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Palaeolimnological evidence for eutrophication in Malham Tarn (SSSI), North Yorkshire

Final report to Natural England

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1   Executive Summary

This is the final report to Natural England on the project "Palaeolimnological evidence for eutrophication in Malham Tarn (SSSI), North Yorkshire". The aim is to seek palaeolimnological evidence for eutrophication in Malham Tarn both to complement and cross-validate contemporary and other historical evidence for such at the site, as well as to establish whether eutrophication-related changes in the aquatic macrophyte community occurred before the invasion of *Elodea canadensis* in 1962. Palaeolimnology is also used to assess whether there is evidence for eutrophication extending back to the 18th century as has been suggested (Pentecost, 1998; Bradley, 2007), and to aid in describing the unimpacted state of Malham Tarn and the setting of conservation targets.

One fat piston sediment core (MALH7) was collected from the northern end of the Tarn in January 2011 and sliced at 1 cm intervals. Pigments were analysed from each level. However, in order to obtain sufficient sediment for other analyses adjacent levels were subsequently amalgamated and 16 samples were analysed for macrofossils and subfossil cladocerans. The core was dated by the ^{210}Pb method. Owing to unreliable and absent sediment accumulation since the 1960s, surface sediment grabs were used instead of the top layer for the latter two biological analyses.

The core record most likely extends to the Mediaeval period and therefore both climatic and catchment processes are captured. While there is some uncertainty as to the interplay between these two factors in the older, undated sediment layers, the aims of the project were satisfied. Firstly, changes unique to the uppermost levels of the core show that Malham Tarn has experienced recent change since the late 1800s and today supports biological communities considerably different from those present in the more distant past. Increases in the overall abundance of fossil cladocerans, and specifically taxa associated with macrophytes and the pelagic zone, indicate an increase in microalgal production since the late 19th century. While species sensitive to eutrophication remain in the Tarn, there has been an increase in the abundance of species associated with eutrophication (*Chydorus sphaericus, Daphnia pulex*) and therefore a decrease in the proportional abundance of species typically associated with low-nutrient, clearwater lakes (*Acroperus harpae, Chydorus piger, Alonopsis elongata*). The macrofossil record indicates decreases in the abundance of broad-leaved *Potamogeton* and an increase in charophytes, consistent with historical records. The timing of the change predates the invasion of *E. canadensis* (1962) and therefore the invasive species cannot be solely responsible for the changes in macrophyte community composition observed since the 1960s although it may have played a part. np The pigment record reveals relatively large increases in microalgae since what may be the 18th century, indicating long-term, gradual eutrophication confirming previous suspicions. However, these concentrations exceed concentrations found deeper in the core mostly only after the first two decades of the 20th century, suggesting production has exceeded more naturally occurring levels relatively recently. On the other hand, qualitative changes are indicated by the sustained increase in cryptophyte pigments since the the 18th century, and macrofossils of the colonial nitrogen-fixing cyanobacterium *Gloeotrichia* since the early 1900s. The major conclusions and recommendations emerging from this study are:

- The core macrofossil record portrayed neither the macrophyte nor the mollusc community adequately when compared with historical records and the surface sediment grabs. Multiple cores and more comprehensive dating would be required to elucidate the ecological development of Malham Tarn more fully.

- When combined with historical data there is a strong case for a reference state characterised by higher macrophyte species diversity, yet lower macrophyte abundance. Lower microalgal productivity, both in the pelagic and macrophyte zones, in turn translates into lower cladoceran abundances and qualitatively different species assemblages.

- The Tarn is currently impacted and its nutrient load should be reduced imminently in order retain the population of the rare *Aegagropila linnaei* (Boedeker and Immers, 2009) and to promote a reversal in species assemblages while seed banks and remnant populations persist.

- Continued monitoring of both the macrophyte community and nutrient concentrations are recommended in order to capture decadal-scale variability and to identify any future ecological damage such as reductions in macrophyte colonisation depth, increases in filamentous algae, phytoplankton and pelagic cladocerans, and loss of species diversity and evenness.

2   List of Contributors

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3 Study rationale and objectives

Malham Tarn is a very shallow (mean depth $<3\,\mathrm{m}$) marl lake in North Yorkshire. It formed part of a PhD project focused on the ecological responses to eutrophication of marl lakes in the UK (Wiik, 2012). Evidence from historical and anecdotal records of macrophytes as well as phytoplankton, and from a two-year limnological monitoring programme of the tarn from 2009 to 2010, suggest that the Tarn has become increasingly eutrophic over the 20th century. This ecological change specifically involves a loss in macrophyte species diversity, including the loss of associate species of marl lakes (JNCC, 2005), and relatively recent establishment of eutrophic species such as *Potamogeton crispus* and *Zannichellia palustris* combined with the expansion of filamentous algae in the inflow area. Palaeolimnological analyses were not conducted owing to poor core chronologies of cores collected in 2009. However, in January 2011 a further core (MALH7) was collected and successfully dated from Malham Tarn and pigments were analysed in collaboration with Suzanne McGowan at the University of Nottingham.

Using further analysis of core MALH7, this report assesses the palaeolimnological evidence for eutrophication in Malham Tarn against the other available data, for three major objectives, (i) To find evidence for increases in pelagic productivity and food availability through the analysis of subfossil cladocerans and pigments, in absence of solid contemporary evidence for such increases through, for example, decreases in macrophyte cover and colonisation depth, and (ii) To assess whether macrofossil data can capture the presence and absence of *Potamogeton* species as well as the composition of the macrophyte community as recorded historically and presently, and (iii), by going beyond historical data, to shed light on earlier signs of eutrophication as well as reference conditions of the site within the limits of the methods employed.

4 Study site

Malham Tarn is a very shallow ($Z_{max} = 4.4\,\mathrm{m}$, $Z_{mean} = 2.4\,\mathrm{m}$), large ($60\,\mathrm{ha}$) mesotrophic (mean TP $18\,\mathrm{\mu g\,L^{-1}}$) lake in Craven, North Yorkshire (Figures 1a, 1b, 1c). At $375\,\mathrm{m}$ a.s.l., it is the highest marl lake in the UK and is part of the Malham Tarn National Nature Reserve. The Tarn is designated a Site of Special Scientific Interest (SSSI), a RAMSAR site as well as a Special Area of Conservation. The $11.5\,\mathrm{km^2}$ catchment consists of a mixture of improved and natural cattle and sheep pastures, scattered farms and holiday lets, and the Field Studies Council centre located on the northern edge of the Tarn.

The lake is exposed, with limited sheltering to the north by a wooded slope. Dominant and often strong southwesterly winds result in a well mixed water column throughout the year. The main inflow is a large stream at the northwestern end, but the lake also receives water from springs to the north. The outflow to the south is controlled by a weir constructed in 1791. The estimated retention time of the Tarn is 0.33 years, but flushing rate varies seasonally.

The present macrophyte community is dominated by the Characeae (especially *Chara globularis* and *Nitella flexilis* agg.) and the invasive *Elodea canadensis* which has increased in abundance since it was first observed in 1962. Regular interannual fluctuations in overall macrophyte coverage and the proportion of *Chara* spp. and *E. canadensis* have been recorded over the last few decades (Hinton, 2005). Lesser components of the macrophyte flora include *Callitriche hamulata, Fontinalis antipyretica, Lemna minor,*
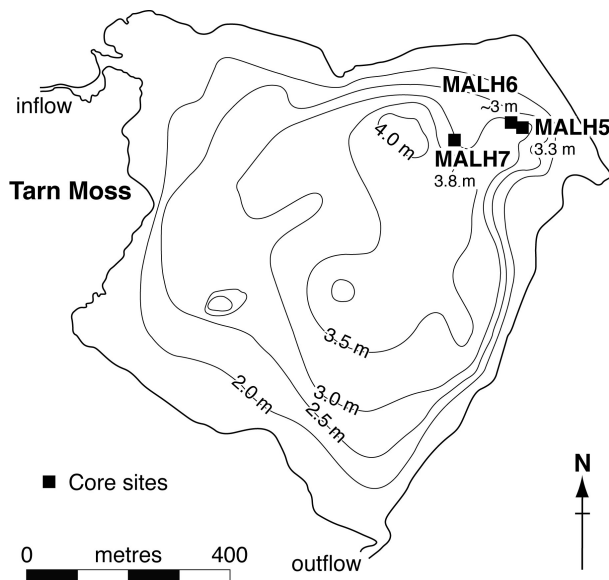
a Bathymetry and coring location, including coring locations where sedimentation is unreliable for palaeolimnology (MALH5, MALH6). MALH7 is not placed on a depth contour corresponding to the coring depth of 4.2 m, and this may be due to GPS and/or echosounder error.

b Core MALH7, showing an upcore transition to more organic material at 42 cm depth

c Malham Tarn from the northeast bank in June 2009.

Figure 1: Malham Tarn site and coring information.

Potamogeton berchtoldii, Potamogeton crispus, Potamogeton lucens, Zannichellia palustris and the rare ball growth form of *Aegagropila linnaei* (see e.g. Pentecost, 2009; Boedeker and Immers, 2009; Boedeker et al., 2010).

