Using novel palaeolimnological techniques to define conservation objectives for Hatch Mere

Report for Cheshire Wildlife Trust

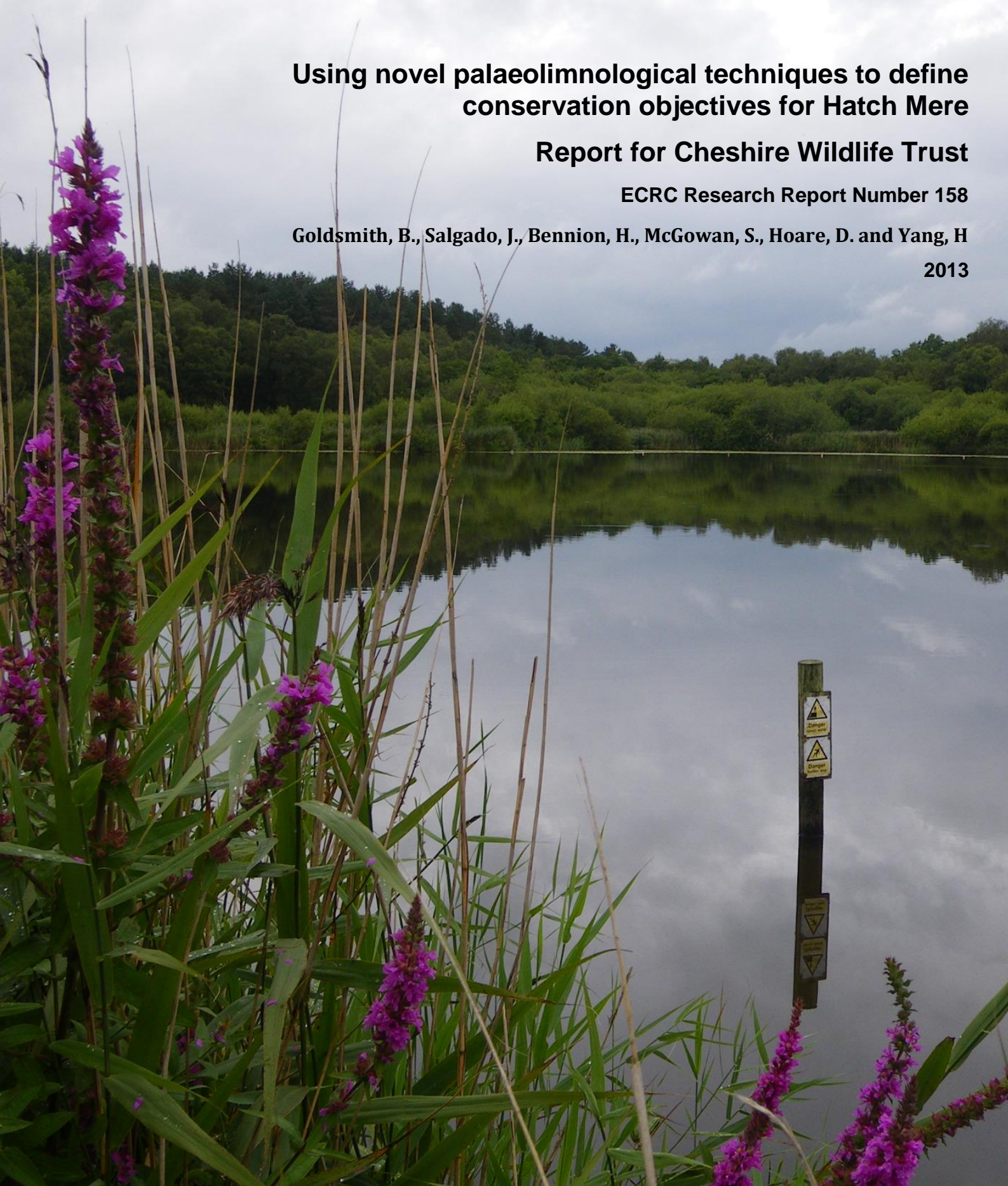Goldsmith, B., Salgado, J., Bennion, H., McGowan, S., Hoare, D. and Yang, H

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Acknowledgements

Summary

This is the final report to Natural England on the project 'Using novel palaeolimnological techniques to define lake conservation objectives for Hatch Mere'. The aim is to use existing and recently developed palaeoecological techniques to define reference conditions and assess the condition of Hatch Mere Special Scientific Interest (SSSIs) in the Cheshire meres, and thereby assist in the setting of conservation objectives and management goals.

Two sediment cores (one open water and one marginal), approximately 1 m in length, were collected from Hatch Mere in August 2011. The cores were sampled at 1 cm intervals throughout and approximately ten samples from each site were analysed for diatoms, Cladocera, macrofossils, geochemistry (XRF) and pigments. The cores were dated using radiometric techniques in order to place the fossil remains within a known time frame. An existing diatom-total phosphorus (TP) transfer function was applied to the diatom data to reconstruct the nutrient history of the mere.

The dating results suggest that the open water core (HAT3) extends back to ~1800 AD and the marginal core extends back beyond ~17o00 AD. The palaeoecological data indicate that the site has been a moderately enriched lake for the whole of the period represented by the cores with diatom-inferred TP concentrations of ~30 µg L^{-1} in the lower part of the record. However, there were marked changes across a range of indicators from the early 1800s indicative of enrichment, which has continued through the twentieth century. The key changes were the expansion of the eutrophic diatom species *Cyclostephanos dubius* and hence an increase in diatom-inferred TP to ~84 µg L^{-1}, a steady increase in pigment concentrations from all algal groups, and shifts in the zooplankton community indicative of increased pelagic productivity. Eutrophication has resulted in marked changes in the aquatic plant community from a structurally diverse flora with abundant Charophytes, nymphaeids and taxa with a mix of seasonalities to the current state with no submerged flora and only *Nuphar lutea.* The most notable changes in the macrofossil record have occurred from the mid-1800s and are, therefore, coincident with the main phase of enrichment. The dominance of the upper sediments by planktonic zooplankton and abundant *Daphnia* ephippia towards the top of the core, lends further weight to a plankton dominated system. This study provides information on the plant and animal communities that were present in the lake prior to the major eutrophication phase and this significantly alters the generic target previously set for the lake and will be valuable for setting targets for future management of the site.

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1 Introduction

Hatch Mere forms part of the West Midland meres, a group of waterbodies mostly of glacial and periglacial origin scattered across the counties of Shropshire, Cheshire and Staffordshire. The meres and the associated wetlands known as 'mosses' are recognised as an important nature conservation area and many are designated as SSSIs and included within the Midlands Meres and Mosses Ramsar site. The Meres have been described as Britain's naturally eutrophic lakes (e.g. Reynolds & Sinker, 1976), largely owing to the naturally high levels of phosphorus (P) in the drift derived soils, and the long history of blue-green algal blooms (McGowan *et al.*, 1999). Nitrogen is scarce relative to P, particularly in the deeper lakes (Moss *et al.*, 1994). There has been much debate over whether the meres are indeed naturally rich systems or whether in fact they have simply been impacted over long timescales (Anderson, 1995). Several long term palaeolimnological studies provide evidence of anthropogenically induced eutrophication dating back to at least Medieval times (see Anderson, 1995) whilst sediment studies focusing on the last few hundred years indicate a period of enhanced productivity associated with intensification of agriculture during the 20th century (e.g. Brooks *et al.,* 2001).

Hatch Mere lies within an area of acid heath and bog and is thought likely to have once had a mesotrophic flora. This is substantiated by early botanical accounts of *Potamogeton alpinus* and *P. gramineus* in the mere (Madgwick, 2009), the latter species still present in 1960 (Wiggington 1980). By 1979 however, the aquatic vegetation shows the site to have deteriorated significantly, having only a few submerged species and no pondweeds (Wiggington 1980). The most recent survey results available (Goldsmith, 2011) show the site to have lost all submerged species, with *Nuphar lutea* as the only common aquatic plant remaining. High nutrient concentrations and high algal biomass are likely to have contributed to this decline and the site is classified as unfavourable with respect to its flora.

Given the long history of impact in the region, historical records and palaeoecological studies provide the only means by which past conditions can be reconstructed. A palaeoecological study with the same aims as the current project has recently been completed on three Cheshire Meres: Melchett Mere, Tatton Mere and Comber Mere by ENSIS-ECRC and has demonstrated the value of palaeo-techniques for providing information on past plant and animal communities and for assessing the timing and degree of eutrophication (Bennion *et al.*, 2010).

The primary objective of this project is to use existing and recently developed palaeoecological techniques to define reference conditions and assess the condition of Hatch Mere, and thereby to assist in the setting of conservation objectives and management goals for the site. 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 and the Cheshire Wildlife Trust are currently engaged in defining and implementing the necessary management. The outputs of this project will be used to assist progress towards achieving the PSA target.

The specific objectives of the project are:

1. To reconstruct the historic plant communities and applicable NVC type at each site.

2. To reconstruct past nutrient loadings in particular phosphorus concentrations.

3. To suggest/discuss reasons for the current state of the mere and timing of change in conditions.

4. To suggest possible approaches to restoration.

2 Methods

2.1 Core collection

Two sediment cores (~1 m in length), one from the open water and one from the marginal zone, were collected from Hatch Mere 15-17 February 2010. The open water core (HAT3) was taken using an adapted 'fat' Livingstone piston corer (Livingstone1955) and the marginal core (HAT2) taken using a similar apparatus named the 'Big Ben", a piston corer developed in-house at the ECRC for obtaining higher volumes of sediment (Patmore *et al.* in press). 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 was 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.

The cores were extruded in the field at 1 cm intervals to provide a resolution approximating to 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) which gives a measure of the organic matter content and the percentage carbonate (CO_3) content were undertaken using standard techniques (Dean, 1974; Heiri *et al.,* 2001) on selected sub-samples from each core.

Selected samples from the open water core (HAT3) were sub-sampled for diatom and Cladocera analysis, and selected samples from the marginal core (HAT2) sub-sampled for macrofossil analysis. Previous studies have shown that abundance and diversity of macrofossils are greater in marginal cores than those taken from the deeper open water as heavy remains such as seeds do not travel far from their source plant (Davidson *et al.*, 2005; Zhao *et al.*, 2006). However, diatom and Cladocera analyses are typically carried out on open water cores from the deepest basin where the full range of habitats including planktonic and non-planktonic forms are well represented (e.g. Battarbee *et al.*, 2001). Additionally sub-samples from the open water core (HAT3) were frozen and delivered to University of Nottingham for pigment analyses. Finally, both cores were sub-sampled and freeze-dried for radiometric analyses, the method used here to date the cores.

2.2 Sediment dating

In order to place the findings from the sediment cores in context, it is necessary to date the sediments. Very small amounts of naturally occurring Lead-210, with a half-life of 22.3 years, can be measured and therefore provide an ideal measurement of time in sedimentary environments.

Its capacity to provide age information, especially with regards to sedimentation rate, in recent depositional environments provides an excellent tool for assessing recent natural and socio-geographic impacts in depositional systems. The optimal material for lead-210 is undisturbed sediments (e.g. low energy lake sediments) under-going a constant rate of deposition. Lead-210 is a naturally-produced radionuclide, derived from atmospheric fallout (termed unsupported ^{210}Pb). Cesium-137 (^{137}Cs, half-life is 30 years) and americium-241 ([241]Am, half life 432 years) are artificially produced radionuclides, introduced to the study area by atmospheric fallout from nuclear weapons testing and nuclear reactor accidents. They have been extensively used in the dating of recent sediments. Dried sediment samples from cores HAT2 and HAT3 were analysed for ^{210}Pb, [226]Ra, ^{137}Cs and [241]Am by direct gamma assay in the Environmental Radiometric Facility at University College London, using ORTEC HPGe GWL series well-type coaxial low background intrinsic germanium detector. Lead-210 was determined via its gamma emissions at 46.5 keV, and [226]Ra by the 295 keV and 352 keV gamma rays emitted by its daughter isotope [214]Pb following 3 weeks storage in sealed containers to allow radioactive equilibration. Cesium-137 and [241]Am were measured by their emissions at 662 keV and 59.5 keV (Appleby et al, 1986). The absolute efficiencies of the detector were determined using calibrated sources and sediment samples of

known activity. Corrections were made for the effect of self absorption of low energy gamma rays within the sample (Appleby *et al*, 1992).

