ECRC

Environmental Change Research Centre

Research Report No. 135

Using novel palaeolimnological techniques to define lake conservation objectives (Phase 2)

Final Report to Natural England

H. Bennion, R. Rawcliffe, A. Burgess, T. Davidson, C. Sayer and N. Rose

March 2009

ISSN: 1366-7300

Environmental Change Research Centre
Department of Geography
University College London
Pearson Building, Gower Street
London, WC1E 6BT

Executive summary

This is the final report to Natural England on Contract No: SAE03/02/054 ‘Using novel palaeolimnological techniques to define lake conservation objectives: Phase 2’. 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 to assist in the setting of conservation objectives and management goals. The project is divided into four main tasks. Task 1 involved the collection, processing and dating of cores from the study sites and was reported in Phase 1 (Bennion *et al.*, 2008a). Here, in Phase 2, we describe the results of Tasks 2 and 3 which involve 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 conducted and a diatom-phosphorus transfer function was applied to assess changes in water quality.

A single sediment core, approximately 1 m in length, was collected from each site during the period 14-21 January 2008 using a wide-diameter piston corer. Dating of the cores was carried out using spheroidal carbonaceous particle (SCP) analyses in Phase 1. Cores from Cunswick Tarn, Over Water, Sunbiggin Tarn and Hornsea Mere all exhibited typical features of SCP profiles for UK lakes and therefore a chronology could be derived for these four sites. However, additional samples were analysed from Sunbiggin Tarn and Hornsea Mere in an attempt to provide more robust dates and the results are reported here. At Aqualate Mere, the SCP record was somewhat irregular and appeared to be truncated but nonetheless several dates could be derived.

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 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* 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 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.

The study has successfully determined the reference communities and the degree of ecological change for the five sites. However, given that only five samples were analysed, 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.

List of contributors

Helen Bennion, Ruth Rawcliffe, Amy Burgess, Tom Davidson, Carl Sayer and Neil Rose
ENSIS Ltd. / Environmental Change Research Centre
University College London
Pearson Building
Gower Street
London
WC1E 6BT

Acknowledgments

The authors would like to thank the site managers and owners, and colleagues at Natural England, for permission to carry out the study and assistance with the fieldwork. Thanks also to Kevin Roe for technical support.

Cover photograph: Over Water, Cumbria (January 2008).

Table of Contents

List of Figures **Page**

List of Tables

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 to 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 four main tasks. Task 1 involved the collection, processing and dating of cores from the study sites and the results of this first phase of the project were reported in Bennion *et al*. (2008a). Tasks 2 to 4 each have their own objective with Task 2 to focus on three lakes where new palaeolimnological studies are required to help define conservation objectives, Task 3 to employ macrofossil studies at two marl systems to determine reference conditions and ecological change, and Task 4 to provide a detailed multi-proxy analysis at one selected site to demonstrate the value of the approach for understanding shifts in ecological structure and function and for setting ecosystem reference conditions. Here, in phase 2 of the project, we describe the results of Tasks 2 and 3 which are outlined in more detail below.

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.,* 2008b).

A knowledge of past vegetation is important for two key pieces of legislation. The European Council (EC) Water Framework Directive (WFD) requires reference conditions to be determined for a range of biological elements and macrophytes are one of the elements that must be defined for lakes. Under Article 11 of the EC Habitats Directive, Member States are required to undertake surveillance of protected habitats and species, and hence the development of a common standards monitoring protocol for standing water habitats which sets out targets for assessing whether these water bodies are in favourable condition. Macrophyte community composition and structure are two key elements of the habitat features assessment and aquatic vascular plant features are also assessed directly.

This task involves macrofossil analysis of five samples per core from Aqualate Mere, Hornsea Mere and Over Water, 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 marl lakes, Cunswick Tarn and Sunbiggin Tarn. The latter site 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 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. Further details of the cores are given in Bennion *et al.* (2008a).

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 (Table 1). 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. The results are described in Bennion *et al*. (2008a).

Dating

Dating of the cores was carried out using the well established technique of spheroidal carbonaceous particle (SCP) (Rose, 1994; 2008). 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. The results are reported in Bennion *et al.* (2008a) and have been used to ascribe the dates to the cores as shown in the stratigraphic diagrams in this report. Further to the work in Phase 1, additional samples were analysed from Sunbiggin Tarn and Hornsea Mere in an attempt to provide more robust dates and the results are reported here.

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*. unpublished)

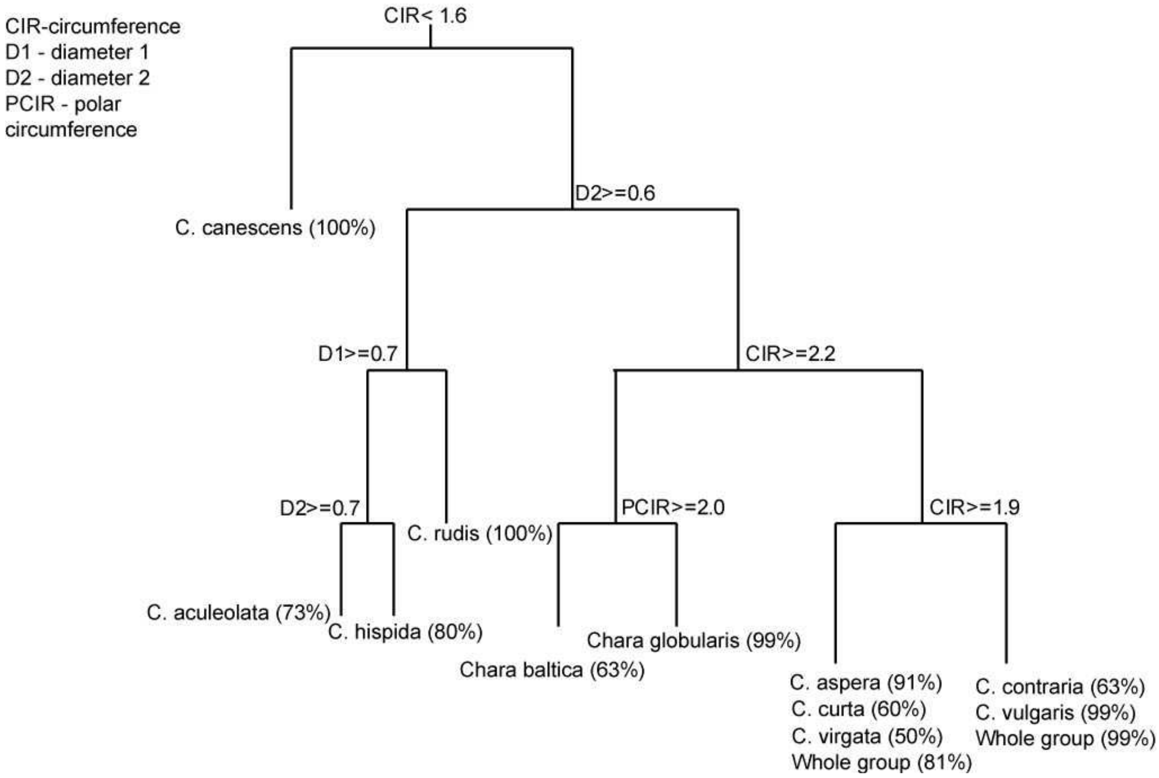


Table 1 Details of the sediment cores collected from five study sites in Tasks 2 and 3

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-Jan 08 (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
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
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
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
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

AQUALATE MERE

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 description and stratigraphy is given in Bennion *et al*. (2008a). The SCP derived chronology is summarised in Table 2.

Table 2 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 2).

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* dominating, and remains of *Ranunculus* sect *Batrachium*, *Potamogeton crispus*, *Myriophyllum spicatum* and *Zannichellia palustris* were also found. *Juncus*, terrestrial mosses and *Gleotrichia* spp. 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 3).

Zooplankton ephippial remains were scarce at the base of the core with relatively low numbers of *Simocephalus* spp., *Daphnia pulex* and *Daphnia hyaline.* 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 chitinous remains is recommended to further explore changes in the zooplankton community.