5 Methods

5.1 Coring and lithostratigraphic analyses

One core (MALH7, 91 cm) was taken in January 2011 at a depth of 4.2 m from the northeastern end of the lake using a "fat" Livingstone piston corer (internal diameter 71 mm). Visible changes in sediment colour or structure in the core were noted in the field. The core was extruded at 1 cm intervals, and subsamples for pigment analysis were immediately frozen.

Carbonate and organic matter content were quantified for every cm between the core surface and a depth of 11 cm, and every other cm thereafter, using the loss on ignition (LOI) procedure following Dean (1974).

The percentage dry weight (%dw) for each sample was calculated by weighing between 1 and 2 g of wet sediment in a pre-weighed crucible, from each pre-homogenised sediment layer, drying the sediment at 105°C overnight, then reweighing the crucible. Approximate organic matter content was then determined (as a percentage loss on ignition - %LOI) by placing the crucible containing the dried sediment in a muffle furnace at 550°C for two hours and then reweighing. This was repeated at 950°C for four hours. Weights after combustion were recorded as percentages of dry weight. For percentage carbonate, the weight lost was first multiplied by 1.36 to account for the difference in molecular weight of CO_2 and CO_3^{2-}.

5.2 Radiometric dating

Core MALH7 was dated radiometrically with ^{210}Pb, a naturally produced radionuclide derived from atmospheric fallout (termed unsupported ^{210}Pb) with a half-life of 22.3 years. Sediment ^{210}Pb concentration profiles can yield accurate stratigraphic dates for the past 150 years. ^{137}Cs (half-life 30 years) and ^{241}Am (half-life 432.2 years) are artificially produced radionuclides, deposited as atmospheric fallout from nuclear weapons testing and nuclear reactor accidents, and were used as markers to secure the chronology indicated by ^{210}Pb data.

Freeze-dried sediment samples were analysed for ^{210}Pb, ^{226}Ra, ^{137}Cs and ^{241}Am by direct gamma assay in the Bloomsbury Environmental Isotope Facility (BEIF) at University College London, using an ORTEC HPGe GWL series well-type coaxial low background intrinsic germanium detector. ^{210}Pb was determined via its gamma emissions at 46.5 keV, and ^{226}Ra using the 295 keV and 352 keV gamma rays emitted by its daughter isotope ^{214}Pb following three weeks of storage in sealed containers to allow radioactive equilibration. ^{137}Cs 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) .

5.3 Pigment analysis

Pigments were analysed for all MALH7 sediment intervals at the University of Nottingham laboratories following McGowan et al. (2012). All samples were wrapped in foil to prevent photodegradation, and dried with an Edwards Modulyo 4k freeze-drier prior to analysis, and kept frozen in the dark thereafter. Samples were extracted overnight at 4°C in a mixture of acetone, methanol and water (80 : 15 : 5). Extracts were filtered with a 0.22-lm PTFE filter, dried under N_2 gas and redissolved in a 70 : 25 : 5 mixture of acetone, ion pairing reagent (IPR 0.75 g tetrabutyl ammonium acetate and 7.7 g ammonium acetate in 100 mL water) and methanol. Thereafter, analysis was undertaken using an Agilent Technologies 1200 Series high-performance liquid chromatographer (HPLC) fitted with a Thermo Scientific ODS Hypersil reverse phase column (205 x 4.6 mm, 5 μm particle size). An injection volume of 100 μL was used. Analysis followed the method outlined in Chen et al. (2001), with slight modification (Table 1). Between 0.1 and 0.4 g of freeze-dried sediment was required to attain sufficient colour for analysis. All samples were analysed in random order and kept in low light conditions at all times. HPLC solvents were degassed before use (Decon® FS200b sonicator). All runs included a green standard derived from grass, serving the purpose of showing the retention times of key pigments, and were calibrated against

Table 1: Modifications of the HPLC solvents used by Chen et al. (2001). A: 80% methanol 20% 0.5 mol ammonium acetate, B: 90% acetonitrile 10% deionised water, C: HPLC-grade ethyl acetate

Time (min)	A	B	C	Flow mL min^{-1}
0	100	0	0	1
4	0	100	0	1
38	0	25	75	1
39	0	25	75	1
43	100	0	0	1
52	100	0	0	1

Table 2: In order to obtain sufficient volumes for analysis, adjacent levels were amalgamated such that the depth indicated is the midpoint of two consecutive levels - the approximate time bracket, and errors, are given as per ^{210}Pb chronology.

Core level	Time bracket	Error bracket
surface	Last few years to Jan 2011	NA
3	post-1963	NA
6	1958-1963	1953-1967
8	1941-1946	1934-1952
11	1931-1936	1923-1943
14	1914-1920	1902-1930
17	1888-1896	1866-1908

commercial standards to convert peak areas to concentrations.

Pigment preservation was regarded satisfactory due to presence of the degradation-prone fucoxanthin throughout the core. Changes in pigment concentrations downcore were interpreted as independent of preservation effects where the ratios of chlorophylls and their degradation products are relatively unchanging. The identified pigments were divided into groups such that total primary production is indicated by the generic pigments chlorophyll a and its degradation products as well as β-carotene; cryptophytes are indicated by alloxanthin; cyanobacteria by canthaxanthin and zeaxanthin, and chlorophytes by lutein, chlorophyll b and pheophytin b (McGowan et al., 2005). The pigment chlorophyll a' refers to the oxidative degradation product divinyl chlorophyll a.

5.4 Subfossil cladocerans

Preparation of subfossil cladoceran samples followed the principles outlined in Korhola and Rautio (2000). Approximately 1 g of wet sediment was analysed at selected intervals (Table 2) from MALH7. Due to high concentrations of carbonate in the sediment, samples were treated with 10% HCl prior to 10% KOH and deionised water. All samples were sieved to avoid damage that can be caused by centrifugation. Each sample was divided into size fractions retained by meshes of 150 and 45 μm (Davidson et al., 2007). Counting was performed using both a Lund cell (smaller remains) and a Sedgwick rafter cell (larger remains) up to a minimum count of 300 individuals as determined by the most abundant remain for each species. Where this number was not attained within the time budget of the project, owing to scarcity of remains, counting was stopped sooner, although numbers of individuals always exceeded 200. The proportion of sample analysed was estimated based on the difference in original sample weight before and after analysis. Data are expressed as the number of individuals per g of wet sediment.

Not all remains could be assigned to a species. Post-abdominal claws may represent several species in-

cluding *Ceriodaphnia* spp. and *Daphnia* spp., both of which have been recorded in the lake. *Daphnia pulex*, on the other hand, due to additional smaller spines at the base of the claws, were identifiable. *Chydorus* remains were variable in size, which can be attributed to morphological plasticity within the species. All these remains were identified as *Chydorus sphaericus sensu lato*. The *Bosmina* found in the core were identified as *Bosmina* cf. *longispina*, however, historical records from the Tarn only include *Bosmina longirostris* (Fryer, 1993). The naming *Bosmina* cf. *longispina* is kept in all diagrams although the possibility of it being *Bosmina longirostris* needs to be acknowledged.

Identification was performed using Frey (1965), Flößner (2000) and Szeroczyńska and Sarmaja-Korjonen (2007). Cladocerans were divided into types by habitat preference in order to tease out the balance between bottom-dwelling ("bot"), macrophyte-associated ("veg") and pelagic ("pel") cladoceran abundance. Typing was based on species descriptions by Whiteside (1970); Whiteside et al. (1978); Hofmann (1996); Flößner (2000); Tremel et al. (2000); De Eyto et al. (2002, 2003); Davidson et al. (2007); Drinan et al. (2013), and also through descriptions of taxa historically sampled in the Pennines and also within the Tarn itself (Fryer, 1993). *Chydorus sphaericus* and daphniids (identified as post-abdominal claws) were placed in an "NA" category, the former owing to habitat flexibility, the latter due to variability in habitat preferences of the species within the aggregate. While several of the species, for example the smaller *Alona* species, are also recorded in vegetation, they are likely in Malham Tarn to show preference for bottom habitats and are therefore placed in the bottom-dwelling category. The large *Alona* species are frequently reported to be more abundant on benthic than vegetation surfaces (Whiteside et al., 1978; Fryer, 1993; Tremel et al., 2000; Flößner, 2000) and are also grouped into the "bot" category. *Camptocercus rectirostris*, which according to Fryer (1993) has been found in Malham Tarn in stones in shallow water, has been reported as strongly associated with vegetation, specifically *Chara* (Whiteside et al., 1978), supported by general descriptions of morphological adaptation and habits (Fryer, 1968), and therefore is placed in the "veg" category.

5.5 Macrofossils

Macrofossils of macrophytes, Cladocera, Trichoptera, algae, Bryozoa and Mollusca were enumerated from 16 samples selected throughout the core (Table 2). Between 30 and $100\,\text{cm}^3$ of sediment, determined by water displacement, was analysed for each level, depending on how much mud was available. Samples were soaked in 5% KOH overnight in order to break down sediment flocs, followed by sieving through meshes of 125 μm and 300 μm. Counting was undertaken under a Wild M3Z dissecting microscope. All material of the larger size fraction, and a homogenous subsample of approximately 15% of the smaller size fraction, was analysed. All macrofossil counts are expressed as numbers per $100\,\text{cm}^3$ wet sediment. Macrofossils counted as halves (for example ephippia, statoblasts) are expressed as the minimum number of individuals.

