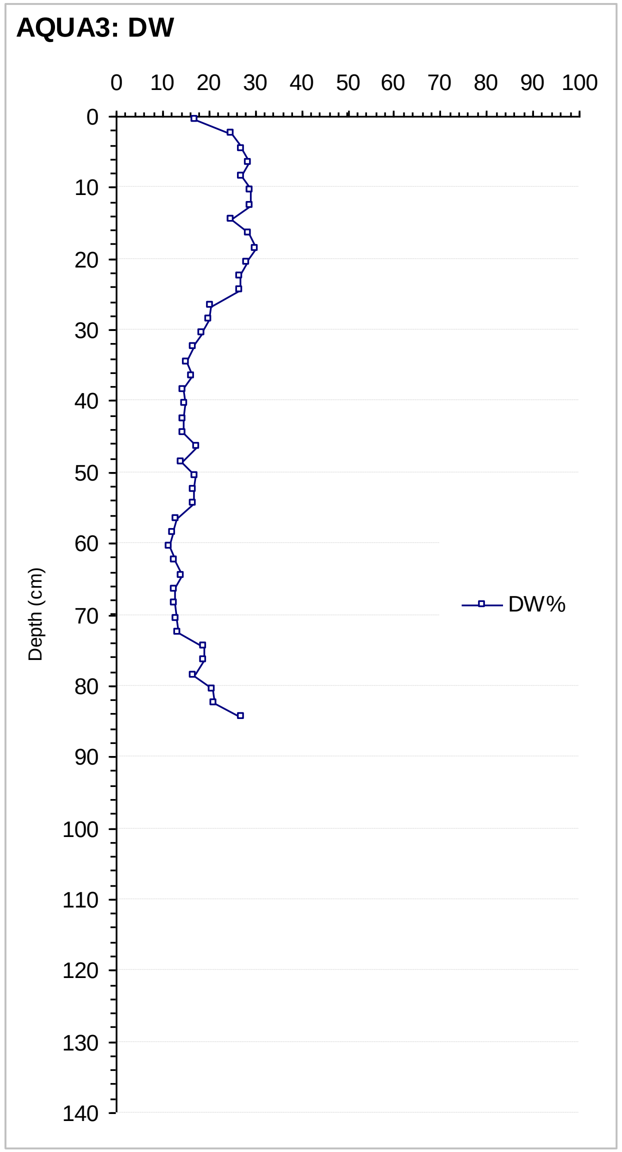
Figure 2 Sediment core stratigraphy of AQUA3

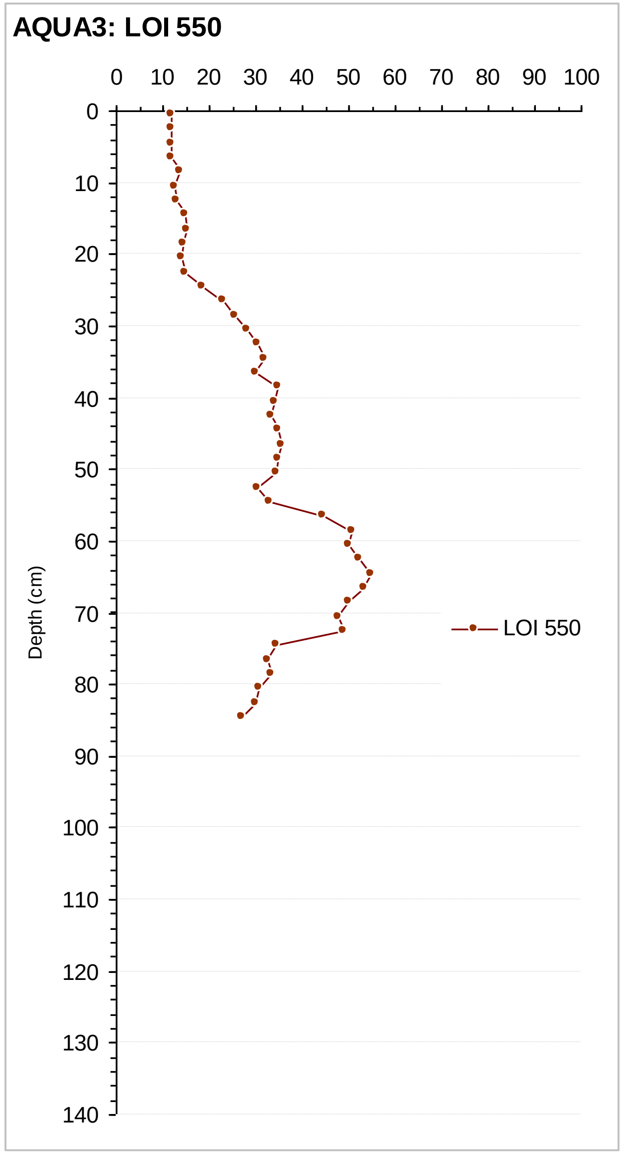
Depth (cm)	Sediment colour
0-28	Mid-brown
28-73	Dark brown
73-85	Dark brown (abundant molluscs)
85-86	Peat (abundant molluscs)

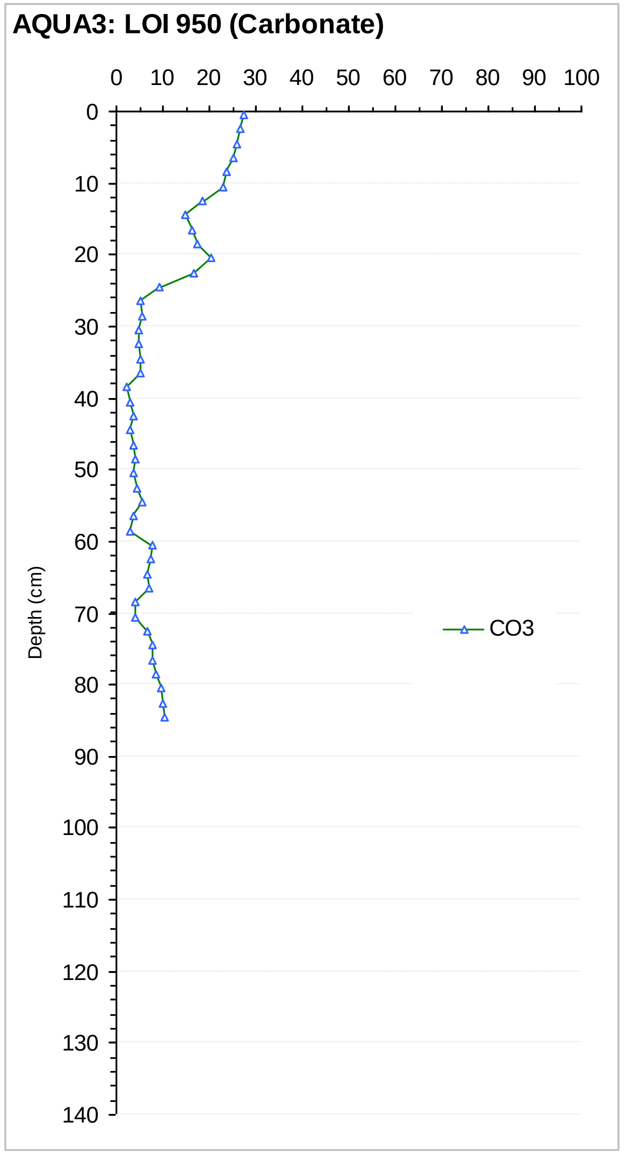
Stratigraphic analyses

The core, AQUA3, was relatively dense but organic in the lowermost section below ~73 cm with LOI 550 values of ~30% (Figure 3). Above this was a highly organic layer extending from ~58-73 cm with LOI 550 values of ~50%. Subsequently, the organic matter content gradually declines upwards through the core before stabilising at low LOI 550 values of 10-15% in the upper 25 cm. The uppermost 25 cm has relatively high DW values of 25-30% and higher percentage carbonate than the lower core with LOI 950 values reaching a maximum of 27% at the surface.

Figure 3 Stratigraphic data for AQUA3







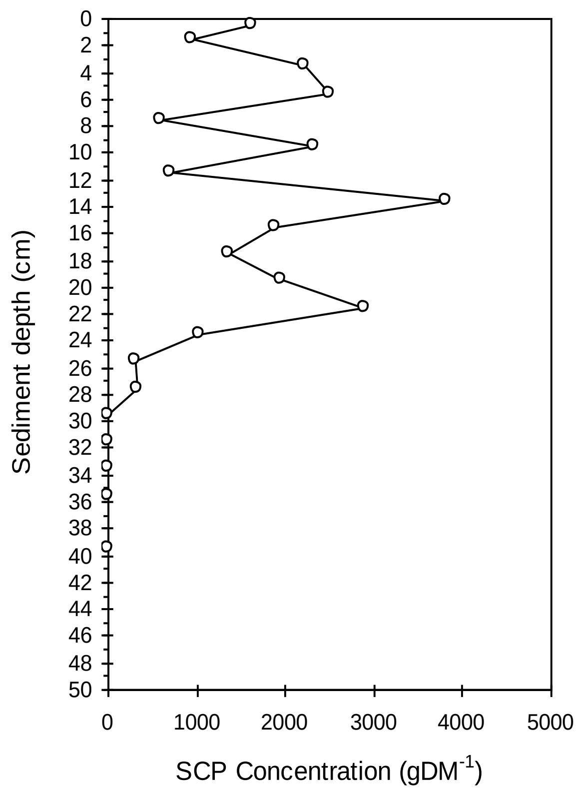
Spheroidal carbonaceous particle analysis

The SCP profile from AQUA3 is rather irregular with a series of peaks and troughs throughout (Table 2, Figure 4). The first presence of SCPs occurs at 27-28 cm while the peak concentration of almost 4000 gDM^{-1} occurs at 13-14cm. It seems likely that this SCP profile does not represent the full industrial record of deposition since 1850, but rather is truncated at a point where SCP concentrations fall below the analytical detection limit. This is quite common in sediment cores of rapid accumulation or where sediment accumulation is less consistent.

Table 2 SCP concentrations for AQUA3

Mean depth (cm)	SCP conc (gDM^{-1})	90% C.L. (gDM^{-1})
0.5	1619	600
1.5	944	534
3.5	2211	969
5.5	2507	929
7.5	589	408
9.5	2321	928
11.5	691	479
13.5	3813	1036
15.5	1893	927
17.5	1362	597
19.5	1958	858
21.5	2897	856
23.5	1026	581
25.5	315	309
27.5	327	321
29.5	0	0
31.5	0	0
33.5	0	0
35.5	0	0
39.5	0	0
59.5	0	0
79.5	0	0

Figure 4 SCP profile for AQUA3



Although the peak concentration is represented only by a single data point, it is clearly higher than any other point on the profile. If we assume that this is the maximum concentration then we can ascribe this the date of 1978 ± 4. Given the sampling resolution this peak could lie between 12 and 15 cm which would provide a mean sediment accumulation rate of 0.4-0.5 cm yr^{-1} for the post-1978 period. Extrapolating this rate would place 1950, the time at which a rapid increase in SCP concentration is usually observed, between 23.5 and 29 cm. The profile would suggest that this feature occurs at ~25 cm indicating a good agreement and suggesting that the sediment accumulation rate in this core is reasonably consistent over the last 50-60 years. This would also imply that the profile is truncated at around this time and that the start of the record occurs where the SCP concentration exceeds the analytical detection limit for the first time as a result of the rapidly increasing deposition of SCPs in the 1950s (Rose *et al.*, 1995). Although it is not possible to provide any further dates below this time from the SCP record this rate would place 1850 between 63 and 79 cm depth. The best available chronology is summarised in Table 3.

Table 3 The SCP derived chronology for AQUA3

Sediment depth (cm)	Age (Years)	Date
0	0	2008
5	11 ± 2	1997 ± 2
10	23 ± 3	1985 ± 3
15	34 ± 4	1974 ± 4
20	45 ± 5	1963± 5
25	56 ± 8	1952 ± 8
30	68 ± 10	1940 ± 10

Macrofossil analysis

Plant macrofossils
The cluster analysis identified two zones in the plant macrofossil record (Figure 5).

The lower zone (Zone 1) was dominated by terrestrial mosses, *Juncus* and *Typha* (data not shown) though *Chara* and *Nitella* oospores were present at densities of 20 and 40 oospores per 100 cm^3, respectively. The aquatic species diversity increased in the early 1900s (Zone 2) with C*hara* and *Nitella* spp. dominating, and remains of *Ranunculus* sect *Batrachium*, *Potamogeton crispus*, *Myriophyllum spicatum* and *Zannichellia palustris* were also found. *Juncus*, terrestrial mosses and *Gleotrichia* spp., a blue-green alga, were still prevalent in the upper levels. However, the abundance of charophytes declined in the uppermost samples (from ~1960) whilst numbers of *Zannichellia palustris* seeds increased.

Zooplankton ephippia
The cluster analysis identified two zones in the ephippia record (Figure 6).

Zooplankton ephippial remains were scarce at the base of the core with relatively low numbers of *Simocephalus* spp., *Daphnia pulex* and *Daphnia hyalina.* In Zone 2, from the mid-1950s, *Leydigia* spp. and *Alona* spp. started to appear in larger numbers. The surface sample has the most abundant and diverse remains, with very high abundance of *Daphnia hyalina* and the large-bodied pelagic species *Daphnia magna* present in relatively high numbers.

Discussion

The macrofossil data suggest that Aqualate Mere formerly supported charophytes including *Chara* and *Nitella* taxa. The diversity of the plant community appears to have increased in the early 1900s with *Ranunculus* sect *Batrachium*, *Potamogeton crispus*, *Myriophyllum spicatum* and *Zannichellia palustris* all being recorded in the sediment core. However, it should be noted that the 43 cm sample contained considerably more plant remains than the other four samples and therefore the increased diversity could simply be a function of higher macrofossil density. The analysis of additional samples is, therefore, recommended in order to provide a more robust interpretation of the changes in vegetation. Nevertheless, from the mid-1900s, the charophyte community appears to have been in decline, *Potamogeton crispus* appears and *Zannichellia palustris,* a species associated with elevated nutrient levels (e.g. Davidson *et al*., 2005), dominates the most recent period. This agrees with plant data from a survey conducted by UCL in 2004 which records *Zannichellia palustris* as the dominant species with presence of *Potamogeton crispus* and *Potamogeton pectinatus*.

The timing of the initial decrease in charophyte remains is coincident with a change in the sediments from a more organic dark brown, fine lake mud to an inorganic silt-clay at ~30 cm (~1940). Studies of multiple cores from Aqualate Mere have shown that this boundary is recorded across the lake and most likely reflects the in-wash of material from the Shropshire

Union canal (Hutchinson, 2004; 2005; Hutchinson *et al*., in prep.). A further decline in abundance of charophyte oospores occurs in the upper 20 cm of the core (post-~1960). Hutchinson (2005) reported that sediment erosion from agriculture in the catchment, supplying nutrients and other compounds, was an important source of the silt-clay sediments and he recorded the highest levels of most pollutants in the uppermost (post-1950s) part of the sediment profile. Therefore, the observed changes in the plant macrofossil record have most likely resulted from a combination of enrichment of the lake and enhanced sedimentation, both of which would impact negatively on the light climate and would be unfavourable for charophyte growth. Mean water chemistry data for Aqualate Mere collected in 2004-2005 by the Environment Agency indicates that the lake is currently highly eutrophic with total phosphorus (TP), soluble reactive P (SRP), total nitrogen (TN) and chlorophyll a concentrations of 300 $\mu g\ l^{-1}$, 200 $\mu g\ l^{-1}$, 6 $mg\ l^{-1}$ and 30-40 $\mu g\ l^{-1}$, respectively.

Low numbers of *Chara* oospores were found in the surface sediments. It is not certain whether this reflects actual presence of stoneworts in the lake or whether this is a function of sediment reworking. Aqualate Mere is very shallow with a water depth of approximately 1 m over much of its area and therefore the surface sediments are susceptible to wind mixing (Hutchinson *et al*., in prep). Hutchinson (2004) noted that the transition in sediment type was not uniform across the lake and attributed this to the shallow and wind stressed characteristics of the site which appear to lead to significant sediment remobilisation and focussing (e.g. Hilton *et al.* 1986).

The inferred enrichment is supported by the *Daphnia* ephippia data as the dominance of planktonic taxa and the decline in *Simocephalus* spp., a plant associated species, in the upper zone suggests an increase in pelagic productivity reflecting more eutrophic conditions (Vadeboncoeur *et al.,* 2003). The high numbers of *Daphnia magna* in the surface sediment could possibly arise from a fish kill associated with low oxygen conditions which would release the grazing pressure on the large-bodied zooplankton. However, fish data are required to reach any firm conclusions. Furthermore, zooplankton populations are controlled by a multitude of factors, many of which interact, including fish predation, habitat availability and food source, and therefore it is difficult to be certain of the mechanisms responsible for the observed changes (e.g. Davidson *et al*., 2007). Given the relatively gradual rise in *Daphnia* ephippia numbers over the period represented by the core it is unlikely that a change in fish community is the only factor controlling their abundance. The analysis of the Cladocera chitinous remains (i.e. carapaces, head-shields and post-abdomens), which provides information on a broader range of genera than the ephippia data, is recommended to further explore changes in the zooplankton community and to better infer shifts in habitat structure.

In summary, the data suggest that the present day plant community has few taxa in common with those observed in the reference assemblages, having experienced a reduction in charophytes, with fine-leaved pondweeds, particularly *Zannichellia palustris*, becoming the dominant component of the aquatic vegetation.