Radiometric chronologies were calculated for both cores using the Constant Rate of Supply (CRS) dating models, the Constant Initial Concentration (CIC) methods being precluded due to irregular sedimentation rates (Appleby and Oldfield, 1978). The Caesium-137 deposition peak of 1963 was used to confirm and calibrate sediment accumulation rates for the upper parts of the cores.

2.3 Diatom analysis

Standard diatom analysis (Battarbee *et al.*, 2001) of ten samples from the open water core (HAT3) was carried out. 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 data were entered into Excel spreadsheets and are included as tables in Appendix 1. Diatom data are presented as a series of summary stratigraphic plots showing change in frequency of the major taxa through time, produced using C2 software (Juggins, 2003).

The technique of weighted averaging (WA) regression and calibration, has become a standard technique in palaeolimnology for reconstructing past environmental variables (e.g. ter Braak & van Dam, 1989). A predictive equation known as a transfer function is generated that enables the inference of a selected environmental variable from fossil diatom assemblages, based on the relationship between modern surface-sediment diatom assemblages and contemporary environmental data for a large training (or calibration) set of lakes. This approach has been successfully employed to quantitatively infer lake total phosphorus (TP) concentrations (e.g. Anderson *et al.*, 1993; Bennion, 1994; Bennion *et al.*, 1996), whereby modern diatom TP optima and tolerances are calculated for each taxon based on their distribution in the training set, and then past TP concentrations are derived from the weighted average of the optima of all diatoms present in a given fossil sample. More recently the technique has been improved by extension to a method called WA partial least squares (WA-PLS) (ter Braak & Juggins, 1993). This method overcomes some of the limitations of simple WA by using the residual correlation in the diatom data to improve the estimates of the taxa 'optima' or regression coefficients, as shown by Bennion *et al.* (1996). WA-PLS can, however, result in over-fitting and the various advantages and problems of the technique are fully discussed by Birks (1998).

An existing diatom- TP transfer function which includes data from 33 West Midlands Meres (Bennion *et al.*, 1996) was applied to the diatom data to reconstruct the nutrient history of the lake (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 WA-PLS one-component (WAPLS1) and two-component (WAPLS2) models, respectively. The reconstruction was implemented using C2 (Juggins, 2003). Currently there is no such model for reconstructing nitrogen (N) concentrations. Nevertheless the diatom-TP inferences can be used to infer changes in overall trophic status of the lakes.

2.4 Macrofossil analysis

Macrofossil analysis involves the study of sediment core samples for preserved the 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 perhaps 40x magnification (Lowe & Walker, 1997; Birks, 2001). Macrofossil analysis was performed on ten samples from the marginal core (HAT2), selected to cover the period of interest and to enable the pre-twentieth century conditions to be determined. A measured volume of sediment (~50-80 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 cm3 of wet sediment and are illustrated in a series of summary stratigraphic plots showing change in abundance of the major taxa through time, produced using C2 software (Juggins, 2003). The data were entered into Excel spreadsheets and are included as tables in Appendix 2. Where possible the findings are compared with historical plant survey data for the study sites.

2.5 Cladoceran analysis

Cladocera are free-swimming microscopic crustaceans (zooplankton) with chitinous exoskeletons which upon death are preserved well in lake sediments. When recorded in sediments, they can be used to infer changes in fish population density and shifts in habitat structure (i.e. macrophytes) (e.g. Jeppesen *et al.*, 1996, 2001; Davidson *et al.*, 2007). They are particularly valuable in the context of this project in that they can be used to infer changes in macrophyte density with enrichment (e.g. Davidson *et al.*, 2010). Given their intermediate and important position in the food-web the Cladocera data can complement the diatom and macrofossil records.

Cladocera analysis was carried out on ten samples from the open water core (HAT3). The selected sub-samples were prepared using an adaptation of the standard sub-fossil Cladocera preparation technique (Korhola & Rautio, 2001). This method is based on that currently employed by colleagues working on Danish lakes (Jeppesen *et al.*, 1996; Jeppesen, 1998). For each sample at least 5 cm^3 of sediment was heated in a deflocculating agent (10% potassium hydroxide, KOH) and sieved at 150 µm and 63 µm. The retents of the two sieves were then washed into separate pots and safranin stain was added to highlight the chitinous remains. A sub-sample (of known volume) was screened with a compound microscope and the chitinous remains of the Cladocera were identified with reference to Flössner (1972), Frey (1958, 1959) and Alonso (1996). Carapaces, head-shields and post-abdomens were recorded separately. All Cladocera data are expressed as percentage relative abundance. The data were entered into Excel spreadsheets and are included as tables in Appendix 3.

2.6 Pigment analysis

Pigments of photosynthetic organisms including chlorophylls (Chls), carotenoids, photoprotective compounds and their derivatives are common in the sediments of aquatic environments (McGowan, 2007). They are produced by algae, phototrophic bacteria and aquatic plants and may also be present in detritus from terrestrial or resuspended material and in some invertebrate animals. Soft-bodied, remains often decay in sediments and in such cases, biochemical fossils such as pigments may be the only signatures left behind. Pigments can be used to estimate past primary production in aquatic systems, and because many pigments show a degree of taxonomic specificity, they can provide information about past communities of algae or photosynthetic bacteria (e.g. McGowan *et al.*, 2005).

Pigment analysis was carried out on all samples from the open water cores in the pigment analytical facility at the University of Nottingham under the supervision of Dr S. McGowan. Pigments were quantitatively extracted in an acetone: methanol: water (80:15:5) mixture. The extracts were left overnight at -20 ºC, filtered with a PTFE 0.2 µm filter and dried down under nitrogen gas. A known quantity was re-dissolved into an injection solution of a 70:25:5 mixture of acetone, ion-pairing reagent (IPR; 0.75g of tetra butyl ammonium acetate and 7.7g of ammonium acetate in 100ml water) and methanol and injected into the HPLC unit. Pigment extracts were separated in an Agilent 1200 series separation module with quaternary pump. The mobile phase consisted of Solvent A (80:20 methanol: 0.5 M ammonium acetate), solvent B (9:1 acetonitrile: water) and solvent C (ethyl acetate) with the

stationary phase consisting of a Thermo Scientific ODS Hypersil column (205 x 4.6 mm; 5 µm particle size). Eluted pigments passed through a photo-diode array detector and UV-visible spectral characteristics were scanned at between 350-750 nm. Peak areas were calibrated to commercial standards (DHI, Denmark). Quantification was based on scanning peak areas at 435nm and calibrating to a set of commercial standards (DHI Denmark). Pigment concentrations are reported as molecular weights of pigments per unit weight (in sediments).

2.7 XRF analysis

X-ray fluorescence (XRF) is a useful tool for the determination of chemical composition in sediments. In particular, where eutrophication is suspected at a site XRF can provide an estimate of the phosphorus load in the sediment. The units are slightly complicated in that they are estimates of concentration in mg g^{-1} of sediment expressed as diphosphorus trioxide (P_2O_3). The method provides no information of the form of phosphorus and does not differentiate between absorbed, adsorbed or co-precipitation with carbonate. Thus, no information on bioavailability or mobility of P is provided, but it does provide an estimate of P loading over time and sediment content over-time. Furthermore the sediment concentrations cannot be related to pore water as the analysis takes place on dried sediments. Thus, the method provides no means of reconstructing values for phosphorus concentrations in the water column, but does provide an impression of the direction and magnitude of change in loading over time.

2.8 Data analysis

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

The degree of floristic change in the diatom assemblages and faunistic change in the Cladocera assemblages between the bottom sample and every other sample in the core was assessed using the squared chord distance (SCD) dissimilarity coefficient (Overpeck *et al.*, 1985) implemented in C2 (Juggins, 2003). This is preferred to other dissimilarity measures as it maximises the signal to noise ratio, it performs well with percentage data and has sound mathematical properties (Overpeck *et al.*, 1985). The scores range from 0 to 2 whereby 0 indicates that two samples are exactly the same and 2 that they are completely different. Scores less than 0.29, 0.39, 0.48 and 0.58 indicate insignificant change at the 1st, 2.5th, 5th and 10th percentile, respectively (Simpson, 2005; Simpson *et al.*, 2005). It is advised that the 2.5th percentile (score <0.39) is used here to define sites with low change between the bottom and every other sample. The SCD scores were not calculated for the macrofossil assemblages owing to the difficulty of applying this technique to abundance data, especially where the amount of the identifiable remains varies between plant taxa.

Indirect ordination techniques (principal components analysis – PCA) (ter Braak & Prentice, 1988) were used to analyse the variance downcore within the diatom and Cladocera assemblages using C2 (Juggins, 2003). The technique summarises the main changes in the data and helps to identify zones of change within complex species-rich data sets. The sample scores for PCA axis 1 are given. Where scores between two neighbouring samples in the core differ markedly this indicates that the assemblages have undergone substantial change between these two points in the core. The scores are also plotted in the stratigraphic diagrams to illustrate the timing of any shifts and whether these were gradual or abrupt. The PCA scores were not calculated for the macrofossil assemblages owing to the difficulty of applying this technique to abundance data (see above).

3 Results

3.1 Core descriptions

Two cores were collected from Hatch Mere on 4 August 2011. One large diameter (140 mm) "Big Ben" core from 2 m water depth, near to the north-east margin (HAT2) and a smaller diameter (74 mm) 'fat Livingstone" core (HAT3) from the deepest recorded point of 3.3 m water depth (Table 3.1).

Table 3.1 Summary details for the Hatch Mere sediment cores taken 4th August 2011

| Core Code	Core type	Location (OS Landranger)	Water depth (m)	Core length (cm)
HAT2	Big Ben	SJ5529372257	2.0	105
HAT3	Fat Livingstone	SJ5531072185	3.3	100

3.1.1 Core HAT2

The core had two visible horizons (Figure 3.1). The upper 30 cm of the core was dark brown in colour and comprised of relatively fine material. The section below 30 cm was lighter brown in colour and had many more larger organic remains, mainly reed stems and roots.

The different nature of the core section below 30 cm from that above this depth was also reflected in the stratigraphic data (Figure 3.1). The % dry weight values were slightly higher above 30 cm, but only reaching a maximum of 20% and falling to approximately 10% below 30 cm, indicating slightly denser material in the upper part of the core. Organic content (expressed as % loss on ignition) was lower in the upper 20 cm with a sharp rise seen after 21 cm from ~35-40% to >60% at 30 cm. Below 30 cm there was a gradual decline in %LOI from ~65% to ~46% at 67 cm after which is increased gradually to the base of the core where it was again in the region of 65%. Carbonate was low throughout the core.

3.1.2 Core HAT3

There was less visible change observed in core HAT3, taken from the deeper open water area (Figure 3.2). A slight colour change was seen from dark brown to slightly lighter brown at approximately 50 cm. The sediments were noticeably more consolidated and appeared to have finer grain structure towards the base of the core.

The dry weight increased gradually from ~5% at the sediment surface, to ~20% at the base of the core. A similarly gradual decrease was seen in organic content, which fell from ~45% at the top of the core to ~27% at the base (Figure 3.2). A single high value for %LOI was recoded at 95-96 cm with a corresponding low %DW value. This may represent an organic rich layer in the core, but is though more likely to be an error in the data.