Macrofossils were identified using a dedicated reference collection of plant and animal parts and relevant publications held at UCL Geography. Where species-level detail was not attainable, remains represent species aggregates. These include *Daphnia hyalina* agg. ephippia and broad-leaved *Potamogeton* leaf fragments. Not all molluscan fossils were identifiable due to breakage. To better capture mollusc abun-

dance, mollusc fragments were also given an abundance score between 1 and 5. Molluscs were mostly identified to family or genus level only. Charophyte oospores are very difficult to identify to species level due to substantial morphological variability and they were therefore separated into different morphotypes, selected specimens of which were identified using the UCL reference collection and an identification key (Haas, 1994).

5.6 Data analysis

All data analysis was performed with R version 2.12 (R Development Core Team, 2010) using packages analogue (Simpson, 2007; Simpson and Oksanen, 2011), vegan (Oksanen et al., 2011), and lattice (Sarkar, 2008). In order to assess points of compositional change, cluster analysis using Ward linkage was performed on the macrofossil (plant and animal fossils together) and cladoceran data sets. Ephippia counts were removed from the macrofossil data set in order not to duplicate community change shown by the cladoceran data set. Because all cladoceran counts are assumed to have equal abundance representation, the data were Hellinger-transformed prior to the calculation of Euclidean distances (Legendre and Gallagher, 2001). Because this assumption does not hold for macrofossils, these data were $\ln(x + 1)$-transformed followed by calculation of Bray-Curtis dissimilarities.

6 Results
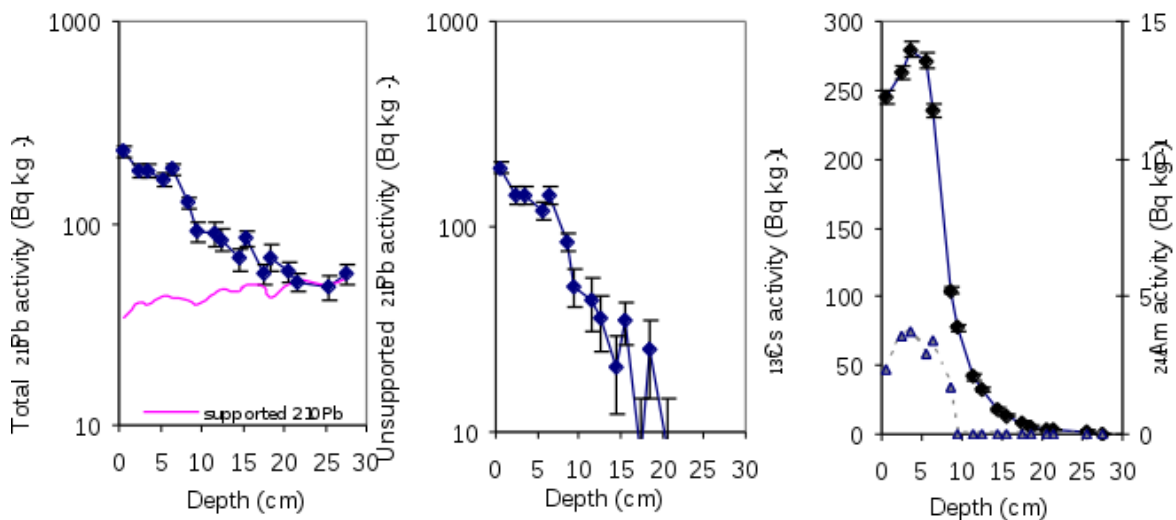
6.1 Core lithostratigraphy and radiometric dating

Figure 2: MALH7 radiometric data, showing the lack of the 1986 Chernobyl ^{137}Cs peak and a very broad 1963 weapons testing peak. *Analyst: Handong Yang*

Core MALH7 was collected at the approximate location where core MALH2 was collected in 1995 (Bennion et al., 1997), yet the two are remarkably different. The latter yielded a reliable radiometric dating profile and encompassed the time period between the mid-19th century and 1995 in 40 cm of sediment. Sedimentation rate estimates generally increased towards the top of MALH2. In contrast, it appears that most of the recent sediment in MALH7 is missing. The ^{137}Cs weapons testing peak for 1963 is relatively broad, and the Chernobyl peak for 1986 is completely missing. It is possible that the coring location has

Table 3: ^{210}Pb-derived chronology for MALH7 excluding data after 1963. SR = sedimentation rate

Core level	Year (AD)	Error (± yrs)	SR (g cm^{-2} yr^{-1})	SR (cm yr^{-1})	Error (± %)
5.5	1963	4	.0356	.216	14.3
6.5	1958	5	.0255	.157	14.2
8.5	1946	6	.0292	.174	17.4
9.5	1941	7	.0416	.229	26.6
11.5	1931	8	.0361	.192	36
12.5	1926	9	.0377	.171	38.7
14.5	1914	12	.045	.182	51.6
15.5	1905	15	.0202	.075	46.1
17.5	1888	22	.0532	.198	111
18.5	1876	29	.0114	.042	93.4

been disturbed by anchor setting during previous monitoring of the lake. Given these problems, sediment above the 1963 peak is treated as "more recent" than sediment below the peak, however no reference to any particular year is made. It was considered important to obtain valid macrofossil and cladoceran data for recent years, and therefore an amalgamation of surface sediment from the top slices (ca 1 cm) of three Glew cores collected in January 2011 were analysed as "0 cm" for MALH7. The surface samples were originally collected in order to acquire recent cladoceran remains representing the whole lake, and are therefore from various locations. It follows that the spatial representation of these fossils is wider than of fossils from core MALH7 only. Pigments were analysed prior to core dating and therefore pigment data for the surface sediment sample are not available.

Sedimentation rates for MALH7 are approximately half those for MALH2, which results in lower resolution in analyses and also a broader temporal representation. Taking the average of the two oldest sedimentation rates and extrapolating downcore indicates that the 1750s in MALH7 are approximately around 30 cm, the 1700s around 35 cm, and the 1650s around 40 cm. Extrapolation beyond these depths is highly speculative.

Core organic content shows a relatively complacent profile compared with carbonate content (Figure 3), fluctuating between 13.4 and 24.6 %. No clear trend in direction is apparent below 24.5 cm, upcore of which there is an increasing trend, with maximal values recorded at 7.5 cm (ca 1950). Upcore, organic content decreases again, however the values remain higher than those recorded below 24.5 cm. Carbonate content fluctuates more, between values of 14.7 and 41.7 %. The highest values lie below 42.5 cm, with the maximal value at 72.5 cm. There is a dramatic drop spanning 25 % in carbonate content between 42.5 (ca 1600s) and 34.5 cm (ca 1700s), which is not mirrored by organic content (Figure 3). Rather, this proportional decrease in carbonate is compensated for by an increase in other mineral matter. Upcore of 34.5 cm, the relationship between organic matter and carbonate becomes more inverse again and the proportion of other material decreases (Figure 3). Carbonate content generally increases towards the core top, where it comprises 32 % of dry matter.

6.2 Pigments

The profiles of chlorophylls *a* and -*b* and their degradation products indicate that preservation has been variable through time, with no clear trend. Therefore data from the core base and top are comparable. Unlike the other proxies, pigments were analysed for the entire core, spanning from the top to 91 cm. The
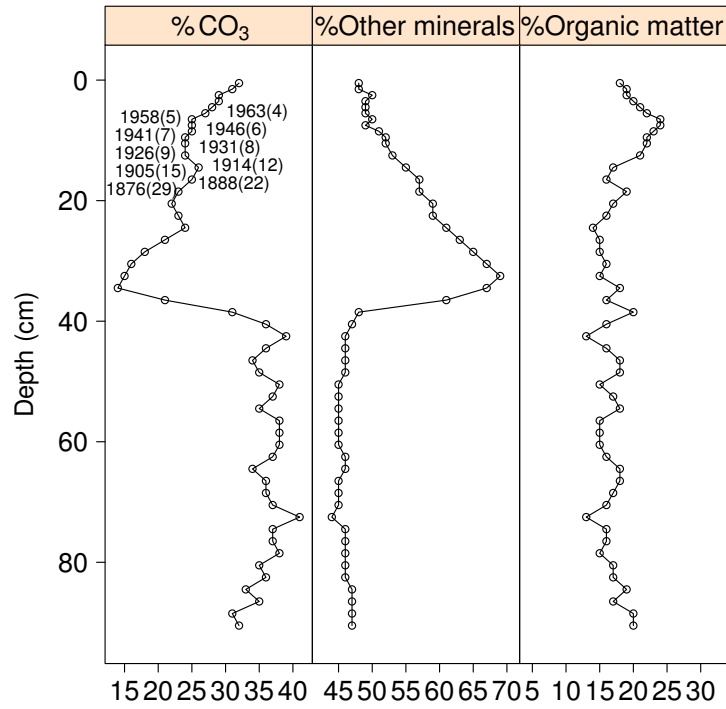
Figure 3: LOI data for core MALH7, including ^{210}Pb-derived dates with error margin ($\pm$ in years)

compositional zones derived through cluster analysis of subfossil cladocerans are indicated in Figure 4 for reference.