Figure 5 Summary plant macrofossil diagram for Aqualate Mere, core AQUA3
(Note variable scaling on the x axis)

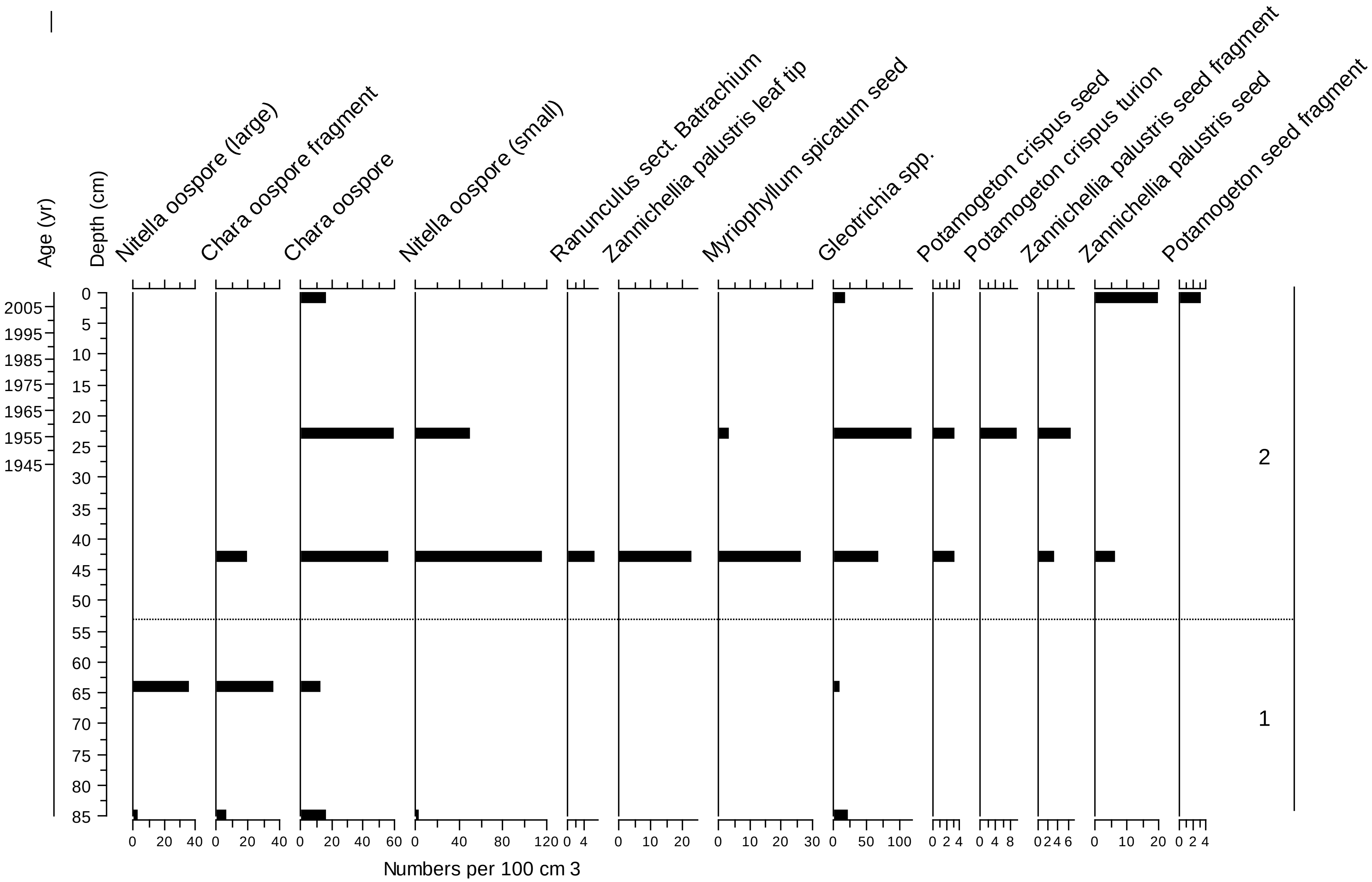
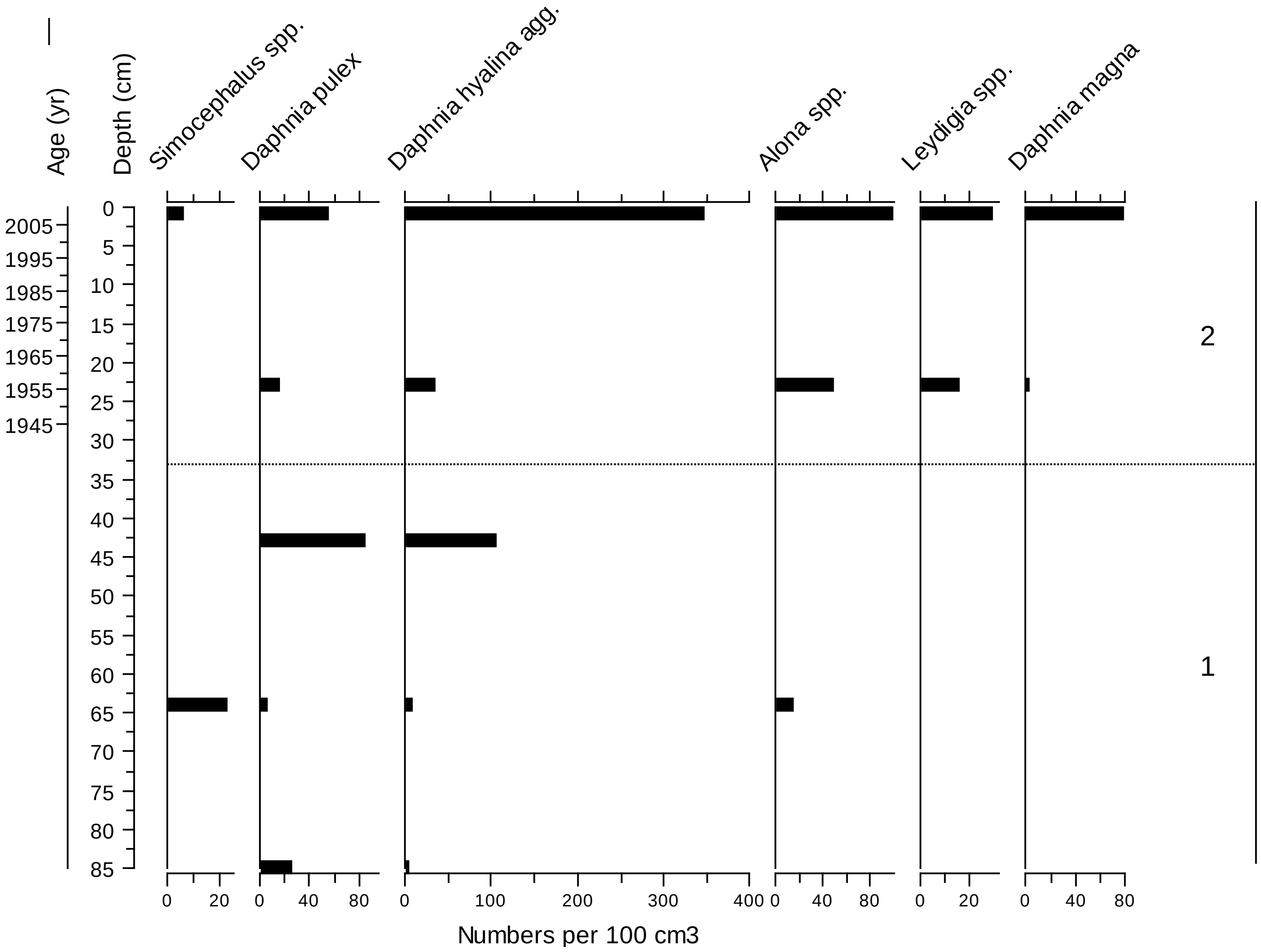


Figure 6 Summary zooplankton ephippia diagram for Aqualate Mere, core
(Note variable scaling on the x axis)



HORNSEA MERE

Site description

Hornsea Mere (NGR: TA190469) was first designated as a SSSI in 1951. It is considered of national importance for wintering and breeding birds and as an example of a large (120ha.) shallow, naturally eutrophic lake. The mere is a relic of a once extensive series of lakes and marshes in the Holderness area.

Whilst the mere continues to support a range of eutrophic aquatic plant species there are signs that the site has suffered from nutrient enrichment and periodic cyanobacterial blooms occur. It is hypothesised that the shallow nature of the mere makes it vulnerable to recycling of nutrients from the sediments. Some progress has been made in reducing point sources of nutrients to the mere and the catchment is currently included in the England Catchment Sensitive Farming Delivery Initiative aimed at tackling diffuse nutrient inputs. Preservation problems have limited the value of previous palaeolimnological work using fossil diatoms. A macro-fossil approach was considered likely to yield an alternative record for past changes in the mere and help determine restoration targets.

Core description

A piston core, 1.32 m in length, was collected from Hornsea Mere on 21-Jan-08 in 1.75 m water depth, approximately 20 m from the shore on the northern side of the lake. At the time of coring, the water level was up by approximately 0.5 m due to recent heavy rainfall and the water was very turbid. Marginal vegetation was comprised principally of *Phragmites*.

The core was homogeneous and mid-brown in colour throughout the upper 90 cm with little visible colour change except for a slight lightening to a greyish brown, slightly denser material below 90 cm (Figure 7). Photographs were taken but were of poor quality owing to the adverse weather conditions and are therefore not shown.

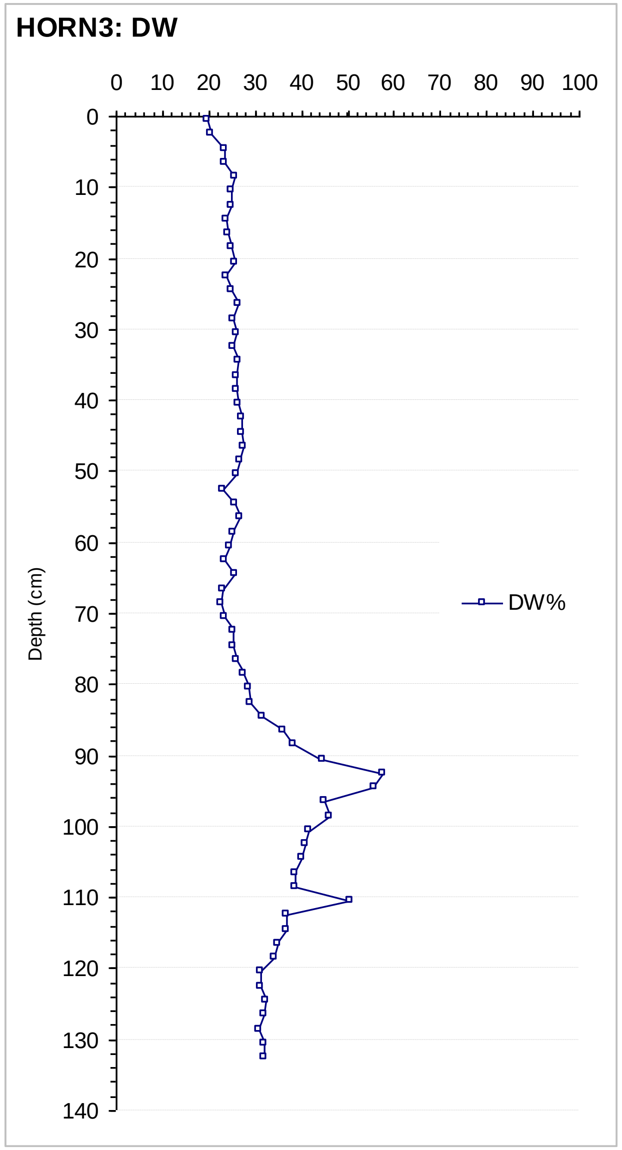
Figure 7 Sediment core stratigraphy of HORN3

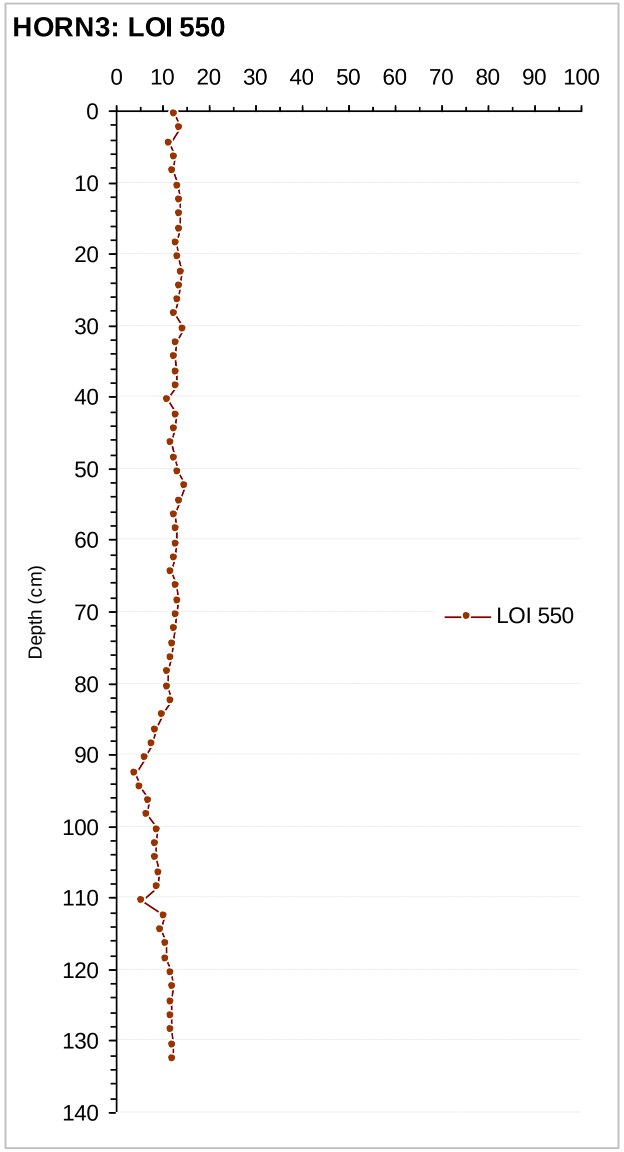
	Depth (cm)	**Sediment colour**
No photo	0-90	Mid-brown
	90-132	Greyish brown

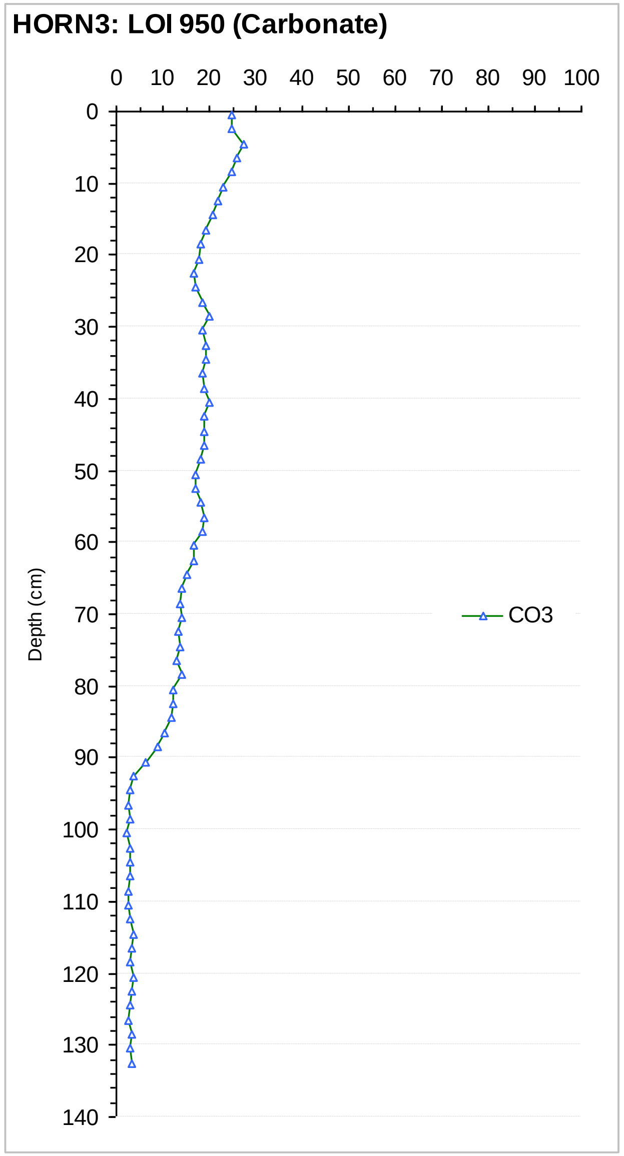
Stratigraphic analyses

The core, HORN3, was generally low in organic matter with relatively stable LOI 550 values of ~10-15% throughout (Figure 8). However, the lowermost section below ~90 cm was markedly denser than the upper core with DW values in excess of 30% (maximum 58%) compared with values of 20-25% throughout the upper core. Below this same depth, the carbonate content was stable and markedly lower than that above 90 cm with values of only 2-3%. The carbonate content gradually increased from the 90 cm level upwards to values of ~25% at the surface.

Figure 8 Stratigraphic data for HORN3







Spheroidal carbonaceous particle analysis

The SCP profile from HORN3 shows a SCP profile with clearly defined peak of over 4400 gDM^{-1} at 10-11 cm although the rapid increase feature expected in 1950 is less obvious (Table 4, Figure 9). If the SCP peak is ascribed to 1978 ± 2 then this indicates a mean sediment accumulation rate of 0.35 cm yr^{-1} over the last 30 years. Extrapolating this rate would place 1950 at around 20 cm which, from the profile, seems quite possible. This would suggest that the mean sediment accumulation rate in HORN3 has remained reasonably stable over the last 50-60 years. Further extrapolation would place 1850 at ~55 cm. However, the SCP record finishes between 45 and 50 cm, suggesting that the record may be slightly curtailed. This may be due to a reduction in sediment accumulation rate but is more likely a result of SCP concentrations falling below the detection limit of the technique in these lower sediment levels. Table 5 summarises the best estimate of the chronology for the HORN3 core.

Table 4 SCP concentrations for HORN3

Mean depth (cm)	SCP conc (gDM^{-1})	90% C.L. (gDM^{-1})
0.5	294	288
2.5	2005	695
4.5	2497	679
6.5	2923	1013
8.5	2179	955
9.5	2118	928
10.5	4428	1204
12.5	3891	1348
14.5	3779	1852
16.5	1954	724
18.5	2719	1007
19.5	1285	630
22.5	1496	846
24.5	1133	785
27.5	938	531
30.5	688	477
32.5	674	467
34.5	1083	613
37.5	325	319
39.5	0	0
42.5	1078	1057
45.5	272	266
47.5	0	0
50.5	0	0
55.5	0	0
59.5	0	0
79.5	0	0

Figure 9 SCP profile for HORN3

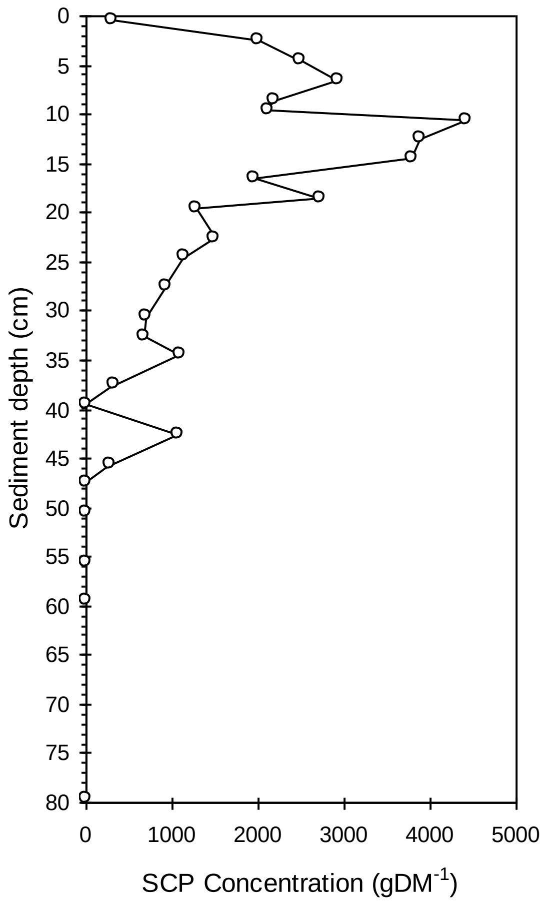


Table 5 The SCP derived chronology for HORN3

Sediment depth (cm)	Age (Years)	Date
0	0	2008
5	14 ± 2	1994 ± 2
10	28 ± 2	1980 ± 2
15	43 ± 3	1965 ± 3
20	57 ± 5	1951 ± 5
25	71 ± 10	1937 ± 10
30	86 ± 15	1922 ± 15
35	100 ± 20	1908 ± 20
40	114 ±20	1894 ± 20

Macrofossil analysis

Plant macrofossils

The cluster analysis identified two zones in the plant macrofossil record (Figure 10).

The basal zone (pre-1920) was dominated by *Chara* oospores. *Zannichellia palustris* appeared in the record at 41 cm, when the numbers of *Chara* oospores started to decline. In Zone 2 (post ~1920) there was a shift to a species assemblage composed of more nutrient-tolerant fine-leaved *Potamogeton* taxa and *Zannichellia palustris*.

