

Final Report

Project WFD08

**Identification of reference lakes and evaluation of
palaeoecological approaches to define reference conditions for
UK (England, Wales, Scotland & Northern Ireland) ecotypes**

August 2004



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Executive Summary

This is the final report to the Scotland and Northern Ireland Forum for Environmental Research (SNIFFER) under project no. WFD08, '*Identification of reference lakes and evaluation of palaeoecological approaches to define reference conditions for UK (England, Wales, Scotland & Northern Ireland) ecotypes*', funded by SNIFFER. This project forms part of the UK Strategy for the implementation of the European Council Water Framework Directive (WFD) which requires reference conditions to be determined for all water body types including lakes. This study aims to use palaeoecological techniques to identify reference sites, describe reference conditions and assess ecological status for a set of UK lakes. In contrast with previous detailed studies on a limited number of sites, we collate existing data from large numbers of lakes in the UK to aid implementation of the WFD at the national level. Furthermore, unlike earlier studies where the interest has been in determining the causes and extent of water quality change of impacted systems, this project aims to identify reference lakes and hence new sediment cores were collected from lakes thought to be relatively unimpacted.

The study focuses largely on the analysis of diatom (*Bacillariophyceae*: siliceous algae) remains in sediment cores. Diatoms are sensitive to water quality changes and shifts in the diatom community often correspond closely to changes in other biological elements. A number of other groups that preserve in the lake sediments, representing a range of biological elements relevant to the WFD, are examined in two of the four work packages, including chironomids (Diptera), cladocera (zooplankton), aquatic pollen and plant macrofossils. The report is comprised of four main chapters, each dedicated to a work package.

Work package 1 aims to classify lakes (from across the UK) based on diatom reference conditions and to compare the classification with the GB Lake Typology. Diatoms were analysed in the bottoms (reference condition) of sediment cores from a large set of lakes (N=219) covering the range of types found in the ecoregion. Two Way Indicator Species Analysis (TWINSpan) was employed to classify the reference samples according to their diatom assemblages, and thereby characterise the reference floras of the different lake types. TWINSpan identified eight site end-groups, each with a characteristic diatom assemblage although there was some overlap in the taxa present in the groups. The diatom groups were compared with the GB Lake Typology to assess the ecological relevance of the typology scheme. There is close congruence between the two datasets, indicating that the criteria of geology (reflecting alkalinity) and, to a lesser extent, lake depth used in the latter does result in ecologically meaningful typologies. The comparison highlighted a number of lakes that had been misclassified by the GB Lake Typology.

Diatoms were analysed in the surface samples (present day conditions) of the 219 cores. The degree of floristic change between the reference and surface sample of each core was assessed using a squared chord distance dissimilarity coefficient which ranges from 0 (no difference) to 2 (completely different). A score of <0.475 (5th percentile) is used here to define reference sites (i.e. those with low floristic change between the two samples). The scores for the 219 lakes range from 0.13 to 1.77, with 79 lakes (36% of the dataset) experiencing low floristic change. In the low, medium and high alkalinity lake types, approximately 40%, 30% and 30% of the lakes, respectively, have a score <0.475 and, therefore, good examples of reference lakes are available for these lake types. However, ~50% of lakes in the existing dataset exhibit considerable floristic change with scores >0.58. In the low alkalinity lakes, these changes appear to largely reflect acidification, whereas in the medium alkalinity, high alkalinity and marl groups, the diatom changes are indicative of eutrophication.

Work package 2 aims to identify a set of reference lakes for each ecotype based on analysis of diatom assemblages preserved in lake sediment cores. Sediment cores (expected to represent the period from at least ~1850 AD to the present day) were taken from 34 sites in the UK selected as potential reference lakes. Diatom assemblages were analysed in approximately four to five samples from 31 of the cores (poor preservation prevented analysis of the remaining three sites) to allow the reference condition and general trend in water quality to be determined. In the absence of a chronology, samples spanning the complete length of the cores were analysed and the bottom-

most samples taken to represent reference conditions. Detrended correspondence analysis, squared chord distance dissimilarity measures and diatom transfer functions were applied to the data to assess the nature and degree of floristic and chemical change at each site. Thirteen sites provide good examples of reference lakes based on the low degree of floristic change observed throughout the sediment record: Buttermere, Crummock Water (low alkalinity, deep); Loch Lonachan, Black Loch, Ullswater (medium alkalinity, deep); Loch Cill Chrìosd, Little Sea Mere (medium alkalinity, shallow); Loch Achnacloich (high alkalinity, deep); Burton Mill Pond, Frensham Great Pond, Llyn Llygeirian, Loch Watston, Loch Watten (high alkalinity, shallow). A further set of five lakes could be classified as good status, exhibiting only slight deviation from the assemblages in the bottom samples: Muckle Water, Loch Skealtar, Lough Lattone, Lough Scolban (medium alkalinity, deep); Loch Mahaick (medium alkalinity, shallow). Thirteen lakes exhibit considerable changes in the diatom assemblages and are thus considered to be at less than good status. The two examples of low alkalinity, shallow lakes have experienced significant floristic change and, therefore, reference lakes are not identified for this type. Reference lakes are not determined for the marl lakes owing to data interpretation problems caused by diatom dissolution.

Application of the diatom transfer functions enabled typical ranges of 'reference' total phosphorus (TP) concentrations to be determined for the main lake types: Low alkalinity lakes $< 10 \mu\text{g l}^{-1}$, Medium alkalinity lakes $10\text{-}20 \mu\text{g l}^{-1}$, High alkalinity and Marl lakes $20\text{-}40 \mu\text{g l}^{-1}$. These values should be used as guidelines only because TP concentrations are clearly site specific.