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

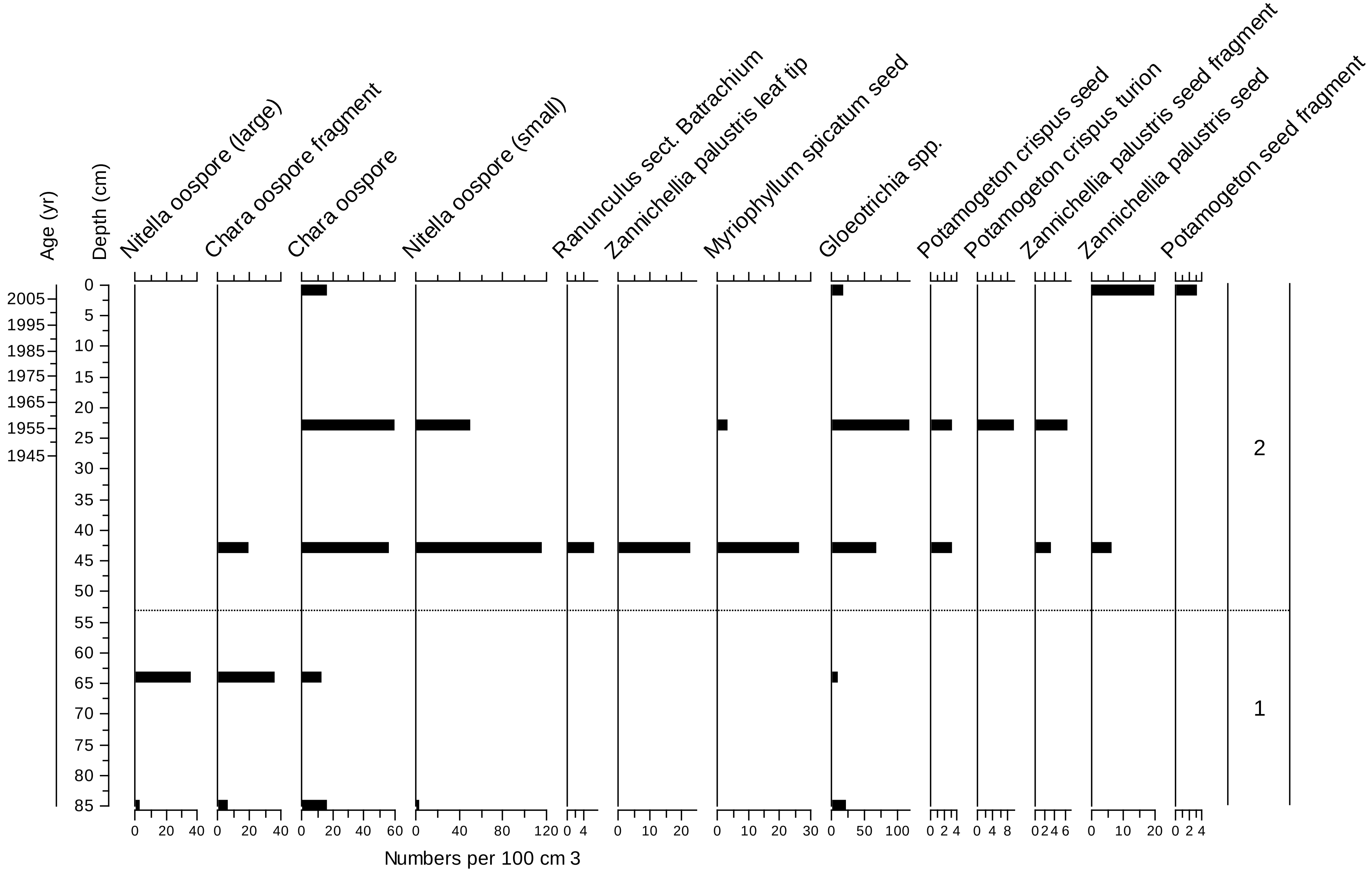
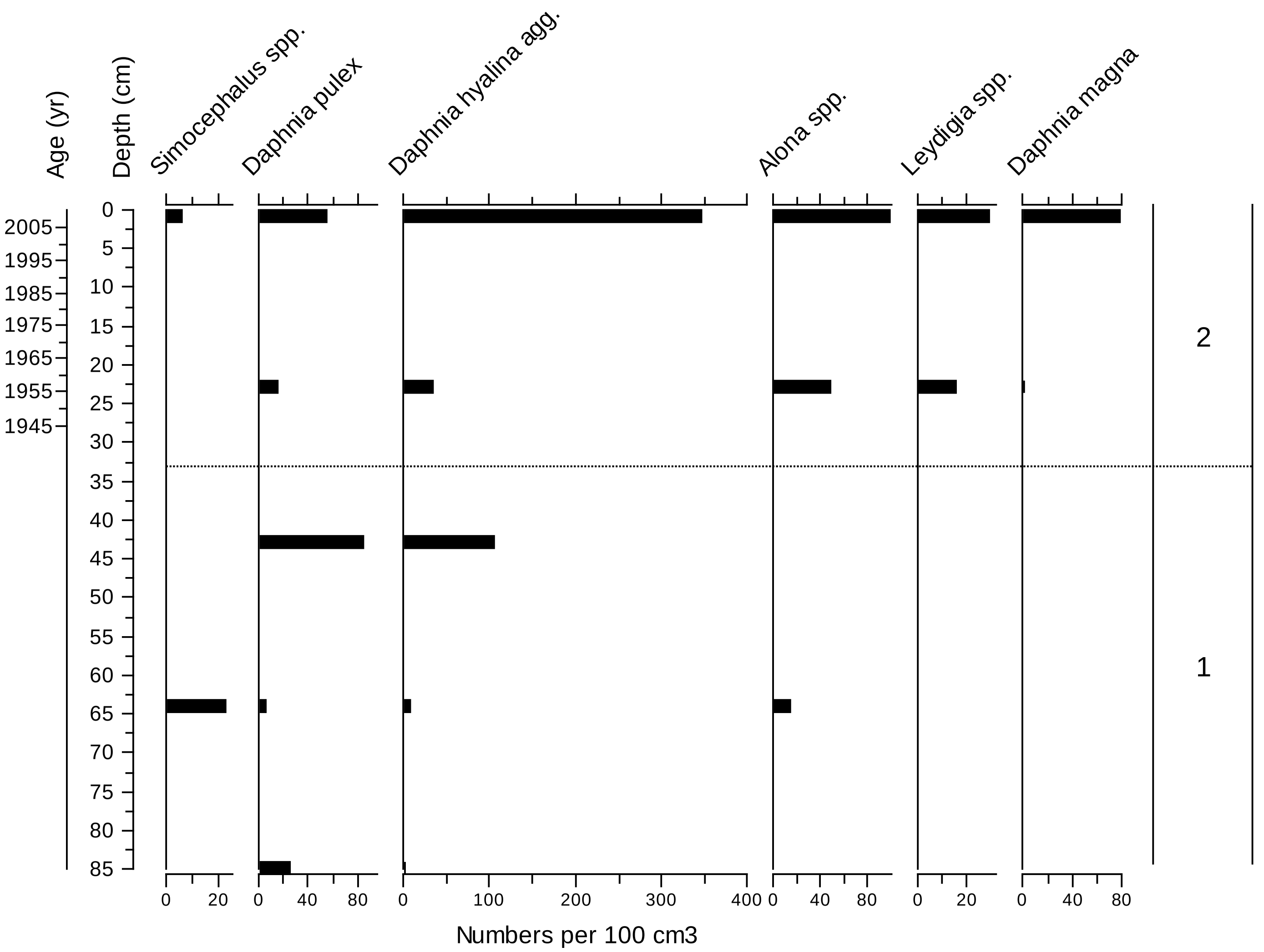


Figure 3 Summary zooplankton ephippia diagram for Aqualate Mere, core
(Note variable scaling on the x axis)



HORNSEA MERE

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 description and stratigraphy is given in Bennion *et al*. (2008a).

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 3, Figure 4). 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 additional analysis shows that 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 4 summarises the best estimate of the chronology for the HORN3 core.