Zooplankton ephippia

The cluster analysis identified two zones in the ephippia record (Figure 11).

Ceriodaphnia spp. were the dominant taxa in the bottom of the core with *Daphnia hyalina* also abundant in Zone 1 (pre-1960). In Zone 2, *Ceriodaphnia* spp. abundance declined whilst the number of *Daphnia hyalina* remains increased. The abundance of *Daphnia pulex* and *Daphnia magna* increased in Zone 2 and *Simocephalus* spp. was also present. *Daphnia* spp. were the dominant taxa in the upper zone (1960s to present day).

Discussion

The macrofossil data suggest that the aquatic flora of Hornsea Mere was formerly dominated by *Chara* spp., taxa characteristic of high alkalinity waters in good condition. However, similarly to Aqualate Mere, from the early 1900s, the charophyte community started to decline as more nutrient-tolerant species, namely *Zannichellia palustris,* expanded. By ~1925 another fine-leaved pondweed, *Potamogeton pusillus* agg., arrived reflecting enrichment of the lake. *Chara* oospores were not found in the uppermost part of the core, being lost from the record at some time since the mid-1960s. The findings are in good agreement with the recent plant data, based on a survey conducted by UCL in 2004, which recorded *Zannichellia palustris* and *Potamogeton pusillus* as abundant. Several other taxa were observed in the survey including *Potamogeton pectinatus, Myriophyllum spicatum, Ceratophyllum demersum* and one *Chara* species, *C. globularis*. However, remains of these taxa were not found in the surface sample.

The ephippia data are in agreement with the plant macrofossil data as the increase in pelagic *Daphnia* spp. in the core indicates greater availability of planktonic algae as a food source, thus suggesting enhanced pelagic production most likely driven by eutrophication. Whilst phosphorus data were not available, the annual mean chlorophyll a concentration recorded by the Environment Agency in 2003-4 was 26 µg l^{-1}, indicating high algal biomass.

In summary, the aquatic plant community of Hornsea Mere has undergone a marked shift from charophyte to fine-leaved pondweed dominance over the last century, probably associated with enrichment of the lake. The changes have been gradual suggesting an insidious rather than a stochastic forcing mechanism.

Figure 10 Summary plant macrofossil diagram for Hornsea Mere, core HORN3
(Note variable scaling on the x axis)

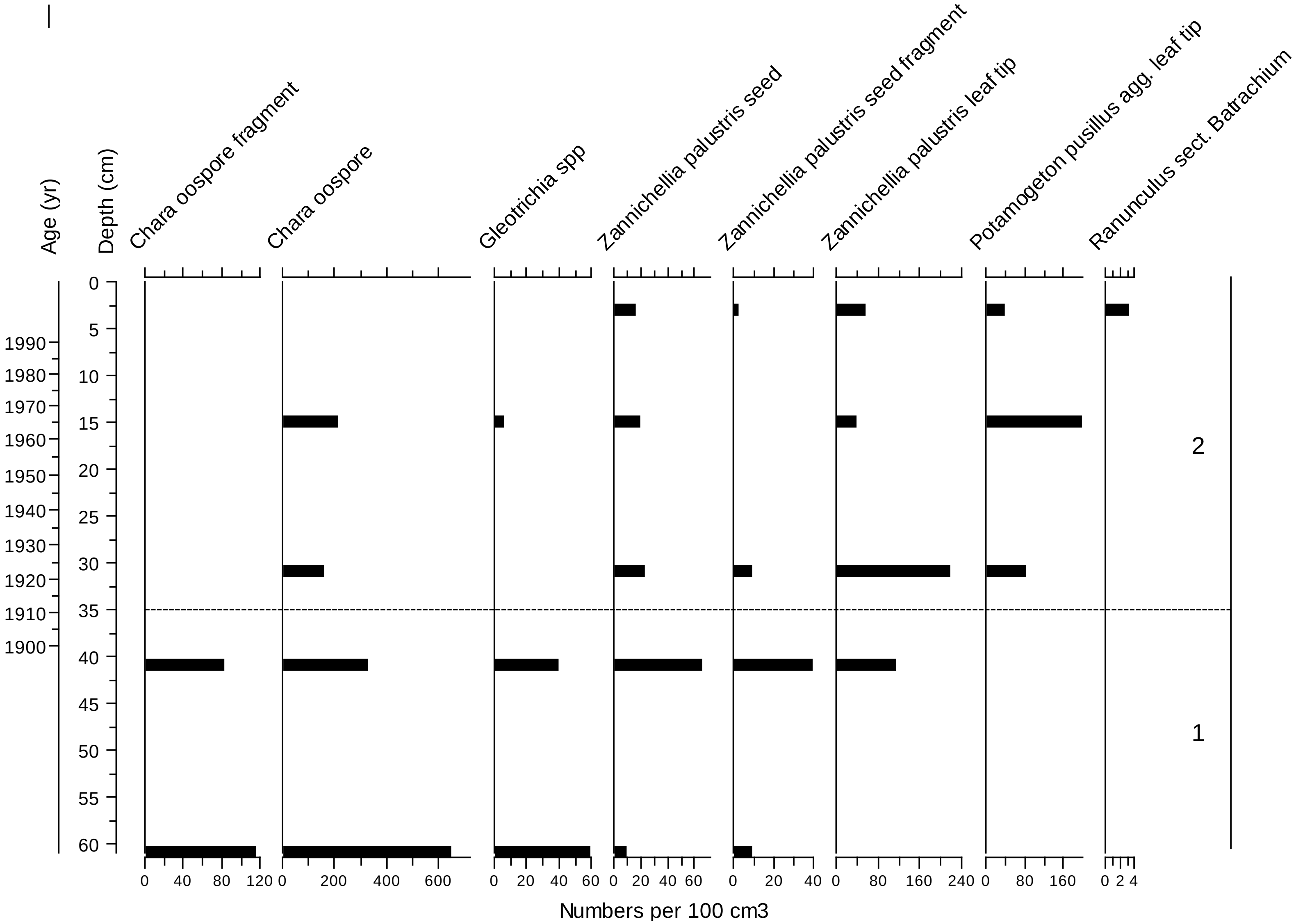
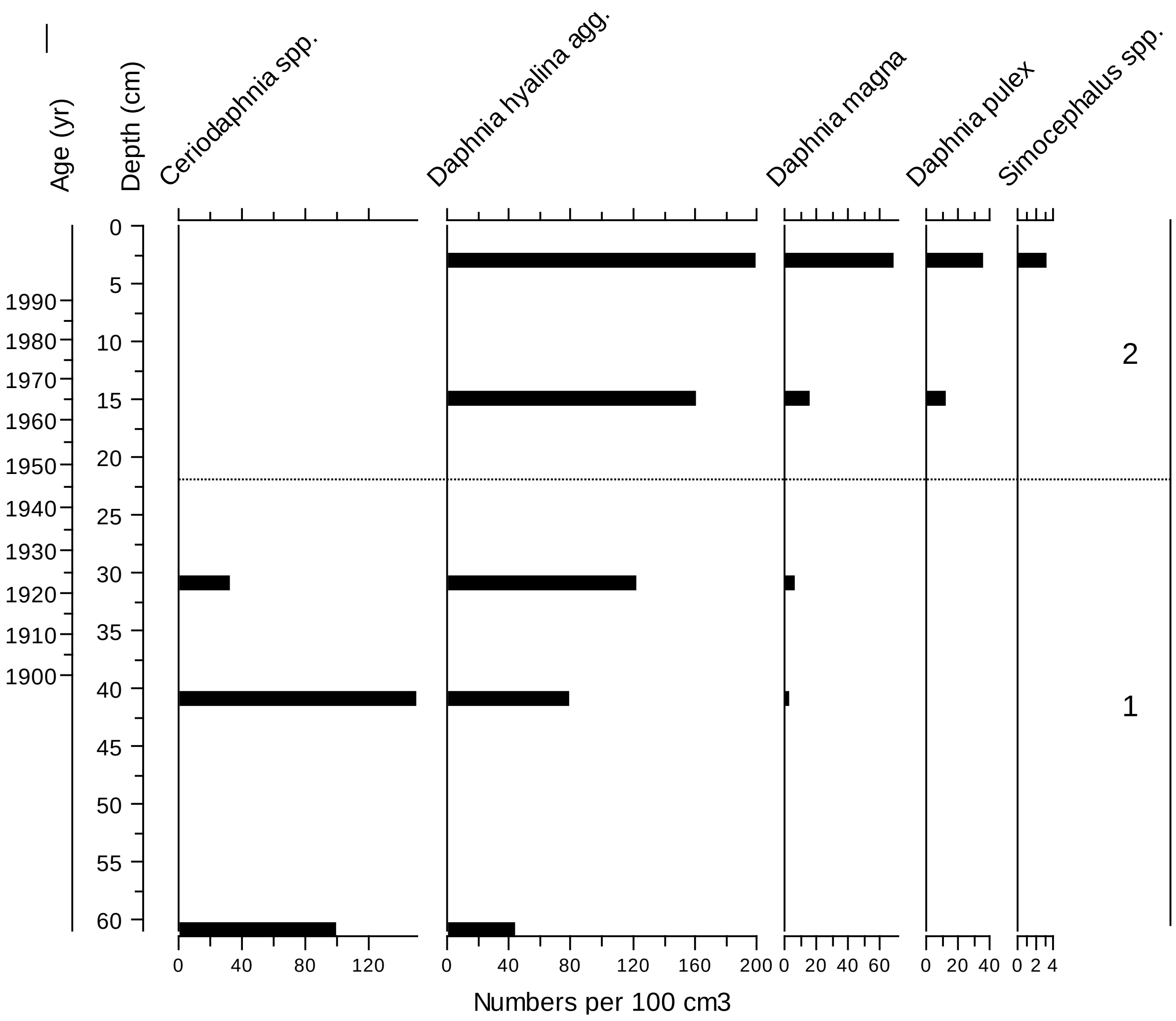


Figure 11 Summary zooplankton ephippia diagram for Hornsea Mere, core HORN3
(Note variable scaling on the x axis)



OVER WATER

Site description

Over Water (NGR: NY251350) is a small (~20ha.) mesotrophic lake lying to the north of the Lake District National Park. At the time of designation as SSSI the lake supported a species rich mesotrophic flora including six pondweeds, six-stamened waterwort as well as isoetid species more characteristic of oligotrophic conditions.

In recent years there has been some concern about a loss of species diversity (Natural England, 2006) and the impact of extensive water-level draw-down during summer months. The open water areas was artificially increased through the construction of a retaining dam in the early twentieth century. Water is now regularly abstracted from Over Water to supplement levels in a neighbouring reservoir. Natural England and the Environment Agency have commissioned work by the Centre for Ecology and Hydrology to investigate the potential impact of this abstraction on the submerged plant community (see Thackeray & Maberley, 2007). This current palaeolimnology work was instigated to look at the longer term changes at the site and in particular to look at whether there was a signal of gradual nutrient enrichment which may have also affected the plant community**.**

Core description

A piston core, 1.35 m in length, was collected from Over Water on 17-Jan-08 in 2.8 m water, approximately 20 m from the shore on the west side of the lake. Marginal vegetation was comprised principally of *Phragmites* and the submerged taxa *Callitriche hamulata* and *Elodea canadensis* were observed during sampling.

The core had two distinct horizons (Figure 12). The upper 80 cm was grey-brown and the section below 80 cm was dark grey and was more consolidated with higher clay content. Two slightly paler layers were observed whilst extruding at ~27 cm and ~97 cm, although these were not clearly visible when the core was in the tube. *Chara* encrustations were abundant at 127-128 cm.

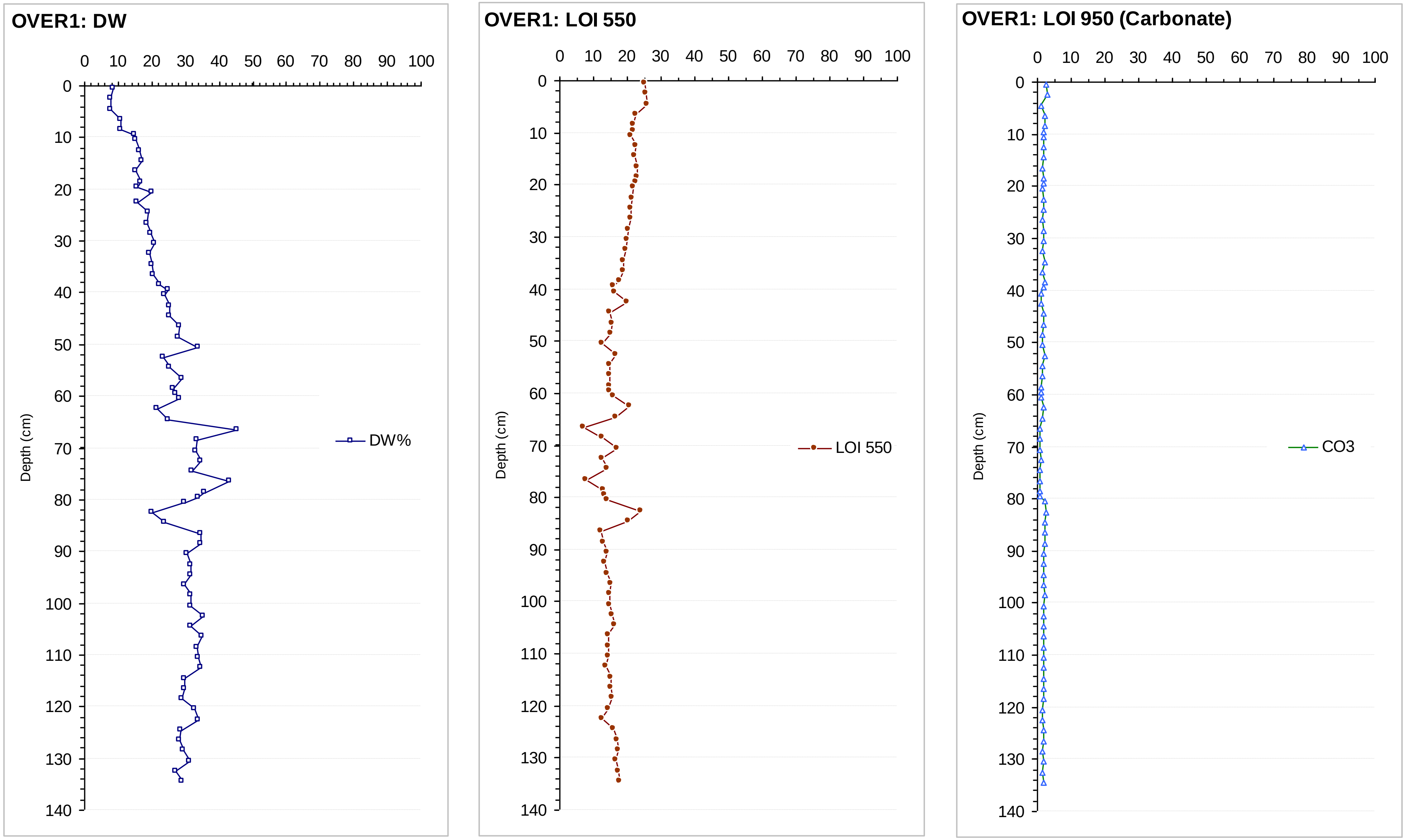
Figure 12 Sediment core stratigraphy of OVER1

Depth (cm)	Sediment colour
0-80	Grey-brown
80-135	Dark grey

Stratigraphic analyses

The core, OVER1, was relatively inorganic and had low carbonate content (<3%) throughout. LOI 550 values in the lower section, below ~65 cm, were 15% whilst DW values were reasonably high at ~30-40% (Figure 13). Above this the sediment became gradually less consolidated with DW values decreasing to ~10% and LOI 550 increasing to ~25% at the surface.

Figure 13 Stratigraphic data for OVER1



Spheroidal carbonaceous particle analysis

The SCP profile from OVER1 shows a SCP profile with clearly defined peak and rapid increase features (Table 6, Figure 14). The first presence of SCPs occurs at 35-36 cm while the peak concentration of almost 7000 gDM^{-1} occurs at 11-12 cm. It seems likely that this SCP profile does not represent the full industrial record of deposition since 1850, but rather is truncated at a point where SCP concentrations fall below the analytical detection limit.

If we ascribe the SCP concentration peak at 11-12 cm to 1978 $\pm$ 2 then this indicates a mean sediment accumulation rate over the last 30 years of 0.38 cm yr^{-1}. However, the rapid increase feature occurs at ~25 cm indicating that the sediment accumulation rate has not been consistent throughout. Instead this suggests a higher mean sediment accumulation rate between 1950 and 1978 of 0.48 cm yr^{-1}. Both rates indicate that the full SCP profile is truncated and if this earlier rate continues below 1950 then it would imply that the observed SCP record begins in the 1930s. Although it is not possible to provide any further dates below 1950 from the SCP record this rate would place 1850 between 70 and 75 cm depth. The best available chronology is summarised in Table 7.

Table 6 SCP concentrations for OVER1

Mean depth (cm)	SCP conc (gDM-1)	90% C.L. (gDM-1)
0.5	1444	708
1.5	2163	865
3.5	4580	1696
5.5	4724	1464
7.5	3818	1128
9.5	2518	933
11.5	6757	1770
13.5	5768	1413
15.5	5634	1531
17.5	4294	1331
19.5	4789	1355
21.5	5072	1572
23.5	3162	1095
25.5	1023	709
27.5	1170	662
29.5	381	373
31.5	358	351
33.5	1470	832
35.5	409	401
37.5	0	0
39.5	0	0
42.5	0	0
45.5	0	0
50.5	0	0
55.5	0	0
59.5	0	0
79.5	0	0

Figure 14 SCP profile for OVER1

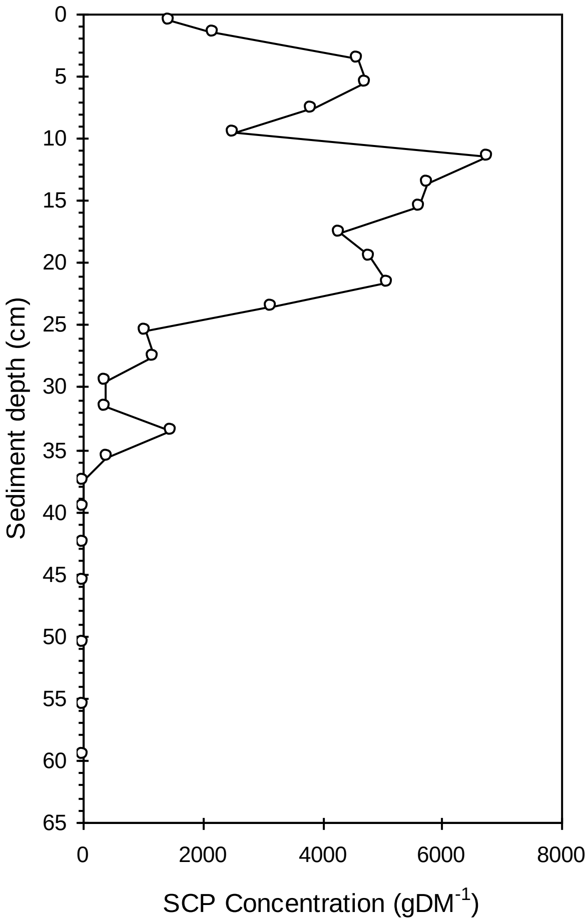


Table 7 The SCP derived chronology for OVER1

Sediment depth (cm)	Age (Years)	Date
0	0	2008
5	13 ± 2	1995 ± 2
10	26 ± 3	1982 ± 3
15	38 ± 5	1970 ± 5
20	48 ± 8	1960± 8
25	59 ± 10	1949± 10
30	69 ± 10	1939 ± 10
35	80 ± 15	1928 ± 15

Diatom analysis

The cluster analysis identified four zones in the diatom record (Figure 15).