Work package 3 aims to demonstrate the value of the multi-proxy palaeo-record for defining site-specific ecological reference conditions at lake ecotypes where reference sites cannot be found in the current UK lake population. Multi-proxy analysis of fossil remains (diatoms, chironomids, cladocera, plant macrofossils and pollen) in reference samples (~1850 AD) and surface samples of two lakes, Lake of Menteith and Llangorse Lake, demonstrated the potential of the fuller palaeoecological record for defining reference conditions for a range of biological elements and for assessing ecological change. The multi-indicator data reflect a shift in the functioning of both lakes from benthic-littoral to planktonic dominated production.

The data for the reference samples of the Lake of Menteith cores indicate a healthy ecosystem at ~ 1850 AD with diverse communities of diatoms, chironomids, cladocera and aquatic macrophytes, and assemblages typical of a relatively nutrient poor, circumneutral system. Eutrophication appears to have had a cascading effect through the whole system. The plant macrofossil and aquatic pollen records suggest a reduction in plant abundance in the open water and a shift towards more nutrient tolerant plants. This is reflected in the cladocera community where a decline in plant associated taxa in the open water was observed. The system is now plankton dominated with greater abundance of planktonic cladocera and diatoms, and a less diverse chironomid community.

The data for the reference samples of the Llangorse Lake cores indicate a healthy ecosystem in the past with numerous plant-associated cladocera taxa, attached forms of diatoms and diverse chironomid and plant communities. The assemblages are typical of an alkaline system of intermediate trophic status. The data indicate a decline in the areal coverage of plants in the open water and a change in plant composition away from charophytes toward more nutrient-tolerant species. A general shift from a littoral, plant dominated system to a more pelagic system has occurred with the planktonic diatoms and pelagic cladocera expanding at the expense of the plant-associated and bottom-dwelling taxa. A general shift towards a more nutrient tolerant chironomid fauna was observed. The data indicate that the lake was already relatively nutrient-rich around 150 years ago but that it has undergone enrichment over the last 100-150 years.

Work package 4 aims to demonstrate analogue matching as a technique for identifying the most appropriate reference sites to be used to formulate restoration targets for lakes impacted by eutrophication. An analogue matching training set was developed comprising 30 lakes, 266 diatom taxa and 41 cladocera taxa. Three subsets of the training set were applied to the reference samples (~1850 AD) of three lakes, i) diatom data, ii) cladocera data, and iii) diatom and

cladocera data combined. The squared chord distance dissimilarity coefficient was employed to determine the best analogues for the 'reference' assemblages of three test lakes.

For Loch Davan, a medium alkalinity, shallow lake, Black Loch (diatoms), Little Sea Mere (cladocera), Bayfield Loch (combined), Loch Grogary (cladocera and combined), and Llyn Fanod (cladocera and combined) were the best matches. These are all medium alkalinity waters and are currently mesotrophic with diverse plant populations covering a large proportion of the lake bed. Their selection as potential reference sites for medium alkalinity, shallow lakes such as Loch Davan, therefore, seems appropriate. For Felbrigg Lake, a high alkalinity, shallow lake, Llyn Helyg (cladocera), Loch Watston (diatoms, cladocera), Frensham Great Pond (diatoms, cladocera, combined) and Oxwich Pool (diatoms, cladocera, combined) were the best matches. Similar matches were found for Groby Pool, another currently high alkalinity, shallow lake, with Llyn Llygeirian (diatoms), Llyn Helyg (cladocera), Broomlee Lough (cladocera), Loch Ardnave (cladocera), Frensham Great Pond (cladocera, combined), Oxwich Pool (diatoms, cladocera, combined) and Loch Watston (diatoms, cladocera, combined) providing the best matches. Oxwich Pool and Loch Watston currently support diverse, abundant macrophyte populations, and the latter has been identified as a good example of a reference lake for the high alkalinity, shallow waterbody type. Validation of the choice of reference sites for Felbrigg Lake and Groby Pool using the fuller palaeoecological record suggests that the selected analogues are appropriate for these lakes. However, there were few lakes in the current population with good matches to the Groby Pool pre-enrichment macrophyte assemblage which was comprised of relatively nutrient-poor taxa. The analogue matching technique has the potential, therefore, to be a useful tool for identifying reference sites for lakes impacted by eutrophication, although a larger training set with a greater number of reference lakes is required to improve the diatom analogues.

In conclusion, simple methods such as ordination, clustering and dissimilarity measures applied to palaeoecological data, combined with transfer functions, offer powerful techniques for characterising and validating lake types, identifying reference lakes, defining ecological and chemical reference conditions, and assessing deviation from the reference state. On the basis of this study, a protocol is recommended for using palaeoecological techniques to identify lake reference conditions according to the WFD. The use of a range of biological indicators, in addition to diatoms, such as chironomids, cladocera and macrofossils is advocated. The project illustrates that palaeolimnological studies need not always be highly detailed and thus expensive, and that valuable information can be produced from relatively low resolution studies at large numbers of lakes to aid implementation of the WFD at the national level.

Key words: chironomids, cladocera, diatoms, ecological status, lakes, macrofossils, multi-proxy, palaeolimnology, reference conditions, Water Framework Directive.