Figure 3.1 Sediment core stratigraphy of HAT2
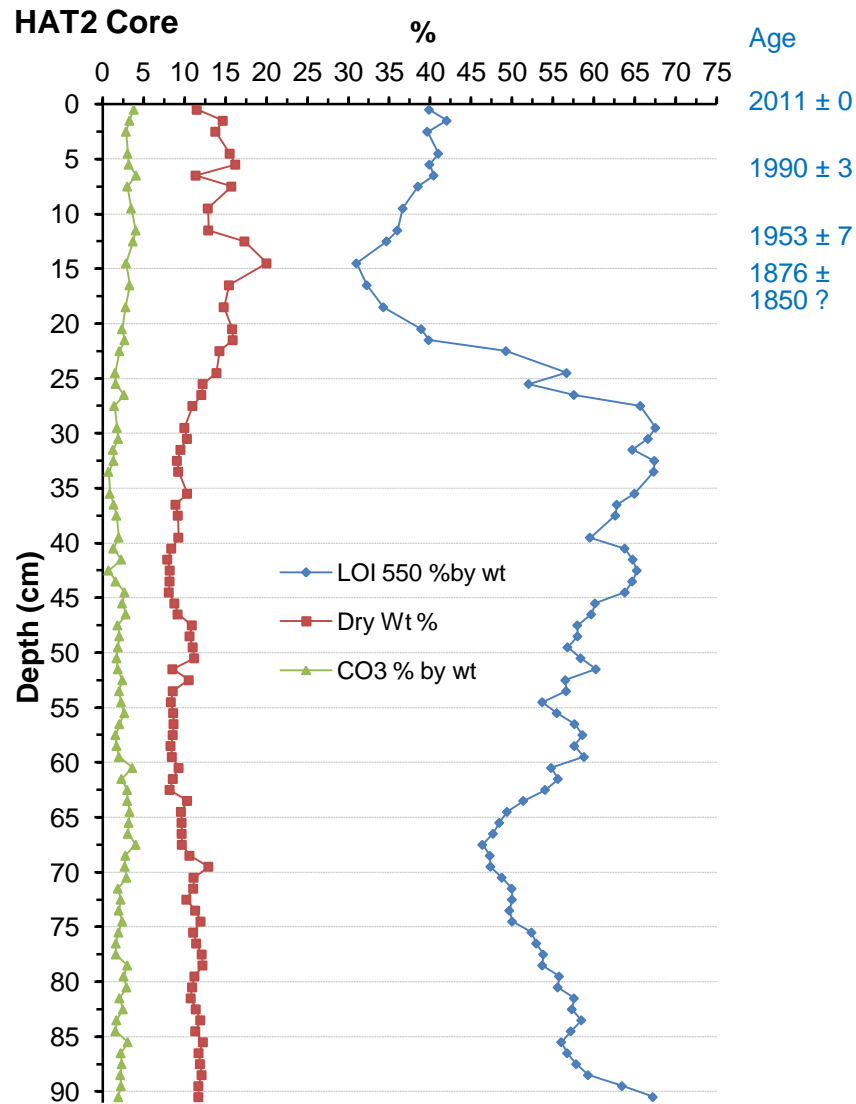
Depth (cm)	Sediment colour
0-30	Dark brown
	1850 extrapolated from younger dates
30 -100	Slightly lighter brown.
	Many organic remains
Base of core not analysed	

Figure 3.2 Sediment core stratigraphy of HAT3
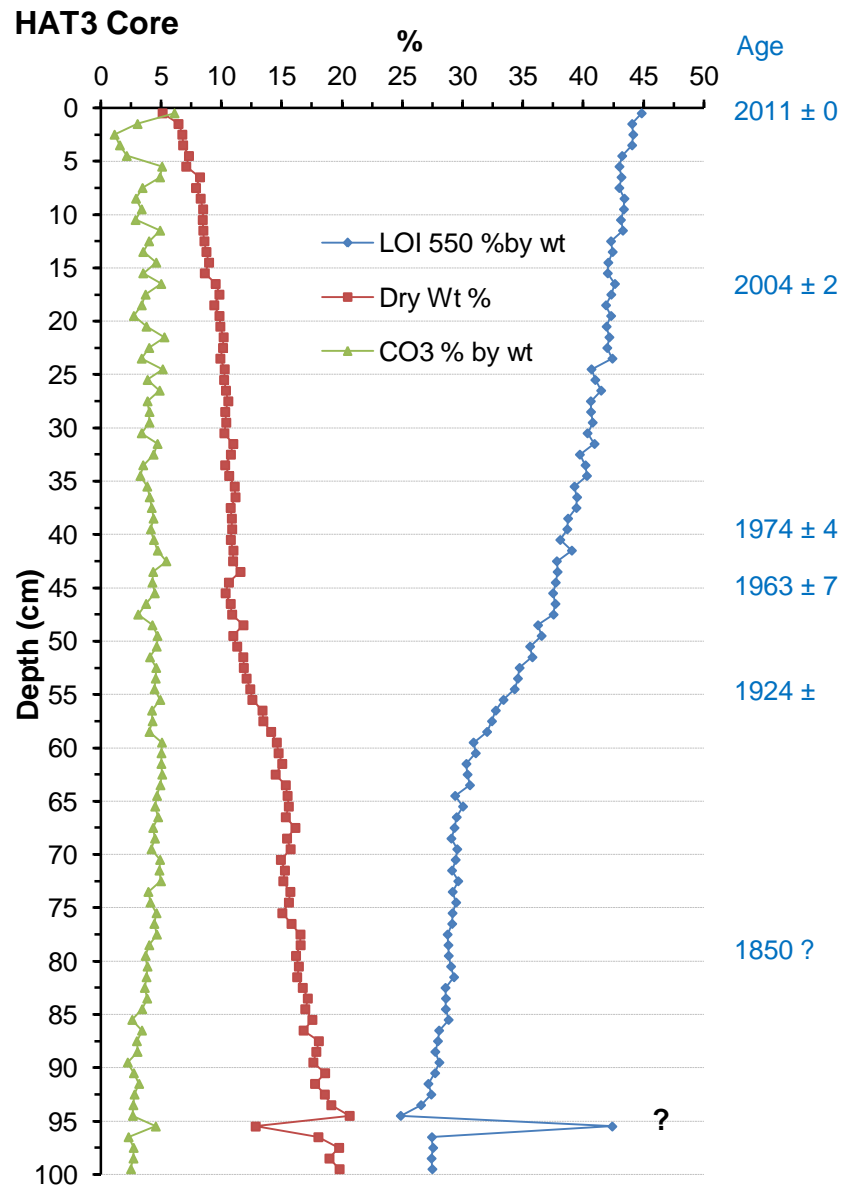
Depth (cm)	Sediment Colour / notes
0-50	Dark brown
50 -100	Slightly lighter brown. 1850 extrapolated from younger dates. ? - Possible error

3.2 Sediment dating

3.2.1 HAT2

Equilibrium depth of total lead 210 (^{210}Pb) activity with the supporting ^{210}Pb is at approximately 17 cm level of the core. Unsupported ^{210}Pb activity, calculated by subtracting supporting ^{210}Pb activity from total ^{210}Pb activity, decline irregularly with depth (Figure 3.4b. There is small decline in the top 11 cm, indicating an increase trends in sediment accumulation in recent years. Below 11 cm, unsupported ^{210}Pb activities decline more or less exponentially with depth, suggesting a relatively stable sedimentation period.

With respect to other radionucleotides, the caesium 137 (^{137}Cs) profile (Figure 3.4c) shows a relatively well-resolved peak at 11.5 cm, which can be attributed with high confidence to be derived from the 1963 fallout maximum from atmospheric testing of nuclear weapons. A trace of ^{241}Am was also detected at this depth.

^{210}Pb dates were calculated using the constant rate of supply (CRS) model (Appleby, 2001), which attributes 11.5 cm to 1962 and is in good agreement with the ^{137}Cs record. The CRS model chronologies and sediment accumulations calculated using ^{210}Pb data in the core are shown in Figure 3.3 and Table 3.2. Sedimentation rates calculated from the ^{210}Pb dates suggest sedimentation rates to have been slowly increasing since about 1930 (<1 mm per year) with a more dramatic increase after 1970 to a current rate of approximately 3.3 mm per year. It should be noted here that this core was taken from a marginal area of the mere and that sedimentation is generally higher in the deeper, open-water areas (see HAT3 below).
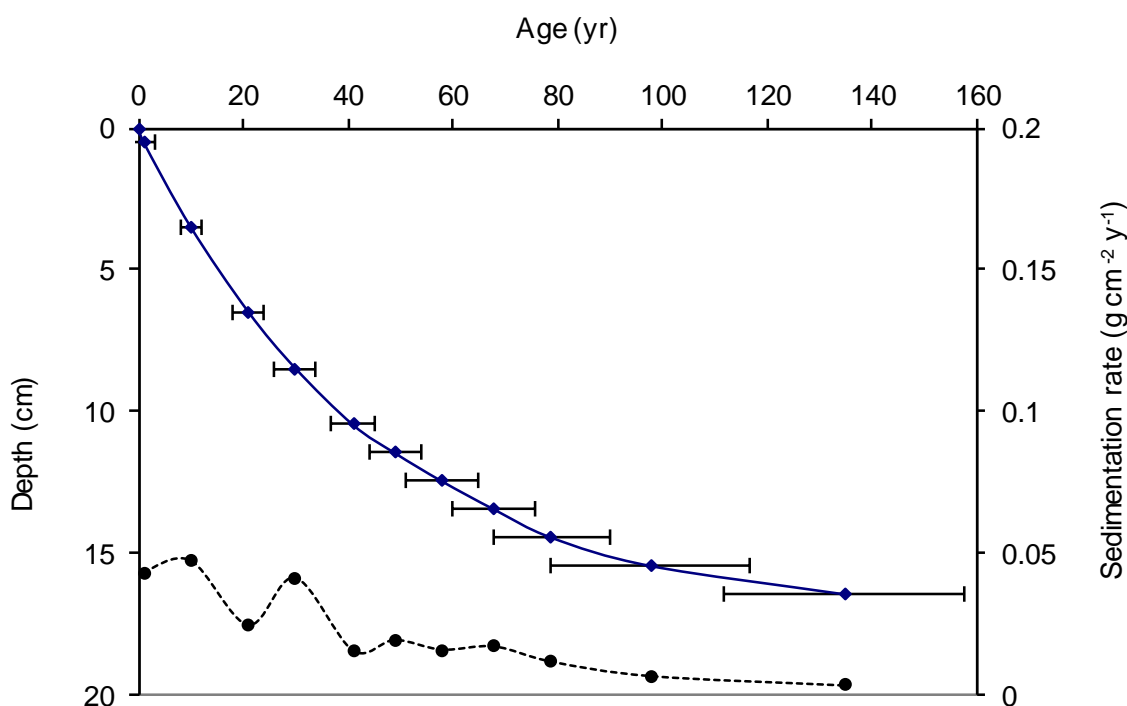

Figure 3.3 Radiometric chronology of HAT2, showing the CRS model ^{210}Pb dates and sedimentation rates. The solid line shows age while, the dashed line indicates sedimentation rate.