Zone 1 (42-31.5 cm; pre-1935 AD)
Zone 1 is characterised by a diverse range of diatom periphyton and only low relative abundances of planktonic taxa. The dominant periphytic taxon is *Achnanthidium minutissimum* (23%) and other periphytic taxa recorded in this zone include *Navicula cryptocephala* (9%), *Fragilaria vaucheriae* (6%), small *Fragilaria* spp. (~6%, including *Staurosirella pinnata*, *Staurosirella construens* var. *venter*, *Pseudostaurosira pseudoconstruens* and *Staurosira elliptica*) and *Rossithidium pusilla* (3%). Planktonic taxa in this zone are *Cyclotella radiosa* (9%), *Cyclotella comensis* (4%) and *Tabellaria flocculosa* (3%) all of which are associated with circumneutral waters of low to moderate nutrient status. Reconstructed DI-TP concentrations for the 41.5 cm sample (~1915) are 33 µg l^{-1} (WA-PLS1) and 37 µg l^{-1} (WA-PLS2). These values largely reflect the dominance of *A. minutissimum* (TP optimum = 36 µg l^{-1}). Samples below the 42 cm sample were scanned and revealed that there was no significant change in the diatom assemblage between 42 cm and the core base.

Zone 2 (31.5-15.5 cm; 1935-1970 AD)
Zone 2 records an increase in the importance of planktonic taxa: *Aulacoseira subarctica* (25%) appears for the first time and the relative abundance of *C. radiosa* increases to 17%. Zone 2 sees the continued presence of *A. minutissimum* and *N. cryptocephala* but at considerably lower relative abundances (6% and 1%, respectively). Reconstructed DI-TP concentrations for the 21.5 cm sample (~1957) are slightly lower than those calculated for Zone 1 [30 µg l^{-1} (WA-PLS1) and 27 µg l^{-1} (WA-PLS2)], reflecting the dominance of *A. subarctica* (optimum = 39 µg l^{-1}) and *C. radiosa* (optimum = 35 µgl^{-1}) but also the lower relative abundance of *N. cryptocephala* (optimum = 128 µg l^{-1}).

Zone 3 (15.5-2.5 cm; 1970-2000 AD)
Zone 3 sees the appearance of the planktonic taxa *Aulacoseira ambigua* (12%) and *Fragilaria capucina* var. *mesolepta* (4%), both of which are associated with waters of moderate nutrient status. This zone also sees the decline in relative abundance of taxa associated with low to moderate nutrient levels e.g. *A. subarctica* (6%), *C. radiosa* (5%) and *C. comensis* (~1%), further suggesting enrichment. Reconstructed DI-TP concentrations for the 21.5 cm and 10.5 cm samples (1957 and 1982, respectively) are 32-34 µg l^{-1} (WA-PLS1) and 29-34 µg l^{-1} (WA-PLS2). These values reflect the presence of a broad range of diatom taxa with moderate TP optima. Diatom frustules in this zone were often broken, tentatively suggesting a lowering of the water level and an increase in turbidity due to wind stress.

Zone 4 (2.5-0 cm; 2000-2008 AD)
Zone 4 sees the appearance, albeit at low relative abundance, of *Asterionella formosa* (2%), a taxon associated with moderately enriched waters. The presence of this taxon in the surface sediment suggests enrichment and is unlikely to be the result of a seasonal artefact

(i.e. a ‘bloom’ immediately prior to sampling), since it is not recorded in the 2.5 cm sample or further down the core. This zone also sees the continued presence of *A. ambigua*, *A. subarctica*, *F. capucina* var. *mesolepta* and *A. minutissimum* at similar abundances to those recorded in zone 3. The relative abundance of *C. radiosa* (3%) continues to decrease. Reconstructed DI-TP concentrations for the 0.5 cm sample (2008) are 45 µg l^{-1} (WA-PLS1) and 38 µg l^{-1} (WA-PLS2). These values reflect the presence of diatom taxa with relatively high TP optima e.g. *A. formosa* (optimum = 76 µg l^{-1}). Both the floristic changes and reconstructed DI-TP concentrations for Zone 4 suggest increasing nutrient levels.

Macrofossil analysis

Plant macrofossils

The cluster analysis identified two zones in the plant macrofossil record (Figure 16).

Zone 1 is characterised by *Chara, Nitella* and *Isoetes lacustris*, the latter dominating, with a high abundance of terrestrial mosses and *Juncus* (not shown). There were no aquatic plant remains in the 70 cm sample. In Zone 2 (from ~1920) the terrestrial species decline and *Nitella* and *Isoetes lacustris* remains disappear. *Chara* oospores are still present but the aquatic species assemblage shifts towards one comprised of fine-leaved *Potamogeton* spp., *Callitriche* and *Myriophyllum spicatum* in the upper part of the record.

Zooplankton ephippia

The cluster analysis identified two zones in the ephippia record (Figure 17).

Ephippial remains were scarce in Zone 1 (pre~1950) with dominance by *Daphnia hyalina*. In Zone 2 (from ~1950) *Daphnia hyalina* continues to dominate but the remains of pelagic species are considerably more abundant and include *Daphnia pulex* and *Ceriodaphnia* spp.

Discussion

There has been a moderate degree of diatom floristic change in the Over Water core. The diatom species shifts provide evidence for gradual nutrient enrichment. However, the DI-TP reconstruction suggests relatively stable nutrient levels throughout most of the core and only indicates enrichment in recent years, coincident with the appearance of *Asterionella formosa*. This is largely because *Aulacoseira subarctica* occurs in relatively high abundance in Zone 2 and this taxon has a low TP optimum in the training set. Nevertheless, the decline in *A. minutissimum* and expansion of the planktonic taxa, *A. subarctica* and *C. radiosa,* in the mid-1900s does mark the first sign of increased production. The DI-TP values for the surface sample are in good agreement with the recent measured TP concentration for Over Water of 45 µg l^{-1} (Environment Agency data, September 2005). Longer term phosphate data for the period 1985-1989 gives a mean of 17 µg l^{-1} and this was estimated to equate to a mean TP concentration of ~30 µg l^{-1} by Thackeray & Maberly (2007). Therefore, the DI-TP values for this period closely match the measured values. There is tentative evidence for lowered water levels during the 1980s and 1990s provided by increased breakage of diatom frustules throughout this period but this is not conclusive.

The plant macrofossil data indicate that Over Water formerly supported *Isoetes lacustris*, a species typically associated with low alkalinity, relatively unproductive waters, as well as *Nitella* and *Chara* spp. Scarcity of aquatic plant remains, high between-sample variability, and the relatively small number of samples analysed makes it somewhat difficult to interpret the shifts in any detail but both *Isoetes lacustris* and *Nitella* spp. were lost from the sediment record some time between 1920 and 1950. The timing of this loss is, therefore, coincident with the first changes in the diatom assemblages, indicative of enrichment. *Chara* oospores are still present in the surface sample but the aquatic species assemblage shifted towards one comprised of fine-leaved *Potamogeton* spp., *Callitriche* and *Myriophyllum spicatum* from around the mid-1950s. Based on the ecology of these taxa, the shifts observed in the diatom record, and the currently high phosphorus concentrations in the lake, these changes are most likely driven by progressive eutrophication. The changes in the *Daphnia* ephippia are also coincident with those in the plant macrofossil record as there is a marked increase in open water taxa from the mid-1950s suggesting enhanced pelagic productivity.

The findings are in accordance with recent aquatic macrophyte surveys that suggest that the site has deteriorated, and has lost characteristic species for which the site was originally notified (Natural England, 2006). Over Water is used for water supply and there are concerns that the fluctuating water levels may also have had a detrimental effect on the aquatic plant community. Based on hydroacoustic surveys and modelling of macrophyte distribution under various drawdown scenarios, Thackeray *et al*. (2007) concluded that there would be a rapid reduction in macrophyte cover with drawdown, particularly over the first 2 m below top water level. During a plant survey conducted by UCL in 2005, the shallow water zone, up to approximately 1 m water depth, was exposed and dry (Goldsmith, pers. comm.). Furthermore, the non-native, invasive species, *Elodea nuttallii,* now dominates the submerged community and this may have out-competed some of the native species. This species does not produce viable remains and is therefore not recorded in the macrofossil data.

In summary, Over Water has experienced a loss of isoetids and replacement by elodeids over the period represented by the core. This is most likely associated with gradual eutrophication but alterations in water level and the introduction of *Elodea nuttallii* may also be contributing factors.

Figure 15 Summary diatom diagram of Over Water, core OVER1, with diatom-inferred total phosphorus (DI-TP) reconstruction
(species occurring at >2% relative abundance)

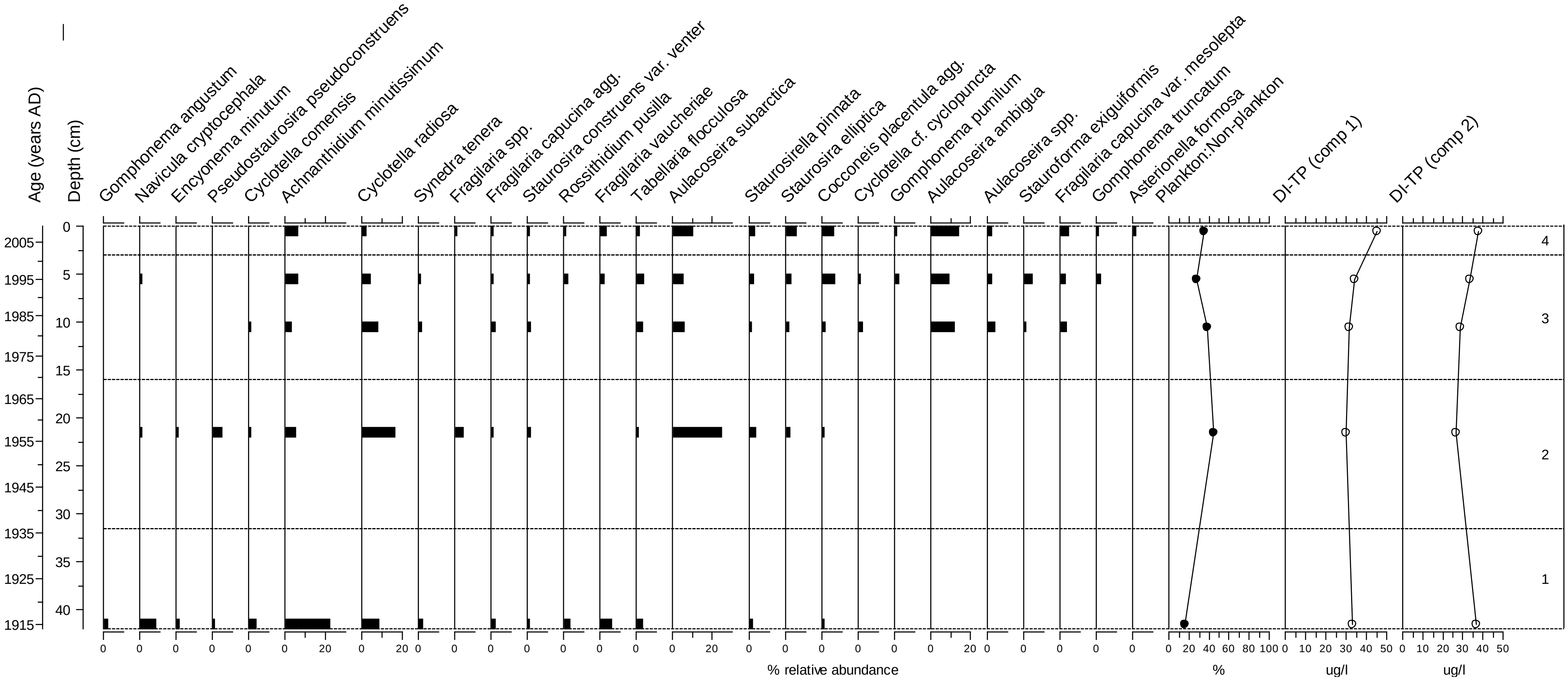


Figure 16 Summary plant macrofossil diagram for Over Water, core OVER1
(Note variable scaling on the x axis)

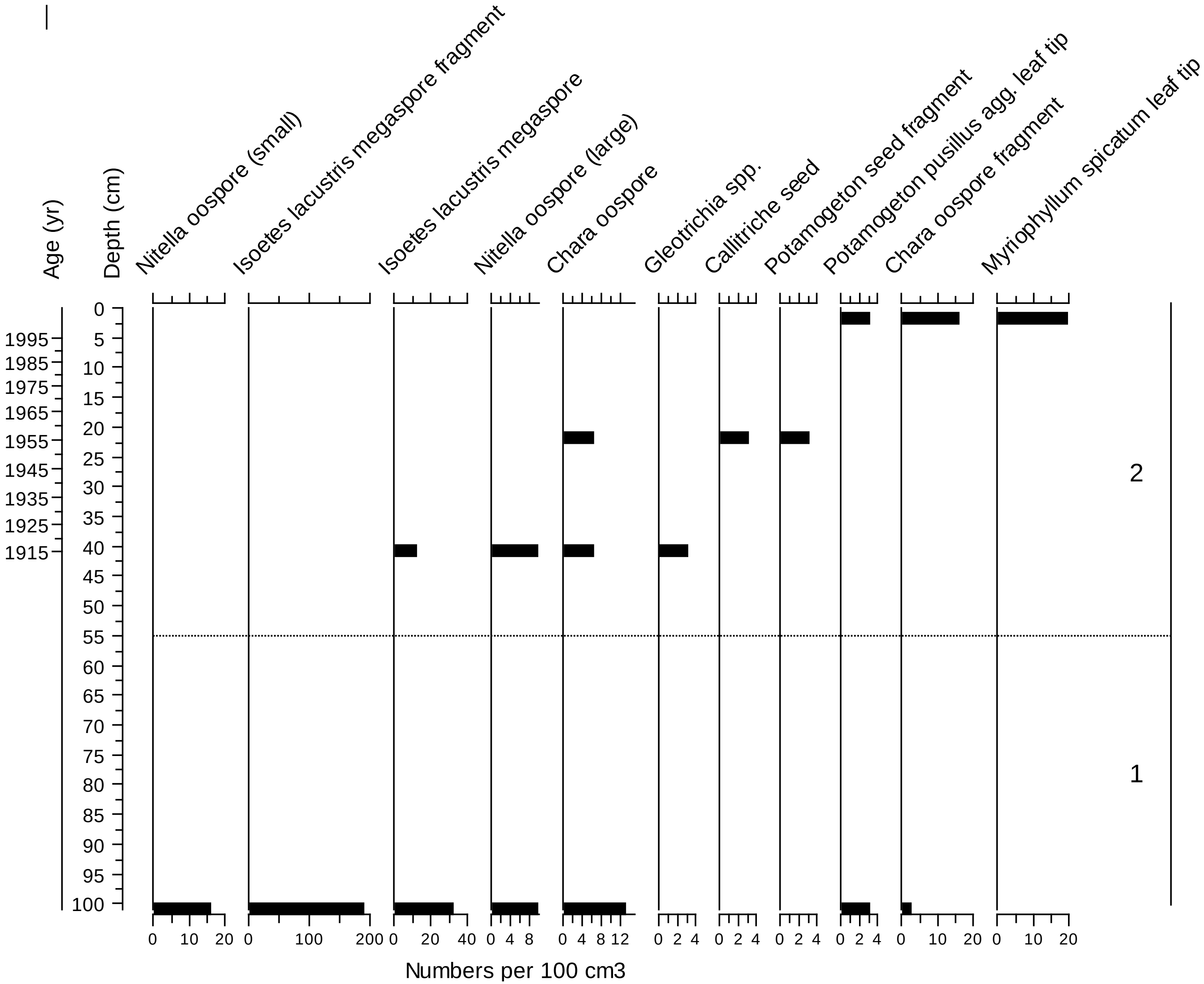
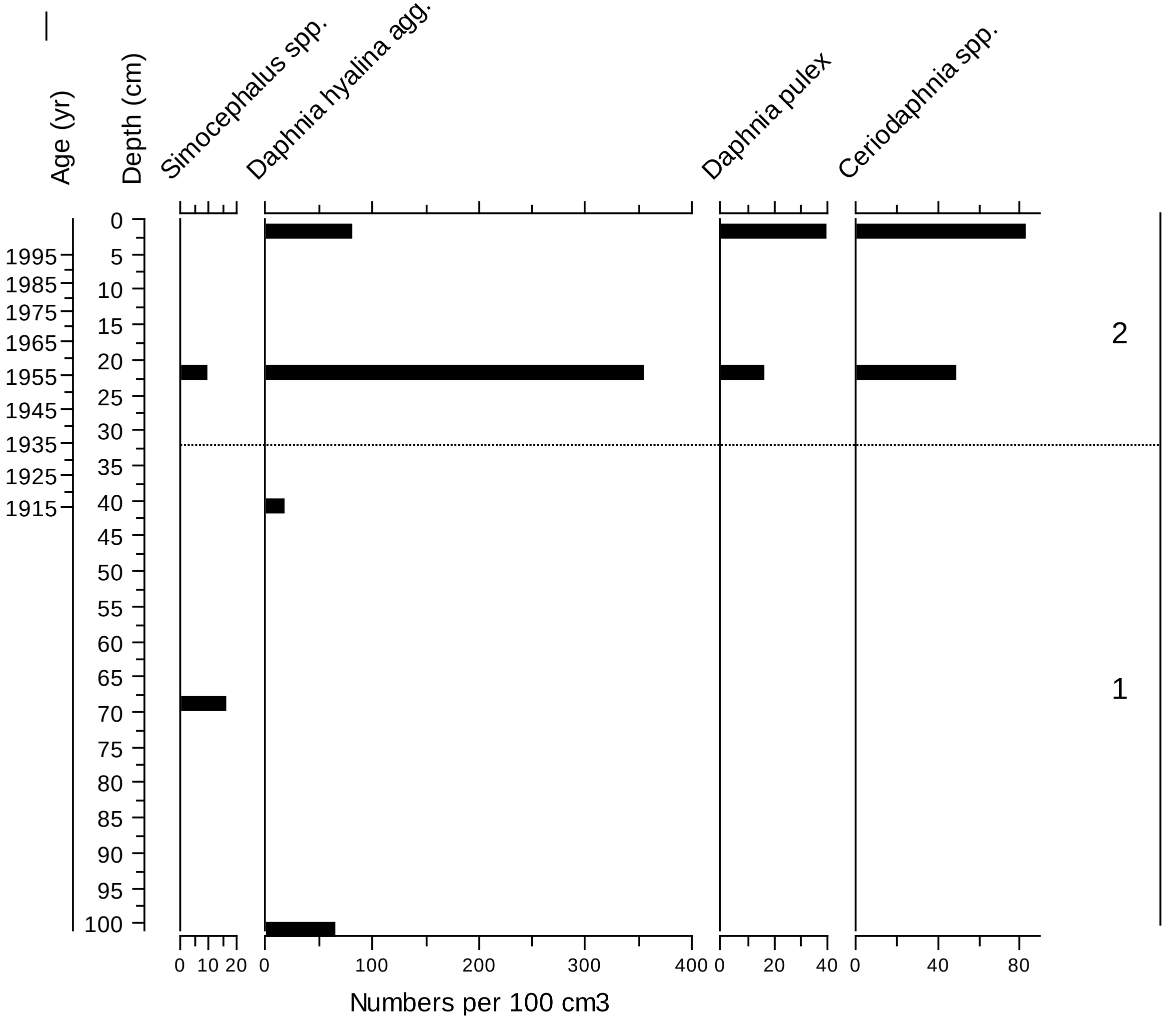


Figure 17 Summary zooplankton ephippia diagram for Over Water, core OVER1
(Note variable scaling on the x axis)



CUNSWICK TARN

Site description

Cunswick Tarn (NGR: SD489937) was first designated as a SSSI in 1954. This small waterbody (0.8 ha) is situated at the foot of a Carboniferous limestone ridge. At the time of designation the tarn was considered to be eutrophic and very little information exists about the composition of the plant community. The geological setting of the tarn suggests that naturally it might be base-rich and support a plant community typical of a marl lake i.e. abundant charophytes. However, the citation and Stokoe's survey of the late 1970s (Stokoe, 1983) suggest that the site has not supported a diverse charophyte community for some time (Stokoe records *Chara hispida* as present). The purpose of this work was to attempt to reconstruct the plant community of the tarn prior to any anthropogenic enrichment and hence determine reference conditions and lake type.