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1. INTRODUCTION

1.1 Study rationale

The European Council Water Framework Directive (WFD) 2000/60/EC came into force in 2000 (European Union 2000) and aims to achieve good ecological quality in all relevant waters within 15 years. It requires that biological, hydromorphological and chemical elements of water quality should be based on the degree to which present day conditions deviate from those expected in the absence of significant anthropogenic influence, termed reference conditions. The WFD specifically requires the determination of reference conditions for different waterbody types in order to identify sites of High status, i.e. where the various elements correspond totally or almost totally to undisturbed conditions. The four categories of Good, Moderate, Poor and Bad status are defined according to the degree of deviation from the reference High quality state. In the absence of long-term data, the WFD states that reference conditions based on modelling may be derived using hindcasting methods, and palaeolimnology, the study of the lake sediment record, is given as one such technique (Pollard & Huxham 1998, European Union 2000).

There is a pressing need for simultaneous progress along several fronts in gaining understanding of lakes in the United Kingdom (UK). Specifically annex II of the WFD requires a Typology to be developed, and the identification of candidate reference lakes; and for annex V, the development of tools for determining reference condition and classifying status. For lakes, the use of palaeolimnological techniques has the potential to contribute to the delivery of these requirements. Consequently, as part of the UK Strategy for the implementation of the WFD, SNIFFER provided funding for the current project '*Identification of reference lakes and evaluation of palaeoecological approaches to define reference conditions for UK (England, Wales, Scotland & Northern Ireland) ecotypes*'. This study aims to use palaeoecological techniques to identify reference lakes, describe reference conditions and assess ecological status for a set of UK lakes. The project builds on ideas derived from the existing body of work on the palaeolimnology of UK lakes including the SNIFFER funded *Palaeolimnological Investigation of Scottish Freshwater Lochs* (SR(00)02 F) (Bennion *et al.* 2001b). It utilises existing palaeolimnological data held by the Environmental Change Research Centre (ECRC) at UCL, data from academic sources in Northern Ireland, as well as new data collected as part of the project.

1.2 Background

The study of the sediment accumulated in a waterbody can provide a record of its past biology and chemistry, a science known as palaeoecology. Diatoms (*Bacillariophyceae*: single-celled, siliceous algae) are commonly used in such studies because they are sensitive to water quality changes and are, therefore, good indicators of past lake conditions such as lake pH (Battarbee *et al.* 1999, 2001) and total phosphorus (TP) concentrations (Hall & Smol 1999). In recent years, transfer functions have been developed to model the relationship between diatom assemblage composition and water chemistry in a training set of lakes. Once calibrated, such models are then applied to fossil diatom assemblages in sediment cores to infer past water chemistry. Weighted averaging (WA) regression and calibration (ter Braak & van Dam 1989) and its extension WA partial least squares (WA-PLS) (ter Braak & Juggins 1993) are the most widely used techniques for reconstructing past environmental variables in this way (Birks 1998). Of the biological elements relevant to the WFD, diatoms represent components of both the phytoplankton and phytobenthos, but importantly shifts in the diatom community often correspond closely to changes in other biological groups (e.g. Kingston *et al.* 1992). The diatom record is a potentially useful tool, therefore, for assessing water quality and defining lake reference conditions, both chemical and ecological (e.g. Kauppila, Moisiö & Salonen 2002). There are, however, a number of other biological groups that preserve in the lake sediments, representing a range of biological elements relevant to the WFD. For example, chironomids (Diptera) are non-biting midges whose larval head capsules are preserved; cladocera are microscopic crustaceans (zooplankton) that are represented by a variety of body parts; and aquatic pollen and plant macrofossils can be used to assess vegetation change.

The use of palaeoecological techniques for establishing reference conditions for lakes is well established with many examples of their application to aquatic management and conservation (e.g. Battarbee 1999, Stoermer & Smol 1999). However, such investigations have tended to focus on detailed studies of a limited number of sites (e.g. Sayer *et al.* 1999, Bennion *et al.* 2000, 2004). Here we take a different approach by collating existing data from large numbers of lakes in the UK to aid implementation of the WFD at the national level. Furthermore, the majority of previous studies have explored the causes, rates and magnitude of water quality change resulting from pressures such as eutrophication (e.g. Bennion *et al.* 2004) and acidification (e.g. Jones *et al.* 1993), and have therefore focused on impacted systems. In contrast, this project specifically sets out to identify reference lakes and, therefore, new sediment cores were collected from lakes thought to be relatively unimpacted.

1.3 Objectives

The project objectives are divided into four work packages which are set out in further detail in the chapters that follow:-

- 1) To classify lakes (from across the UK) based on diatom reference conditions and compare with the GB Lake Typology.
- 2) To identify a set of reference lakes for each ecotype based on degree of change estimates from the palaeolimnological record (diatom data).
- 3) To demonstrate the value of the multi-proxy palaeo-record for defining site-specific ecological reference conditions at lake ecotypes where reference sites cannot be found in the current UK lake population.
- 4) To demonstrate analogue matching as a technique for identifying the most appropriate reference sites to be used to formulate restoration targets for lakes impacted by eutrophication.

Chapters 2 to 5 report on work packages 1 to 4, respectively. Each chapter describes the aims of the work package, the methods employed and the key results, and discusses the findings in the context of the WFD. Chapter 6 provides an overview and synthesis of the project, focusing on the use of palaeoecological techniques for identifying reference conditions for UK lakes according to the WFD.

2. WORK PACKAGE 1: CLASSIFICATION OF LAKES BASED ON REFERENCE CONDITIONS (DIATOM DATA) AND COMPARISON WITH GB LAKE TYPOLOGY

2.1 Objectives

The objective of work package 1 is to classify lakes based on reference conditions (diatom data) and compare the diatom based classification with the GB Lake Typology to identify gaps in existing palaeolimnological data and to test the ecological relevance of the typology scheme.