Table 3 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 4 SCP profile for HORN3

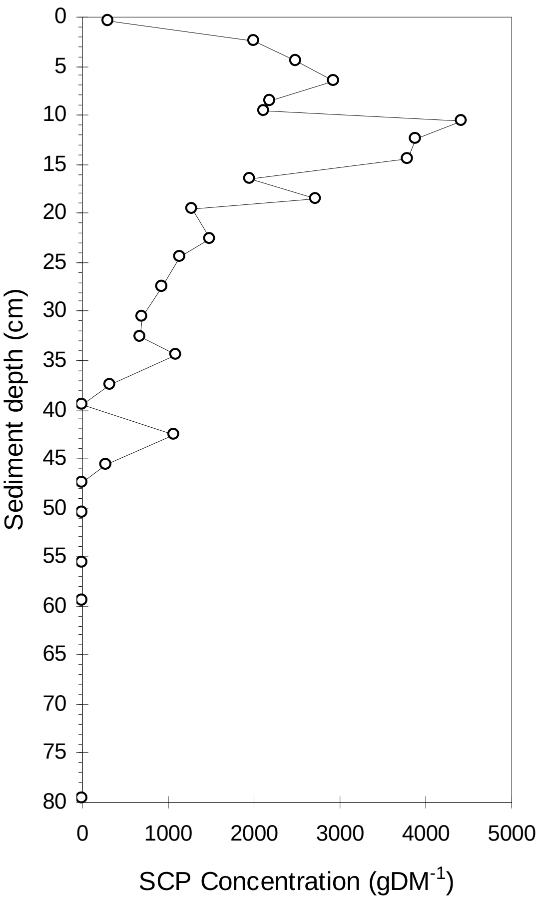


Table 4 The SCP derived chronology for HORN3

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 5).

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 6).

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 expanded. 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 5 Summary plant macrofossil diagram for Hornsea Mere, core HORN3
(Note variable scaling on the x axis)

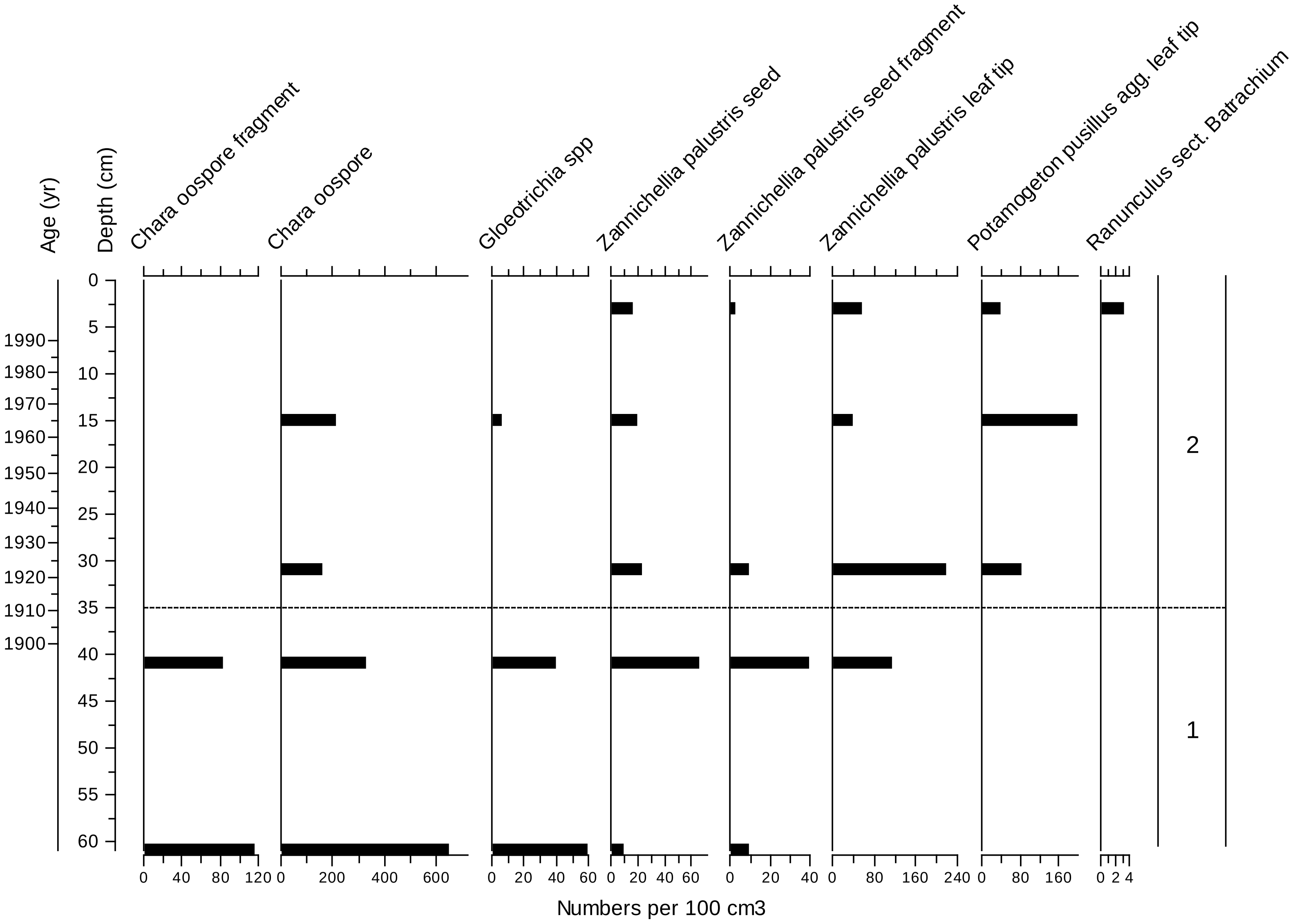
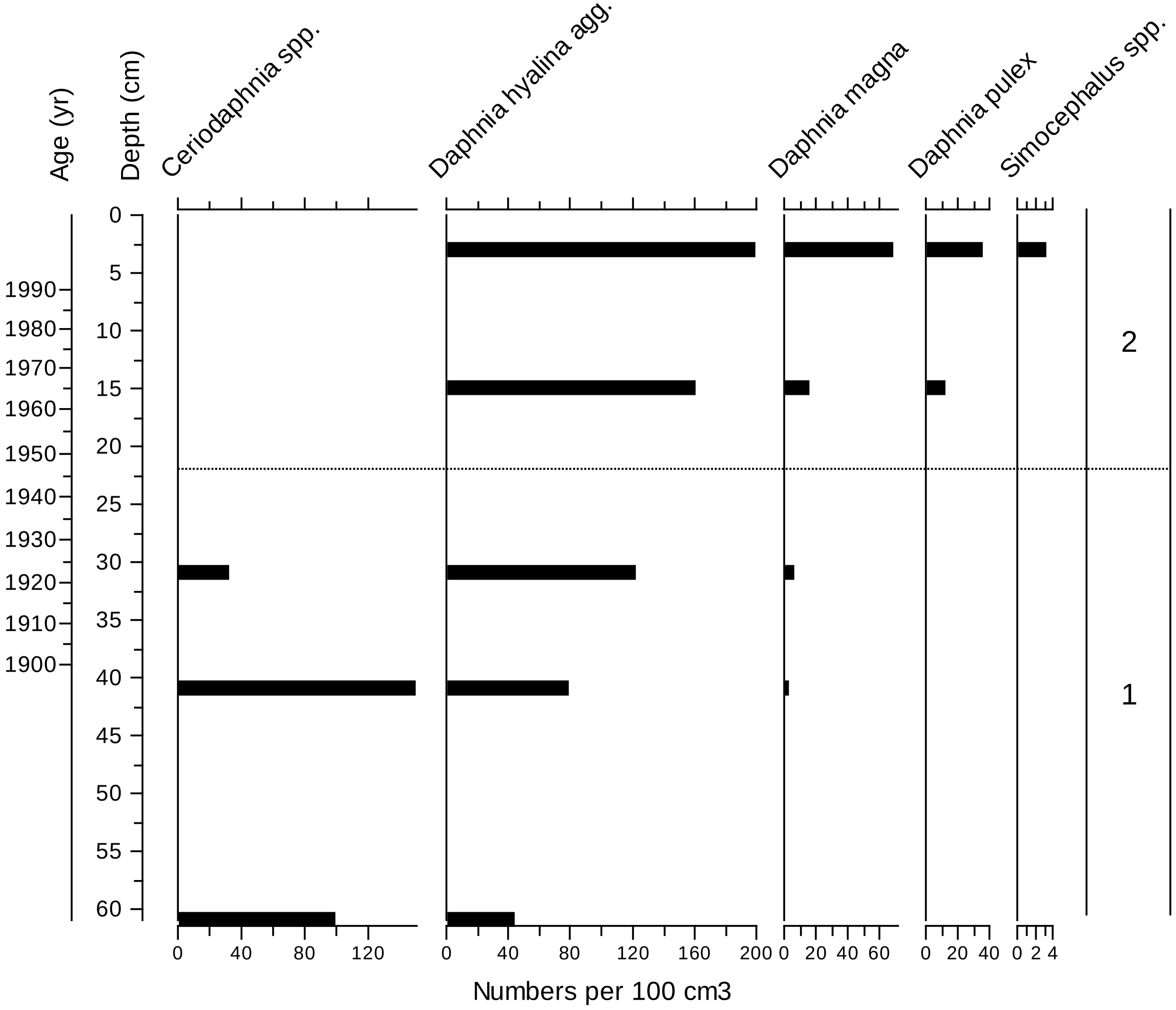