Core description

A piston core, 0.74 m in length, was collected from Cunswick Tarn on 16-Jan-08 in 2.4 m water, approximately 10 m from the shore on the west side of the lake. Marginal vegetation included *Phragmites, Salix, Alnus*, and beds of *Nuphar lutea*. Fragments of *Elodea canadensis* and a fine-leaved *Potamogeton* (probably *berchtoldii*) were also seen during coring. The lake is used for wildfowl shooting and has several hides and feeders. There was evidence of trampling and reed cutting.

The core had several visible stratigraphic horizons (Figure 18). The upper 17 cm was dark brown with very few molluscs but the 9-10 cm sample was notably full of root remains. The section from 17-32 cm was also dark brown but contained more molluscs than the upper core. The section 32-55 cm was light brown with abundant molluscs and *Chara* encrustations. A light grey band seen in the tube at 40-44 cm was not visible when extruding. The lowermost section from 55-74 cm was mid-brown but molluscs were absent and the *Chara* encrustations disappeared. The basal sample was dense with high clay content and contained fibrous root material.

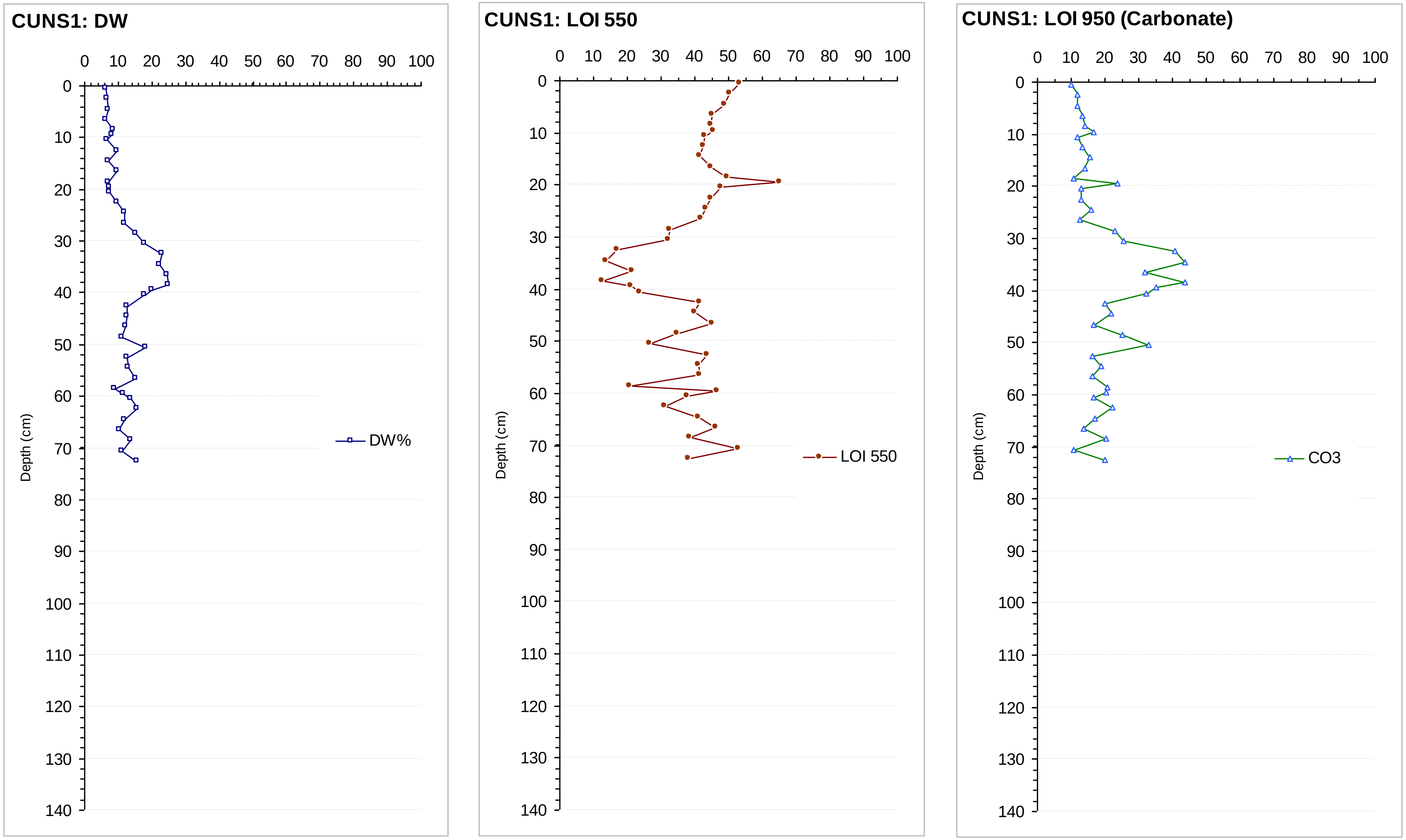
Figure 18 Sediment core stratigraphy of CUNS1

Depth (cm)	Sediment colour
0-17	Dark brown (few molluscs)
17-32	Dark brown (abundant molluscs)
32-40	Light brown (abundant molluscs and *Chara* encrustations)
40-44	Light grey
44-55	Light brown (abundant molluscs and *Chara* encrustations)
55-74	Mid-brown (molluscs absent, few *Chara* encrustations)

Stratigraphic analyses

The core, CUNS1, was organic in the lower section below ~40 cm with LOI 550 values of ~40-50% (Figure 19). Above this was a denser, carbonate rich layer extending from ~32-40 cm with LOI 950 values of ~40%, coincident with the section in which abundant molluscs and *Chara* encrustations were observed during extrusion. In the upper 30 cm of the core, LOI 550 increased gradually to a maximum of ~65% at 20 cm before declining to values of ~40-50% in the uppermost section. Both DW and LOI 950 exhibited a general decrease in the upper 30 cm to values of less than 10%, highlighting the organic nature of the upper core.

Figure 19 Stratigraphic data for CUNS1



Spheroidal carbonaceous particle analysis

The SCP profile from CUNS1 shows a typical SCP profile with clearly defined peak and rapid increase features (Table 8, Figure 20). The first presence of SCPs occurs at 39-40 cm while the peak concentration of 7400 gDM^{-1} occurs at 7-8 cm. As sampling resolution at this point is reasonably good we can ascribe the date of 1978 ± 2 to 7-8 cm with reasonable confidence. This indicates a mean sediment accumulation rate over the last 30 years of 0.25 cm yr^{-1}. However, extrapolation of this rate would place 1950 at 14-15cm but the feature appears to fall below this depth at 17-19 cm. This indicates that sediment accumulation has not been consistent. If 1950 is ascribed to 17-19 cm then this suggests a mean sediment accumulation rate of 0.34-0.41 cm yr^{-1} for the period 1950-1978. If the first presence of SCPs at 39-40 cm represents 1850 then the mean sediment accumulation rate between 1850 and 1950 is ~0.215 cm yr^{-1}. This is slightly less than the rate over the most recent 30 years and suggests a probable gradual increase in sediment accumulation rate over the last ~150 years with a period of more rapid accumulation in the 1950s and 1960s. The derived chronology is shown in Table 9.

Table 8 SCP concentrations for CUNS1

Mean depth (cm)	SCP conc (gDM^{-1})	90% C.L. (gDM^{-1})
0.5	1600	784
1.5	1764	864
3.5	5839	1587
5.5	5675	1605
7.5	7400	1938
9.5	5500	1348
11.5	5409	1417
13.5	5656	1431
15.5	3513	1217
17.5	3779	1400
19.5	1421	696
21.5	1928	945
25.5	1200	679
29.5	643	445
33.5	357	350
37.5	0	0
39.5	874	605
41.5	0	0
45.5	0	0
49.5	0	0
53.5	0	0
57.5	0	0

Figure 20 SCP profile for CUNS1

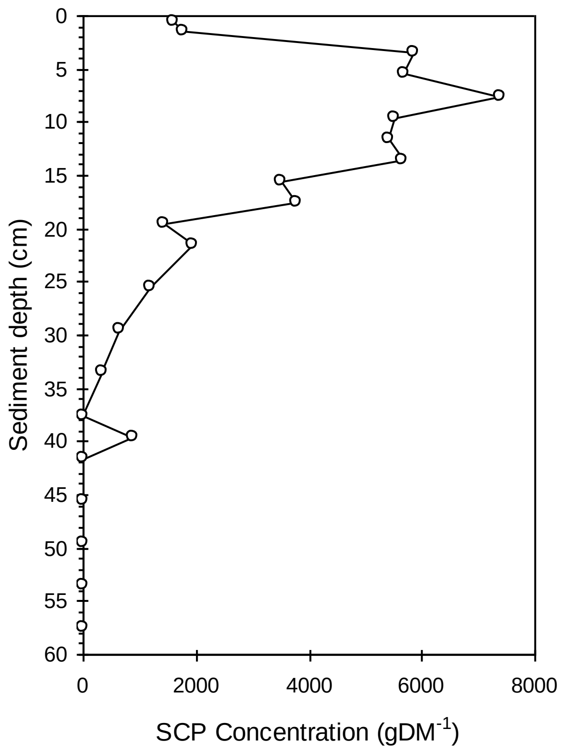


Table 9 The SCP derived chronology for CUNS1

Sediment depth (cm)	Age (Years)	Date
0	0	2008
5	20 ± 2	1988 ± 2
10	37 ± 3	1971 ± 3
15	51 ± 4	1957 ± 5
20	64 ± 8	1944± 8
25	87 ± 10	1921± 10
30	110 ± 15	1898 ± 15
35	133 ± 20	1875 ± 20
40	155 ± 25	1853 ± 25

Macrofossil analysis

Plant macrofossils

The cluster analysis identified two zones in the plant macrofossil record (Figure 21).

Characeae dominated Zone 1 (pre ~1900). Five distinct morphotypes of oospore were identified using the identification model (Davidson *et al*. in prep). *C. vulgaris* 'type' dominated the 70 cm sample but small numbers of *C. rudis* 'type'' and *C. aspera* 'type' were also found. In the 35 cm sample, *C. rudis* 'type' oospores dominated and *C. globularis* 'type' was also abundant. Additionally, *C. aspera* 'type' was present and one oospore was identified as *C. aculeolata* 'type', although given that this is based on one specimen there is much greater uncertainty associated with this identification. The only other plant remains found in Zone 1 were *Potamogeton* cf*. praelongus* seeds. In Zone 2 (from ~1940) *Chara* oospores become scarce and the record is dominated by *Nymphaeaceae* trichosclereids (water lily remains). *Potamogeton* species were still present and *Callitriche* seeds were found in the surface sample. Terrestrial mosses, *Juncus* and *Cyperaceae* also appear in Zone 2 (data not shown).

Zooplankton ephippia

The cluster analysis identified two zones in the ephippia record (Figure 22).

Zooplankton ephippial remains were scarce in Zone 1 with few remains found in the 40 and 70 cm samples. In Zone 2, *Daphnia hyalina* and *Ceriodaphnia* spp. first appeared in the record at 35 cm (~1875) and their abundances increased towards the top of the core. *Daphnia hyalina* was the dominant species in this zone but the large-bodied *Daphnia pulex,* a pelagic species, was also abundant and *Simocephalus* spp., associated with plant beds, was recorded in low numbers.

Discussion

The plant macrofossil data indicate that, prior to ~1900, Cunswick Tarn supported a diverse charophyte community. The oospore identification model suggests that there were at least five different types. This agrees with early plant records for the site that indicate that the flora was typical of a mesotrophic, calcareous (marl) lake (Group I in Duigan *et al*., 2007). Various surveys reported occurrence of *Chara aculeolata, Chara globularis* agg. and *Chara curta* in ~1900 (Stewart, 2006). However, interestingly the oospore types found in the 35 cm sample (~1875) are different to those in the lowermost sample which may reflect a shift in the charophyte flora to a more marl lake type. For example, *C. vulgaris* 'type' was found at the base of the core where carbonate content was low whilst *C. rudis* 'type' and *C.* cf. *aculeolata* 'type', taxa typically associated with base-rich conditions, were found at 35 cm which coincides with high carbonate content in the 30-40 cm section of the core. This could represent either localised marl precipitation around the plant beds themselves or possibly lake wide precipitation of marl. Given that only five samples were analysed here and accepting that macrofossil and plant records are patchy, firmer conclusions cannot be drawn from this analysis. However, further samples will be analysed for plant macrofossils and Cladocera remains by Emma Wiik as part of an ongoing PhD on the lake.

The abundance of *Chara* oospores declined markedly some time between around 1880 and the mid-1900s and the charophytes were replaced by elodeids. From around 1950 the macrofossil record was dominated by *Nymphaeaceae* trichosclereids. The timing of the shift is synchronous with the change in sediment composition as the carbonate content declines again in the upper 30 cm of the core, potentially signalling the cessation of marl precipitation. The changes are also coincident with those in the ephippia record which exhibit a marked increase in open water *Daphnia* spp., particularly since ~1950, indicative of enhanced pelagic production. The palaeoecological results are in accordance with observed changes in the aquatic plant community of the lake. In a survey undertaken in 2005, only *Nuphar lutea* was recorded (Stewart, 2006) and in 2004 *Nuphar lutea* was dominant although small fragments of *Potamogeton pusillus* and *Potamogeton obtusifolius* were also found (Darwell, 2004). Indeed at the time of the 2005 survey, a moderate blue-green algal bloom was present. There is, therefore, strong evidence that the aquatic flora of the lake has undergone profound changes and this is most likely associated with enrichment. The site is currently used for wildfowling with several shooting butts on the shore. Grain is introduced to attract the wildfowl which has resulted in some filamentous algal growth in the vicinity (Stewart, 2006). Diffuse pollution may also be a potential source of nutrients.

In summary, the aquatic plant community of Cunswick Tarn has shifted from a charophyte dominated flora typical of a mesotrophic, calcareous (marl) lake, to a sparsely vegetated one dominated by *Nymphaeaceae* and elodeids, most probably caused by eutrophication.

Figure 21 Summary plant macrofossil diagram for Cunswick Tarn, core
(Note variable scaling on the x axis)

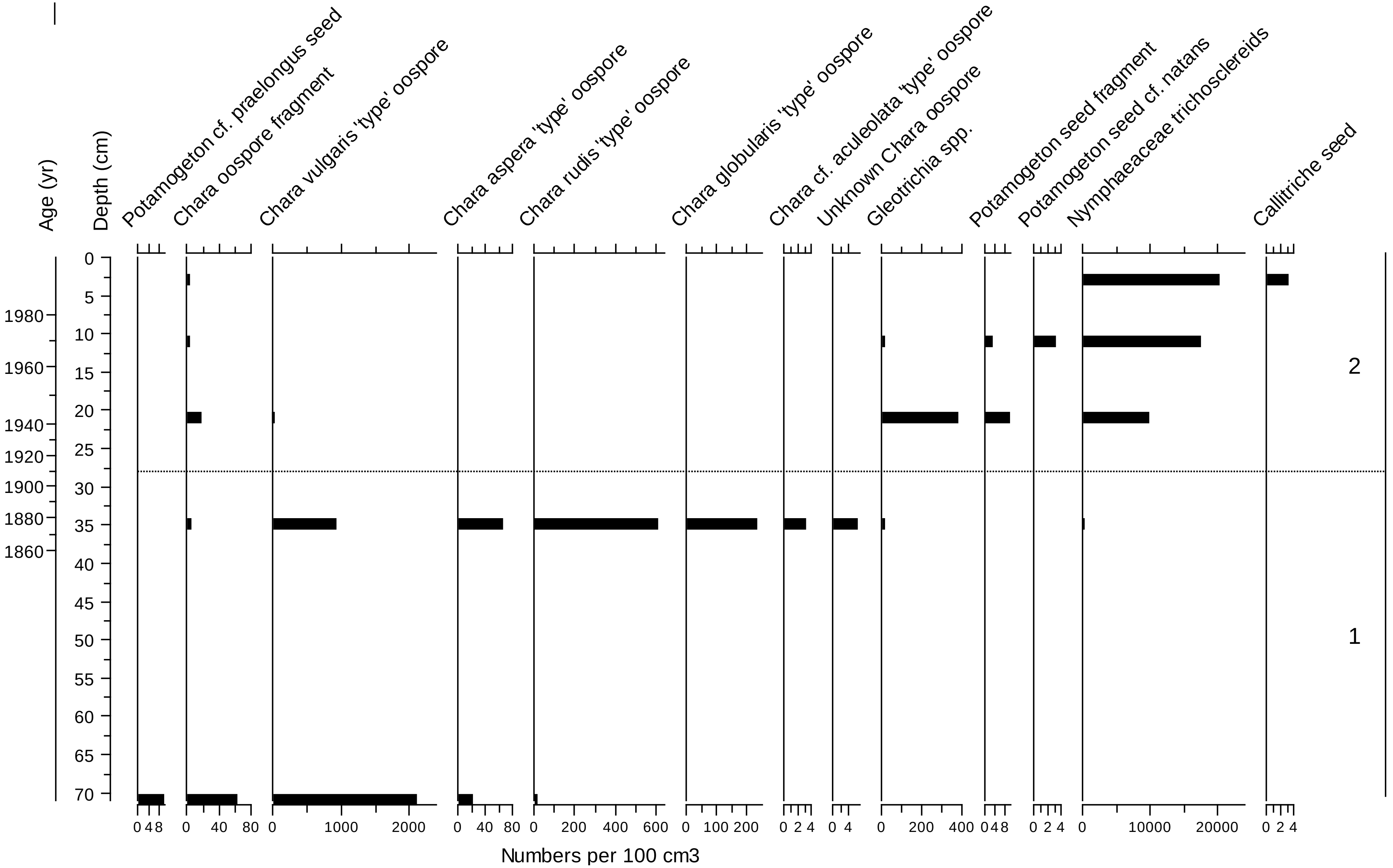
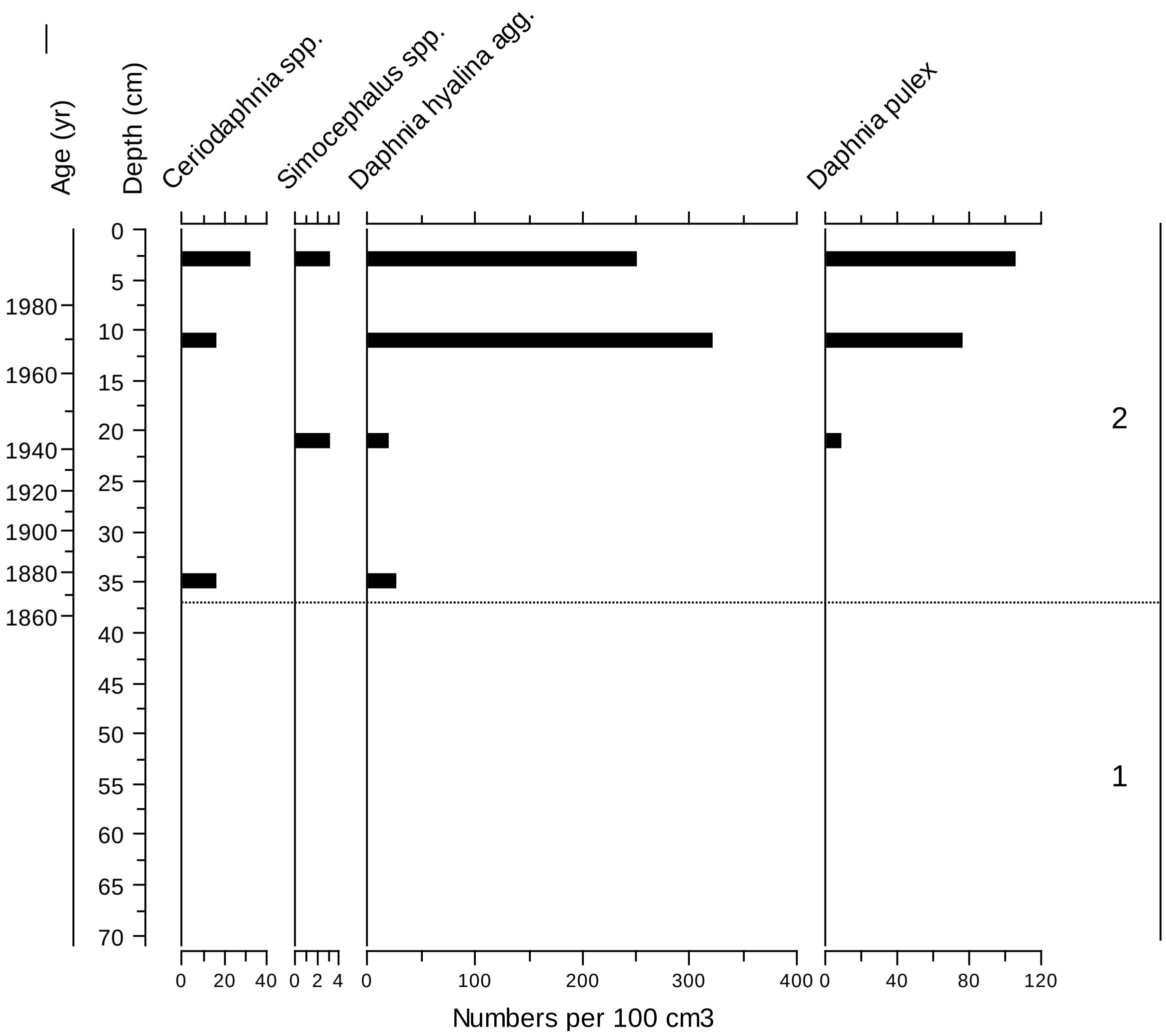