2.2 Methods

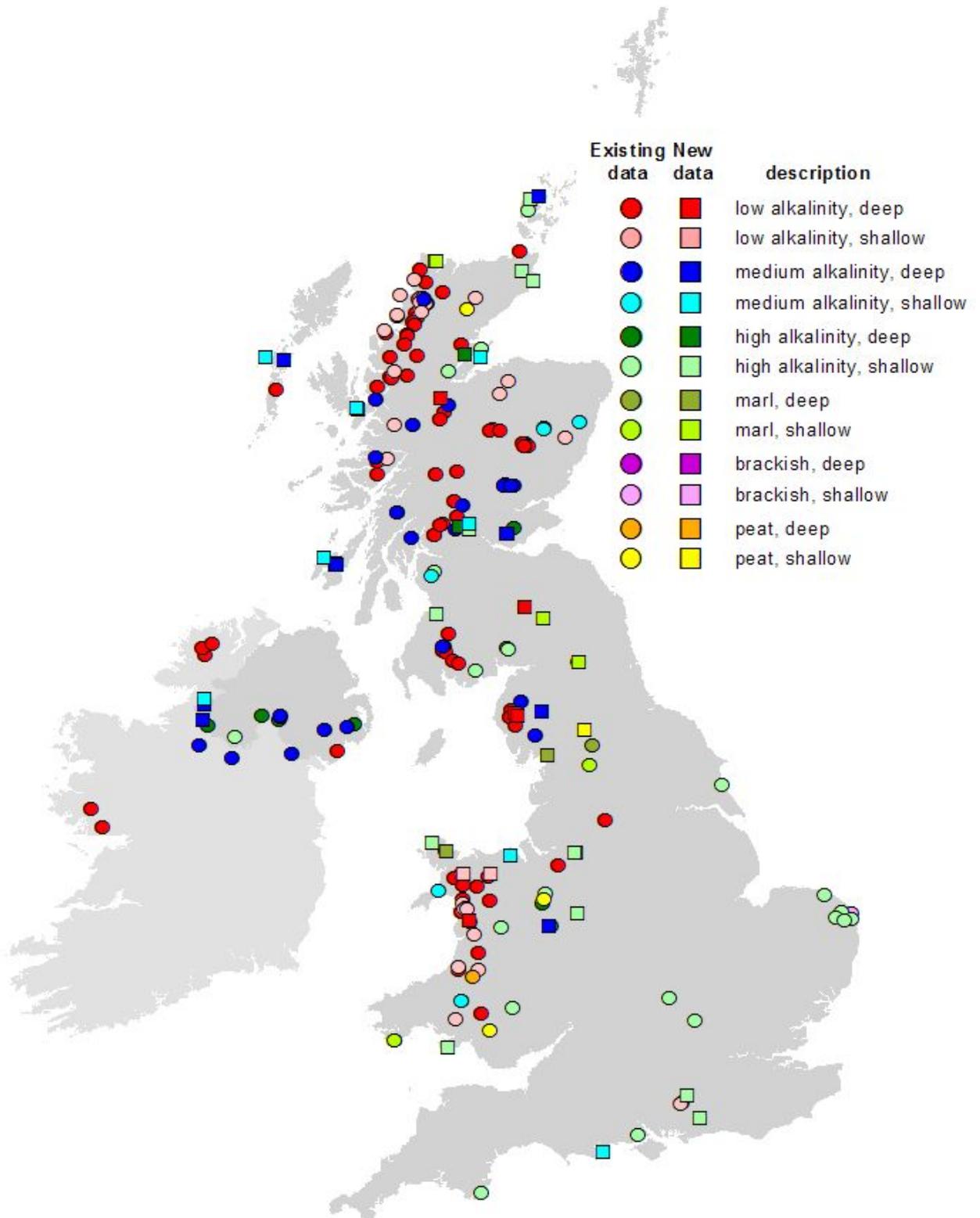
The dataset

Work package 1 aims to classify lakes based on diatom reference conditions using fossil diatom data from lake sediment cores held in the ECRC's database at University College London. At the outset of this project we held such data for 176 UK lakes. These existing data are indicated by circles in Figure 2.1 and are colour coded according to the GB Lake Typology, developed for delivery of WFD outputs. This typology is based on catchment geology and lake mean depth data held in the GB Lakes Inventory and results in 12 lake types. A separate, though similar, typology has been developed for lakes in Northern Ireland but for consistency in this study, the GB typology has been applied to all lakes. The diatom data have been derived from a large number of separate projects undertaken by the ECRC over the last few decades. Many of the previous projects focused on areas sensitive to acidification and hence there is a strong bias towards low alkalinity systems, particularly in Scotland and upland areas of England and Wales (Figure 2.1). The numbers of medium and high alkalinity lakes in the diatom database are relatively few. Furthermore, many of the lakes were studied because of concern over acidification or eutrophication and therefore the majority of existing sites are impacted to some degree. Therefore, in summer 2002, sediment cores were collected from 34 new sites (see work package 2, chapter 3), and in summer 2003 from a further 15 sites (see work package 4, chapter 5), most of which were medium or high alkalinity waters in predominantly low lying areas of the UK, and which were chosen as minimally impacted examples of their type. These lakes are indicated by squares in Figure 2.1. The 49 new cores were prepared for diatom analysis using the techniques described in Chapter 3. Analysis could not be carried out at six sites owing to poor diatom preservation down the cores. The diatom data from the 43 new sites were added to those from the existing 176 lakes to give a total dataset of 219 lakes. The number of lakes of each type in the final dataset is shown in Table 2.1 and a complete site list is given in Appendix 1. The 219 lakes in the final diatom dataset represent a broad range of UK lake types with good geographical coverage (Table 2.1 & Figure 2.1).