Figure 6 Summary zooplankton ephippia diagram for Hornsea Mere, core HORN3
(Note variable scaling on the x axis)



OVER WATER

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* spp. and *Elodea* spp. were observed during sampling. The core description and stratigraphy is given in Bennion *et al*. (2008a). The SCP derived chronology is summarised in Table 5.

Table 5 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 7).

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 8).

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 9).

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, dilute 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 7 Summary diatom diagram of Over Water, core OVER1, with diatom-inferred total phosphorus (DI-TP) reconstruction
(species occurring at >2% relative abundance)

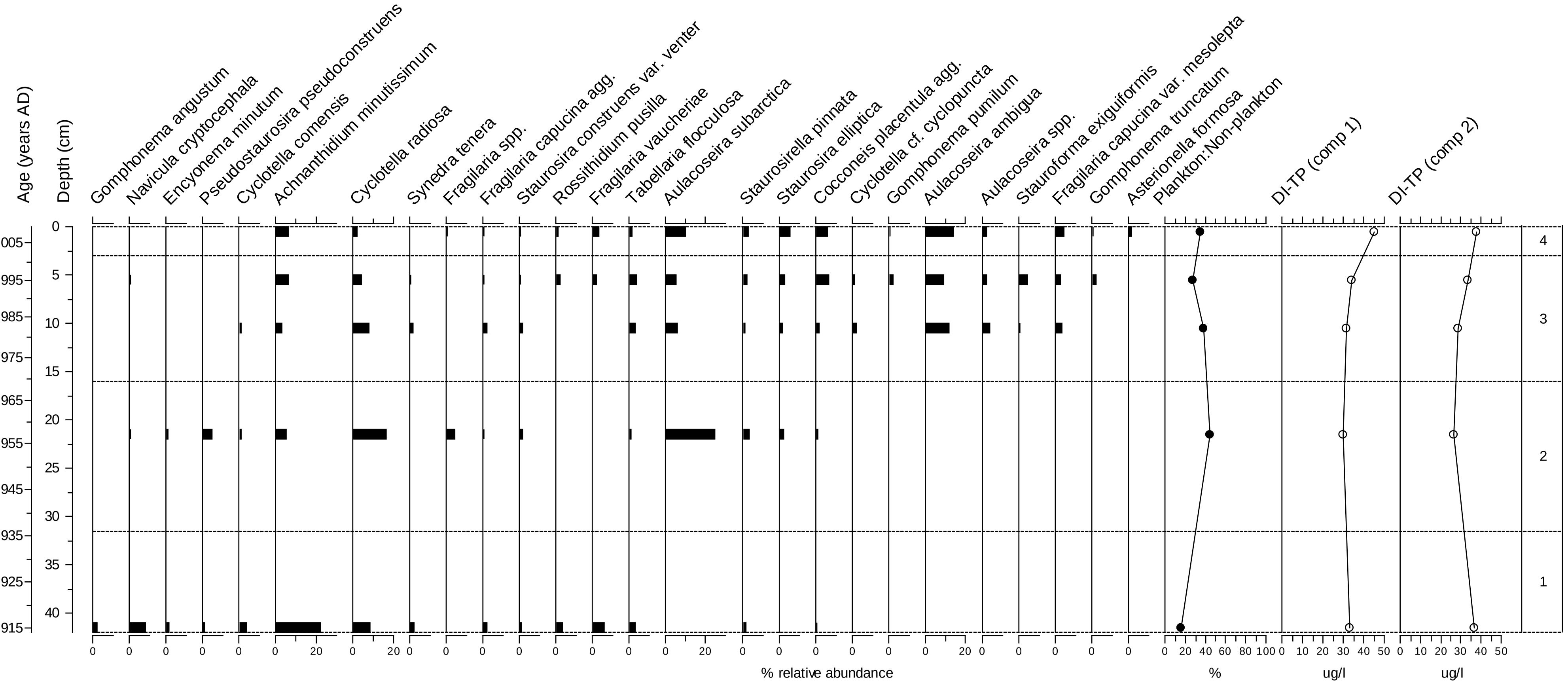


Figure 8 Summary plant macrofossil diagram for Over Water, core OVER1
(Note variable scaling on the x axis)