Figure 22 Summary zooplankton ephippia diagram for Cunswick Tarn, core CUNS1
(Note variable scaling on the x axis)



SUNBIGGIN TARN

Site description

Sunbiggin Tarn (NGR: NY676076) is a small upland tarn (3.7 ha) situated on carboniferous limestone. The tarn is included in Sunbiggin Tarn and Moors and Little Asby Scar SSSI and is designated as a Special Area of Conservation under the EC Habitats and Species Directive as an example of habitat 3140 'hard oligo-mesotrophic waters with benthic vegetation of *Chara* spp.'. The site has been the subject of a number of studies and surveys and there is a general consensus that the macrophyte interest of the site has declined as a result of nutrient enrichment and/or sedimentation (Goldsmith *et al*., 2003). The tarn was included in this study because it was considered that application of the recently developed charophyte oospore technique might offer more information on past vegetation changes and that plant macrofossils in general might allow a more complete reconstruction of past conditions in combination with previous diatom work.

Core description

A piston core, 1.35 m in length, was collected from Sunbiggin Tarn on 19-Jan-08 in 2.3 m water depth, approximately 15 m from the shore on the southern side of the lake. At the time of coring, the water level was up by approximately 0.5 m due to recent heavy rainfall. Marginal vegetation was comprised of *Typha* and *Phragmites*.

The core had two distinct horizons (Figure 23). The upper 30 cm was mid-brown and the section below 30 cm was lighter greyish brown with a marl-like consistency and was rich in ostracod remains. *Chara* encrustations were abundant from 86 cm downwards

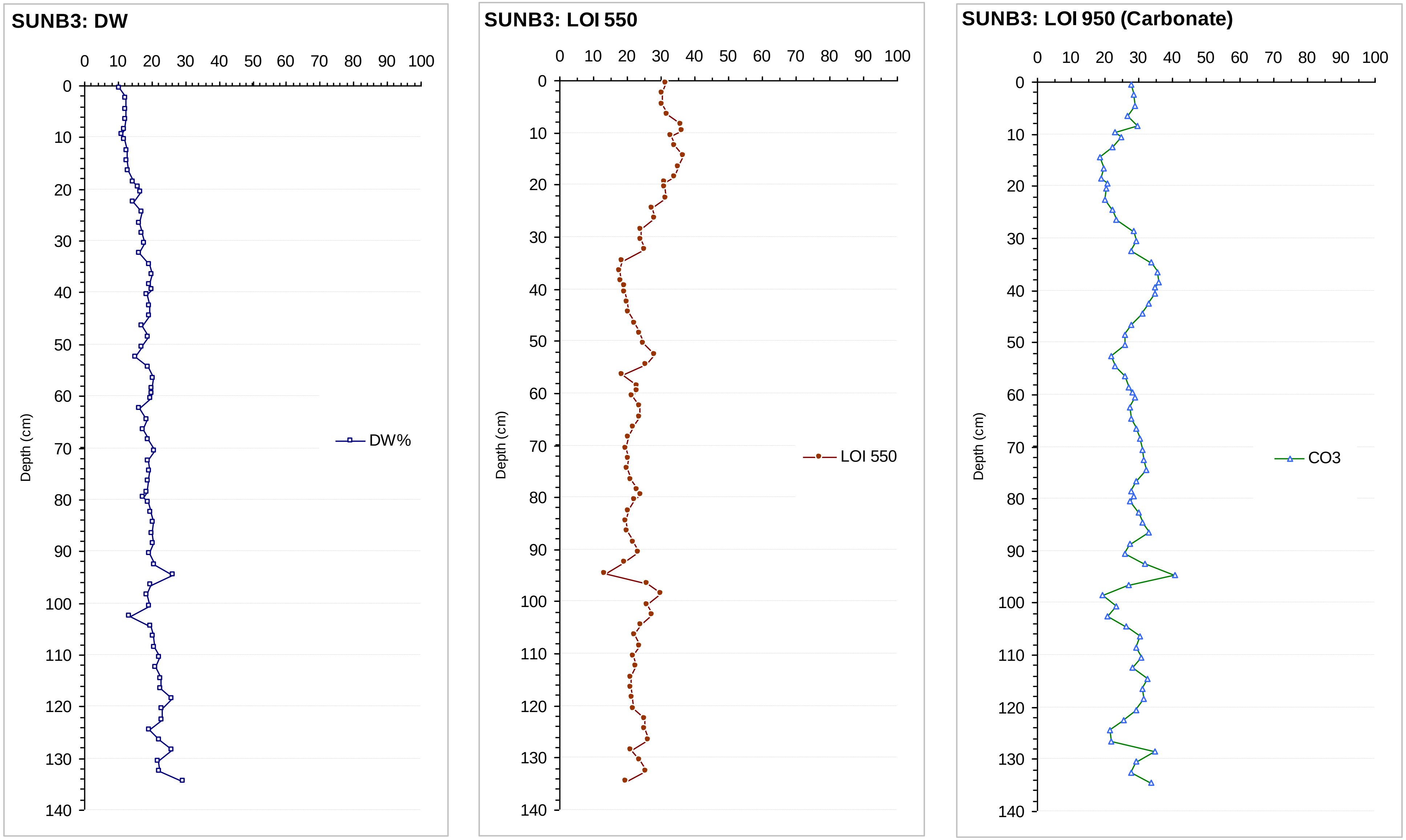
Figure 23 Sediment core stratigraphy of SUNB3

	**Depth (cm)**	**Sediment colour**
	0-30	Mid-brown
	30-135	Light greyish brown

Stratigraphic analyses

Despite marked visible stratigraphy in SUNB3 (Figure 23), the profiles were relatively stable with only modest fluctuations and indicate that there have been no major changes in sediment type throughout the record (Figure 24). The DW values decrease gradually from ~30 to 10% reflecting the reduced consolidation of the younger sediments. The LOI 550 values fluctuate between ~20 and 35% with the highest organic content in the lowermost (below 95 cm) and uppermost (above 35 cm) sections and somewhat lower values in the mid section. Carbonate content is relatively high with values of ~20-30%, the lowest values occurring in the upper 30 cm.

Figure 24 Stratigraphic data for SUNB3



Spheroidal carbonaceous particle analysis

The SCP profile from SUNB3 shows a SCP profile with clearly defined peak of over 4300 gDM^{-1} at 34-35 cm (Table 10, Figure 25). If this peak is ascribed the date of 1978 ± 2 then this indicates a rapid mean sediment accumulation rate of 1.15 cm yr^{-1} over the last 30 years. Extrapolating this rate would place 1950, the time at which a rapid increase in SCP concentration is usually observed, at ~66 cm. The profile would suggest that this feature probably occurs slightly above this at ~60 cm indicating a mean sediment accumulation rate of ~1.0 cm yr^{-1} for the period 1950-1978 and a slight increase in accumulation rate in recent decades. The SCP record finishes between 89-99 cm, suggesting that the record may be curtailed, probably as a result of the detection limit of the technique in this rapidly accumulating core. The best available chronology is therefore summarised in Table 11.

Table 10 SCP concentrations for SUNB3

Mean depth (cm)	SCP conc (gDM^{-1})	90% C.L. (gDM^{-1})
0.5	344	337
4.5	1202	589
9.5	0	0
14.5	975	676
19.5	758	525
24.5	790	447
30.5	2049	898
34.5	4359	1068
37.5	3811	1078
39.5	1844	738
42.5	1573	689
44.5	2568	890
47.5	934	916
49.5	958	664
52.5	1975	1117
54.5	1173	813
57.5	1656	1148
59.5	313	306
64.5	742	514
70.5	624	611
74.5	658	644
79.5	371	364
89.5	324	318
99.5	0	0
109.5	0	0
119.5	0	0
129.5	0	0
134.5	0	0

Figure 25 SCP profile for SUNB3

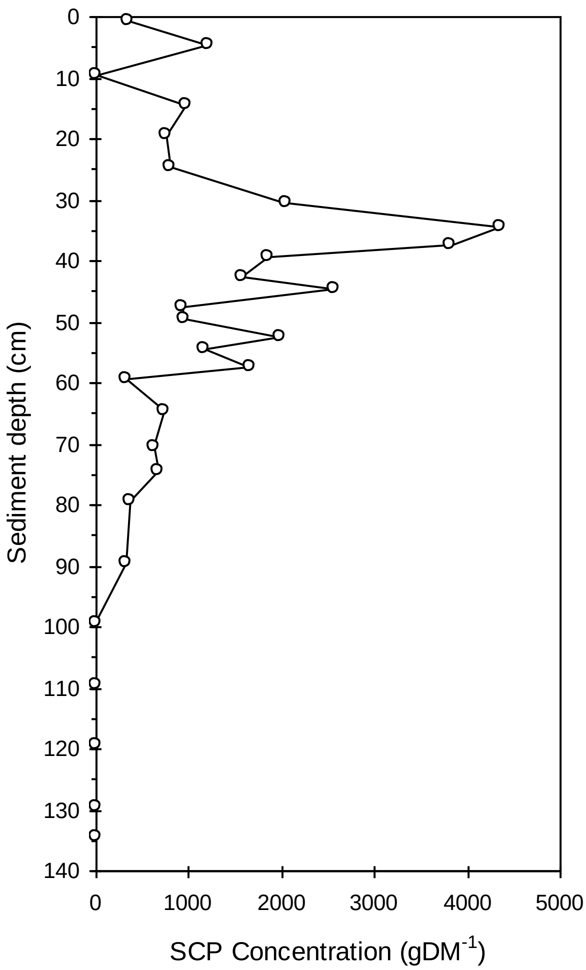


Table 11 The SCP derived chronology for SUNB3

Sediment depth (cm)	Age (Years)	Date
0	0	2008
10	9 ± 2	1999 ± 2
20	17 ± 2	1991 ± 2
30	26 ± 3	1982 ± 3
40	36 ± 5	1972± 5
50	46 ± 15	1962± 5
60	56 ± 8	1952 ± 8
70	66 ± 10	1942 ± 10
80	76 ± 15	1932 ± 15

Macrofossil analysis

Plant macrofossils
The cluster analysis identified two zones in the plant macrofossil record (Figure 26).

Zone 1 (pre-1950) was dominated by terrestrial mosses and *Juncus* seeds (not shown). *Chara* oospores first appeared in the record at 97 cm (~1900) and were most abundant in Zone 2 in the 30 cm sample (~1982) although at relatively low abundances. Three distinct morphotypes of oospore were identified using the identification model (Davidson *et al*. in prep): *C. vulgaris* 'type', *C. rudis* 'type' and *C. aspera* 'type'. However, given that these identifications are based on small numbers of oospores, there is some uncertainty associated with them. *Myriophyllum* leaf tips and *Nitella* oospores were also recorded in Zone 1. In the 65 cm sample only (mid-1940s) *Potamogeton crispus* turions were abundant. In Zone 2 (post-~1980) *Zannichellia palustris* arrived. Other remains in Zone 2 include *Nitella* oospores and *Callitriche* spp. but *Chara* oospores were notably absent from the surface sample. Terrestrial mosses, *Juncus* seeds and *Cyperaceae* were still relatively abundant, although in lower numbers than in Zone 1 (not shown).

Zooplankton ephippia
The cluster analysis identified two zones in the ephippia record (Figure 27).

The ephippial remains of *Chydorus sphaericus*, a littoral-benthic species, dominated at the base of the core and increased in number throughout Zone 1 (pre-1950). *Simocephalus* spp. was also present. In Zone 2 (from ~1982) the remains of *C. sphaericus* were no longer present and the numbers of pelagic species, *Daphnia hyalina* and *Daphnia pulex,* increased markedly, peaking in the 30 cm sample. This peak in *Daphnia* spp. corresponded to a high number of macroinvertebrate remains and was the depth at which *Cyprinid* scale fragments were found (data not shown). Ephippial remains in the surface sample were scarce.

Discussion

The plant macrofossil data indicate that Sunbiggin Tarn supported charophytes including potentially three *Chara* types and *Nitella* spp., and elodeids, including *Myriophyllum* (probably *spicatum*) and *Potamogeton crispus,* prior to around 1960. The latter two taxa disappeared from the fossil record some time between 1950 and 1980 but the charophytes were still abundant in the 1980s. By ~1980 *Zannichellia palustris* appeared in the record perhaps signalling enrichment given that this is a nutrient tolerant plant. The surface sediment contained remains of only *Nitella* spp. and *Z. palustris* suggesting that there has been a decline in the *Chara* community since the mid-1980s although this may be a function of the low density of remains in this uppermost sample. The change in the ephippia record is synchronous with the main shifts in the plant remains with the major increase in open water *Daphnia* taxa occurring between 1950 and 1980, indicating higher pelagic production.

However, as with the other cores in this study, the patchy nature of the macrofossil record and the low number of samples makes it difficult to interpret the shifts with great confidence and analysis of further samples, including addition of chitinous zooplankton remains, is recommended.

Nevertheless, the findings are in good agreement with plant survey data for the lake. Several aquatic vegetation surveys carried out over the past fifty years (Holdgate, 1955; Welsh, 1982; Stokoe, 1983; English Nature, 1994) suggest a possible decline in species richness, attributed to eutrophication (English Nature, 1994). The deterioration has been noted for submerged macrophyte communities in recent decades, especially charophytes which are known to be out-competed by more nutrient-tolerant species in enriched waters (e.g. Haycock & Duigan, 1994; van den Berg, 1999; van Nes *et al.,* 2002). For example, in a survey undertaken in 1982 (Welsh, 1982) only scraps of unhealthy *Chara* and no higher plants were recorded, with much *Aphanizomenon* (Cyanobacteria) washed up along the shore, and *Myriophyllum spicatum* and *Potamogeton pusillus* (probably *P. berchtoldii*) have been recorded as more abundant in the past (Natural England, unpublished records). In a macrophyte survey carried out by UCL and CEH in August 2002 (Goldsmith *et al*., 2003), the submerged vegetation was dominated by *Chara vulgaris* var. *contraria* and *Zannichellia palustris* with a more species-rich patch of submerged and floating-leaved species present along the south-eastern corner, dominated by *Potamogeton crispus.* This led Goldsmith *et al.* (2003) to conclude that the changes since the early 1980s may signal improvement in the site condition of Sunbiggin Tarn, which now has a fairly healthy flora typical of an upland marl lake, albeit of fairly low diversity. A higher resolution analysis of the upper part of our core would be required in order to explore whether such an improvement was detectable in the sediment record.

Current water chemistry data for the lake suggests that the site is moderately productive with annual mean TP concentrations of ~40 µg l^{-1}, SRP of < 10 µg l^{-1} and chlorophyll a of < 7 µg l^{-1} (Goldsmith *et al.*, 2003; Environment Agency data for 2004, unpublished). The tarn supported 25,000 breeding pairs of black-headed gulls in the 1980s and there have been concerns over the possible effects that this has had on the nutrient status of the site. However, diatom analysis of a sediment core showed no conclusive evidence of eutrophication although habitat shifts in the diatom species in the early 1990s did suggest possible physical disturbance (Goldsmith *et al.*, 2003). Gull numbers are now negligible and the 2002 macrophyte survey revealed no overall degradation in species composition at the site compared to surveys conducted prior to the expansion of the gull colony.

In summary, the changes in the macrofossil record of Sunbiggin Tarn are rather difficult to interpret owing to the high variability in abundance of remains captured in the relatively small number of samples analysed. Nevertheless, the shifts indicate a possible decline in species richness, particularly in the charophyte community, and dominance of *Zannichellia palustris* since the 1980s.