Table 2.1 The Lake Typology for Great Britain indicating the number of lakes of each type in the diatom dataset (N=219)

Type description	Catchment geology	Mean depth (m)	No. in diatom dataset
Low alkalinity-Deep (LA, D)	>90% siliceous	> 3.0	82
Low alkalinity-Shallow (LA, Sh)	>90% siliceous	<=3.0	29
Medium alkalinity-Deep (MA, D)	50-90% siliceous	> 3.0	36
Medium alkalinity-Shallow (MA, Sh)	50-90% siliceous	<=3.0	14
High alkalinity-Deep (HA, D)	>50% calcareous	> 3.0	12
High alkalinity-Shallow (HA, Sh)	>50% calcareous	<=3.0	30
Marl-Deep (Marl, D)	>65% limestone	> 3.0	3
Marl-Shallow (Marl, Sh)	>65% limestone	<=3.0	8
Brackish-Deep (B, D)		> 3.0	0
Brackish-Shallow (B, Sh)		<=3.0	1
Peat-Deep (P, D)	>75% peat	> 3.0	1
Peat-Shallow (P, Sh)	>75% peat	<=3.0	3

Figure 2.1 Map showing the location and typology of lakes included in the project (the typology is based on the GB Lake Typology)



The top and bottom approach

In this work package, the 'top and bottom' approach was adopted. This approach can be applied to a large number of lakes as it involves the analysis of only two samples per site from a sediment core (Cumming *et al.* 1992). This methodology has been successfully applied by the US Environmental Protection Agency's (USEPA) Environmental Monitoring and Assessment Program for Surface Waters (EMAP-SW) (Dixit *et al.* 1999) and in Canada to infer changes in southeastern Ontario lakes (Reavie *et al.* 2002). The approach makes the assumption that the top and bottom samples represent the present day and reference conditions, respectively. Where core chronologies were available, that is where the core had been dated using either radiometric techniques (Appleby *et al.* 1986) or the spheroidal carbonaceous particle (SCP) profile method (Rose 1994), the sample approximating to ~1850 AD was selected to represent the reference condition, herein termed the reference sample. In the absence of dates, the bottom sample of the core was taken to represent the reference sample. Appendix 1 provides details of the samples selected and the availability of a chronology for each core.

The approach makes the assumption that the reference samples represent the reference conditions. For the UK, it is generally agreed that approximately 1850 AD is a suitable date against which to assess impacts for lakes as this represents a period prior to major industrialisation and agricultural intensification (Battarbee 1999, Fozzard *et al.* 1999). The analysis of reference samples in this way removes the problem inherent in spatial-state schemes in which the lakes have been subject to different pressures and varying degrees of impact. It is accepted, however, that aquatic systems have been subjected to anthropogenic impacts over much longer time-scales and, therefore, our reference conditions are unlikely to equate to the natural or pristine state. The diatom data from the surface (uppermost 0.5 or 1 cm) sample of each of the 219 cores were used to provide information on the current diatom assemblages of the lakes. The surface sediment sample represents the last few years' accumulation of diatoms deposited from a variety of habitats within the lake.

Data analyses

All diatom data were expressed as percentage relative abundance, and were screened and harmonised prior to data analysis. The full dataset of 219 core tops and 219 corresponding reference samples was comprised of 810 diatom taxa. Only those 373 taxa present with a maximum relative abundance of > 1% in > 5 samples were included in the data analyses. A list of the common taxa is given in Appendix 2.

Two Way Indicator Species Analysis (TWINSpan) (Hill 1979) was employed to classify the reference samples according to their diatom assemblages, and thereby characterise the reference floras of the different lake types. Percentage abundances of the taxa were apportioned into five classes using pseudospecies levels as follows: 0, 2, 5, 10, 20 %.

The next objective was to compare the diatom reference sample classification derived from the TWINSpan analysis with the GB Lake Typology in order to examine the degree of overlap and hence assess the ecological relevance of the typology scheme. The TWINSpan end-groups were plotted as polygons on a principal components analysis (PCA) biplot (ter Braak 1987) of the reference samples, implemented using CANOCO version 4.5 (ter Braak & Smilauer 2002). The PCA biplot was then replotted with the samples classified according to the GB Lake Typology, and the two plots were compared.

The degree of floristic change between the reference and surface sample of the 219 cores was assessed using a squared chord distance dissimilarity coefficient (Overpeck *et al.* 1985) implemented in the statistical software R (R Development Core Team 2004). 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 floristic change at the 1st, 2.5th, 5th and 10th percentile, respectively (Simpson 2003). The 5th percentile is used here to define sites with low floristic change between the reference and surface sample.

Where insignificant change is detected, sites can be considered as suitable reference lakes and where significant change is observed, the degree of change from site-specific reference conditions is evaluated to assess ecological status. The scores are summarised for each lake type.

2.3 Results and discussion

Classification of diatom reference samples

The TWINSPAN analysis of the 219 diatom reference samples resulted in eight site end-groups at three levels of division. The number of sites and key indicator taxa (with abundance classes in parentheses; see methods) at each division are shown in Figure 2.2. A summary of the diatom end-groups including the common taxa within these groups and their associated lake types is presented in Table 2.2. The full list of sites with their TWINSPAN end-groups is given in Appendix 3.