Pigment concentrations are low at the core base (Figure 4). From approximately 80 cm to 60 cm there is an increasing trend in concentrations of the ubiquitous pigments β-carotene and chlorophyll a, lutein (chlorophytes), diatoxanthin (diatoms), and canthaxanthin and zeaxanthin (cyanobacteria). The profiles of fucoxanthin (siliceous algae) and alloxanthin (cryptophytes) are complacent in this region.

Upcore of approximately 60 cm, there is a decrease in the non-complacent pigments. The decrease is relatively abrupt for the ubiquitous pigments, whereas that of the cyanobacterial and siliceous algal pigments is more gradual, reaching a minimum at approximately 35 cm. Upcore, they increase again, as do the previously complacent alloxanthin and fucoxanthin. This is in contrast to the more ubiquitous pigments, which show relatively complacent profiles between approximately 57 cm and 16 cm (end of 19th century). Upcore of 16 cm the ubiquitous pigments increase in concentration, and there is also an accelerated increase in the concentrations of lutein and cyanobacterial, cryptophyte and siliceous algal pigments.

Owing to the complications with the core top, there is little confidence in the data of the uppermost 5 cm. Values are generally high, with exceptionally high concentrations at a core depth of 2.5 cm. The large variability in pigment concentrations in the uppermost 5 cm indicates that sediment has not been homogenously mixed by the process that removed surface sediment from the coring location. Due to uncertainty with sedimentation conditions for these levels, these data are not discussed.
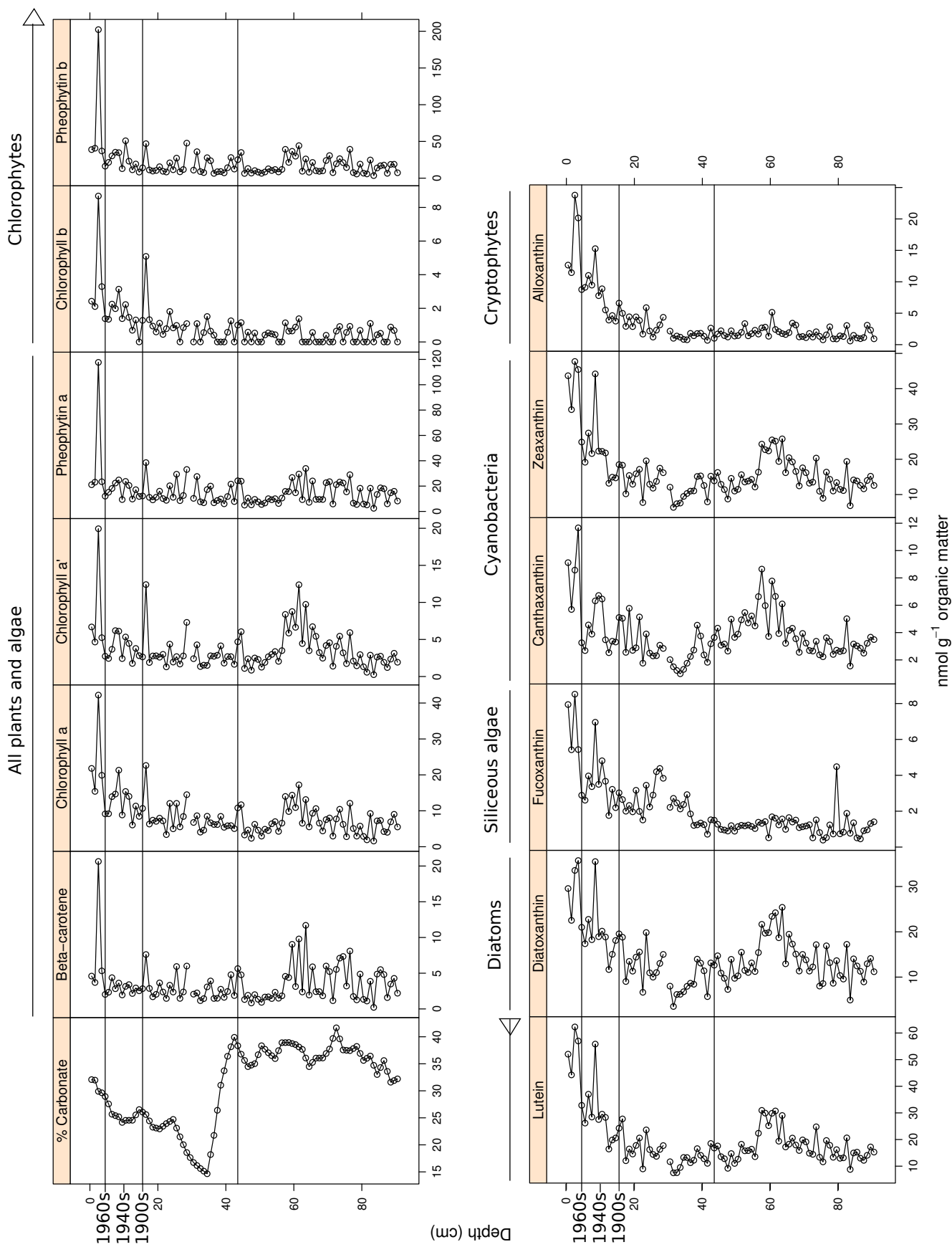
Figure 4: MALH7 pigments arranged according to taxonomic affiliation, and % carbonate shown for reference. Black solid lines indicate compositional zones derived for subfossil cladocerans through cluster analysis.

6.3 Subfossil cladocerans

Four major clusters emerged within the cladoceran data set, with levels 0 - 3 and 6 - 14 cm in one parent cluster, and 17 - 41 and 46 - 71 cm in another. The ephippia counted as macrofossils are discussed in conjunction with the subfossil cladoceran data. The designation "*Alona*, smaller species" contains the species *A. rectangula, A. rustica, A. guttata* of which the post-abdomens of *A. rustica* were most abundant. Owing to the low incidence of diagnostic body parts of these species it can only be assumed that all three species have existed in the Tarn throughout the history represented by MALH7, and no attempt was made to compare their abundances. In total, 25 species were identified in the core as chitinous subfossil remains, 26 when adding the macrofossil ephippia of *Simocephalus* sp. Several taxa, including *Alonopsis elongata, Graptoleberis testudinae* and the small *Alona* spp. exhibit relatively complacent core profiles. Other taxa display species turnover through time. For example, *Chydorus piger* was only found in zones 1 and 2, and *Sida crystallina* in zones 1, 2, and 3. *Oxyurella tenuicaudis* was extremely rare in the core profile and no pattern of presence through time can therefore be ascertained. *Acroperus harpae, Alonella nana, Camptocercus rectirostris, Chydorus sphaericus, Daphnia pulex, Pleuroxus denticulatus, Pleuroxus laevis* and *Pleuroxus trigonellus* all increase in abundance in zones 3 and 4.

The lowest zone (1) is characterised by very little change in species composition (Figure 5) and abundance (Figure 6a). The community is dominated by *Bosmina* cf. *longispina, Alona quadrangularis, Alona affinis, Alonella excisa* and *C. sphaericus*. In terms of habitat, pelagic and benthic cladocerans dominate, with the proportion of macrophyte-associated taxa increasing towards the top of the zone.

In zone 2, the overall abundance of cladocerans decreases (Figure 6a). Pelagic cladocerans decrease in abundance, while macrophyte-associated taxa increase. However, the dominant species remain the same as in zone 1. The proportion of *A. elongata* increases, and *P. trigonellus* and *A. harpae* in particular become more abundant in this zone.

Cladoceran abundance increases throughout zone 3, and there are changes in the balance of the dominant species, of which *A. affinis* and *A. quardangularis* decrease in abundance, while *Bosmina* and *C. sphaericus* increase. There are no records of *C. piger*, and *P. laevis, A. nana* and *C. rectirostris* become more abundant. The first record of *D. pulex* as post-abdominal claws is from the uppermost sample of this zone (6 cm). The species is better represented by ephippia assuming valid identification, showing a marked increase through zone 3. The ephippia of *Simocephalus* sp. and *Pseudochydorus globosus* show a similar but less dramatic pattern. There is a marked increase in the proportion of pelagic cladocerans, reciprocally bottom-dwelling taxa decrease in abundance.

The uppermost two samples form zone 4, which does not deviate from zone 3 in terms of habitat changes. Cladoceran abundance is lower than in zone 3. The most striking difference between the two zones is the increased abundance of *A. nana, P. globosus, Simocephalus* sp. and *P. denticulatus* and the prevalence of *D. pulex*.