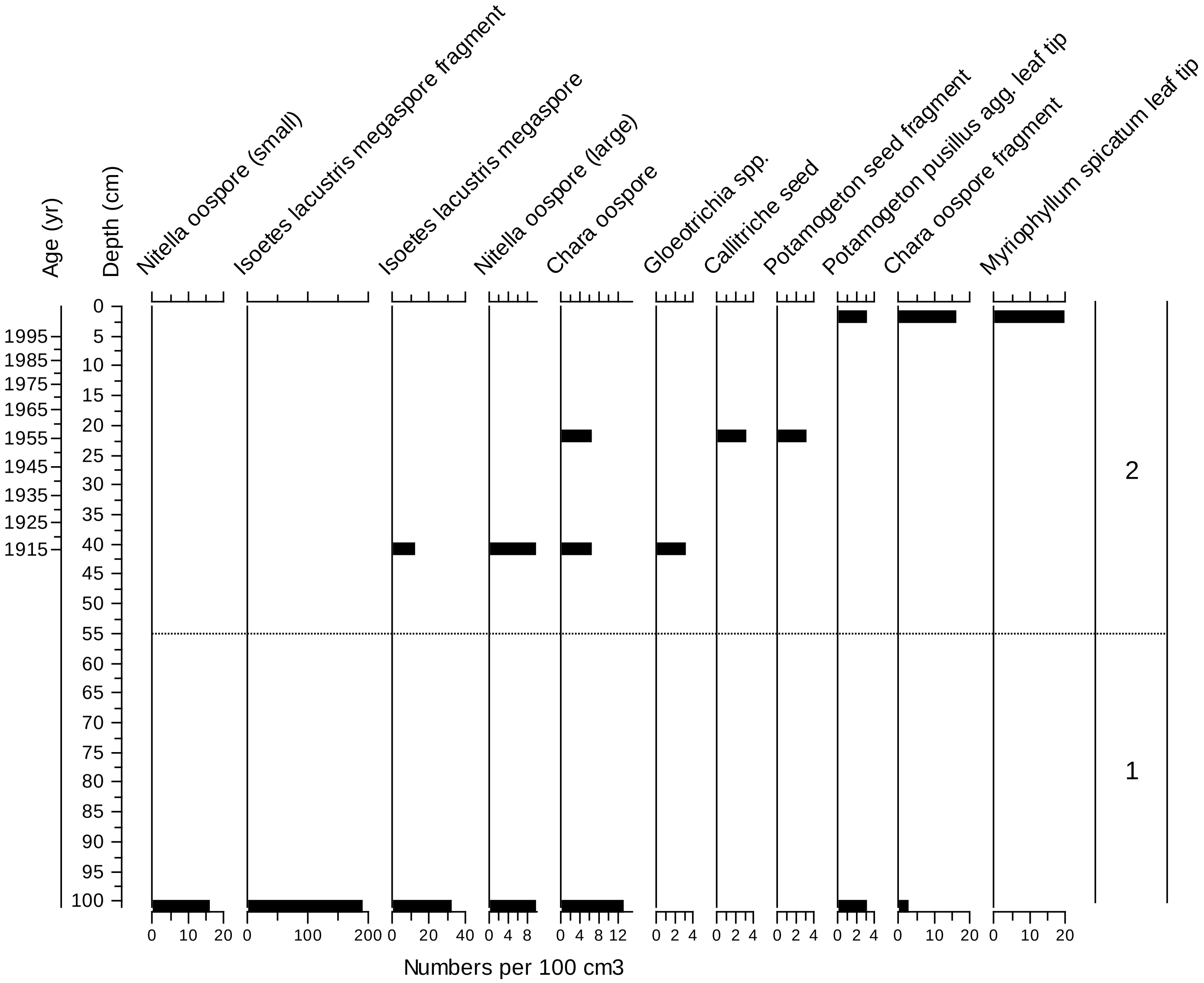
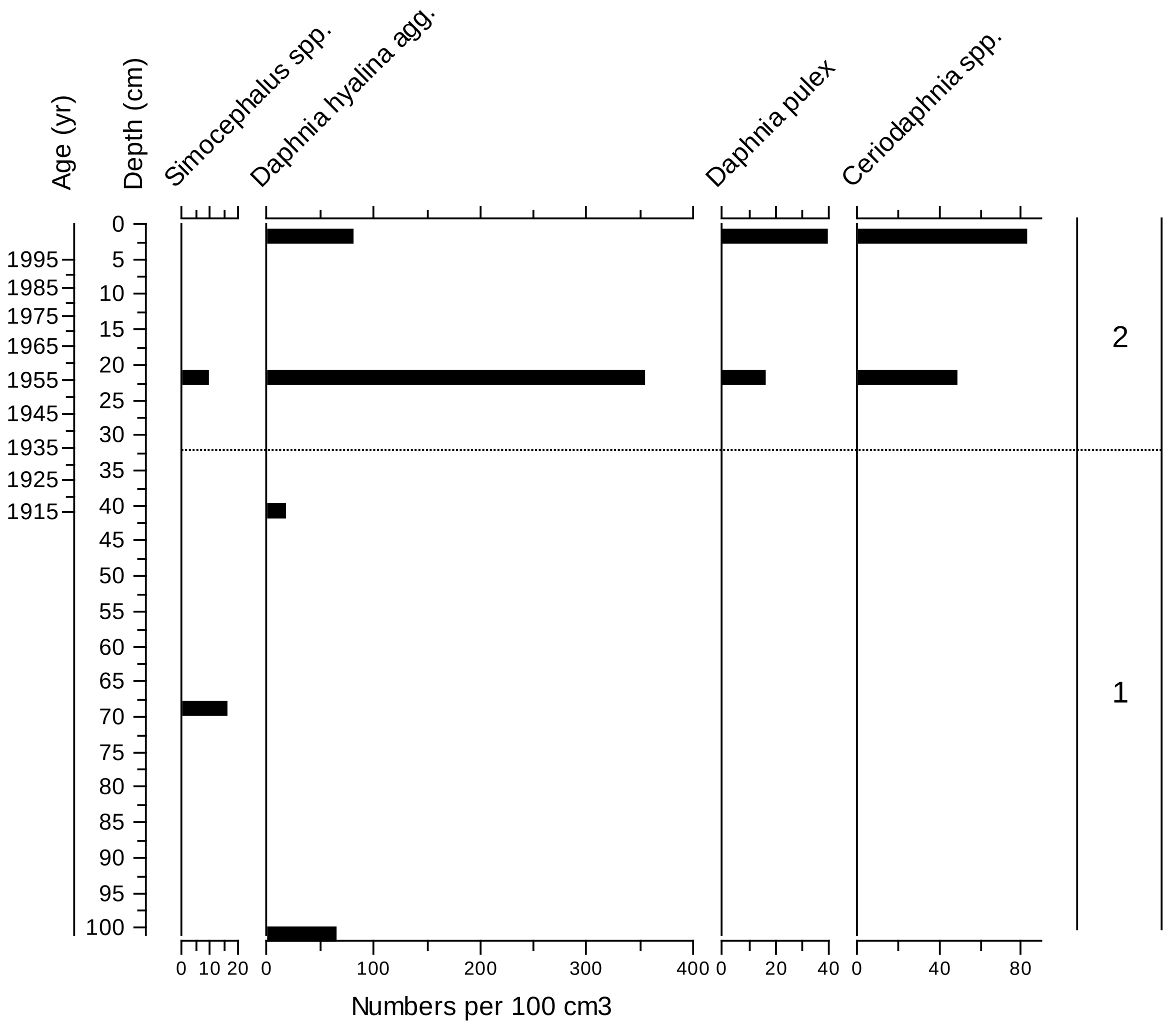


Figure 9 Summary zooplankton ephippia diagram for Over Water, core OVER1
(Note variable scaling on the x axis)



CUNSWICK TARN

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 description and stratigraphy is given in Bennion *et al*. (2008a). The SCP derived chronology is summarised in Table 6.

Table 6 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 10).

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. *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 11).

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 (Type 5A of Palmer *et al*., 1992). 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 (Bennion *et al*., 2008a). 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 one dominated by *Nymphaeaceae* and elodeids, most probably caused by eutrophication.

Figure 10 Summary plant macrofossil diagram for Cunswick Tarn, core
(Note variable scaling on the x axis)