Group 1 and 2 assemblages are comprised largely of non-planktonic taxa, typically found in low alkalinity, acid waters on base poor geology. The only notable differences between Groups 1 and 2 are the absence of *Cymbella hebridica* and fewer *Brachysira vitrea* in the former but otherwise the same taxa dominate both groups. A number of taxa associated with strongly acid waters are present in relatively high abundances (e.g. *Cymbella perpusilla*, *Eunotia incisa*, *Frustulia rhomboides* var *saxonica*, *Pinnularia irrorata*, *Tabellaria quadrisepitata*), indicating that this group of lakes represents those with the lowest alkalinities in the dataset. Not surprising, therefore, that 35 of the 38 lakes in Groups 1 and 2 are classified as Low alkalinity according to the GB Lake Typology, and one as Peat (Llyn Berwyn). These lakes lie in catchments dominated by base-poor geology (e.g. the lochs on granite bedrock in Galloway, Scotland). Only two lakes in this group, Loch Enoch and Loch Bad an Losguinn, are classified as Medium alkalinity. Given that the diatom assemblages are characteristic of low alkalinity waters, it appears that the alkalinity of these two lakes has been misclassified in the GB Typology scheme. The catchment of Loch Enoch in Galloway is dominated by granitic bedrock which would certainly place it in the low alkalinity category. Diatom groups 1 and 2 include both deep and shallow lakes indicating that at low alkalinities it is the chemical condition (i.e. low pH) that is the dominant control on the diatom community. Indeed acid lakes rarely support a planktonic diatom flora.

Group 3 lakes have a non-plankton dominated assemblage with taxa ranging from slightly acid tolerant to circumneutral. The high abundance of two taxa, *Achnanthes minutissima* and *Cyclotella microcephala*, which are infrequent in very acid waters, distinguishes this group from Groups 1 and 2. Furthermore, in contrast to the first two groups, many of the lakes in Group 3 have a high relative abundance of planktonic forms, particularly *Cyclotella kuetzingiana* agg., which is typically associated with nutrient-poor waters. Therefore, whilst this group is comprised of low alkalinity lakes, the diatom assemblages suggest that they are less acid than those of Groups 1 and 2. Many of the lakes in Group 3 are classified as Deep according to the GB Typology and are thus deep enough and productive enough to support diatom plankton. The group includes numerous sites from northwest Scotland and from northern and central regions of Wales. Only one lake in this group, Llyn Hir, is classified as High alkalinity by the GB Typology. Measured data indicate that the lake has been misclassified and should be placed in the Low alkalinity group as it has an average pH of ~5.6 and an alkalinity of ~13 ueq l⁻¹ (Allott & Monteith 1999).

Group 4 is a small group of 9 lakes. The assemblages contain broadly the same taxa as those of Group 3 suggesting that the lakes are chemically similar. The main difference, however, is that the Group 4 lakes are dominated by planktonic forms, notably *Cyclotella comensis* and *Cyclotella kuetzingiana* agg. The most abundant non-planktonic taxon in this group is *Achnanthes minutissima*. These could be described as “*Cyclotella-Achnanthes minutissima*” lakes. They are all relatively large, deep waterbodies of low (to medium) alkalinity (e.g. Loch Shiel, Loch Maree, Llyn Cwellyn).

Group 5 lakes are dominated by non-planktonic taxa associated with higher alkalinity waters than those in the previous groups. There are generally fewer acid tolerant taxa than in the former groups and markedly higher abundances of *Fragilaria* spp. (e.g. *F. pinnata*, *F. brevistriata*) which are commonly observed in circumneutral to alkaline waters. The lakes in this group are predominantly Medium alkalinity and Shallow according to the GB Lake Typology. Therefore, this assemblage appears to be characteristic of shallow lakes of intermediate alkalinity with plentiful habitats for attached forms but lacking in sufficient depth to support large planktonic populations (e.g. Loch Davan, Little Sea Mere).

Group 6 assemblages are dominated by planktonic taxa, commonly found in circumneutral to alkaline conditions. The most common taxa include *Asterionella formosa*, *Aulacoseira subarctica*, *Cyclotella comensis* and *Cyclotella radiosa*. The group is differentiated from the plankton-dominated assemblages in Group 4 on the basis of a higher abundance of taxa associated with intermediate alkalinities and slightly more productive waters. Most of the lakes in Group 6 are classified as Low or Medium alkalinity. The diatom assemblages suggest that those lakes classified as Low alkalinity must have slightly higher alkalinities than their counterparts in the former groups. Furthermore, the majority of lakes in Group 6 are deep (e.g. the lakes of the Cumbrian Lake District) or are shallow, wind-stressed and hence well-mixed (e.g. Loch of Swannay, Loch Hempriggs), allowing planktonic diatoms to thrive in the water column. This assemblage, therefore, appears to be characteristic of deep lakes and shallow, turbulent lakes of intermediate alkalinity.

Group 7 assemblages are dominated by non-planktonic, circumneutral to alkaline taxa, typically found in shallow lakes with relatively high alkalinities. They are distinguished from Group 5 assemblages on the basis of greater abundance of the benthic *Fragilaria* spp. and other taxa commonly observed in alkaline systems, particularly *Cocconeis placentula* and *Amphora pediculus*. Not surprising, therefore, that a large number of the lakes in Group 7 are classified as Medium or High alkalinity according to the GB Lake Typology, and the one Brackish lake (Martham South Broad) and all 11 Marl lakes also fall within this group. The majority of lakes in this group are classified as Shallow, providing abundant habitats on plant, rock and sediment surfaces for the attached diatom forms. Typical examples are the Norfolk Broads, the Hadrian Wall loughs in Northumberland, and the Lily Ponds at Bosherton in Pembrokeshire.