Table 3.2 Summary details for radiometric dating of core HAT2

Depth (cm)	Dry Mass (g cm^{-2})	Chronology			Sedimentation rate		
		Date	Age	±	g cm^{-2} yr^{-1}	cm yr^{-1}	± %
0	0	2011	0				
0.5	0.0270	2010	1	2	0.0428	0.339	16.9
3.5	0.4560	2001	10	2	0.0470	0.373	27.2
6.5	0.9052	1990	21	3	0.0242	0.188	20.5
80.5	1.3867	1981	30	4	0.0409	0.306	48.9
10.5	2.4742	1970	41	4	0.0152	0.113	26.2
11.5	3.0550	1962	49	5	0.0189	0.129	27.4
12.5	3.6513	1953	58	7	0.0155	0.098	30.1
13.5	4.2475	1943	68	8	0.0166	0.105	40.8
14.5	4.8680	1932	79	11	0.0112	0.071	46.2
15.5	5.4885	1913	98	19	0.0061	0.038	65.1
16.5	6.2263	1876	135	23	0.0028	0.017	76.2

Figure 3.4 Fallout radionuclide concentrations in core HAT2, showing (a) total ^{210}Pb, (b) unsupported ^{210}Pb, and (c) ^{137}Cs and ^{241}Am concentrations versus depth.

3.2.2 HAT3

In this core, total ^{210}Pb activity reaches equilibrium depth with the supporting ^{210}Pb at approximately 65 cm. There is little net decline in unsupported ^{210}Pb activities in the top 42 cm, with maximum value at 26.5 cm, indicating an increase in sedimentation rates. Below 42 cm, as in HAT2, there is a section in which unsupported ^{210}Pb activities decline more or less exponentially with depth, also suggesting a relatively stable sedimentation period.

The ^{137}Cs activity versus depth profile (Figure 3c) is similar with HAT2, showing a fairly well-resolved peak at 46.5 cm, derived from the 1963 fallout maximum from the atmospheric testing of nuclear weapons. [241]Am was detected just above this sample.

Using the simple CRS dating model, 1963 occurs at a depth above 41.5 cm, which does not agree with the ^{137}Cs record. The final chronologies and sediment accumulations were therefore calculated using the CRS model with reference to the 1963 depth suggested by the ^{137}Cs record. Similar with HAT2, in this core there is also a relatively stable period in sediment accumulation up to the 1970s, followed by an increase trend to the present day. As expected from an open-water core, the sedimentation rates are much higher in HAT3 than in HAT2 with the current rate being in the region of 20 mm per year. The present-day accumulation rate is significantly higher than values obtained pre-1970 which were in the region of 2-4 mm per year.
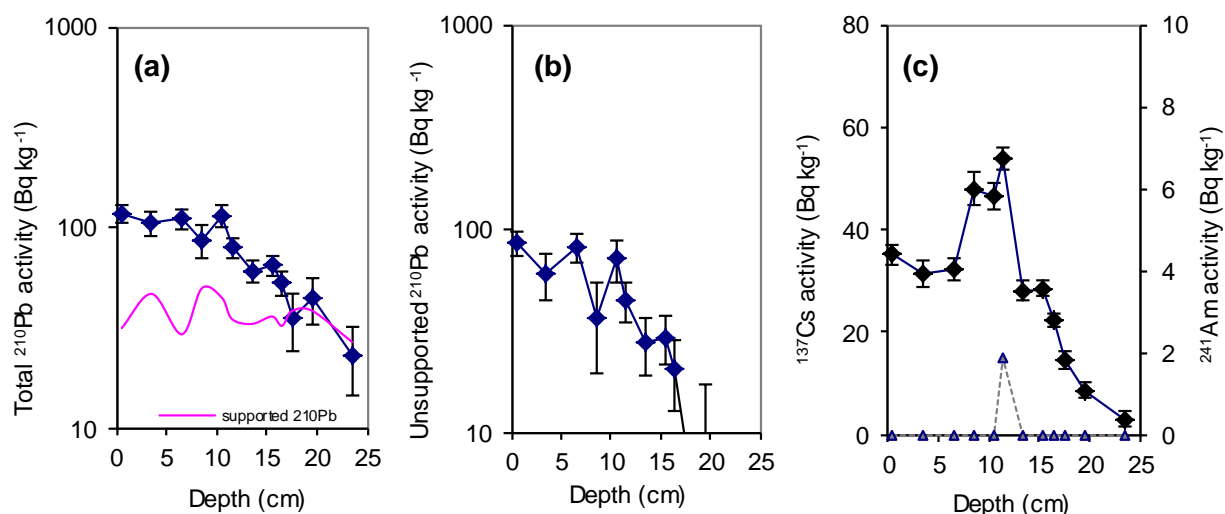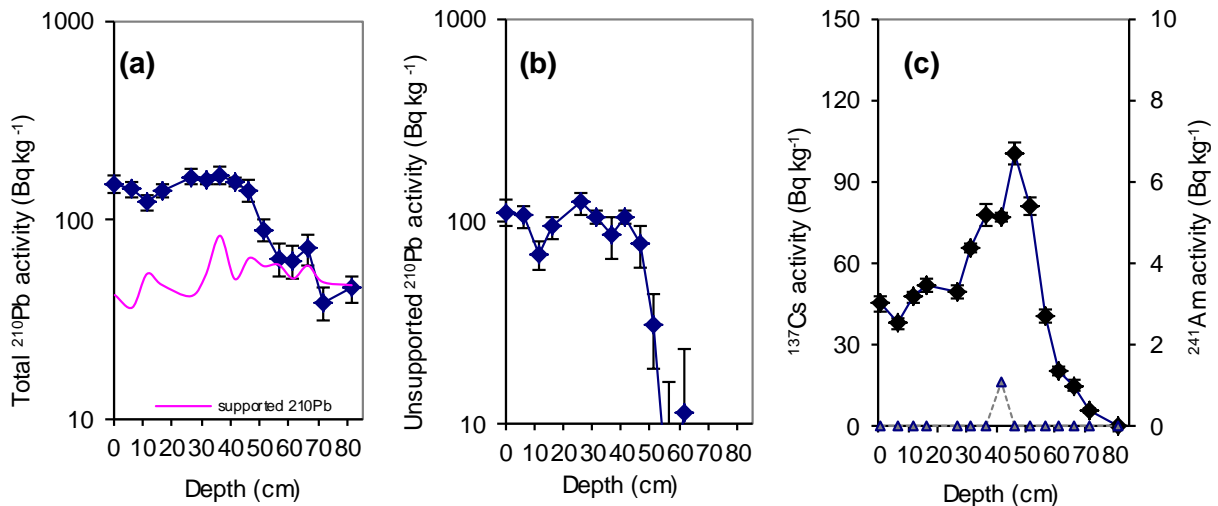

Figure 3.5 Fallout radionuclide concentrations in core HAT3, showing (a) total ^{210}Pb, (b) unsupported ^{210}Pb, and (c) ^{137}Cs and [241]Am concentrations versus depth.
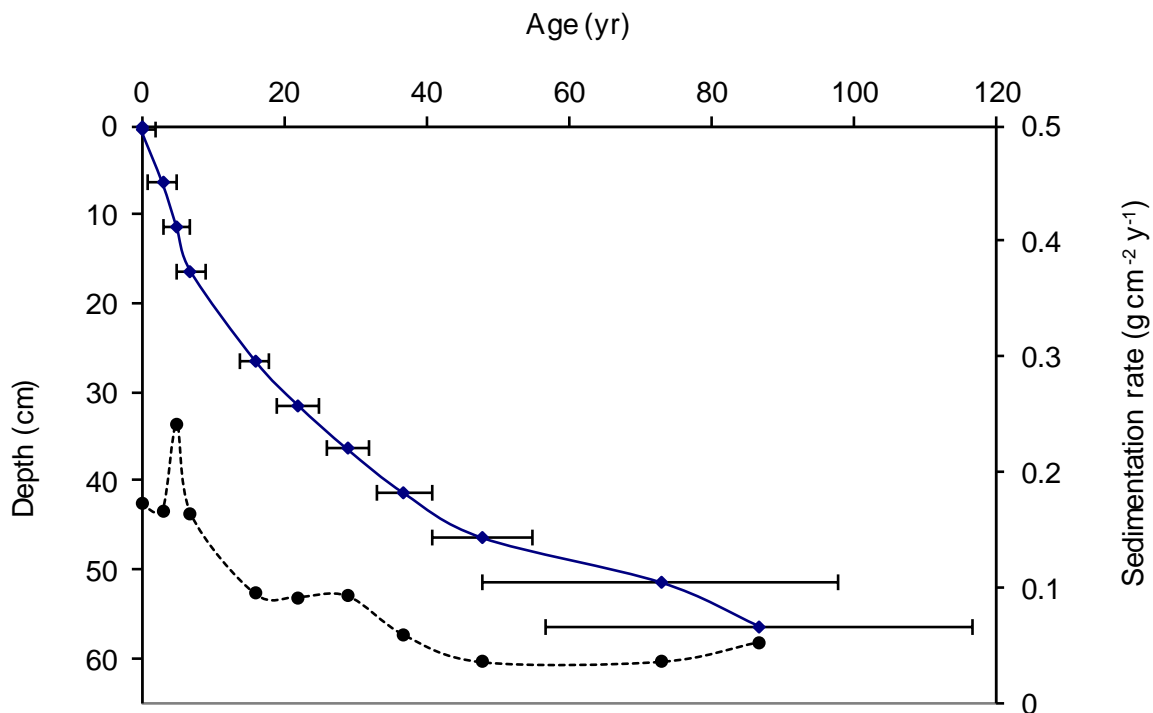

Figure 3.6 Radiometric chronology of HAT3, (CRS model) 210Pb dates and sedimentation rates. The solid line shows age while, the dashed line indicates sedimentation rate.

Table 3.3 Summary details for radiometric dating of core HAT3

Depth (cm)	Dry Mass (g cm⁻²)	Chronology			Sedimentation rate		
		Date	Age	±	g cm⁻² yr⁻¹	cm yr⁻¹	± %
0	0	2011	0				
0.5	0.0270	2011	0	2	0.1727	2.461	15.9
6.5	0.4560	2008	3	2	0.1666	2.087	14.0
11.5	0.9052	2006	5	2	0.2408	2.588	16.9
16.5	1.3867	2004	7	2	0.1631	1.559	14.6
26.5	2.4742	1995	16	2	0.0940	0.845	15.8
31.5	3.0550	1989	22	3	0.0912	0.775	13.4
36.5	3.6513	1982	29	3	0.0920	0.772	26.4
41.5	4.2475	1974	37	4	0.0579	0.476	19.0
46.5	4.8680	1963	48	7	0.0345	0.278	32.7
51.5	5.4885	1938	73	25	0.0348	0.256	66.8
56.5	6.2263	1924	87	30	0.0521	0.353	83.7

3.3 Diatom analysis

Ten samples were analysed for diatoms in the HAT3 core (Table 3.4). Preservation of the diatom valves was good throughout the core making samples satisfactory for counting. A total of 103 diatom taxa were recorded in the core with between 34-65 taxa per sample. The majority of taxa were rare in the samples with only 25 occurring at greater than 2% relative abundance in any one sample and 13 occurring above 5 %. The results for the more abundant taxa are shown in Figure 3.7, and a full species list in Appendix 1.

There were marked changes in the assemblages during the period represented by the core and these can be best described in three main zones: Zone 1 from the core base to ~75 cm (~pre-1850 based on extrapolated dates), Zone 2 from ~75 cm to 45 cm (~1850 to 1970) and Zone 3 from ~45 cm to the core top (post ~1970 to present).