Figure 26 Summary plant macrofossil diagram for Sunbiggin Tarn, core SUNB3
(Note variable scaling on the x axis)

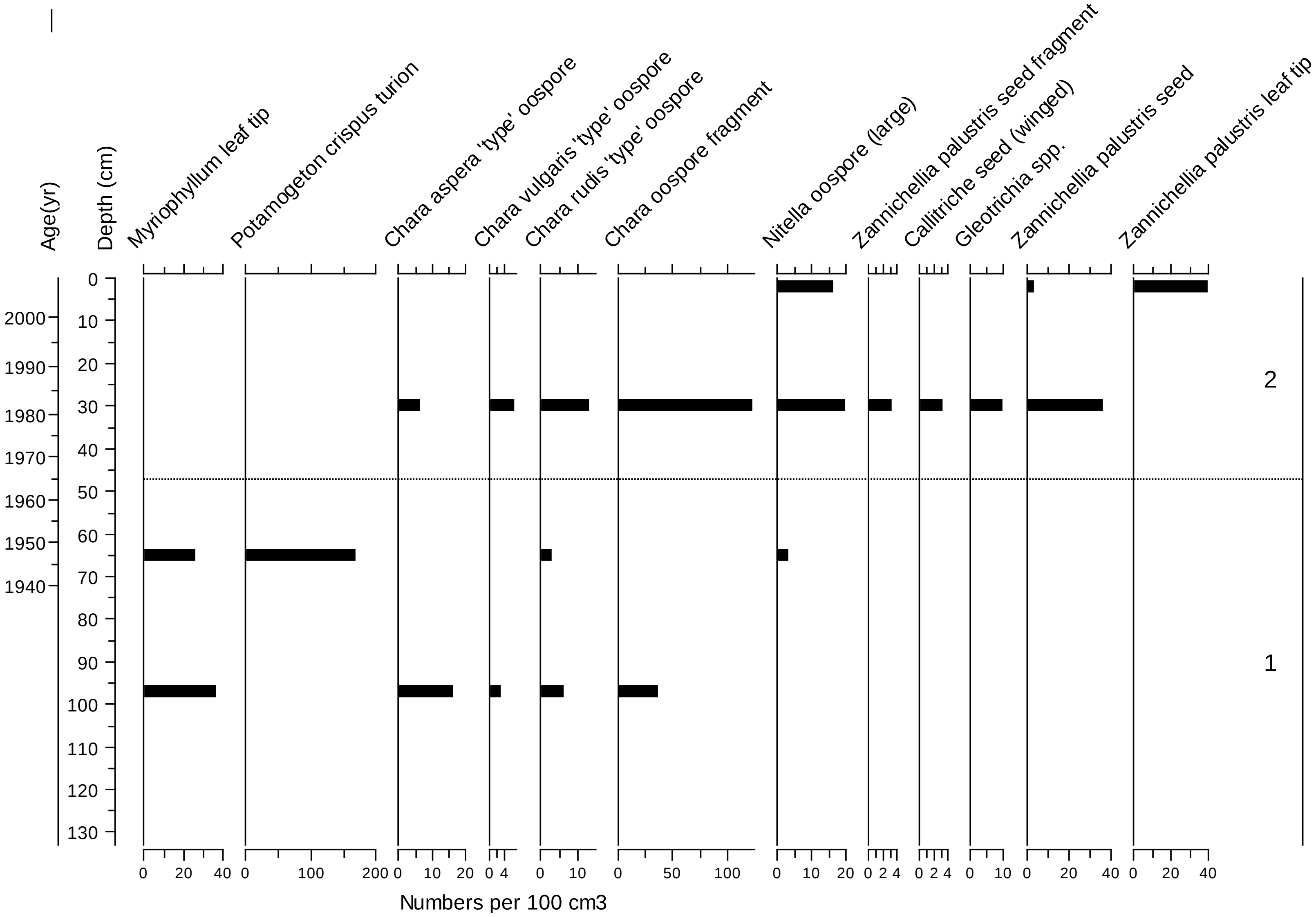
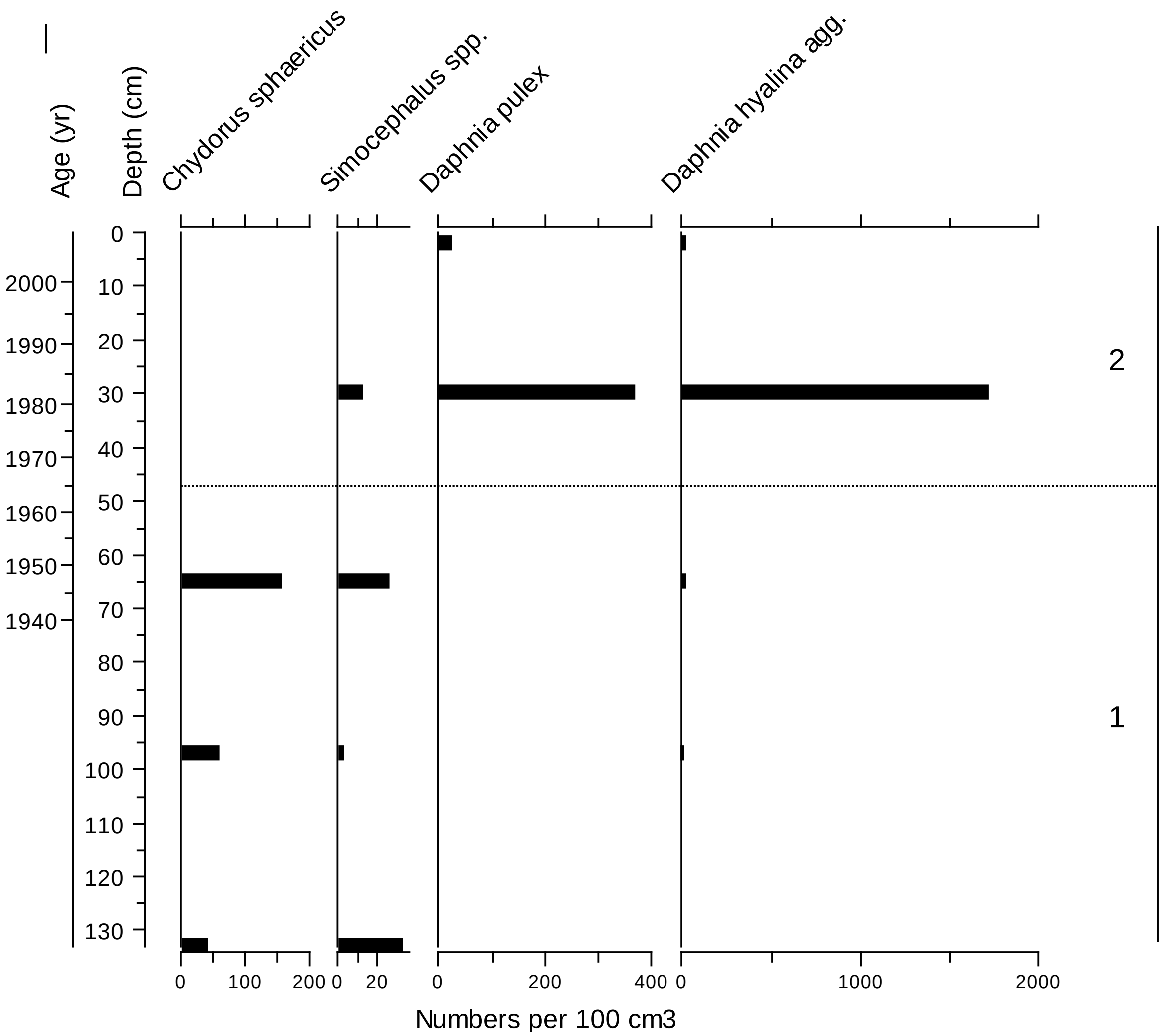


Figure 27 Summary zooplankton ephippia diagram for Sunbiggin Tarn, core SUNB3
(Note variable scaling on the x axis)



HAWES WATER

Site description

Hawes Water SSSI (NGR: SD477766) is a small marl lake (5.7 ha) situated within the Arnside-Silverdale Area of Outstanding Natural Beauty in Lancashire. The site was designated as a SSSI in 1951 and was listed within the Nature Conservation Review (Ratcliffe, 1977). Hawes Water is included within the Morecambe Bay SAC as an example of Habitat 3140 - 'Hard oligo-mesotrophic waters with benthic vegetation of *Chara* spp.' Hawes Water is also an 'Important Stonewort Area' of national importance (Stewart, 2004).

The lake sits within a Carboniferous limestone basin and is surrounded by a mosaic of woodland, fen and carr habitats. The lake has a strong marl influence and supports a number of charophyte species (*Chara aculeolata*, *C. rudis*, and *C.aspera*) in addition to *Potamogeton lucens*, *P. coloratus, Utricularia sp.* and both yellow and white water lilies (*Nuphar lutea* and *Nymphaea alba*). The lake has a well developed marginal fringe and hydrosere which comprises notable species such as *Cladium mariscus*, *Carex vesicaria* and *Carex pseudocyperus*. Hawes Water has long been considered the best example of a lowland marl lake in England but although it retains many of the characteristic species, there are concerns about water quality deterioration. A macrophyte survey in 2005 undertaken by ENSIS Ltd indicated a decline in the extent of charophyte beds relative to the surveys carried out by Chris Newbold in 1984 and 1999. This decline has been linked to a deterioration in water quality which may be the result of diffuse agricultural pollution from the catchment and small unregulated point sources (septic tanks). Further investigation into these nutrient sources and their control is required.

Core description

A piston core, 0.79 m in length, was collected from Hawes Water on 15-Jan-08 in 2.6 m water, approximately 2 m from the shoreline. The coring location was beyond a steep shelf of *Chara aculeolata* and *Potamogeton coloratus* and into *Nymphaea* beds on the east side of lake. Marginal plants included *Cladium, Phragmites* and *Typha angustifolia*.

The core had several clear bands (Figure 28). The upper 10 cm was dark grey marl with the section from 10-26 cm being lighter grey in colour. There was a very light grey band at 26-31 cm followed by a return to a light grey marl from 31-53 cm. At 53-59 cm there was another very light grey band with abundant molluscs and slightly coarser grain size before returning to light grey marl with fewer molluscs from 59-62 cm. At 62-66 cm the sediment was dark brown-grey and was rich in molluscs, followed by light grey marl again from 66-77 cm with abundant molluscs and *Chara* encrustations, and a sulphurous odour. The last section from 77-79 cm was mid-brown in colour and sulphurous, and also contained abundant *Chara* encrustations. The core was markedly different from another core taken at SD 47698 76651 on the west side of lake which was dark brown in colour throughout.

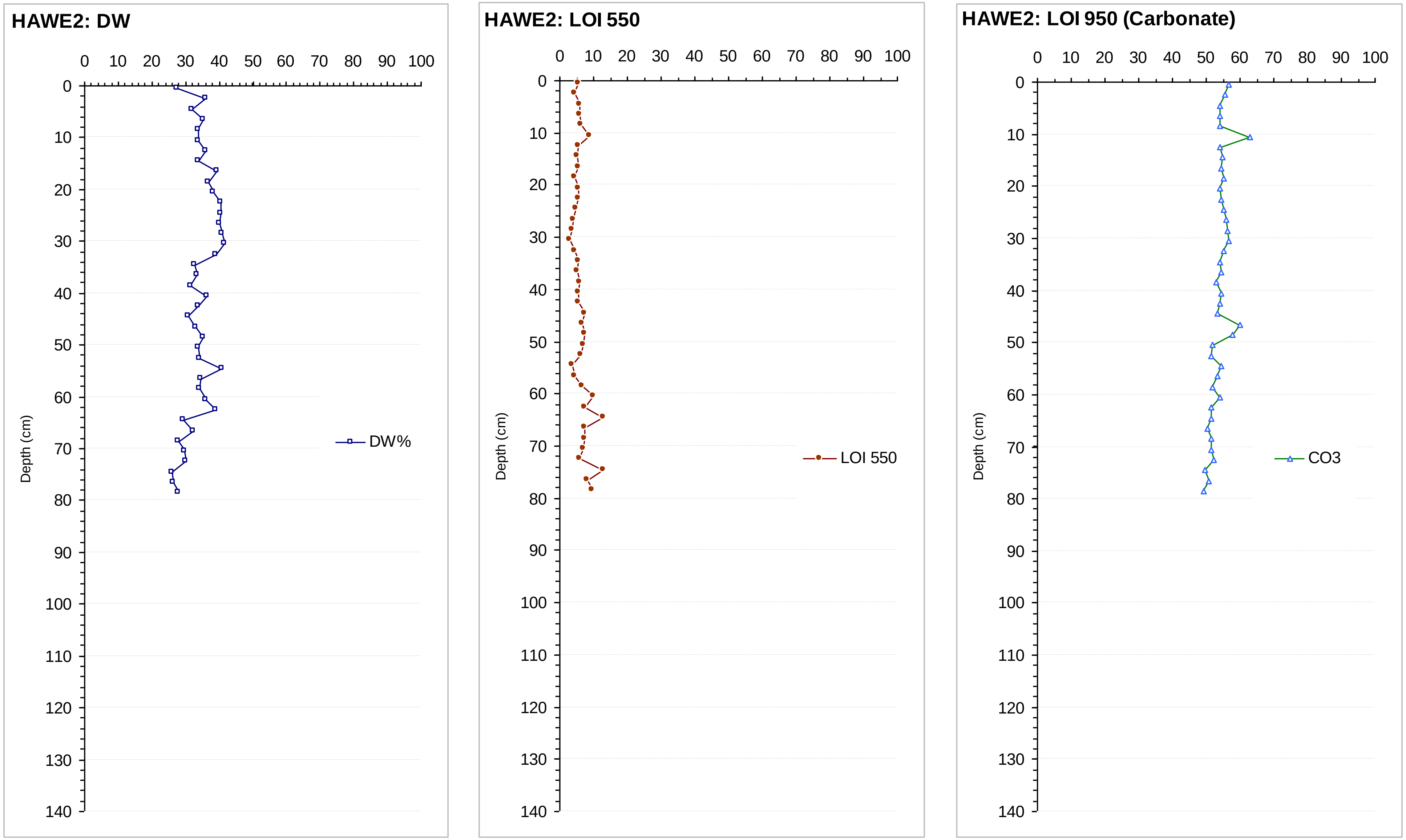
Stratigraphic analyses

The core, HAWE2, was low in organic matter (LOI 550 <10%) and high in carbonate (LOI 950 >50%) throughout with only minor fluctuations in sediment composition (Figure 29). This reflects the carbonate rich nature of the deposits in this marl system.

Figure 28 Sediment core stratigraphy of HAWE2

Depth (cm)	Sediment colour
0-10	Dark grey
10-26	Light grey
26-31	Very light grey
31-53	Light grey
53-59	Very light grey
59-62	Light grey
62-66	Dark brown-grey
66-77	Light grey
77-79	Mid-brown

Figure 29 Stratigraphic data for HAWE2



Spheroidal carbonaceous particle analysis

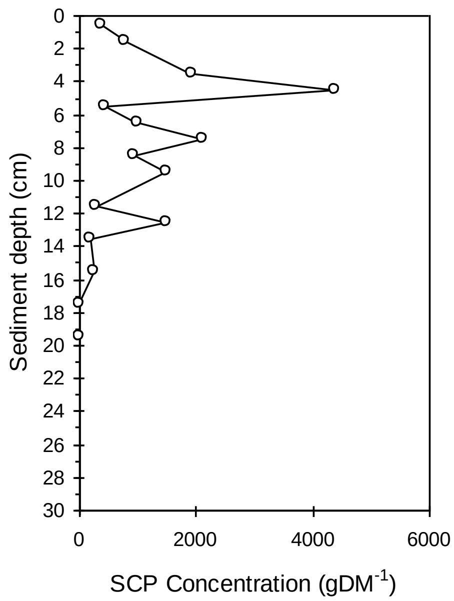
The SCP profile from HAWE2 appears irregular with a series of peaks and troughs (Table 12, Figure 30). The first presence of SCPs occurs at 15-16 cm while a clearly defined peak concentration of over 4300 gDM^{-1} occurs at 4-5 cm. As sampling at this point is contiguous we can ascribe the date of 1978 ± 2 to 4-5 cm with reasonable confidence. This indicates a mean sediment accumulation rate over the last 30 years of 0.15 cm yr^{-1}.

The rapid increase feature is not obvious and extrapolation of the uppermost sediment accumulation rate would place 1950 at 8-9 cm where no feature representing this appears to occur. If the first presence of SCPs at 15-16 cm represents 1850 then the sediment accumulation rate has doubled in recent decades. While that is quite possible, it seems more likely that the full SCP record is not present in HAWE2 and that it is truncated at some unidentified point in time. Without a rapid increase feature to refine the dating we are unable to estimate when this might have occurred. The best available chronology is therefore that 4-5 cm represents 1978 ± 2 and that the core above 16 cm is post-1850. Given the uncertainties associated with the chronology, no further analyses were carried out on this core.

Table 12 SCP concentrations for HAWE2

Mean depth (cm)	SCP conc (gDM^{-1})	90% C.L. (gDM^{-1})
0.5	367	726
1.5	776	1064
3.5	1925	2470
4.5	4370	5884
5.5	440	871
6.5	983	1946
7.5	2099	2827
8.5	942	1355
9.5	1491	2221
11.5	285	564
12.5	1486	2081
13.5	189	375
15.5	256	507
17.5	0	0
19.5	0	0
39.5	0	0
59.5	0	0

Figure 30 SCP profile for HAWE2



SEMER WATER

Site description

Semer Water (NGR: SD919872) was designated as a SSSI in 1975. It is a 28 ha lake located at 246 m altitude in North Yorkshire. The lake is glacial in origin and is dammed by a terminal moraine feature. Although part of the catchment is Carboniferous limestone the lake is also underlain by shales and the feeder streams are very flashy; this leads to frequent and rapid changes in lake level. The lake level was artificially lowered by approximately 50 cm in 1937.

The lake is surrounded by wetland and transitional habitats including a bogbean *Menyanthes trifoliata* swamp. There are good marginal stands of *Carex rostrata* and *C. vesicaria* and an extensive bed of yellow water lilies *Nuphar lutea*. However, recent surveys have failed to locate any stands of submerged macrophytes in the open water. The lake is clearly eutrophic and intensive dairy grazing within the catchment may be the source of a high diffuse nutrient load. There are no good records of submerged plants for the site and it is not clear whether the apparent deterioration is recent or historical. The shallow exposed nature of the lake may make it susceptible to re-suspension of sediments but this is likely to be exacerbated by any elevated sediment loads from the catchment. Given the uncertainty about reference and historical conditions, Semer Water is an obvious candidate for further palaeolimnological study.

Core description

A piston core, 0.91 m in length, was collected from Semer Water on 19-Jan-08 in 2.95 m water depth, approximately 20 m from the shore on the west side of the lake. At the time of coring, the water level was up by approximately 1.5 to 2 m due to recent heavy rainfall and local flooding and the water was turbid. Marginal vegetation was comprised of *Alder* carr.

There were three horizons in the core although there was a gradual transition between them rather than distinct layers (Figure 31). The upper 40 cm was mid-brown. This was followed by a greyish-brown section from 40-60 cm with higher clay content although the transition began at around 25 cm. The lower section from 60-91 cm was mid-brown again with lower clay content than the central section.