Finally, Group 8 assemblages contain a plankton dominated flora with taxa associated with circumneutral to alkaline waters. They are characterised by a high abundance of *Aulacoseira* taxa and *Stephanodiscus parvus*, which distinguishes them from the plankton-rich assemblages in Group 6. Most of the lakes in this group are classified as Medium or High alkalinity, Deep waters. It is apparent that many of these lakes are kettle holes associated with lowland, base-rich, drumlin country of Northern Ireland (e.g. Loughs Brantry and Heron) and the English West Midlands meres (e.g. Crose Mere and Tatton Mere). These lakes appear to have their own characteristic, “*Aulacoseira*-dominated” diatom flora, perhaps owing to their natural productivity and deep basins.

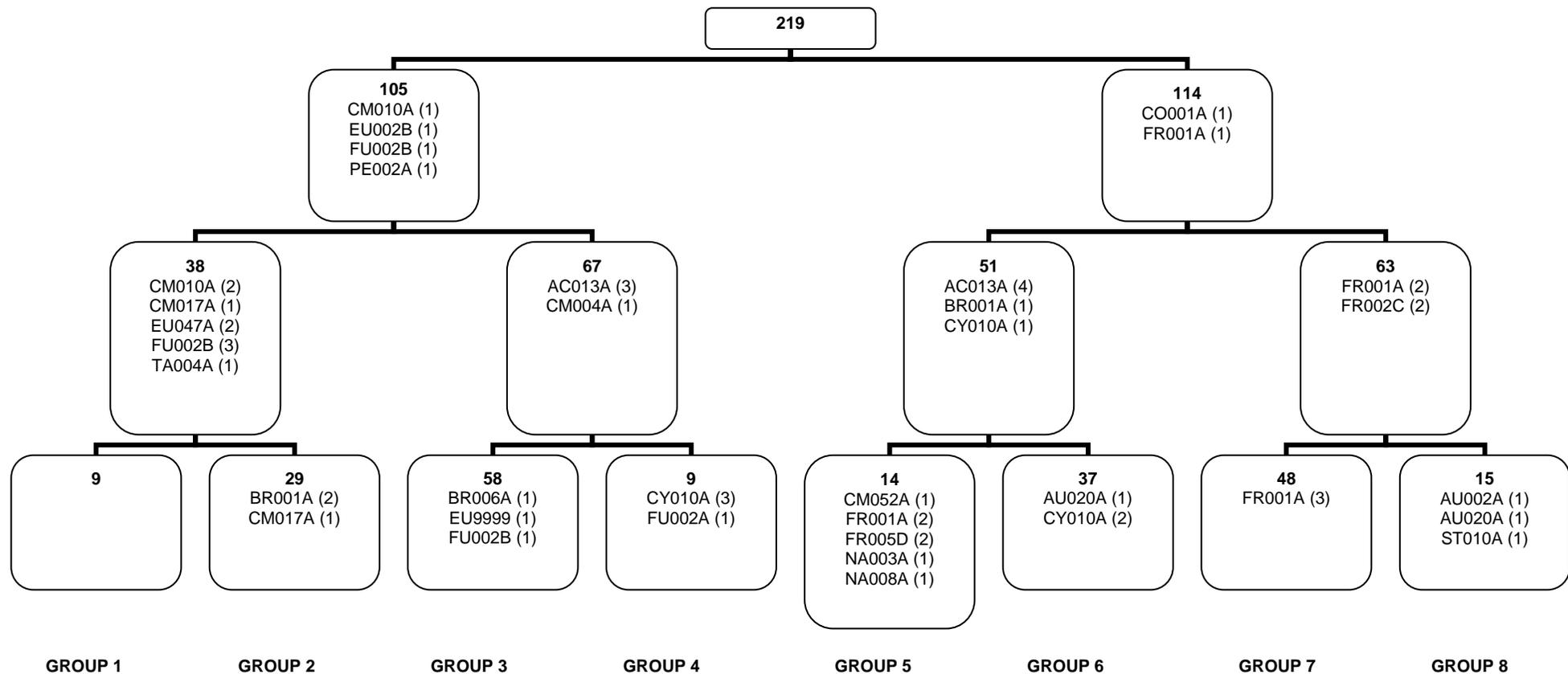


Figure 2.2 TWINSpan classification of the diatom reference samples into eight site end-groups

The number of sites and key indicator taxa (with pseudospecies abundance classes in parentheses; see methods) at each division are shown. See Appendix 2 for full diatom names.

Table 2.2 Summary of the diatom reference sample TWINSPAN end-groups and associated lake types