Zone 1 (100 – 75 cm, pre-1850 AD) lies below the reliable radiometric dating, but based on mean accumulation rates from the 46-57 cm samples (~3 mm per year), AD 1850 lies at approximately 75 cm in the core and thus this zone is thought likely to pre-date AD 1850. The planktonic taxa *Discostella pseudostelligera* and *Cyclotella* aff. *comensis* are most abundant in this zone along with *Achnanthidium minutissimum* and small benthic species such as *Fragilaria virescens* var. *exigua* and *Staurosira construens* var. *venter*, most typically found growing on plants and the submerged stems of reeds. Towards the top of this zone, there is a slight decline in *D. pseudostelligera* and *C.* aff. *comensis,* coupled with the increase in *Cyclotella radiosa, Aulacoseira subarctica* and *A. ambigua* (Table 3.4). These assemblages are typical of moderately enriched waters, but the presence of a high proportion of non-planktonic taxa suggest water clarity was relatively good and; i.e. allowing light to reach the benthic habitats of the mere.

In Zone 2 (43 – 75 cm, c.1850 – 1970 AD), *D. pseudostelligera* and *C.* aff. *comensis* almost disappear and are replaced by other planktonic taxa, *Cyclotella radiosa, Aulacoseira subarctica* and *A. ambigua* as well as *Asterionella formosa, Cyclostephanos dubious* and *Stephanodiscus parvus,* the latter species dominating the assemblage at the 45 cm level. Benthic taxa remain present, but decline as a proportion of the total assemblage towards the top of Zone 2. The planktonic taxa in this zone are typical of more productive conditions and the top of this zone appears to mark the period when planktonic species become dominant in the site.

Zone 3 (0 – 43 cm, post-1970 AD) is dominated by planktonic species, with *Cyclostephanos dubious* and *Aulacoseira* species accounting for approximately 50% of the total assemblage. The proportion of benthic taxa is relatively low and dominated by '*Fragilaria*' type taxa which are often found growing on submerged reed stems.

The diatom inferred total phosphorus (DI-TP) reconstruction suggests that TP concentrations were slightly elevated, although stable, prior to c. 1850 AD. The two most reliable DI-TP models place the 95 cm TP at ~23-30 µg L^{-1}. The DI-TP then doubles between 65 and 55cm (Table 3.4) after which there is a more gentle, but nonetheless steady increase to the present day reaching a maximum of ~84-101 µg L^{-1} in the surface sample. The measured mean TP between 2006 – 2008 was 72 µg L^{-1} (Goldsmith 2011) and, therefore, corresponds reasonably very well with the modelled values, the two component WAPLS model being more effective at inferring current conditions.

The diatom record indicates Hatch Mere to have already been relatively nutrient-rich, but stable prior to ~1850. After this time species shifts start to occur with an increase in plankton and then what appears to have been a phase of relatively rapid enrichment around the turn of the 19th Century. The changes in the diatom assemblages through the core are recorded by the PCA axis 1 scores which show a marked down-core increase between 55 – 56 cm. This represents a significant turnover in the species present. The diatom record of Hath Mere indicates the site to have been eutrophic for at least the last ~200 years, but since ~1900 the trophic status has increased steadily, with a shift towards the dominance of planktonic diatoms and hence much more turbid conditions.

Table 3.4 Summary details for the HAT3 diatom analysis

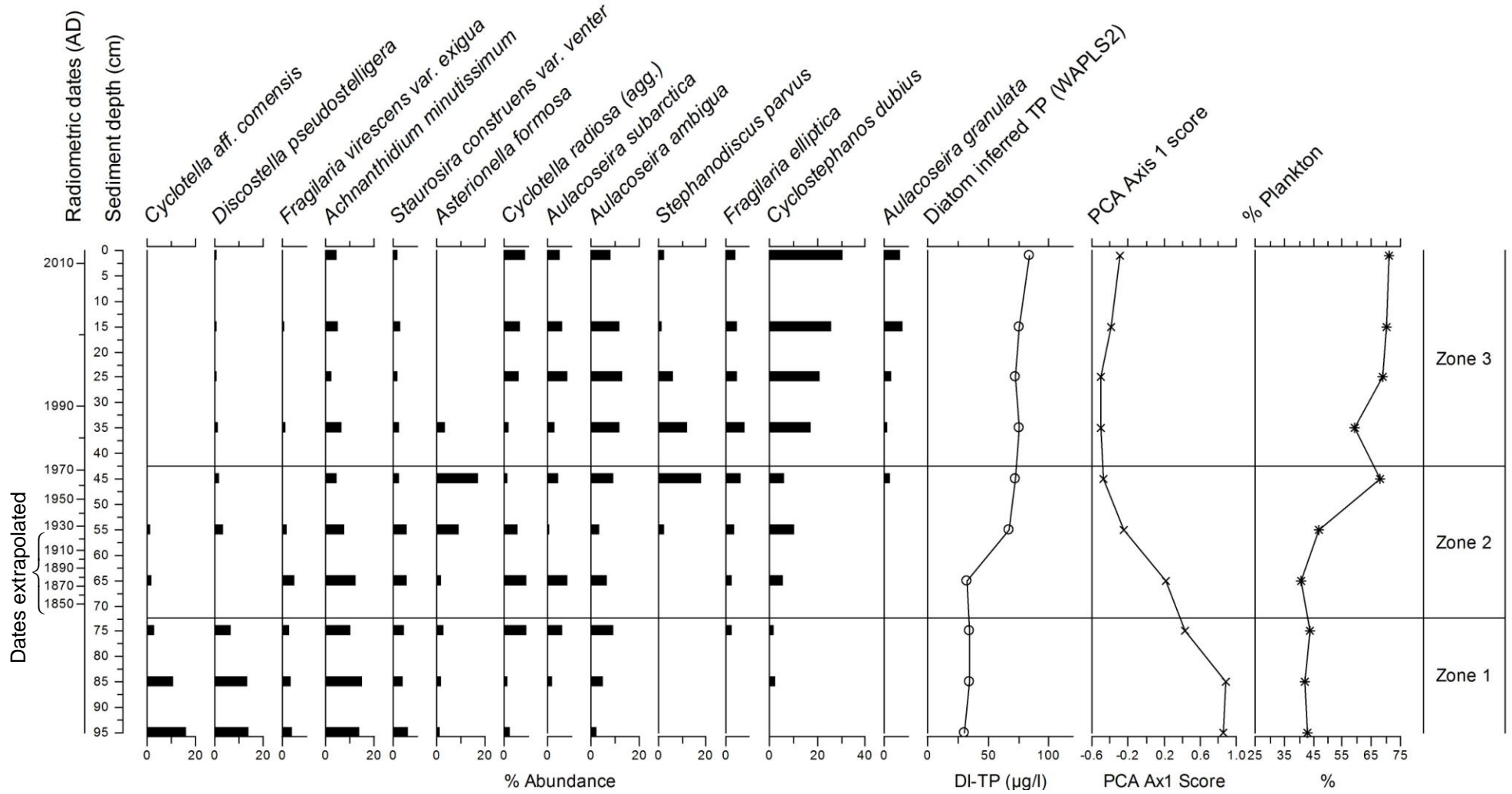| Depth (cm)	Number of Taxa	Hills N2	DI-TP (1) µg L^{-1}	DI-TP (2) µg L^{-1}	% Plankton	% Benthic	PCA Axis 1 Scores
0-1	51	8.0	101.1	84.2	71	29	-0.289
15-16	50	9.3	92.5	75.3	70	30	-0.382
25-26	61	11.5	90.7	73.0	69	31	-0.498
35-36	57	12.7	90.2	75.5	59	41	-0.505
45-46	47	11.0	87.9	73.0	68	32	-0.469
55-56	65	22.7	71.9	67.7	47	53	-0.248
65-66	56	18.8	34.2	32.6	41	59	0.217
75-76	52	20.5	37.4	34.9	44	56	0.432
85-86	51	14.7	29.1	34.5	42	58	0.885
95-96	34	11.9	23.2	30.1	43	57	0.858

Figure 3.7 Summary diatom diagram from Hatch Mere (core HAT3).

3.4 Plant macrofossils

Eleven samples were analysed for plant macrofossil remains in the HAT3 core (Table 3.5). The sub-fossil remains of 20 aquatic plant taxa and a further 18 wetland and terrestrial taxa were observed in the core and a summary diagram for the major taxa is presented in Figure 3.8 and **Error! Reference source not found.**Figure 3.9. The down-core analysis shows two main zones based on composition of the sub-fossils with the main change in aquatic species remains corresponding relatively closely to the terrestrial and wetland taxa. The slow accumulation rate of core HAT2 meant that the resolution at the top of the core was relatively low, with only four samples representing the last 100 years of the mere's history. Samples were not analysed from below 50 cm in the core due to the lower sediments being of unknown age.

Table 3.5 Summary details for the HAT2 plant macrofossil analysis

Depth (cm)	Number of aquatic Taxa	Number of marginal taxa
1-2	11	9
5-6	13	7
9-10	13	10
14-15	11	11
20-21	12	12
25-26	8	11
29-30	8	8
35-36	7	7
39-40	9	5
45-46	9	8
50-51	10	7

Zone 1 (50 – 25 cm) had high numbers of bryophyte remains, including *Sphanum* spp. leaves. The lower samples had relatively high numbers of *Nitella* species oospores including "type b" which was not recorded higher in the core. Low numbers of *Chara* sp. Oospores were also recorded. *Nymphaea alba* seeds were common throughout zone 1, but the leaf cells (trichosclereids) were not recorded in abundance. Other aquatic species were very poorly represented, and no pondweeds recorded. Sub-fossil remains of marginal species were dominated by the seeds of *Typha angustifolia* and *Juncus* species.