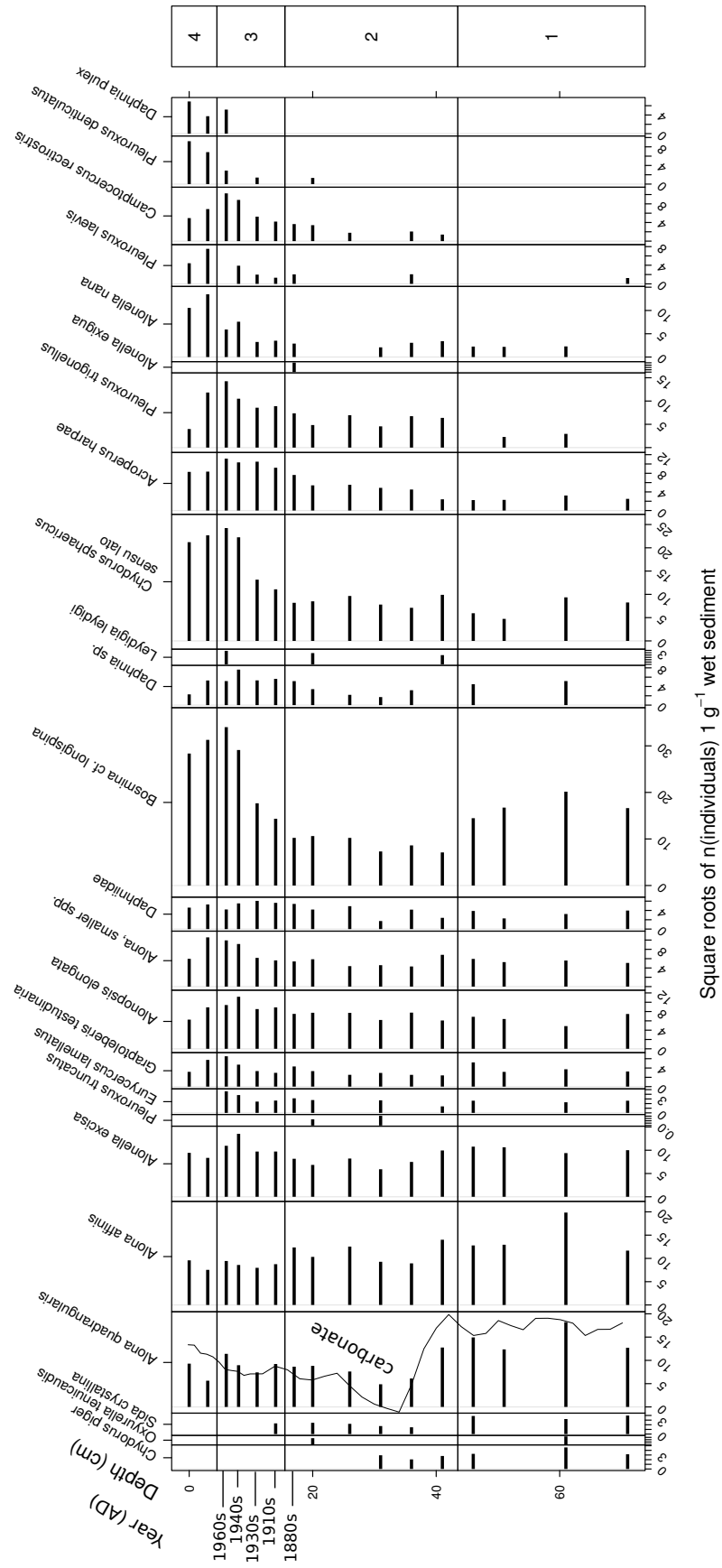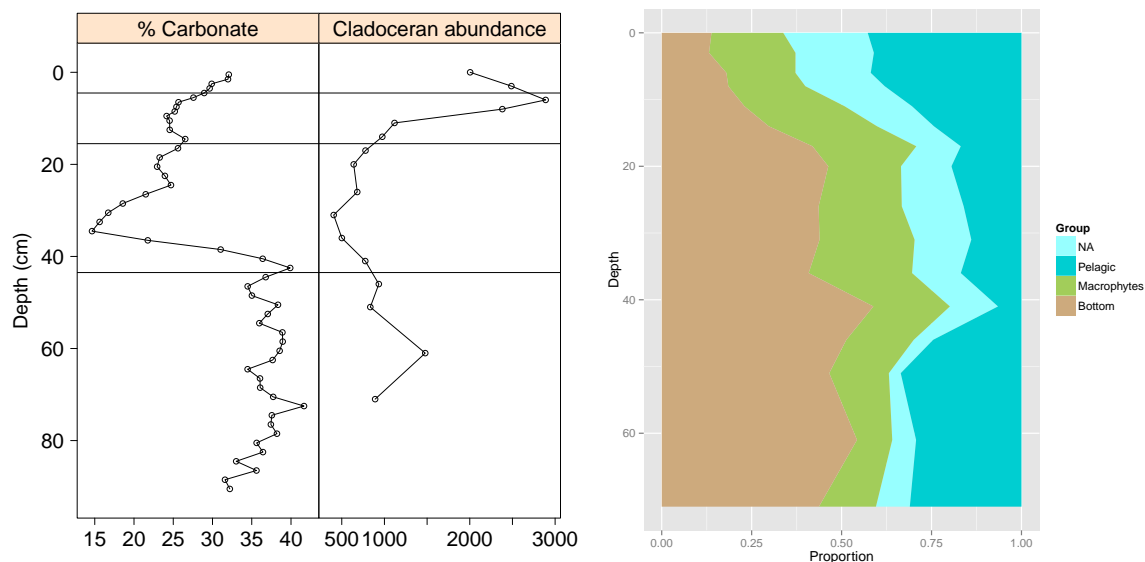Figure 5: MALH7 subfossil cladoceran data shown as square root values to represent relative abundances while preserving differences in absolute abundance. Black solid lines divide the diagram into compositional zones derived by cluster analysis.

a The total abundance of cladocerans displayed with carbonate content (rescaled to fit to display trend) and cladoceran community zones.

b Cladoceran habitat preference types. NA includes *Chydorus sphaericus* and undifferentiated daphniids with variable habitat preferences.

Figure 6: MALH7 cladoceran summary data.

6.4 Macrofossils

Macrofossil abundance in MALH7 was lower than expected, containing very few oospore and mollusc remains as well as encrusted charophyte stems despite historically and presently recorded high abundances of charophytes and molluscs. No Potamogetonaceae fruits were found although leaf remains of broad-leaved species were recorded in several core levels. In contrast, terrestrial fossils were relatively abundant and several were given abundance scores. Constraining clusters to four yielded the same divisions as for cladocerans except for the uppermost zone which consists of the surface sediment sample only. Calcite crystals ("crystal plates") were found in most levels, which were relatively two-dimensional and pure from dirt. It is uncertain how they were originally formed, however they dissolved completely when placed in HCl. It is unlikely that they formed from reworking of biological calcite structures, as high preservation of calcites is indicated by the abundance of ostracods including fragile limnocytherids. Identification of oospores proved ambiguous owing to several of the morphotypes having measures at the edge of definitive identification. Therefore, apart from *Nitella*, most typings should be treated with caution. Certain identifications were of species recorded in the Tarn. Both a round and an oblong morphotype found throughout the core are likely to belong to the *Chara hispida* aggregate group which includes *Chara virgata*. A particularly small oospore also found throughout the core profile is likely to derive from *Tolypella glomerata*. An oospore type found at the base of the core, with a relatively lightly encrustation and a translucent appearance showing a light brown oospore colour, was identified as *Chara globularis*. Alternative identifications frequently led to the *Chara contraria* group. Owing to the uncertainties in identification no relative species abundances are displayed. This could also be misleading as the species vary in their depth distribution and in this core oospores of deep-growing species are likely to occur at greater abundance. Trichoptera and oribatid mites show no trend through the core profile and are not described in detail.
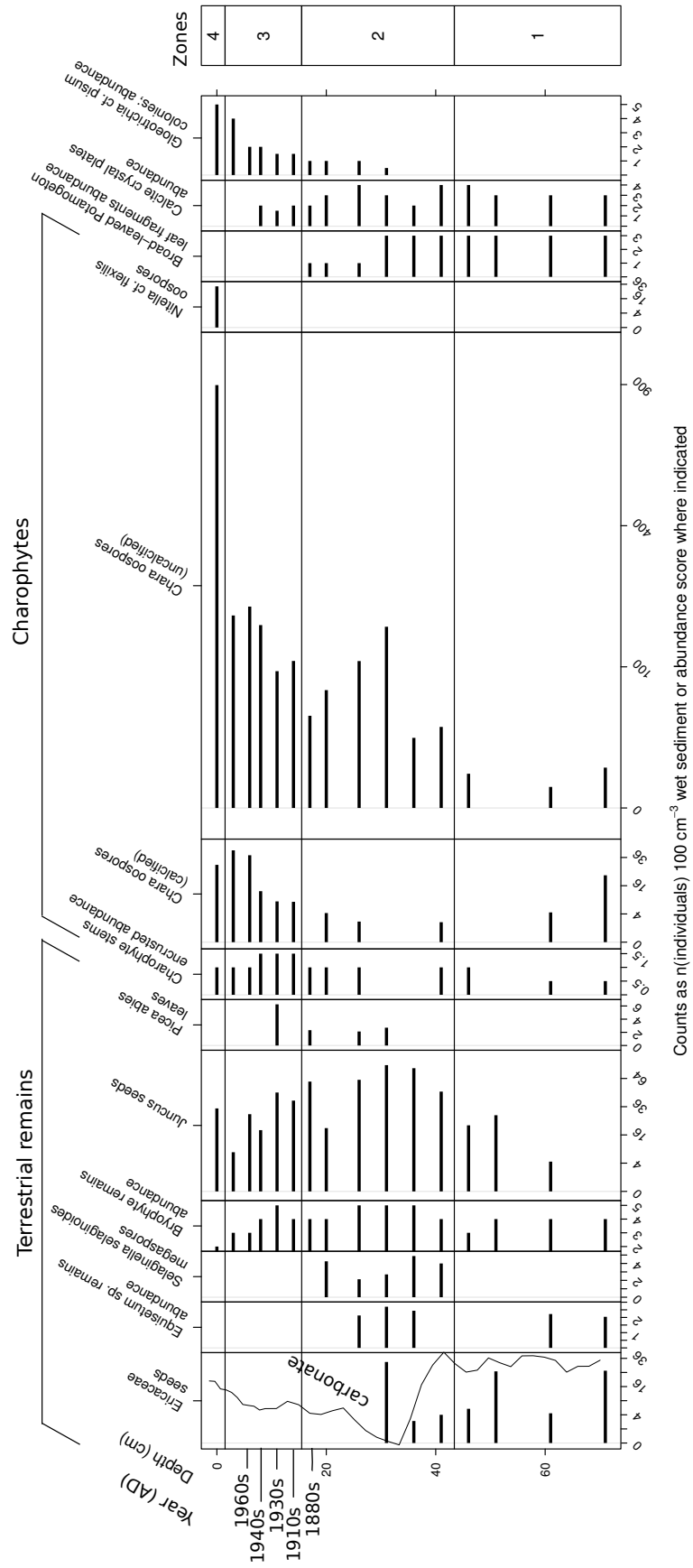
Figure 7: MALH7 plant macrofossil data with zones derived through cluster analysis.