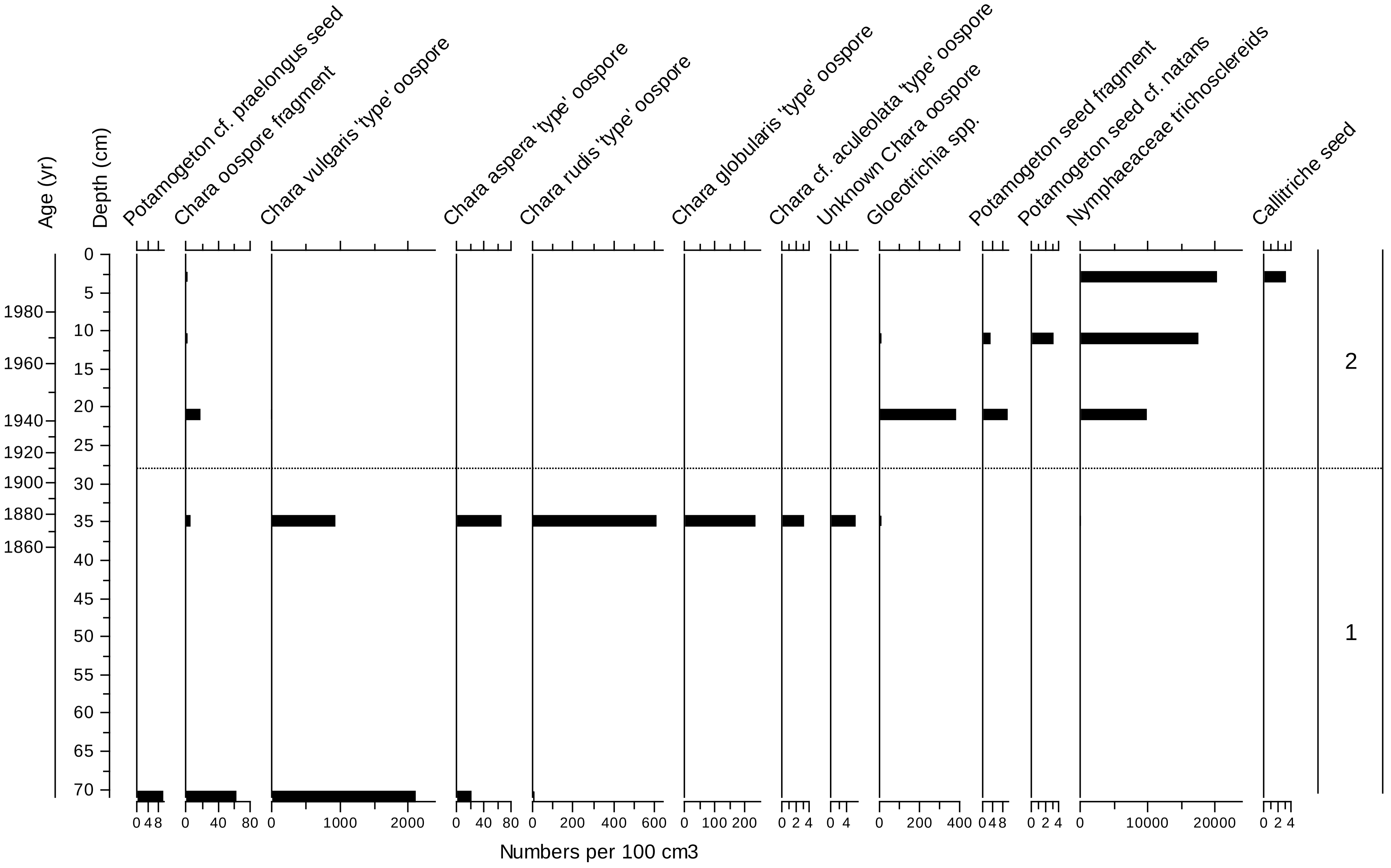
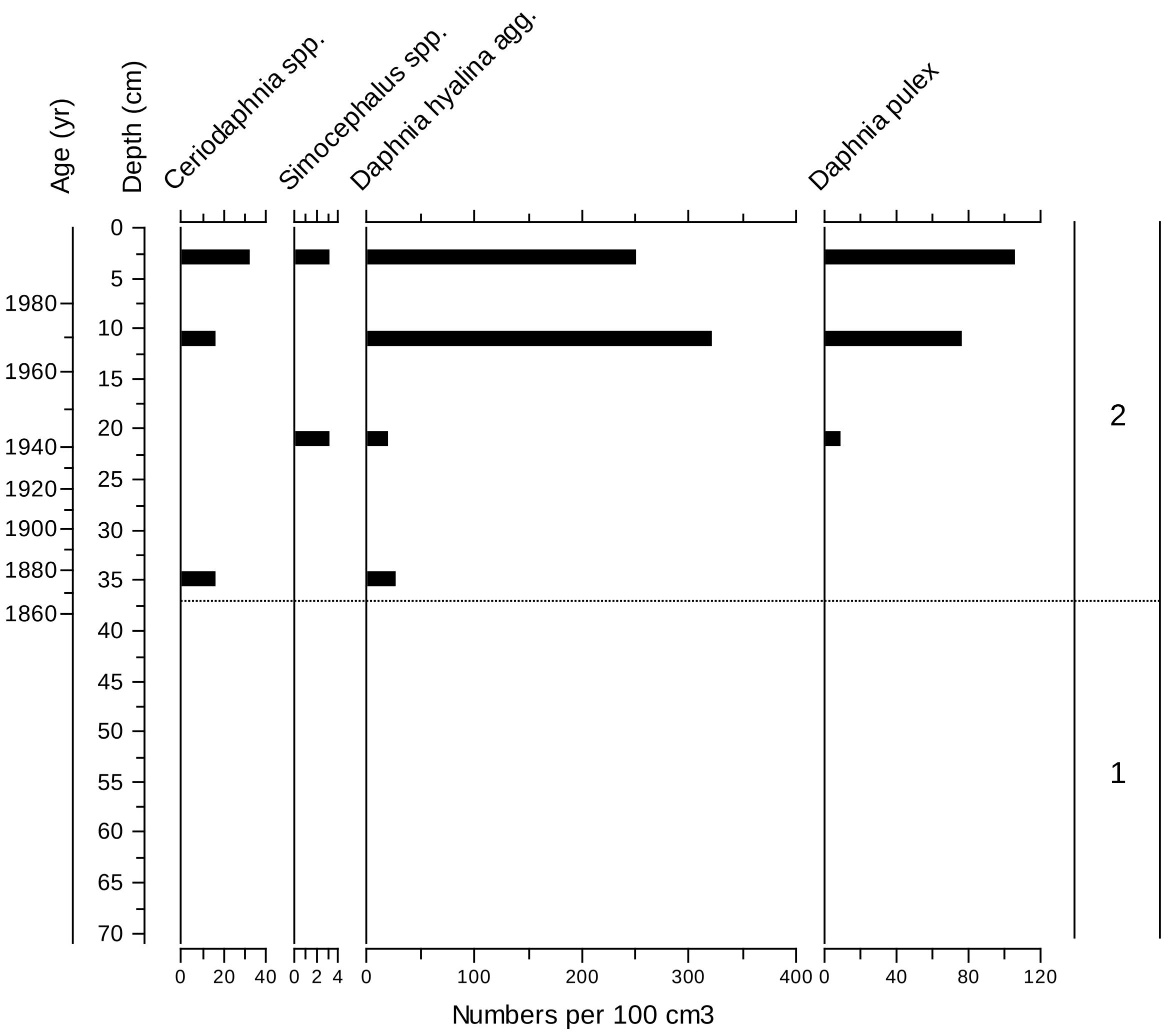


Figure 11 Summary zooplankton ephippia diagram for Cunswick Tarn, core CUNS1
(Note variable scaling on the x axis)



SUNBIGGIN TARN

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 description and stratigraphy is given in Bennion *et al*. (2008a).

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 7, Figure 12). 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. This rapid accumulation rate would also suggest that if it continued below the analysed section then SCPs should still be present at the base of the core at 134-135 cm. However, the additional analysis shows that 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 8.

Table 7 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 12 SCP profile for SUNB3

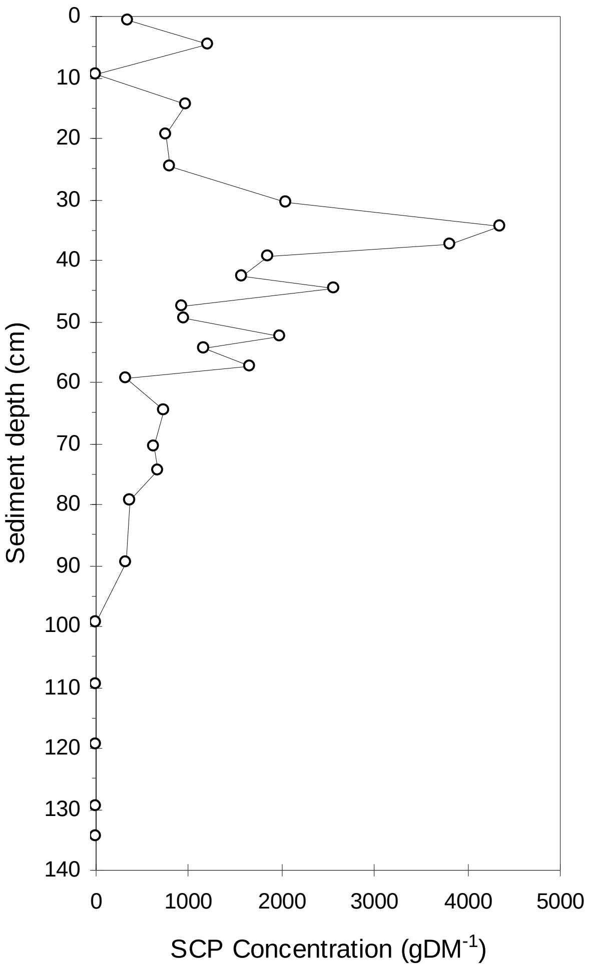


Table 8 The SCP derived chronology for SUNB3

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 13).

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 14).