In Zone 2 (25 - 1 cm) bryophyte remains decreased significantly, *Nitella* (type a) remained common and *Chara* spp. oospores increased slightly. *Nymphaea alba* seeds also reamain common, but this zone is characterised by many more *Nymphaeaceae trichosclereids* in the upper samples. Also of note is the appearance of several remain types from aquatic plant species not recorded lower in the core, e.g. *Potamogeton pusillus / berchtoldii, P. obtusifolius, P. natans* as well as *Myriophyllum* sp. and *Nuphar lutea.* Among the marginal and terrestrial species, numbers of *Juncus* spp. seeds fell towards the core top and overall there were less *Typha* seeds in Zone 2. The appearance of *Papaver* spp. seeds (poppies) in the upper zone is of particular interest and possibly reflects land use changes within the catchment. Species richness was higher for both aquatic and marginal taxa in the upper zone.
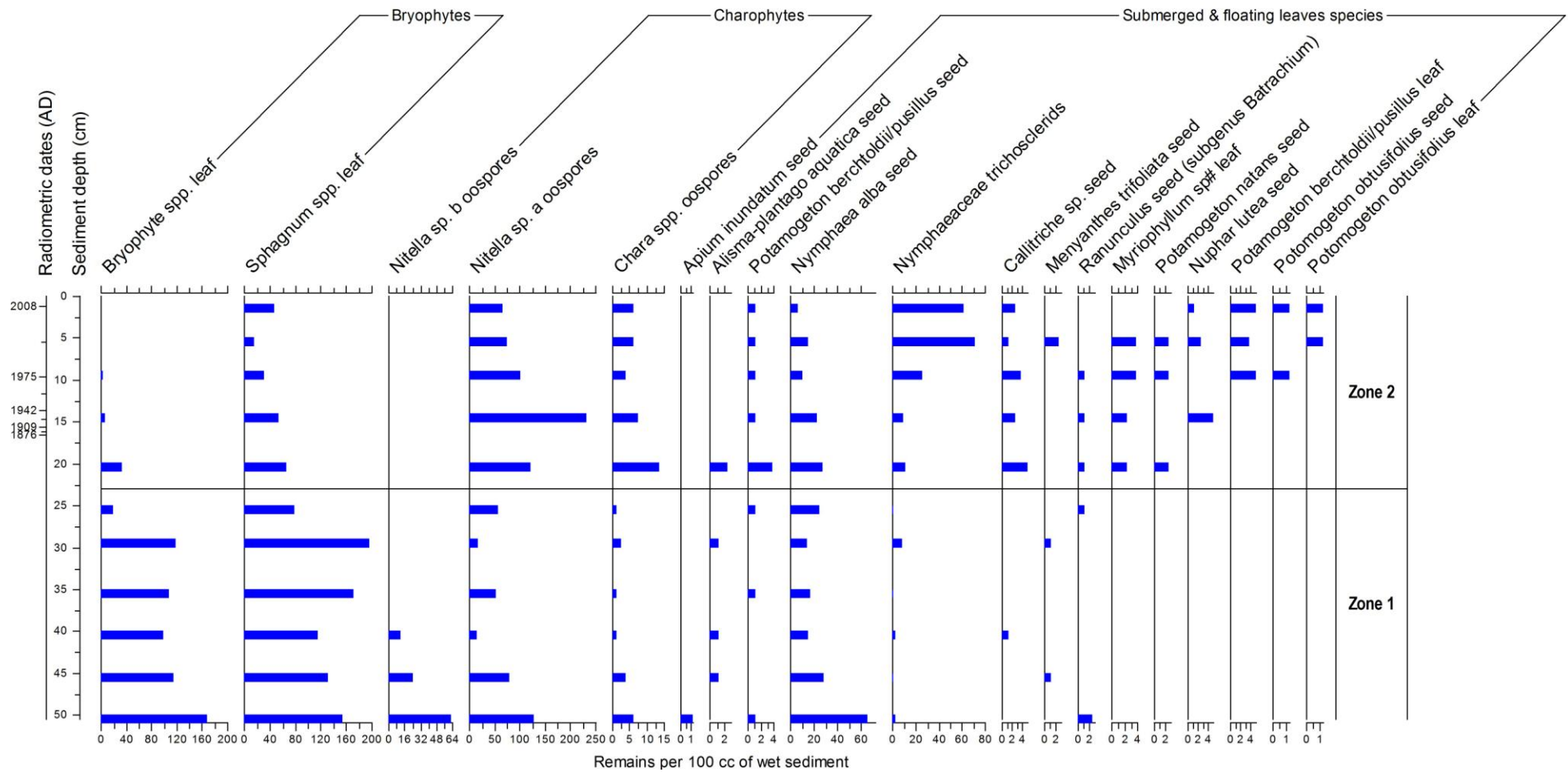
Figure 3.8 Summary plant macrofossil diagram from Hatch Mere: aquatic taxa (core HAT2).
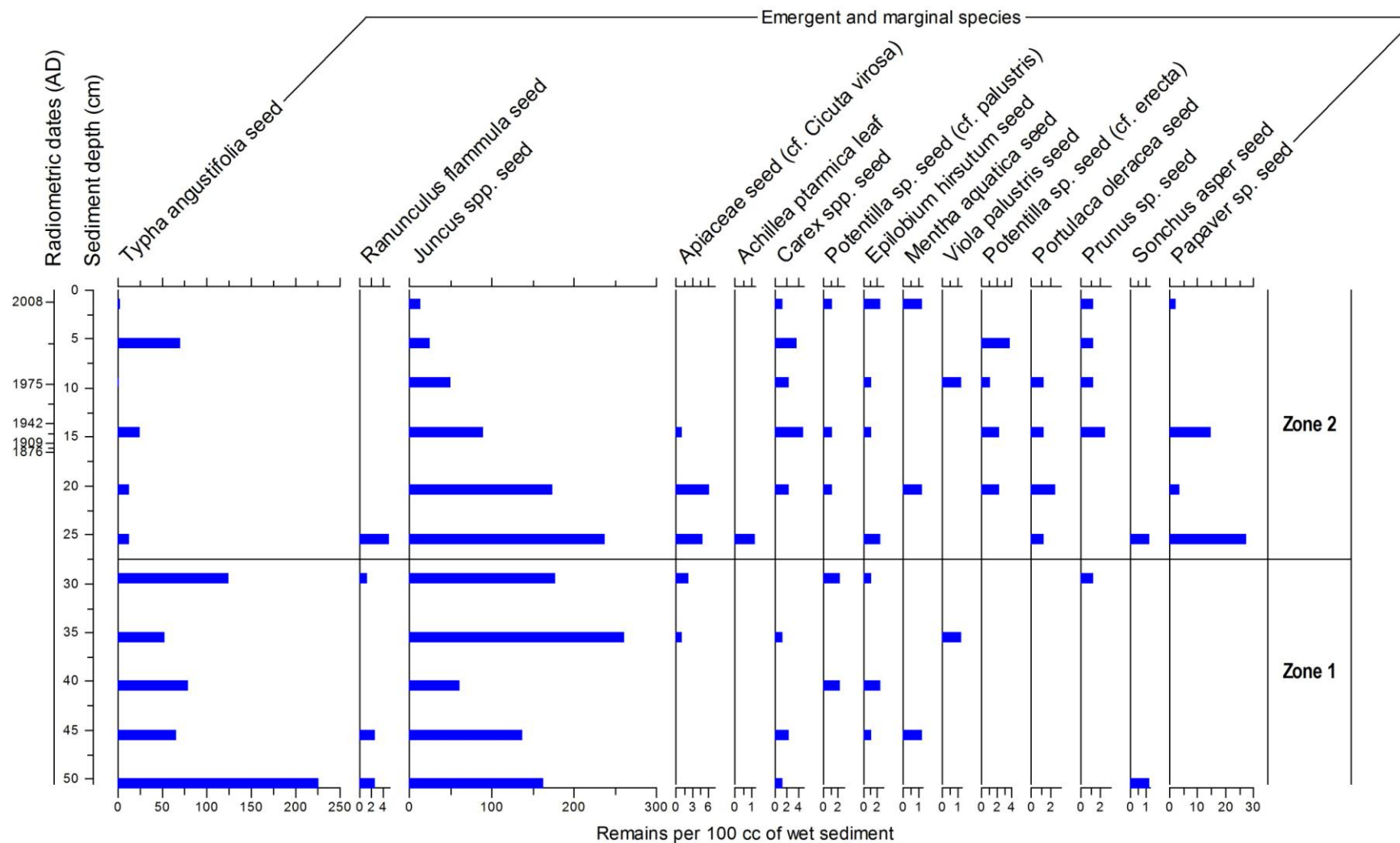
Figure 3.9 Summary plant macrofossil diagram from Hatch Mere: marginal taxa (core HAT2).

3.5 Cladocera analysis

Ten samples were analysed for chitinous cladoceran remains in the HAT3 core (Table 3.6). A total of 19 taxa were observed in the core and a summary diagram for the major taxa is presented in Figure 3.10. The samples were dominated throughout by *Bosmina longirostris*, but two zones were identified.

Table 3.6 Summary details for the HAT3 cladoceran analysis

Depth (cm)	Number of Taxa	Hills N2	PCA Axis 1 Scores
1-2	12	1.24	-0.491
5-6	11	1.43	-0.381
10-11	10	1.54	-0.346
15-16	12	1.72	-0.331
20-21	10	1.72	-0.816
25-26	13	2.11	0.137
30-31	13	2.30	0.071
40-41	9	2.42	-0.018
50-51	12	3.46	1.306
60-61	15	3.32	1.010

Figure 3.10 Summary cladoceran diagram from Hatch Mere (core HAT3).

Zone 1 (61-45 cm ~1900 - 1960) was dominated by the open-water species *Bosmina longirostris* (approximately 60%) with benthic *Alona* species also relatively common. The PCA axis 1 scores were high in these lower two levels and species diversity was also higher than in zone 1.
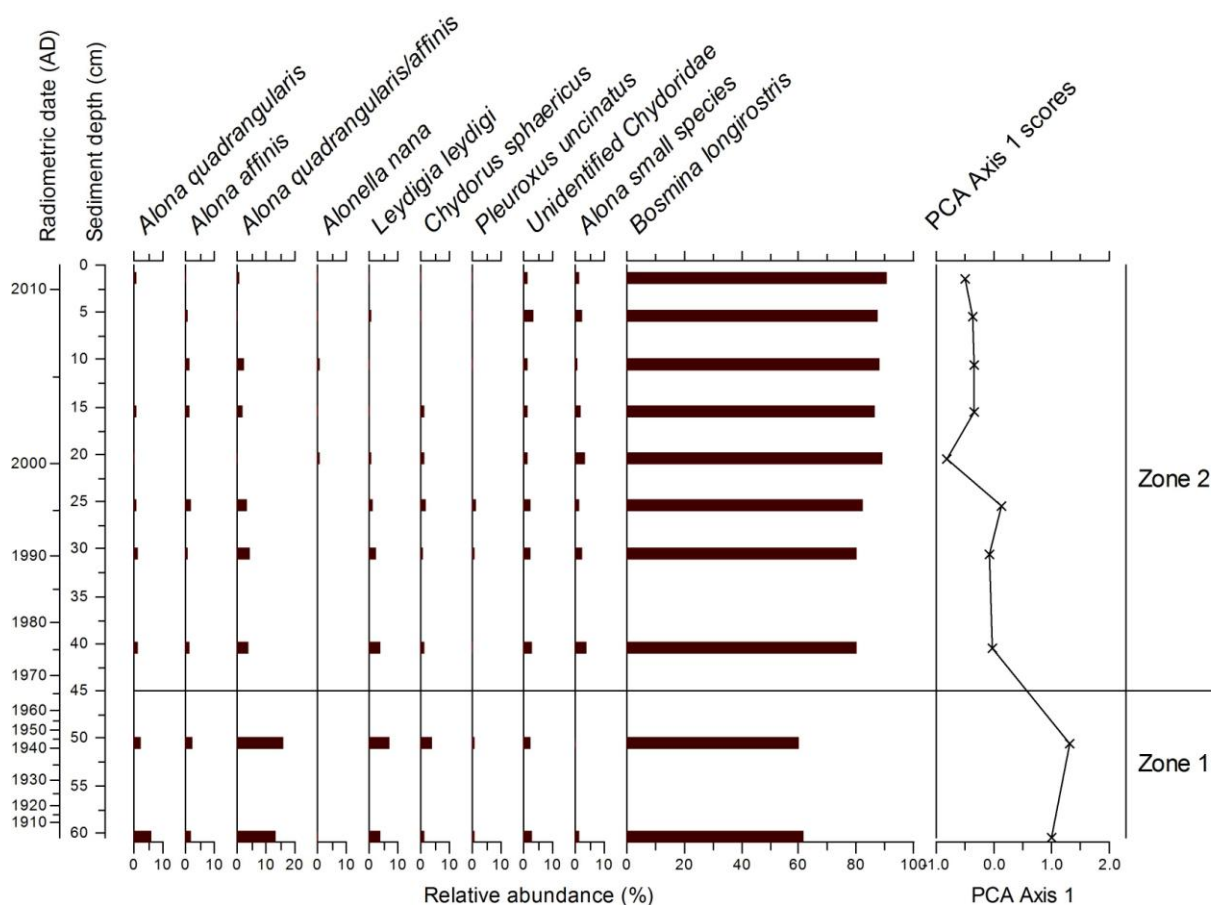
In Zone 2 (45 - 0 cm, ~1960 - 2011) there was a gradual decrease in species diversity (N2) up through the core with the pelagic species *Bosmina longirostris* accounting for most of the fossil remains recorded. *Alona* species decreased above 45 cm suggesting benthic habitats were less available during this period. The PCA axis 1 scores are consistently lower than those in zone 1, indicating a compositional change within the fossil assemblages of the 2 zones.

During the analysis of plant macrofossils from core HAT2, cladoceran ephippia (eggs) were also recorded. *Daphnia pulex / hyalina* ephippia were relatively common throughout the core, but the uppermost samples (post 1960) had significantly higher numbers. This is consistent with the dominance of *Bosmina longirostris* and indicates a plentiful supply of planktonic algal food for these species.