Figure 8: MALH7 animal macrofossils with zones derived through cluster analysis.

Zone 1 contains the highest abundance of broad-leaved Potamogetonaceae leaf fragments, and also a high abundance of crystal plates. The two lowermost levels have a relatively high count of calcified oospores of the *Chara globularis* type. Relatively abundant terrestrial remains include Ericaceae seeds and bryophyte leaves. *Juncus* seeds increase in abundance towards the top of the zone.

Plumatella spp. and *Cristatella mucedo* statoblasts are rare in zone 1. Mollusc remains are most abundant in the bottom half of the zone, containing identifiable remains of *Bithynia leachi + tentaculata*, *Lymnaea* sp., *Valvata* cf. *macrostoma* and the Sphaeriidae.

The leaf remains of broad-leaved Potamogetonaceae are abundant at the base of zone 2 but decrease upcore, as do crystal plates. Uncalcified *Chara* oospores are more abundant here than in the preceding zone, however the abundance of calcified individuals does not change markedly. *Gloeotrichia* cf. *pisum* appears in the upper half of this zone in low abundance. *Juncus* seeds reach maximal abundances in this zone, and the megaspores of the lycopod *Selaginella selaginoides* are exclusive to this zone. The abundance of Ericaceae seeds are not recorded beyond the midpoint of the zone, while *Picea abies* leaves are found in the top half only. By contrast, bryophyte remains are very abundant in zone 2 and show no trend.

There is a remarkable absence of mollusc remains in zone 2. The opercula of *B. leachi + tentaculata* are relatively abundant, but the overall abundance of remains is very low. *Plumatella* spp. are also recorded in very low abundance, and *C. mucedo* not at all.

There are no leaf remains of broad-leaved Potamogetonaceae in zone 3. In contrast, both calcified and uncalcified charophyte oospores increase in abundance through the zone and this is reflected in the abundance of stem encrustations. Crystal plates decrease in abundance and were not recorded in the upper region of the zone. *G.* cf. *pisum* increases towards the top of the zone. Bryophyte remains as well as *Juncus* seeds decrease in abundance towards the top of the zone, and *P. abies* leaves disappear from the record.

Mollusc remains are rare also in zone 3. *B. leachi + tentaculata* persist in low abundance. The upper end of the zone contains the first record of round morphotypes of *Plumatella* statoblasts, and the oblong morphotype recorded previously also increases in abundance towards the top of the zone.

Zone 4, the uppermost sample, is different from the other zones in part by virtue of representing multiple locations in the Tarn. It is defined by higher abundances of *Chara* oospores and the first occurrence of *Nitella* cf. *flexilis* oospores. *G.* cf. *pisum* is at maximal abundance, and bryophytes at a minimum.

Molluscs are extremely abundant in zone 4. In addition to species already mentioned, *Planorbis crista* and *Planorbis* cf. *laevis* are recorded for the first time. In contrast, there are no records of *Bithynia* or *Lymnaea* spp. *Plumatella* spp. reach maximal numbers in zone 4, as does *C. mucedo*.

7 Overall discussion and summary

7.1 The representation of the history of Malham Tarn by core MALH7

7.1.1 Spatial representation of aquatic communities

Current and historical data on the distribution and species composition of macrophytes in Malham Tarn are presented in Wiik (2012, Ch. 2), summarised in Table 4. Macrofossils in MALH7 capture only a small portion of the overall change in the macrophyte community of Malham Tarn as recorded historically. For example, the surface sediment sample, containing an amalgamation of several core top slices and therefore integrating information from several locations from the lake, is the only sample to contain *Nitella* oospores and abundant mollusc remains. For some species the lack of fossil representation is unsurprising. For example, *Littorella uniflora* can only be quantified through pollen analysis and *Elodea* spp. do not leave intact fossil remains. The fruits of Potamogetonaceae are produced in low numbers and also frequently eaten by water fowl, resulting in underrepresentation in the fossil record unless plants are particularly abundant (Zhao et al., 2006). However, given the records of several species of *Potamogeton* and large stands of *Potamogeton lucens* in particular over the 20th century, the absence of seeds in MALH7 was surprising. *Myriophyllum spicatum*, though potentially absent from the Tarn currently, was also relatively frequent earlier in the 20th century and is a species underrepresented in the fossil record (Davis, 1985; Davidson et al., 2005). Broad-leaved *Potamogeton* leaf remains were frequently encountered in the lower levels of the core and are highly likely to belong to *P. lucens, Potamogeton alpinus, Potamogeton praelongus* and/or *Potamogeton polygonifolius*, species historically recorded in the Tarn. Leaf fragments are easily distributed across a lake, also evidenced by frequent observations at the strandline in various lake margins, and therefore these remains are interpreted as an indication of changing abundance in the lake.

The scarcity of oospores in MALH7 was also surprising given the highly abundant community at present and historically. For comparison, maximal abundances per $100 \, \text{cm}^3$ recorded in Cunswick Tarn and Hawes Water are around 8000 and 6000, respectively (Wiik, 2012), compared with 300 in MALH7, and abundant *Chara* oospores were also recorded in the post-glacial sediments of a core taken from Tarn Moss, the raised bog adjacent to the western flank of the Tarn (Pigott and Pigott, 1959) (though see also Zhao et al. (2006); Davidson et al. (2007)). Despite this, the increase in oospore numbers, corresponding to slight increases also in encrusted stem remains, towards the core top of MALH7 indicates increasing abundance of charophytes over the time period covered by MALH7.

7.1.2 Temporal representation of MALH7 and consequences on interpretations of the core record

The lowest dated level of MALH7 is 18.5 cm, however the core is 91 cm long and palaeolimnological analyses were conducted to a depth of 71.5 cm excepting pigments which were analysed for the full core. Extrapolating from sedimentation rates suggests that the 1750s are located at approximately 30 cm, the 1700s at around 35 cm, and the 1650s at around 40 cm. In previous cores collected from the Tarn, the building of the weir in 1791 that increased the water level by approximately 1.2 m (Bradley, 2007) has been identified as a sharp increase in the proportional content of organic matter (Pentecost, 2000). In

Table 4: Historical records of macrophytes in Malham Tarn, and all species recorded in 2009/2010. The growth form of *Aegagropila linnaei* is the globally rare ball (Lund, 1961; Boedeker et al., 2010). Annual (August) surveys of the Tarn have also been conducted by Hinton (2005).

Date	Flora	Source
2009,2010	*Aegagropila linnaei, Chara aspera, Chara globularis, Chara virgata, Nitella opaca (Nitella flexilis), Fontinalis antipyretica, Callitriche hamulata, Elodea canadensis, Equisetum fluviatile, Lemna minor, Menyanthes trifoliata, Potamogeton berchtoldii, Potamogeton crispus, Potamogeton lucens, Zannichellia palustris* + *Hippuris vulgaris* as strandline wash	Surveys by author
2005	*C. aspera, C. globularis, C. virgata, N. flexilis* agg., *N. opaca, Tolypella glomerata, F. antipyretica, C. hamulata, Callitriche* cf. *platycarpa, E. canadensis, L. minor, M. trifoliata, P. berchtoldii, P. lucens, P. crispus, Z. palustris*	Survey by B. Goldsmith and A. Burgess, ENSIS
1995	*A. linnaei, C. globularis, F. antipyretica, C. hamulata, E. canadensis, M. trifoliata, P. crispus, P. lucens*	Bennion et al. (1997)
1993	*Chara* spp. and *M. spicatum* abundant, too early in season for *P. lucens*	Richardson and Magee (1995)
1960s	*A. linnaei, C. aspera, C. globularis, F. antipyretica, E. canadensis* (1962, Rare), *M. spicatum, P. berchtoldii, P. lucens, Potamogeton perfoliatus, Potamogeton gramineus x perfoliatus*	Lund (1961); Holmes (1965), J. Birks, school trip
1950s	*A. linnaei, C. aspera, C. globularis, F. antipyretica, H. vulgaris, M. spicatum, P. berchtoldii, P. lucens, P. natans, P. perfoliatus, P. gramineus x perfoliatus, P. polygonifolius*	Various herbaria collectors (herbariaunited.org), Pigott and Pigott (1959); Holmes (1956, 1965)
1936	*C. aspera, C. globularis, F. antipyretica* ["plentiful in the region round the inlet"], *Hypnum scorpioides, Callitriche stagnalis* ["in the shallow western bay"], *Littorella uniflora* [northeast corner], *M. spicatum, P. alpinus* [by boathouse], *P. lucens* ["locally dominant forming dense beds off the southern and eastern shores"], *P. perfoliatus*; Colonisation through all depth zones, but "much of the central and western part is devoid of bottom vegetation"	Sledge (1936)
1925	"Examining the pondweeds washed up along the edge of the Tarn...": *P. x angustifolius (x zizii), P. lucens, P. lucens* var. *acuminatus, P. perfoliatus, P. praelongus*	Pearsall and Mason (1925)
1741	"There are no weeds in it. In a fine still day, you may see the white chalky bottom, where it is 10 or 12 foot deep."	Fuller (1741)