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 perform badly in nutrient-rich 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 13 Summary plant macrofossil diagram for Sunbiggin Tarn, core SUNB3
(Note variable scaling on the x axis)

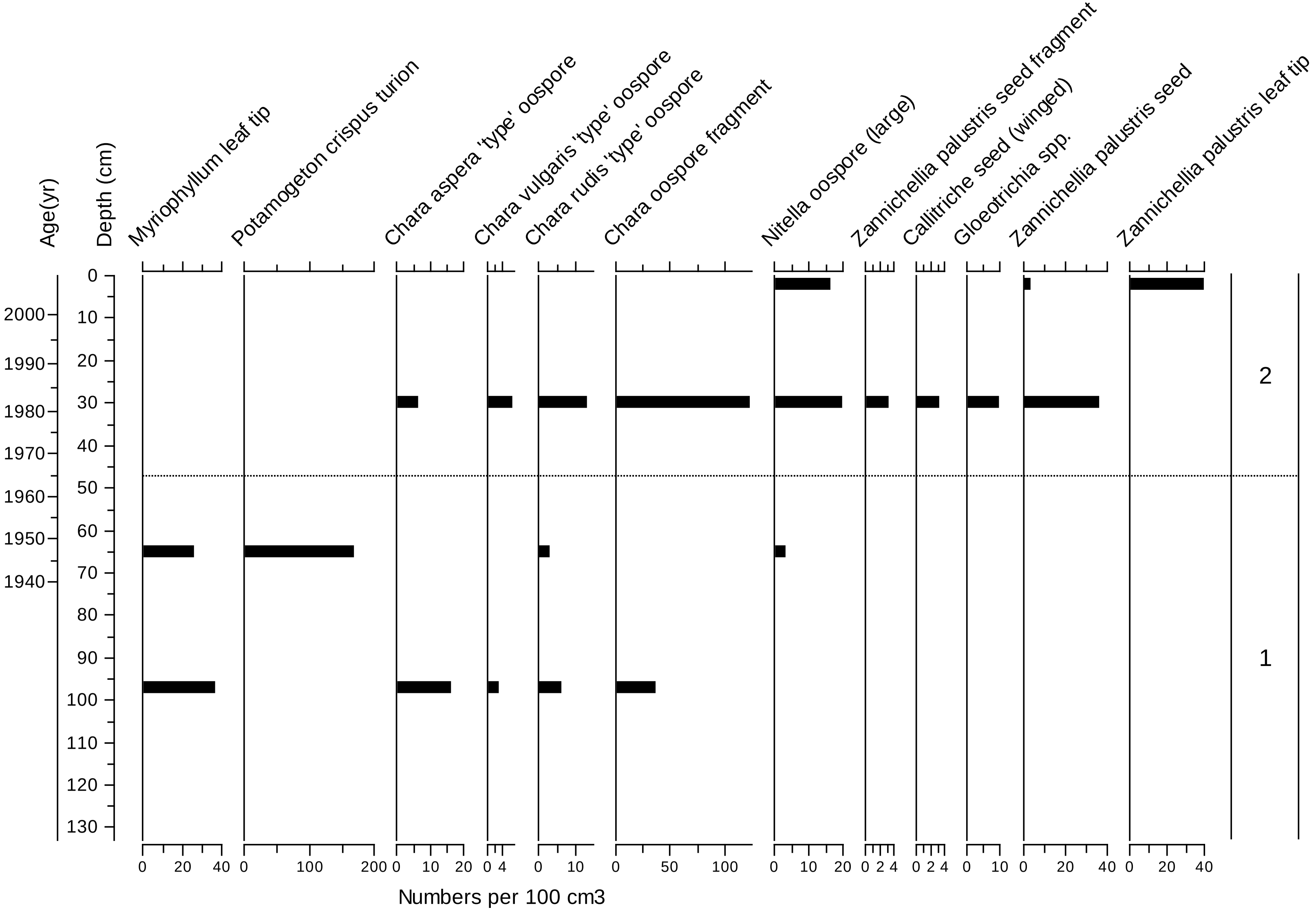
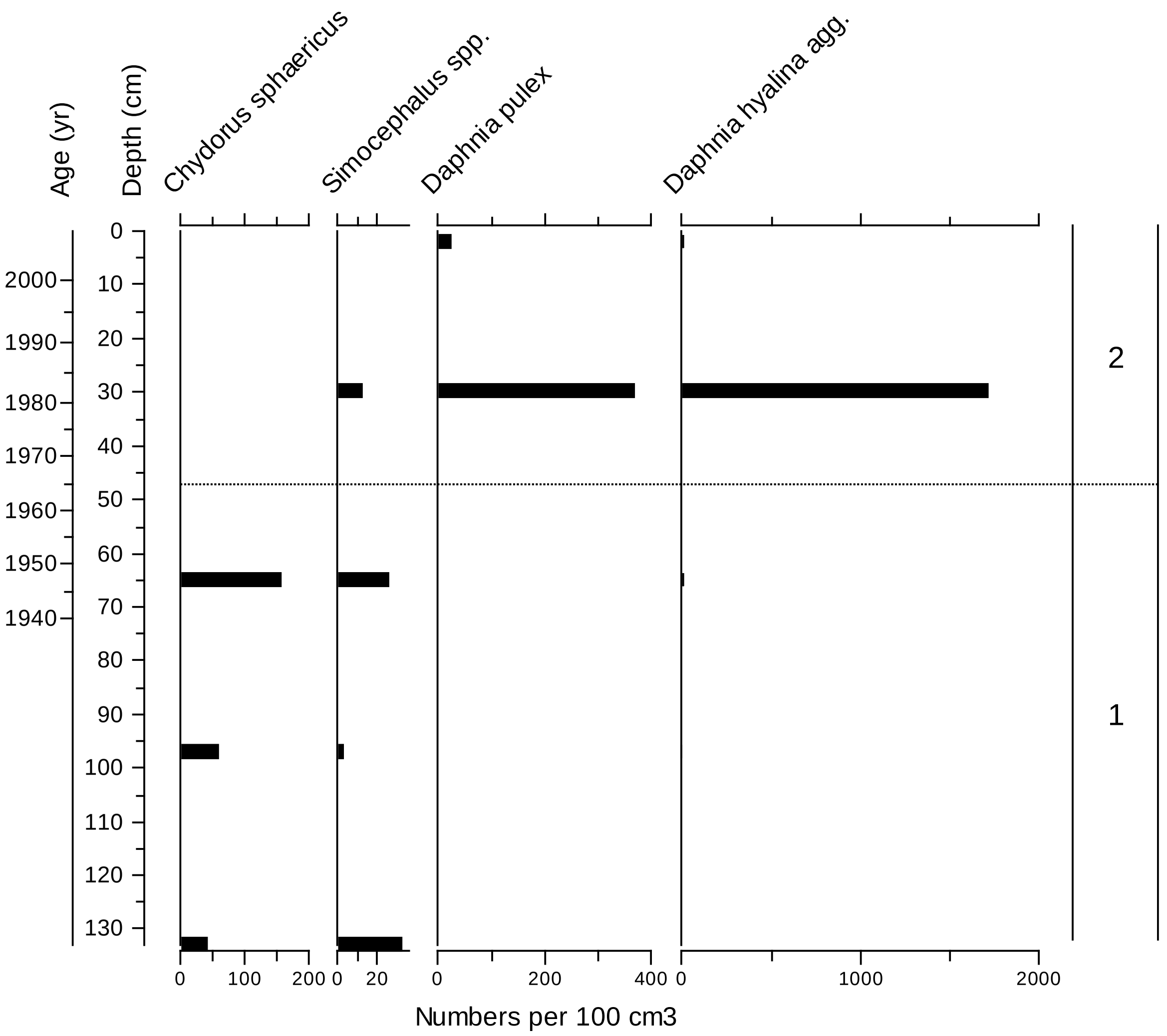


Figure 14 Summary zooplankton ephippia diagram for Sunbiggin Tarn, core SUNB3
(Note variable scaling on the x axis)



SUMMARY

The palaeoecological study has shown that all five study sites 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. However, given that only five samples were analysed, 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.

REFERENCES

Battarbee, R.W., Jones, V.J., Flower, R.J., Cameron, N.G., Bennion, H., Carvalho, L. & Juggins, S. (2001) Diatoms. In: *Tracking Environmental Change Using Lake Sediments. Volume 3: Terrestrial, Algal, and Siliceous Indicators* (eds J.P. Smol, H.J.B. Birks & W.M. Last), pp. 155-202. Kluwer Academic Publishers, Dordrecht, The Netherlands

Bennion, H., Juggins, S. & Anderson, N.J. (1996) Predicting epilimnetic phosphorus concentrations using an improved diatom-based transfer function and its application to lake eutrophication management. *Environmental Science and Technology*, 30, 2004-2007.