3.6 Pigment analysis

Pigments detected in the Hatch Mere sediments included: fucoxanthin and diatoxanthin (siliceous algae), alloxanthin (cryptophytes), chlorophyll *b,* pheophytin *b* and lutein (chlorophytes or higher plants), zeaxanthin, canthaxanthin (all cyanobacteria), myxoxanthophyll, aphanizophyll (filamentous cyanobacteria), chlorophyll *a* and β-carotene (all algae and higher plants), pheophytin *a* and Chl *a'* (breakdown products of chlorophyll *a*) a UVR-absorbing compound. The UVR-absorbing compound was divided by the sum of the most abundant pigments (alloxanthin + diatoxanthin + lutein +zeaxanthin) and multiplied by 100 to normalize the production of UVR relative to algal material and provide an index of UVR penetration to indicate water clarity (see Leavitt *et al.* 1997 for further details). The pigment concentrations are summarised in Figure 3.11.
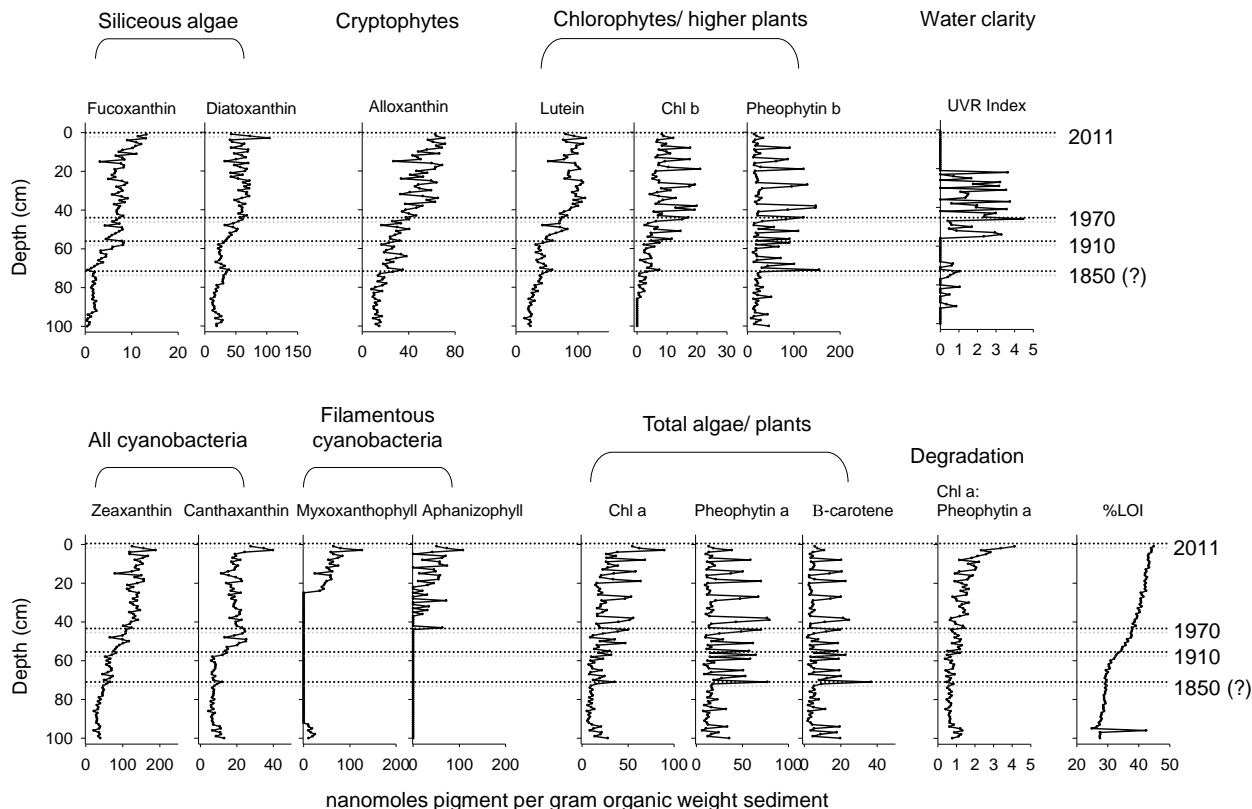

Figure 3.11 Pigment stratigraphy from core HAT3 (nmole pigments g^{-1} organic weight sediment).

Pigment concentrations in the samples were high with an abundance of carotenoids from cyanobacteria (Figure 3.11). The mean Chlorophyll *a*: pheophytin *a* ratio of ~1.1 suggests that the preservation of the pigments was good. Preservation increased slightly above 60 cm, and then more markedly above 15 cm in the core. The most marked changes in pigment stratigraphies occurred coincident with the changes in preservation, consistent with elevated algal production enhancing pigment burial. At ~60 cm pigments from siliceous algae, cryptophytes, chlorophytes and cyanobacteria increased. At the same time, water clarity increased and this may indicate a decline in water colour from dissolved organic carbon (DOC). Enhanced water clarity between 60-20 cm may have stimulated algal production by increasing the depth of the photic zone. Around ~45 cm depth the abundance of filamentous cyanobacteria started to increase (aphanizophyll) with a more pronounced increase in another filamentous cyanobacterial pigment (myxoxanthophyll) above 25 cm.

Pigments from other algal groups (siliceous algae, cryptophytes, chlorophytes) were also seen to increase markedly above 50 cm. The decline in water clarity above 20cm may be related to an increase in DOC, but may also be caused by elevated algal production which would increase water turbidity. One rather unusual feature of this profile is the relatively large variability in the stratigraphy of chlorophylls and pheophytins a and b and β-carotene in comparison to the other carotenoids. One possibility is that this lake has a large amount of allochthonous plant material (e.g. leaf litter) contributing to the pigment record which would be composed of pigments from higher plants. If this is the case they may prove informative in looking at changes in land use history in the catchment.

3.7 XRF analysis
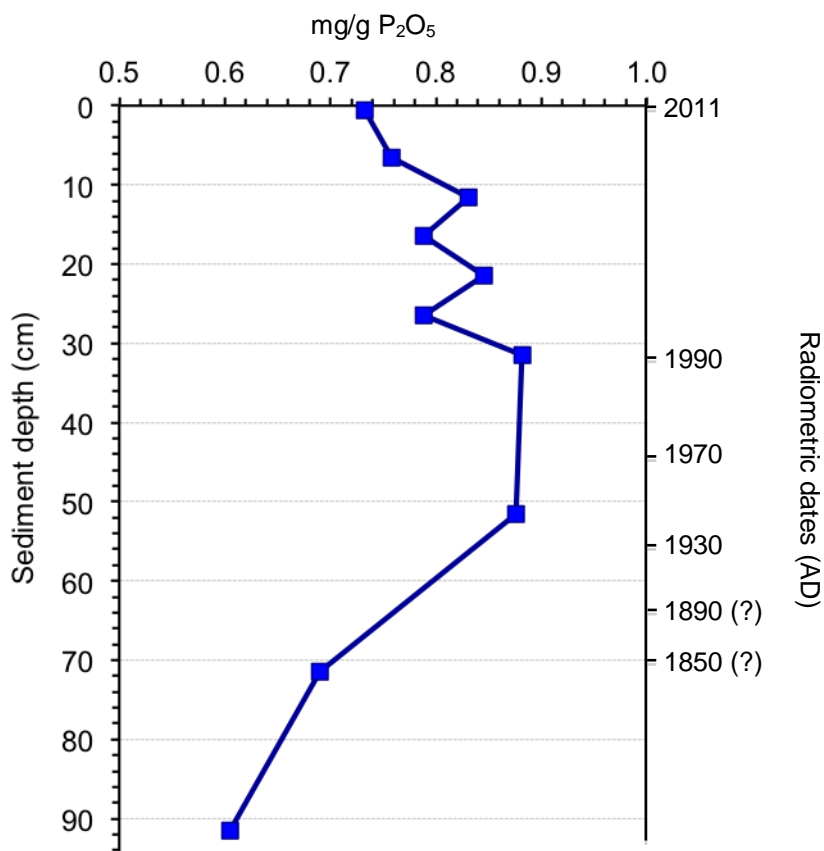
Figure 3.12 XRF sediment P concentrations (mg g^{-1} as P_2O_3) in core HAT3

The was a fairly marked change in the concentration of P in the sediments (Figure 3.12). Pre-1850 the values show a slight increase from 0.6 mg g^{-1} to 0.7 mg g^{-1}, but between c.1850 and c.1940 there is sharp rise which appears to then stabilise at 0.9 mg g^{-1} until 1990. Since 1990

there appears to have been a trend towards lower P concentrations in the sediments with surface sediment measuring 0.73 mg g^{-1}. The resolution is rather low, but the data suggest a net loss of P from the site after c.1990 rather than accumulation.

4 Discussion

When analysing any lake sediment core it is important to be able to put the data in context of time. The two cores from Hatch Mere both dated successfully, but were very different in terms of sediment accumulation rates. The open water core (HAT3) was typical of relatively productive lowland lakes in England with approximately 70 cm of sediment accounting for the last 160 years of accumulation. The marginal core had much slower sediment accumulation, with approximately 17 cm accounting for the last 160 years. Unfortunately, dating was not available for the cores until after the other analysis was finished and therefore the resolution in the marginal core is rather low for the main period of interest. Comparisons between the two cores are however possible.

The dated sections of the two cores, although differing in their accumulation rates, are otherwise quite similar. The organic content (%LOI) of the sediments in both cores is approximately 30% in the late 19th century, and slowly rises to 40% in the marginal core and a little higher in the open water core (Figure 3.1 and Figure 3.2). The marginal core is interesting in that below 20 cm the sediments become very organic. This is suggestive more of peat than lake sediments and possibly indicates that the reed beds once extended out into deeper water or that water levels were once lower and the to core location was in an area of active peat accumulation. We are unaware of any major shifts in water level at Hatch Mere. The decline in maintenance of drainage channels over the past 150 years has been attributed to water level rise in some meres (Reynolds 1979), but this would not account for the 2.0 m change required to place the HAT2 coring site in the littoral zone. In fact, the depth of peat surrounding the site suggests that is was more likely much greater in area than present day (Infanullah and Moss 2005) having slowly in-filled due to hydroseral succession. More likely is that the lake once supported a high biomass of marginal and littoral vegetation (reedswamp, *Sphagnum* spp. beds and possibly Bog bean (*Menyanthes trifoliate*)) which contributed to the high organic content of the older sediments in the lake margins.

From the open water sediment core (HAT3) it is apparent that Hatch Mere has been a relatively productive lake for at least 160 years. There is however a considerable body of evidence to suggest it was once less nutrient-rich in the past than it is today and has become more eutrophic since the latter part of the 19th century. The diatom flora prior to ~1850 is typical of a relatively productive, circum-neutral lake, with species such as *Cyclotella comensis, Discostella psuedostelligera* and *Achnanthidium minutissimum* common in the assemblage at the base of the core. Also of note is the higher relative abundance of non-planktonic (benthic) species in the older sediments, suggesting light penetration and / or available habitat was greater in the past. This may be indicative of clearer waters allowing more light to reach the lake bed, but also that there were plants growing in the lake on which diatoms grow epiphytically. The diatom data are supported by the pigment data in which only low to moderate concentrations of most pigments were recorded in the core samples below 70 cm, suggesting relatively low productivity.