MALH7, there is a change in the trajectory of organic matter content at 24.5 cm above which carbonate content reciprocally decreases (Figure 3). Accepting this as the 1791 marker is not in conflict with the extrapolated age for this core section, and therefore it is plausible that this core section indeed represents the late 18th century. Although it is impossible to assess the age of the lowermost levels of MALH7, the record is likely to extend at least to the 1000s.

The last 1000 years encompass several climatic changes, the major periods of which include the Mediaeval Warm Period (MWP), the Little Ice Age (LIA), the subsequent climatic amelioration, and finally anthropogenic climate change. For the UK, and this region of the UK in particular, the MWP occurred from AD 880 to 1350 (Dong et al., 2012) during which time temperatures were comparable to those of the first half of the 20th century. The LIA that followed was not uniformly cold, but contained phases of variable severity. The LIA was coldest in the late 17th century but another spell of particularly cold

conditions ensued between 1768 and 1817, with climatic amelioration from the 1850s (Johnson, 2010). Anthropogenic climate change is detected in the weather patterns around Malham Tarn, with a 1°C increase in annual mean temperature between the 1960s and the early 21st century (Burt and Horton, 2003), reflected in a decrease in the frequency and duration of ice cover (Bradley, 2007).

Climatic changes have to be taken into consideration when interpreting core signals, as they influence the productivity and community composition of aquatic ecosystems (e.g. Gyllström et al., 2005; Korponai et al., 2011; Jeppesen et al., 2012). Separating the effects of climate change and direct anthropogenic pressure on lake ecosystems can be very difficult, as for example warmer temperatures incur ecological changes much alike those following nutrient enrichment (Blenckner et al., 2002; Paerl and Paul, 2012), and in the most recent centuries such changes have been synchronous. Climatic amelioration after the 1850s coincided with increased imports of fertiliser such as guano, the introduction of nitrogen fertilisers, and the development of drainage systems (Johnson, 2010). Therefore core signals of increased productivity in the later 19th century may reflect either more clement temperature or increased pressure from the catchment, or both. The timing of these events has consequences also for the attempt to define reference conditions for lakes under the European Water Framework Directive (WFD), as "pre-enrichment" conditions are typically set around 1850, which also marks the end of the LIA. Biological communities under a different climatic regime may not be representative of reference conditions presently. Also, under the currently changing climate and therefore moving baseline, it is important to understand the unique effect of warming when assessing ecological change in lakes in terms of eutrophication and remediation measures (Bennion et al., 2012).

7.1.3 Historical changes in land use around the Tarn

The history of catchment use in Malham Tarn is relatively well recorded and discussed in Bradley (2007). Agricultural activity around the Tarn, and also fishing in the Tarn, have a long history. The Norse had early settlements in the area, followed by monastic tenure around the 1100s through to the 1500s. Nutrient pressure on the Tarn during these centuries is likely to have been low, but escalated following the 1740s when land immediately surrounding the water became a site for extensive cattle fairs until the beginning of the 19th century. It is likely that agriculture in the area, including liming, was little affected by the LIA, for example the effects of the cold snap between 1768 and 1817 was in part counteracted by encouraged land improvement following the Enclosure Act (Johnson, 2010). Palaeo pollen work in the Ribblesdale area has not revealed change in vegetation and land use during the LIA (H. Shaw, pers. comm.)

The intensification of farming practices over the 20th century has increased pressure on the Tarn (Bradley, 2007), and long-term monitoring of water chemistry by the Environment Agency reveal relatively high nutrient concentrations in the inflow since the 1970s with a tendency to higher values from the late 1990s (Figure 9). The timing of increasing nutrient pressure is coincident with more recent anthropogenic warming and these effects may not be possible to disentangle in the MALH7 core signal.
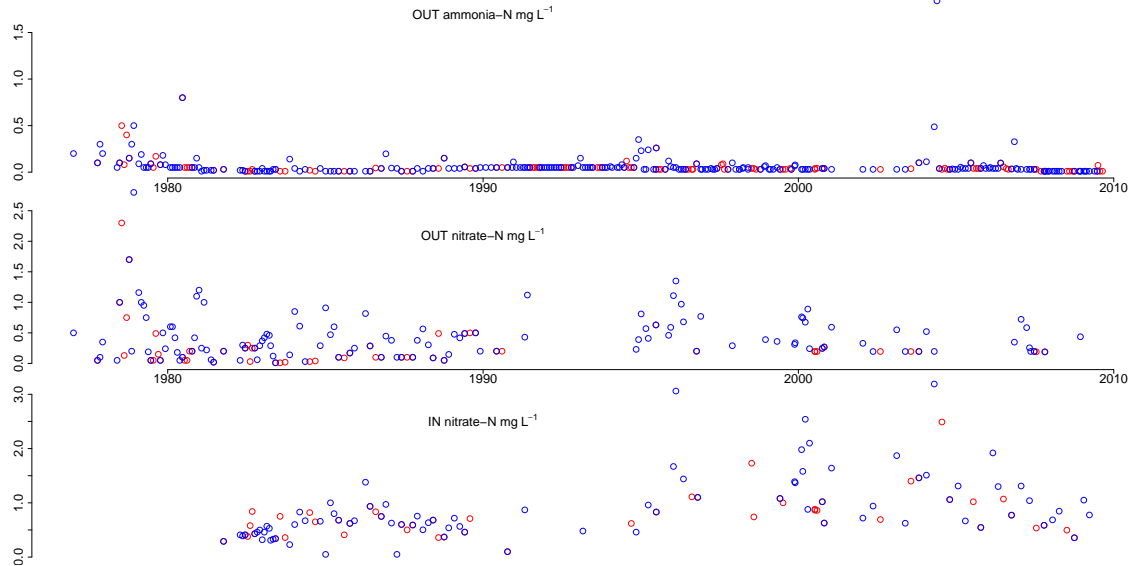
Figure 9: Environment Agency data of Malham Tarn inflow (IN) and outflow (OUT) water. Red dots are summer month data. Phosphorus data are more patchy and are therefore not displayed. *Data courtesy of G. Hinton, Natural England.*

7.2 Evidence of recent eutrophication and consequent ecological change

In search for conclusive evidence of nutrient enrichment in the Tarn it is prudent to focus on core changes that are unique to the uppermost levels in order to control for climatic effects. Key changes in the fossil assemblages are upcore (1) increase in oospores and conversely decrease in Potamogetonaceae leaf fragments (2) increase in *Gloeotrichia* cf. *pisum* (3) increase in *Daphnia + Simocephalus* ephippia and *P. globosus* carapaces. In the subfossil cladoceran profile indirect evidence for unique changes in the upper core sections comes through the designation of zones 3 and 4 into a parent cluster separate from zones 1 and 2. The species characterising these uppermost zones are *D. pulex, P. denticulatus, P. laevis, C. rectirostris, A. nana, C. sphaericus* and to a lesser extent *A. harpae* (Figure 5). *C. piger*, found in zones 1 and 2, on the other hand, is absent in zones 3 and 4.

Eutrophication in lakes naturally containing macrophytes is characterised by a loss of benthic pathways, decreses in light penetration and macrophyte colonisation depth, increases in phytoplankton, and in severe cases change in macrophyte community structure, loss of macrophyte coverage, and even a complete loss of macrophytes and a transformation to a phytoplankton-dominated turbid condition (Jeppesen et al., 2005; Scheffer and van Nes, 2007). These changes are fundamental, and accompanied by changes across most if not all organism groups, with "sensitive" species replaced or numerically dominated by "tolerant species". It should also be noted that in naturally oligotrophic lakes, eutrophication may initially manifest itself as an increase in macrophyte cover as macrophytes cease to be limited by nutrient availability. Malham Tarn, currently with a mean total phosphorus concentration of $18\,\mu g\,L^{-1}$ and abundant macrophyte cover, can clearly not be expected to be symptomatic of advanced eutrophication. However, the earlier, more subtle changes are expected to be present if eutrophication has indeed taken place.