Bennion, H. (ed.) (2004). *Identification of reference lakes and evaluation of palaeoecological approaches to define reference conditions for UK (England, Wales, Scotland & Northern Ireland) ecotypes.* Final Report to SNIFFER, Project WFD08: 149 pp.

Bennion, H., Fluin, J. & Simpson, G.L. (2004) Assessing eutrophication and reference conditions for Scottish freshwater lochs using subfossil diatoms. *Journal of Applied Ecology,* 41,124-138.

Bennion, H., Clarke, G., Davidson, T., Rose, C., Rose, N., Turner , S. & Sayer, C. (2008a) *Using novel palaeolimnological techniques to define lake conservation objectives (Phase 1). Final Report to Natural England*. ECRC Research Report No.126

Bennion, H., Clarke, G., Davidson, T., Morley, D., Rose, N., Turner, S. & Yang, H (2008b) *Palaeoecological study of seven mesotrophic lochs*. Final Report to SEPA and SNH. ECRC Research Report No 121; 105 pp.

Birks, H.H. (2001) Plant Macrofossils. In: Smol J.P., Birks H.J.B., and Last W.M. (eds), *Tracking Environmental Change Using Lake Sediments.* Volume 3: Terrestrial, Algal, and Siliceous Indicators, pp. 49-74. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Breiman, L., Friedman, J.H., Olshen, R.A. & Stone, C.G. (1984) *Classification and regression trees.* Wadsworth International Group, Belmont, California, USA.

Darwell, A. (2004) Scout and Cunswick Scars SSSI; Site Condition Monitoring of the standing water interest at Cunswick Tarn. Report for English Nature.

Davidson, T., Sayer, C., Bennion, H.B., David, C., Rose, N. & Wade, M. (2005) A 250 year comparison of historical, macrofossil and pollen records of aquatic plants in a shallow lake. *Freshwater Biology,* 50, 1671-1686.

Davidson, T.A., Sayer, C.D., Perrow, M.R., Bramm, M. & Jeppesen, E. (2007) Are the controls of species composition similar for contemporary and sub-fossil cladoceran assemblages? A study of 39 shallow lakes of contrasting trophic status. *Journal of Paleolimnology,* 38,117-134.

Davidson, T.A., Sayer, C.D., Morley, D. & Stewart, N. (in prep) A model for species level identification of UK Characeans from their oospores.

Dean, W.E. (Jr.) (1974) Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss-on-ignition: comparison with other methods. *Journal of Sedimentary Petrology,* 44, 242-248.

English Nature (1994). Site of Special Scientific Interest (SSSI) notification sheet under section 28 of the Wildlife and Countryside Act 1981. File Ref. NY60/5 Sunbiggin Tarn and Little Asby Scar. English Nature.

Goldsmith, B.J., Luckes, S.J., Bennion, H., Carvalho, L., Hughes, M., Appleby. P.G. & Sayer, C.D. (2003). *Feasibility studies on the restoration needs of four lake SSSIs*. Final Report to English Nature Contract No EIT 30-05-005. ECRC Research Report No. 87: 109 pp.

Haycock, B. & C. Duigan (1994). Saving stoneworts at Bosherston. *Enact-managing land for wildlife,* 2, 21-23.

Heiri, O., Lotter, A.F. & Lemcke, G. (2001) Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. *Journal of Paleolimnology,* 25,101-110.

Hilton, J., Lishman, J.P. and Allen, P.V. (1986) The dominant processes of sediment distribution in a small, eutrophic, monomictic lake. *Limnology & Oceanogr*aphy, 31, 125-133.

Holdgate, M. W. (1955). The vegetation of some British upland fens. *Journal of Ecology,* 43, 389-403.

Hutchinson, S.M. (2004) Aqualate Mere (Staffordshire): an additional assessment of sediment properties and sediment mapping. Report to English Nature by Centre for Environmental Systems Research, University of Salford.

Hutchinson, S.M. (2005). The recent sedimentation history of Aqualate Mere (central England): assessing the potential for lake restoration. *Journal of Paleolimnology* 33, 205-228.

Hutchinson, S.M., Armitage, R.P & Rose N.L. (in prep) The recent environmental history and implications for lake restoration at Aqualate Mere, UK.

Johnes, P.J., Bennion H., Curtis C., Moss B., Whitehead P & Patrick S (1998). *Trial Classification of Lakes in England and Wales*. R&D *Project Record E2-i721\5*. Final Report to the Environment Agency by ENSIS Ltd. December 1998.

Juggins. S. (1991). ZONE version 1.2 User guide. University of Newcastle, Newcastle upon Tyne, UK.

Juggins. S. (2003). C^2 User guide. Software for ecological and palaeoecological data analysis and visualisation. University of Newcastle, Newcastle upon Tyne, UK. 69pp.

Krammer, K. & Lange-Bertalot, H. (1986-1991) Bacillariophyceae. 1-4 Teil. *Süsswasserflora von Mitteleuropa* (eds H. Ettl, J. Gerloff, H. Heynig & D. Mollenhauer). Gustav Fischer Verlag, Stuttgart.

Lowe, J.J. & Walker M.J.C. (1997). *Reconstructing Quaternary Environments* (2nd ed.). Prentice Hall, London.

Natural England (2006). Over Water Site of Special Scientific Interest. A report on the information held by Natural England about Over Water SSSI, in order to inform the AMP4 process. Natural England AMP4 Report.

Palmer, M. A., Bell, S. L. and Butterfield, I. (1992). A botanical classification of standing waters in Britain: applications for conservation and monitoring. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 2, 125-143.

Rose, N.L. (1994). A note on further refinements to a procedure for the extraction of carbonaceous fly-ash particles from sediments. *Journal of Paleolimnology,* 11, 201-204.

Rose, N.L. (2008). Quality control in the analysis of lake sediments for spheroidal carbonaceous particles. *Limnology and Oceanography: Methods*, 6, 172-179.

Rose, N.L., Harlock, S., Appleby, P.G. & Battarbee, R.W. (1995) The dating of recent lake sediments in the United Kingdom and Ireland using spheroidal carbonaceous particle concentration profiles. *Holocene,* 5, 328-335

Stewart, N. (2006) Common standards monitoring survey of the aquatic vegetation of Cunswick Tarn SSSI, Cumbria. Report for English Nature.

Stokoe, R. (1983). Aquatic macrophytes in the tarns and lakes of Cumbria. FBA Occasional Publication No 18. FBA

Thackeray, S.J. & Maberly, S.C. (2007) Investigation into water level requirements of interest features at Over Water SSSI: Phase 1. Final Report to Natural England by CEH.

Thackeray, S.J., Maberly, S.C. & Winfield, I.J. (2007). Investigation into water level requirements of interest features at Over Water SSSI: Phase 2. Final Report to the Environment Agency by CEH

Vadeboncoeur Y., Jeppesen E., Vander Zanden M.J., Schierup H.H., Christoffersen K. & Lodge D.M. (2003) From Greenland to Green Lakes: cultural eutrophication and the loss of benthic pathways in lakes. *Limnology and Oceanography*, 48, 1408-1418.

van den Berg, M. (1999). *Charophyte Colonization in Shallow Lakes*. PhD. Thesis, Vrije University, Amsterdam. RIZA report 99.015

van Nes, E. H., M. Scheffer, M. van den Berg & H. Coops (2002). Dominance of charophytes in eutrophic shallow lakes - when should we expect it to be an alternative stable state? *Aquatic Botany*, 72, 275-296.

Welsh, P. (1982). Sunbiggin Tarn plant survey - to accompany file ref. NY60/5. English Nature (NCC).

Zhao, Y., Sayer, C., Birks, H., Hughes, M. & Peglar, S. (2006) Spatial Representation of Aquatic Vegetation by Macrofossils and Pollen in a Small and Shallow Lake. *Journal of Paleolimnology,* 35, 335-350.