The macrofossil data (looking at the lower part of zone 2 Figure 3.8) show the mere to have supported Stoneworts (*Nitella* and *Chara* spp.) *Callitriche* sp., *Myriophyllum spicatum,* aquatic *Ranunculus* spp., *Potamogeton natans, P. berchtoldii* and / or *P. pusillus,* as well as *Nymphaea alba.* This points to there having been a mixed plant assemblage present, typical of a moderately productive lowland lake. At this time, the concentrations of total phosphorus in the water are estimated to have been approximately 25 -30 µg L^{-1}, placing it within the Habitats Directive target range for naturally eutrophic lakes (JNCC 2005). A plant assemblage similar to this can be found today in White Mere (SJ415331, Goldsmith unpublished data). The zooplankton data do not extend back to this period. The sediment phosphorus at this time is relatively low compared with more recent sediments, again supporting the evidence that the mere has become more eutrophic in recent years.

As well as the processes occurring within the lake, we can also gain an idea of changes to the vegetation in the immediate vicinity of the lake. The plant macrofossil remain from terrestrial and

wetland species support the idea that the lake would once have been larger and over time was 'terrestrialised' around its margins by the encroachment of *Sphagnum* dominated communities, followed by development of reedswamp (see Tallis 1973). In zone 1 of the macrofossil core (Figure 3.8 and Figure 3.9), which very likely pre-dates 1850 by a significant period, we see extensive remains of *Sphagnum* and other bryophytes, as well as high numbers of *Typha angustifolia* and *Juncus* spp. seeds. This community appears to shift as we move into the 19th century, possibly as the 'terrestrialisation' slows at the point where the mere shelves more steeply to deeper water, and behind the Alder and Birch close the canopy. The onset of anthropogenic eutrophication is most likely to have been related to land use change in the catchment and one possible indicator of this is the appearance of *Papaver* (Poppy) seeds in the core. Poppies are most closely associated with disturbance and particularly agriculture, and thus their appearance in the core may mark the beginning of more intensive farming in the region. The level at which poppies occur in the core could easily extend back to the 1700's based on a crude extrapolation of the dated material.

Moving up in the cores, the diatoms show a gradual displacement of *Cyclotella* and *Discostella* in favour of *Aulacoseira* spp, *Cyclotella radiosa* and *Cyclostephanos dubius*, indicating a relatively rapid change in nutrient status around the turn of the 20th century. The overall planktonic component of the diatom flora starts to increase by the early 1900s and DI-TP concentrations rise above 50 µg L^{-1}. Similar species shifts within the diatom flora have been observed in the palaeoecological record of Betton Pool (Brooks *et al.,* 2001), Comber Mere (Bennion *et al.* 2011) and Crose Mere (N.J. Anderson unpublished) as the lakes became progressively enriched. In accordance with the diatom data, pigments from most algal groups increased slowly from the early 1900s indicating a steady rise in algal productivity. The macrofossil data do not show any appreciable changes in the aquatic flora of the site. Stoneworts remain present alongside a mixed aquatic flora typical of moderately enriched lowland lakes. *Nymphaea alba* appears to have been common at the site throughout the period represented by the core, but only after 1900 do the seeds of *Nuphar lutea* appear in the sediments. The significance of this is not known, but it does suggest there were changes occurring within the aquatic flora in response to eutrophication. The fossil cladocera remains are of intest in this period. While the pelagic species *Bosmina longirostris* dominated throughout the core, *Alona* spp. are present in the first half of the 20th century. This is significant because these species are mainly benthic feeders and therefore require good light penetration in a site to assure a reasonable crop of the benthic algae on which they graze. The dominance of *Bosmina longirostris* does however suggest there was also a plentiful supply of planktonic algae. During this period there also appears to have been a significant increase in the amount of phosphorus accumulating in the sediments (Figure 3.12).

The biggest change in the sediment record is seen from ~1970 to the present day. Most striking is the rapid increase in accumulation rate in both cores suggesting a considerable increase in productivity. The diatoms show the continued expansion of *Cyclostephanos dubius* and *Aulacoseira* spp. and overall dominance by planktonic species. The DI-TP values continue to rise to a maximum of ~85 µg L^{-1} at the surface which is in reasonable agreement with the measured annual mean TP of 72 µg L^{-1} for the years 2006 to 2008 and suggest that the eutrophication trend has continued to the present day. The diatom-inferred values are consistently in excess of the CSM target limit of 50 µg L^{-1} for natural eutrophic lakes (JNCC 2005). The pigment data show a major increase in most algal pigments during recent years, including the appearance of filamentous cyanobacteria.

Additionally there were subtle, changes in the chitinous zooplankton record suggesting a further shift from littoral to plankton dominance with more open water and pelagic taxa found in the upper core. This is supported by the increased abundance of *Daphnia* ephippia in the upper 10 cm of the macrofossil core (HAT2). This is coincident with the decline in aquatic plant remains at the top of the core and suggests a shift within Hatch Mere to greater pelagic production. Indeed the combination of high abundance of *Bosmina longirostris* and the rise in *Daphnia* spp. is indicative of an abundant plantonic algal food source.

The uppermost macrofossil sample suggests the mere to currently support, fine-leaved pondweeds, *Callitriche* sp. and water lilies, but all but the latter elude recent macrophyte surveys (e.g. Goldsmith *et a*l. 2010). Lind (1949) reported *Potamogeton gramineus* present alongside *Sparganium natans* and *Elodea canadensis.* Francis Rose also recorded *Potamogeton gramineus* in 1960 (Wiggington 1980), but a survey by Chris Newbold in 1979 recorded only very sparse populations of *Elodea canadensis, Callitriche platycarpa, C. obtusangula* and *Nuphar lutea* (Wiggington 1980). Remains in the recent sediments may well represent in-washed material from the surrounding fen, or indeed may indicate that small populations of these species do still exist within the less accessible areas of reedswamp around the mere.

Although the resolution is rather low, the sediment chemistry shows a peak in phosphorus concentrations between c.1930 – 1990, after which there is a trend towards lower P in the sediments. While there is no evidence of a reduction of TP in the water column, these data are nonetheless encouraging as they suggest the site is no longer a net sink of P, but instead it is slowly losing P back to the environment. The availability of nutrients continues to drive pelagic production in the mere, but if sediment P continues to drop accompanied by an abatement of catchment nutrients, the water quality is likely to improve, and with it the biological quality.

In summary, the palaeoecological data indicate that Hatch Mere has been a nutrient-rich lake for the whole of the period represented by the sediment cores, i.e. for approximately the last 200 years. Nevertheless the lake was less productive in the past and has experienced recent enrichment starting before 1900 AD, and which has continued to the present day. The data suggest an increase in pelagic productivity and a decline in the aquatic plant community attributable to the eutrophic conditions

Hatch Mere has undoubtedly undergone significant biological change over the last 100-200 years due in part to the natural 'evolution' of the surrounding vegetation communities, but also due to anthropogenic nutrient enrichment. This appears to have resulted in an increase in the pelagic productivity and hence a reduction in the light penetration through the water column due to algal turbidity. It follows that this has been responsible for the loss of submerged aquatic plants from the mere and that the resultant loss of habitat has detracted from the conservation value of the site.

4.1 Recommendations

The following recommendations are for the standing water area of Hatch Mere and do not include the extensive acid bog, acid heath, reedswamp, and wet alder and willow woodlands that adjoin the site and are included within the SSSI.

1. The study suggests that better water quality is key to ensuring any improvement in the mere. A reduction of external nutrients will help facilitate internal loss of nutrients from the sediments and in the longer term reduce the productivity of the water. In so doing it is hoped that increased water clarity will aid the recovery of submerged and floating leaved aquatic plants in the mere. Reducing nutrient inputs will be best informed by a comprehensive survey of both surface water and ground water quality (particularly Nitrogen and Phosphorus) within the catchment to identify any point or diffuse inputs to the system. If identified, mitigation should implemented in order to reduce nutrient inputs to the mere. If sources of pollution from agriculture are identified as the key problem then promotion of catchment sensitive farming is required in order to reduce inputs and runoff to a minimum.

2. Define new base line targets for water quality (<50 µg L^{-1}) and aquatic macrophytes based on the site being naturally eutrophic, not mesotrophic. JNCC (2005) guidance for eutrophic waters suggests a total of six characteristic species present, e.g. *Ranunculus* spp., *Callitriche* spp., *Potamogeton* spp. (not *P. pectinatus,* but inclusive of a broard-leaf species) and *Chara* spp., an assemblage akin to that recorded in the sediments and from past surveys (Madgwick 2009).

3. In light of the planned application of Phoslock to Hatchmere (EA 2013), monitoring of both water quality and biological quality elements (diatoms, invertebrates, phytoplankton, zooplanton and aquatic plants) will be key components of measuring success.

4. Higher resolution analysis of the existing sediment cores is recommended for periods identified as undergoing the greatest change. In the case of HAT2 a focus on the last 70 years is recommended, to full understand the loss of aquatic plants from the mere.

4.2 Concluding remarks

It should be noted that Hatch Mere is currently listed as being an Annex 1 type: H3130: Oligotrophic to mesotrophic standing waters with vegetation of the *Littorelletea uniflorae* and/or of the *Isoëto-Nanojuncetea* (Goldsmith *et al.* 2010). Neither the diatom-based TP model, nor the macrofossil analysis support the site to have ever been typically mesotrophic within the last 150-200 years. Evidence strongly suggests Hatch Mere to have been eutrophic throughout this period and the site is unlikely to have supported a typical mesotrophic flora as specified under the JNCC guidance for standing waters (JNCC 2005). Restoration targets should therefore be set against the current evidence of the mere being naturally eutrophic. This is a key finding of this study which provides a strong evidence base for re-assessing the site designation and hence management targets. Without such work there is a risk that resources would be squandered in trying to restore lake sites to a hypothetical point in which they have not existed and therefore are unlikely to again.

The site condition of over sixty SSSI lakes has recently been assessed by ENSIS (NE Contract SAE03-02-320) based on their current macrophyte flora and nutrient status. The lakes listed in Table 4.1 were all classified as being in unfavourable condition due to a failure to either meet the floristic or water quality targets (or both) as defined within the Common Standards Monitoring Guidance for Standing Waters (JNCC, 2005). While most of these sites have clearly deteriorated over the past ~100 years, the extent to which they have declined in quality is often not known and hence restoration targets tend to be generic for the region and lake type, rather than informed from site specific records. Some sites may never have had the species present that are deemed necessary to comply with the required targets, and while attempts are made to account for this within the CSM assessments, it is often purely speculative rather than based on any factual information. In the absence of historical data, palaeolimnological techniques can provide a valuable tool for defining a range of baseline data to aid the setting of restoration targets and to inform site management (Bennion *et al.,* 2010). In addition to better understanding the past plant communities and other biological components (e.g. macrophytes, algae and zooplankton) at a site, palaeoecological data can also be used to model the trends in nutrient status and hence set realistic chemical targets. Furthermore, the ability to view these changes within a dated timeframe can lead to a better understanding of the causes of the decline (e.g. changes in land management, fish stocking, sewage effluent or industrial development), and hence inform future management and aid long-term recovery.

Table 4.1 List of SSSI Lakes in 'unfavourable condition' where palaeoecological analysis might help inform conservation objectives

Water Body	WBID	Grid Reference
Aqualate Mere	35724	SJ772204
Bar Mere	34328	SJ536478
Brasside Pond	28686	NZ292453
Broomlee Lough	28172	NY790697
Chapel Mere	34162	SJ539518
Crag Lough	28220	NY766679
Crose Mere	35211	SJ430305
Greenlee Lough	28165	NY770696
Loe Pool	46556	SW648248
Malham Tarn	29844	SD893667
Norbury Meres	34260	SJ559493
Oss Mere	34545	SJ566438
Quoisley Meres	34438	SJ549455
Rostherne Mere	32650	SJ744842
Shibdon Pond	28314	NZ194628
Stanford Water	37309	TL860950
Tabley Mere	32960	SJ723769
Tabley Moat	32960	SJ723769

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