Stratigraphic analyses

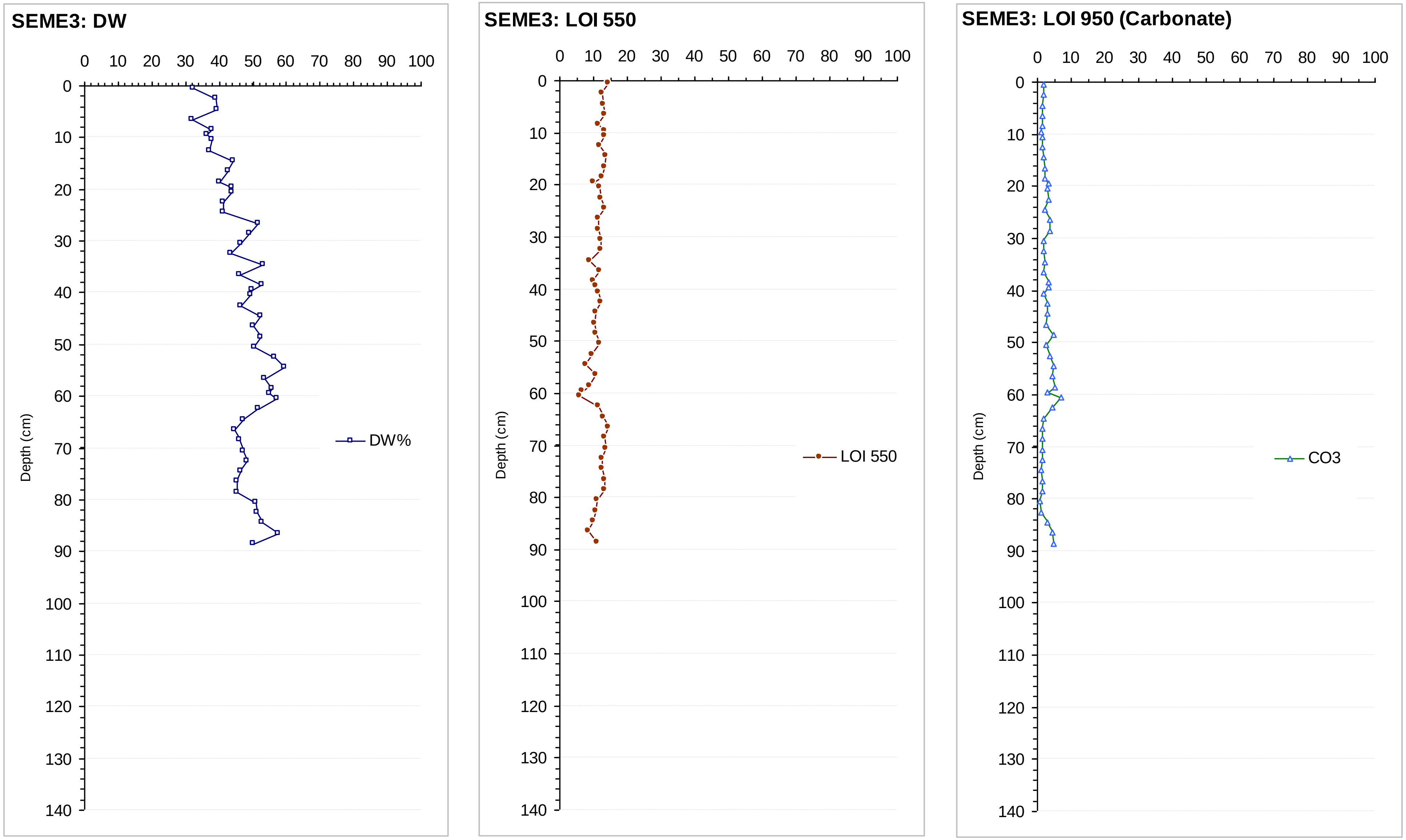
The core, SEME3, was inorganic (LOI 550 10-15%) and low in carbonate (LOI 950 < 5%) throughout (Figure 32). There was little change in percentage organic matter although values were at their highest below ~60 cm. The section from ~65-80 cm had lower DW values (~45%) than the samples below or above it, owing to the higher organic content in this part of the core. The DW values declined steadily from a maximum of ~60% at 55 cm to ~30% at the surface, reflecting the lower density of the upper sediments.

Figure 31 Sediment core stratigraphy of SEME3

Depth (cm)	Sediment colour
0-40 (> 25)	Mid-brown (Transition to greyish brown begins)
40-60	Greyish brown
60-91	Mid-brown

(NB Bottom of core missing from photograph)

Figure 32 Stratigraphic data for SEME3



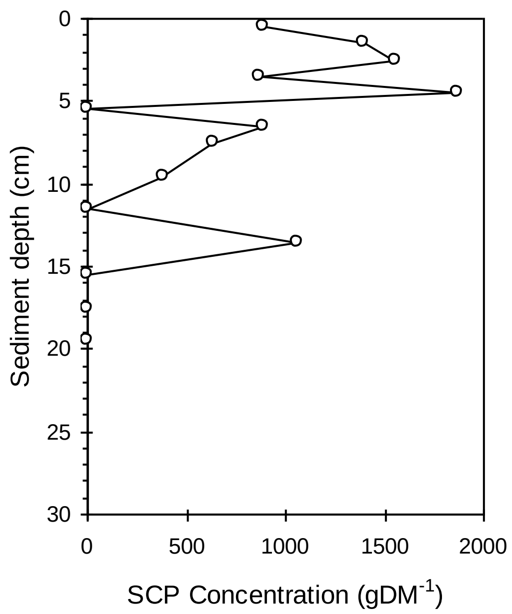
Spheroidal carbonaceous particle analysis

The SCP profile in SEME3 is highly irregular and fragmentary suggesting an incomplete record and possibly discontinuous sedimentation (Table 13, Figure 33). The first presence of SCPs occurs at 11-12 cm and the maximum concentration of almost 2000 gDM^{-1} occurs at 4-5 cm. If this represents the SCP peak, and it is difficult to be certain, then this would imply a mean sediment accumulation rate of ~0.15 cm yr^{-1} over the last 30 years. Extrapolating this would place 1950, and an expected rapid increase feature at 8-9 cm. While this is not inconceivable from the profile, the irregular nature of the observed SCP profile makes confidence in this extremely low. It is therefore not possible to provide a chronology for this core. From the presence of SCPs we can be sure that sediment above 13-14 cm is post-1850 and a best estimate would place the mid-late 1970s at 4-5 cm. However, no further dates can be ascribed and even this date should be treated with caution. Given the uncertainties associated with the chronology, no further analyses were carried out on this core.

Table 13 SCP concentrations for SEME3

Mean depth (cm)	SCP conc (gDM^{-1})	90% C.L. (gDM^{-1})
0.5	889	503
1.5	1398	969
2.5	1553	878
3.5	865	599
4.5	1870	693
5.5	0	0
6.5	892	504
7.5	641	628
9.5	382	374
11.5	0	0
13.5	1058	518
15.5	0	0
17.5	0	0
19.5	0	0
39.5	0	0
59.5	0	0
79.5	0	0

Figure 33 SCP profile for SEME3



MALHAM TARN

Site description

Malham Tarn (NGR: SD893667) is a 60 ha upland lake situated on Carboniferous limestone in North Yorkshire; at an altitude of 375 m it is the highest marl lake in Britain. The tarn sits within an extensive upland limestone landscape of high biological and geological interest. Malham Tarn lies within the large Malham-Arncliffe SSSI which was first notified in 1955. The area is also designated as a SAC and the tarn is included as an example of Habitat 3140 - 'Hard oligo-mesotrophic waters with benthic vegetation of *Chara* spp.' Additionally Malham Tarn is an 'Important Stonewort Area' of national importance (Stewart, 2004). The site was listed within the Nature Conservation Review (Ratcliffe, 1977).

The tarn is strongly marl in character but one shore comprises Tarn Moss, an important raised bog, which lends a peat influence to the lake. Malham Tarn supports an extensive submerged plant community including six charophytes (*Chara aspera*, *C. contraria, C.virgata, C. vulgaris, Nitella opaca*), *Potamogeton lucens*, *P. berchtoldii* and *P.crispus* and the introduced pondweed *Elodea canadensis*. Repeated surveys by George Hinton (1994-present) have indicated a cyclical pattern of dominance between *Elodea* and *Chara* spp. in the tarn. Malham is also one of the most northerly sites for white clawed crayfish *Austropotamobius pallipes*, though in recent years the population has declined dramatically. Work on small point sources adjacent to the Tarn and an end to stocking with trout has resulted in water quality improvements and a more natural ecology.

Core description

A piston core, 1.18 m in length, was collected from Malham Tarn on 20-Jan-08 in 2 m water depth, approximately 100 m from the shore on the north side of the lake. Marginal vegetation was comprised of mixed woodland.

There was one distinct change in the core and several more subtle features (Figure 34). The uppermost 5 cm was mid-brown. The section below this from 5-74 cm was a mid-grey grading to a darker grey by ~ 64 cm. The major change occurred at 74 cm when the sediment changed to a light-mid brown, marl-like material with molluscs and a stiffer consistency. From 92 cm to the core base the material was slightly lighter brown in colour and was less sticky with a drier texture than the marl section but still contained abundant molluscs.

Stratigraphic analyses

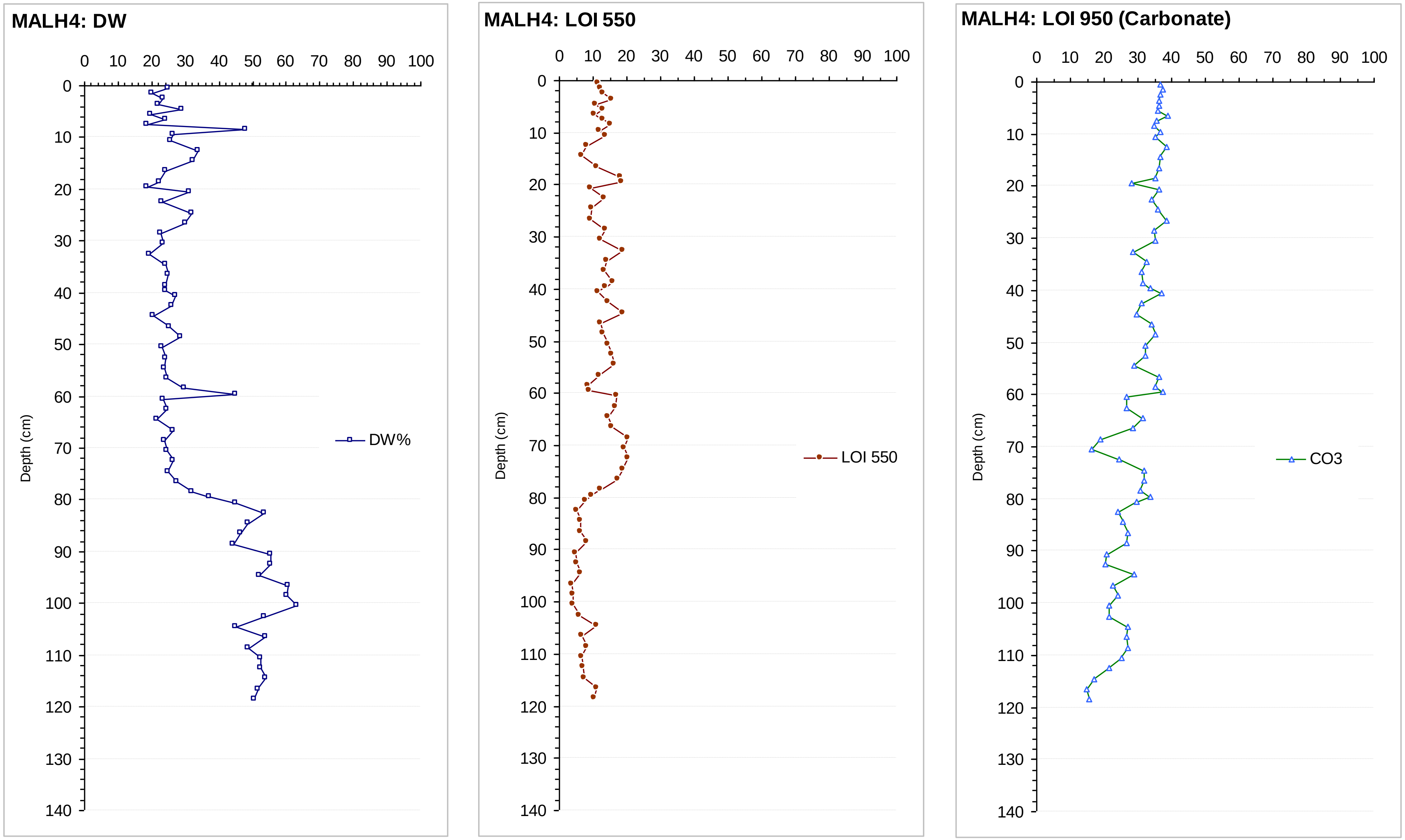
The core, MALH4, was generally low in organic matter (LOI 550 <15%) and high in carbonate (LOI 950 >20%) throughout (Figure 35). However, the lowermost section below ~75 cm was markedly denser and less organic than the upper core with DW and LOI 550 values of ~60% and 5-10%, respectively. In contrast, DW values were typically only 20-30% and LOI 550 values were 10-15% in the upper section. The highest carbonate values of ~35% occurred in the upper core section above 60 cm.

Figure 34 Sediment core stratigraphy of MALH4

<table>
<tr><td rowspan="6"></td><th>Depth (cm)</th><th>Sediment colour</th></tr>
<tr><td>0-5</td><td>Mid-brown</td></tr>
<tr><td>5-67</td><td>Mid- grey

(transition to dark grey)</td></tr>
<tr><td>67-74</td><td>Dark grey</td></tr>
<tr><td>74-92</td><td>Light-mid brown
(molluscs present)</td></tr>
<tr><td>92-118</td><td>Light brown
(molluscs present)</td></tr>
</table>

Figure 35 Stratigraphic data for MALH4



Spheroidal carbonaceous particle analysis

The SCP profile from MALH4 shows clearly defined peak and rapid increase features (Table 14, Figure 36). The first presence of SCPs occurs at 49-50 cm while the peak concentration of over 6000 gDM^{-1} occurs at 9 -10 cm. A previous core from Malham Tarn (MALH2) shows a full SCP record and, in comparison, this MALH4 profile appears slightly truncated i.e. the low SCP concentration 'tail' at lower depths is curtailed.

The SCP concentration peak at 9-10 cm can be ascribed the date 1978 ± 2. The previous ^{210}Pb dated core (MALH2) also shows a well defined peak at this date. This date indicates a mean sediment accumulation rate of 0.31 cm yr^{-1} for the most recent 30 years. Extrapolating this rate would put 1950, and the expected rapid accumulation rate feature, at 18-19 cm, but in MALH4 this appears lower at 22-23 cm indicating a more rapid mean accumulation rate of ~ 0.41 cm yr^{-1} for the period 1950-1978. If extrapolated, both the recent and earlier accumulation rates would place 1850 below the observed first presence of SCPs. Therefore, either the accumulation rate is considerably lower at this time (~ 0.265 cm yr^{-1} for the period 1850-1950) or the profile has been truncated. It seems likely that it is the latter, given the shape of the rest of the profile. If this is the case, then extrapolation of the lower rate would put the start of the SCP record in the 1880s. If the more recent rate is used then the start of the SCP record would be in the 1860s and the profile would therefore be an almost complete industrial record. For information, all accumulation rates for MALH4 appear to be much higher than those for MALH2. A best available chronology for MALH4 is provided in Table 15. Dates prior to 1940 are uncertain and so are not included. Further analyses were not carried out on this core but palaeoecological work will continue on Malham Tarn via a PhD project.

Table 14 SCP concentrations for MALH4

Mean depth (cm)	SCP conc (gDM^{-1})	90% C.L. (gDM^{-1})
0.5	3968	1123
2.5	1982	869
4.5	1321	915
6.5	4193	1186
7.5	4606	1095
9.5	6015	1430
11.5	5331	1847
12.5	5159	1911
14.5	5161	1460
16.5	4811	1491
18.5	4252	1318
19.5	5504	1626
22.5	1663	815
24.5	2780	1362
27.5	957	663
30.5	1062	736
32.5	1452	1006
34.5	1162	569
39.5	801	555
44.5	0	0
49.5	613	601
54.5	0	0
59.5	0	0
79.5	0	0

Figure 36 SCP profile for MALH4

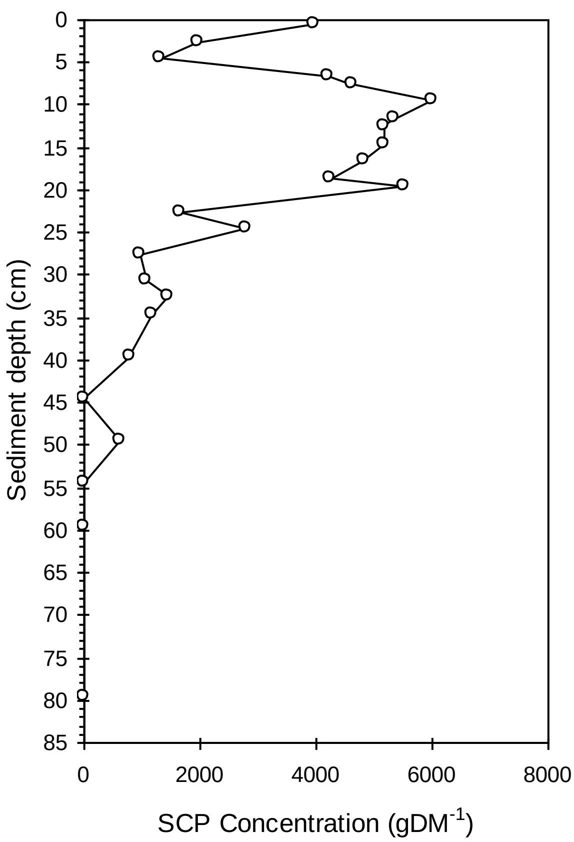


Table 15 The SCP derived chronology for MALH4

Sediment depth (cm)	Age (Years)	Date
0	0	2008
5	16 ± 2	1992 ± 2
10	32 ± 2	1976 ± 2
15	44 ± 3	1964 ± 3
20	56 ± 5	1952 ± 5
25	68 ± 8	1940 ± 8

SUMMARY

The palaeoecological study has shown that all five study sites analysed for biological remains have experienced major shifts in their aquatic plant communities over the period represented by the sediment cores. At the four high alkalinity sites, this shift has taken the form of a decline in the charophyte communities and their replacement with elodeids as the dominant component of the aquatic vegetation. At three of these sites the dominant elodeid species in the upper core was *Zannichellia palustris,* a species associated with elevated nutrient levels, suggesting that enrichment is the most likely explanation for the compositional change. At the low alkalinity site, Over Water, the data indicate that there has been a loss of isoetids and replacement by elodeids. This is most likely associated with gradual eutrophication but alterations in water level and the introduction of *Elodea nuttallii* may also be contributing factors.

The study has successfully determined the reference communities and the degree of ecological change for the five sites and has thereby demonstrated the value of macrofossils for understanding shallow lake dynamics. Indeed, the findings at Aqualate Mere and Hornsea Mere suggest that macrofossil analysis provides an alternative and more informative method to diatoms for establishing reference conditions and environmental change. The application of the new charophyte oospore identification system to the remains in Cunswick Tarn and Sunbiggin Tarn successfully determined the provenance of the fossil oospores to sub-group level with five and three distinct morphotypes of oospore being identified for the two lakes, respectively. This technique clearly expands the potential of palaeolimnology for inferring submerged vegetation histories in marl systems where stoneworts (*Characeae*) often dominate the assemblages.

Finally, the study highlights the need for analysis of more than five samples as high variability in abundance of remains made it difficult to provide a detailed and reliable interpretation based on a small number of samples. Hence, the addition of five further samples (i.e. total of ten samples) for macrofossil analysis is recommended as a minimum to assess changes in the aquatic plant community more fully and to provide a sounder interpretation of the palaeoecological record.

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