The shifts in cladoceran community composition reflect the relatively low nutrient concentrations in Malham Tarn. Some of the species that increase in abundance towards the core top are species associated with relatively low-nutrient sites, such as *A. harpae* and *A. nana* (Whiteside, 1970; Hofmann, 1996; Bos

and Cumming, 2003). Further, *A. elongata*, which displays a relatively complacent profile, has been shown to be unlikely to be abundant or present in Irish lakes with TP towards the more eutrophic side of around $20\,\mu g\,L^{-1}$ (De Eyto et al., 2002). On the other hand, the relative abundance of *C. sphaericus*, a tolerant and ubiquitous species whose abundance is unequivocally associated with more eutrophic conditions (Whiteside, 1970; Hofmann, 1996; De Eyto et al., 2002; Manca et al., 2007), increases steadily upcore through zones 3 and 4. Further, *D. pulex*, which shows a similar pattern, is also frequently associated with relatively eutrophic waters (Bos and Cumming, 2003; Davidson et al., 2007) and has been shown to increase with eutrophication in palaeolimnological studies (Bennion et al., 2009, 2010; Davidson et al., 2011). It is particularly interesting that *D. pulex* does not appear in previous records from the Tarn (Fryer, 1993), yet it was found frequently during sampling undertaken by the authors in 2009 and 2010, indicating the subfossil record correctly portrays relatively recent increases in abundance. It is also interesting that *C. piger*, not present in zones 3 and 4 (following the late 1800s), was also most frequent towards the base of a core from Cunswick Tarn, a presently eutrophic and ecologically damaged lake (Wiik, 2012). The species also decreased in abundance following eutrophication in Lake Maggiore (Manca et al., 2007), and could therefore, as a species sensitive to eutrophication, also be used as an indicator of early ecological degradation.

The cladocerans that increase most through zones 3 and 4 in MALH7 are macrophyte-associated and pelagic taxa. *A. harpae* and *P. laevis* in particular are associated with dense vegetation (Davidson et al., 2007). In addition, the total abundance of cladocerans is higher in these zones than preceding levels (Figure 6a) indicating that both food (Sakuma et al., 2004) and habitat (Thoms et al., 1999; Gyllström et al., 2005; Davidson et al., 2007) are likely to be more abundant. The upcore increase of *P. globosus* supports this, as it is a scavenger feeding on dead crustaceans and therefore increases in its abundance indicate increased food abundance. Cladocerans with reportedly more benthic preferences (*A. affinis, A. quadrangularis, A. elongata*) conversely decline in relative abundance. Together, these patterns indicate that since the early 1900s, food availability in the form of epiphytes as well as phytoplankton, and macrophyte coverage, has increased in Malham Tarn. This is in agreement with signs of moderate eutrophication.

The eutrophication-indicating changes in the cladoceran community are mirrored by other macrofossil evidence. *Gloeotrichia* is a colonial nitrogen-fixing cyanobacterium, presence/abundance of which indicate moderate eutrophication (Laugaste and Lessok, 2004) and/or nitrogen limitation (Vis et al., 2006; Hudon et al., 2009). In agreement, increasing abundance was associated with the early stages of eutrophication also in Cunswick Tarn, followed by a decline as eutrophication became more severe (Wiik, 2012). The increase in its abundance is synchronous with a decrease in broad-leaved Potamogetonaceae leaf fragments, around the late 19th century. Historical records suggest a gradual decline in broad-leaved Potamogetonaceae over the 20th century involving extirpation of seven species including such associated with oligotrophic waters. Therefore it is highly likely that the decline of leaf remains since the mid-late 1800s is representative of a decline in the whole *Potamogeton* population. In this sense, although charophytes are key components of marl lake flora, the upcore increase in oospores may in fact reflect gradual degradation in the ecological quality of the lake. Importantly, because this precedes the introduction of *E. canadensis* in the 1960s, the doubts raised by Bennion et al. (1997) concerning vegetational change owing

to the competitive exclusion by *E. canadensis* cannot be solely responsible for the observed community changes. Instead, the synchroneity with other community changes suggests that eutrophication is indeed the prime driver.

7.3 Uncertainties and further questions

The greatest uncertainty regarding the interpretation of the MALH7 record lies in the assignment of dates to key levels deeper down in the core, such as the point (ca 42 cm, 1600s) at which there is a substantial upcore drop in core carbonate content, and the division of fossil assemblage clusters 1 and 2 in the same core region. Between zones 1 and 2, there is a drop in mollusc and overall cladoceran abundance in addition to *Bosmina*, which would suggest a decrease in (microalgal) productivity. On the other hand, there is an increase in oospore abundance that could indicate an increase in charophyte populations. This pattern could be consistent with climatic deterioration as charophytes overwinter in Malham at present and are therefore not extirpated by cold conditions. However, to ascertain whether these changes are primarily climate-driven, it would be essential to obtain radiometrically derived dates for these core sections.

The problem of date assignment also applies to changes further downcore. The pigment profile shows interesting changes around 60 cm and in fact does not display major changes around 40 cm in contrast to macrofossil and cladoceran data. The concentrations of several microalgal and generic pigments increase from ca 80 cm to ca 65 cm and decline thereafter. Interestingly, for generic but not microalgal pigments, these concentrations generally exceed those close to the core top. The scarcity of charophyte oospores in this region, and the relatively high overall abundance of molluscs as well as cladocerans including *Bosmina* specifically, would suggest Malham Tarn supported greater pelagic and microalgal production than during the later period of zone 1. It would be tempting to invoke climatic changes as an explanation for this likely Mediaeval phase, however again independent verification would be essential. Given more information on the temporal representation of the core, it would be interesting to continue macrofossil and cladoceran analysis further downcore, at higher resolution, to shed more light on the change in pigments.

Finally, whether the remarkable change in carbonate and other mineral composition in MALH7 is replicated in other cores is worthy of further investigation. The change is particularly interesting because the decline in carbonate is very rapid (less than 10 cm) whereas the increase thereafter is gradual, such that relative compositions similar to those downcore of the change are only attained at the core top. In loose correspondence to this change, there is a decrease in Ericaceae seeds and *P. abies* leaves appear in the record for the first time. *P. abies*, the Norway spruce, disappeared from the UK during the last glaciation and has been artificially reintroduced. Therefore, it is possible that the increase in mineral matter could be the result of changes in land use for example from heathland to spruce plantations, perhaps coupled with deteriorating climate involving wet winters and therefore increased sediment loads.

The last record of spruce leaves are from core levels corresponding to the 1930s, and the author cannot remember seeing spruce around the Tarn at present. "Plantations" in a nascent state are mentioned in an account of the Tarn from 1786 (Hurtley, 1786) and it is possible that woods have been managed around

Malham for a very long time. The mixed woodland currently lining the northwestern flank of the Tarn seems to have been planted in the 19th century (Disney, 1975).

7.4 Reference conditions of Malham Tarn

Reference conditions for Malham Tarn are based on accepting eutrophication as the primary driver for changes unique to the uppermost core levels, and the likelihood of the lower levels of the core to predate the Little Ice Age and therefore to be more representative of the lake in the present climate. On the basis of increases in the abundance of macrophyte-associated cladoceran taxa towards the core top, reference conditions for Malham Tarn are in contrast likely to involve relatively low macrophyte cover at all depths combined with relatively low yet sustained productivity in the plankton. A diverse community of Characeae and Potamogetonaceae would characterise the vegetation of Malham Tarn in a largely natural state. Among the cladocerans, the relative contribution of *C. sphaericus* would be low, whereas *C. piger* would be more common than at present. *Bosmina* and large *Alona* spp. would be the dominant species out of those recorded through subfossil cladoceran analysis.

The current mean TP of $18\,\mu g\,L^{-1}$ is much higher than values averaging $9.5\,\mu g\,L^{-1}$ recorded through 1985-1987 (MAL - PROC 2011). Pentecost (MAL - PROC 2011) estimated that P from the catchment limestone alone would contribute to lake concentrations by approximately $4\,\mu g\,L^{-1}$ and therefore natural concentrations would probably be similar to this estimate.

8 Conclusions and management implications

The palaeolimnological record shows that Malham Tarn has undergone a slow yet steady eutrophication process for several centuries. Pigment data suggest that the cattle markets beginning in the late 1700s may have begun the enrichment process as indicated by coincident increases in microalgal pigments. A more marked increase in pigment concentrations since the late 1800s, combined with the synchronous onset of eutrophication indicated by cladoceran and macrofossil data suggest a more pronounced phase over the late 1800s and 1900s. The most recent change in the sediment record, over the latter part of the 20th century, is supported by long-term high nutrient inputs revealed by the water chemistry data courtesy of the Environment Agency, as well as through thorough contemporary monitoring and available historical records as discussed by Wiik (2012). It is clear that the lake is not in a natural state and therefore action should be taken to reduce nutrient inputs from the catchment, especially once information regarding the contribution of various sources is obtained through the nutrient budget work carried out by Natural England at present.

It would be extremely valuable to maintain monitoring of the lake and the cessation of monitoring by the EA is therefore regrettable. It would also be valuable to regularly sample the cladoceran and macrophyte communities, as these assemblages have changed significantly within the most recent decades. Due to concerns of the levels of nutrients also in rainwater in the area (Holmes, 1965; MAL - PROC 2011), this source should be included in the nutrient budget work being carried out, both for forms of phosphorus and nitrogen.

9 Acknowledgements

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