Diatom group	Group description	Common taxa	No. of lakes	Lake types
1 and 2	Non-plankton dominated assemblage, with acidophilous taxa and a number of taxa typically associated with strongly acid waters	<i>Brachysira vitrea</i> <i>Cymbella hebridica</i> <i>Cymbella perpusilla</i> <i>Eunotia incisa</i> <i>Fragilaria virescens</i> var. <i>exigua</i> <i>Frustulia rhomboides</i> var. <i>saxonica</i> <i>Tabellaria quadrisepata</i>	38	Low alkalinity (and Peat) Deep and shallow
3	Non-plankton dominated assemblage, with acidophilous to circumneutral taxa and some planktonic taxa (fewer strongly acid taxa than Groups 1 & 2)	<i>Achnanthes minutissima</i> <i>Brachysira vitrea</i> <i>Cyclotella kuetzingiana</i> agg. <i>Cymbella microcephala</i> <i>Fragilaria virescens</i> var. <i>exigua</i>	58	Low alkalinity (and Peat) Deep and shallow
4	Plankton dominated assemblage, with acidophilous to circumneutral taxa (differentiated from Group 3 by greater abundance of <i>Cyclotella comensis</i>)	<i>Achnanthes minutissima</i> <i>Brachysira vitrea</i> <i>Cyclotella comensis</i> <i>Cyclotella kuetzingiana</i> <i>Frustulia rhomboides</i>	9	Low alkalinity Deep
5	Non-plankton dominated assemblage, with circumneutral taxa (fewer acidophilous taxa than Groups 1 to 4 and more <i>Fragilaria</i> spp.)	<i>Achnanthes minutissima</i> <i>Cymbella microcephala</i> <i>Fragilaria pinnata</i> <i>Fragilaria brevistriata</i> <i>Fragilaria virescens</i> var. <i>exigua</i>	14	Medium alkalinity Shallow
6	Plankton dominated assemblage, with circumneutral to alkaline taxa (differentiated from Group 4 by greater abundance of planktonic forms typical of circumneutral, mesotrophic waters)	<i>Achnanthes minutissima</i> <i>Asterionella formosa</i> <i>Aulacoseira subarctica</i> <i>Cyclotella comensis</i> <i>Cyclotella radiosa</i>	37	(Low to) Medium alkalinity Deep
7	Non-plankton dominated assemblage, with circumneutral to alkaline taxa (differentiated from Group 5 by greater abundance of alkaline taxa)	<i>Amphora pediculus</i> <i>Cocconeis placentula</i> <i>Fragilaria brevistriata</i> <i>Fragilaria construens</i> <i>Fragilaria construens</i> var. <i>venter</i> <i>Fragilaria pinnata</i> .	48	Medium to High alkalinity (and Marl) Shallow
8	Plankton dominated assemblage, with circumneutral to alkaline taxa (differentiated from Group 6 by greater abundance of <i>Aulacoseira</i> spp.)	<i>Asterionella formosa</i> <i>Aulacoseira ambigua</i> <i>Aulacoseira granulata</i> , <i>Aulacoseira subarctica</i> <i>Cyclotella radiosa</i> <i>Stephanodiscus parvus</i>	15	Medium to High alkalinity Deep

Comparison of the diatom classification and lake typology

The eight TWINSpan end-groups are indicated by polygons on a PCA biplot of the diatom reference samples in Figure 2.3. Groups 1 to 4, representing the sites with taxa associated with acidic conditions are positioned towards the left of the plot. Groups 5 and 6 which include the sites dominated by circumneutral taxa are located towards the centre of the plot, and Groups 7 and 8 with assemblages comprised largely of alkaline taxa are positioned to the far right of the diagram. Axis 1, which explains 19% of the variance in the diatom data, therefore appears to represent an alkalinity gradient. The second axis explains 11% of the variance and appears to represent a habitat gradient with the non-planktonic dominated Groups 1, 2, 5 and 7 towards the bottom of the plot and the plankton dominated Groups 4, 6 and 8 towards the top.

Figure 2.4 presents the same PCA biplot of the diatom reference samples as that shown in Figure 2.3 but here the lake samples are colour coded according to the GB Lake Typology rather than the TWINSpan site end-groups. There is a clear overall pattern with low alkalinity lake types (red and pink) on the left of the diagram, medium alkalinity lake types (blue) in the centre and high alkalinity lake types (green) on the right. Within these three broad groups, indicated by ellipses on the graph, there is some separation of the deep and shallow lakes. For example the shallow lakes are located towards the lower part of Figure 2.4 (pink, light blue and pale green for low, medium and high alkalinity, respectively) and the deep lakes are located towards the upper part (red, dark blue and dark green for low, medium and high alkalinity, respectively). Whilst brackish, peat and marl lakes are relatively few, the peat lakes are situated amongst the low alkalinity waters as one would expect, and logically the marl and brackish lakes are situated amongst the high alkalinity waters.

The comparison of the diatom classification and the GB Lake Typology shows close congruence between the two datasets and indicates that the criteria of geology (reflecting alkalinity) and, to a lesser extent, lake depth used in the latter does result in ecologically meaningful typologies. We can conclude that in Figure 2.4, Axis 1 represents the alkalinity gradient and Axis 2 represents the lake depth gradient.

The analysis is useful for highlighting sites that have potentially been allocated to the wrong typology. For example, Loch Enoch and Loch Bad an Losguinn are assigned to the medium alkalinity, deep lake type but in fact have a diatom flora typical of very low alkalinity lakes (shown by arrows in Figure 2.4). Errors in typology may arise for two reasons: i) the alkalinity type is based on the percentage of either siliceous or calcareous geology in the lake catchments and these data are derived from national geology maps rather than from high resolution local data and thus problems of scale can occur; ii) lake mean depths have been modelled for many lakes because bathymetric data are not available. There is, therefore, a risk of misclassification.

There are no discrete groups of lakes in nature and this explains the large degree of overlap at the borders of the low to medium alkalinity and the medium to high alkalinity groups. Even within each lake typology class, lakes are likely to cover a broad alkalinity range and, therefore, we might expect poor cross matching of the diatom groups and the lake typology at these boundaries. For instance the diatom data indicate that the low alkalinity group is comprised of lakes with a strongly acidic, non-planktonic dominated flora as well as lakes with more circumneutral, planktonic taxa. Nevertheless, on the whole, the diatom classification and the lake typology show good agreement. The analysis of the reference diatom assemblages from large numbers of lakes has, therefore, enabled us to characterise the diatom reference conditions for the main lake types (Table 2.2).

It is recommended that a similar classification is carried out using chironomids and cladocera to further validate the GB Lake Typology. Whilst alkalinity and water depth are likely to be important for these biological groups, factors such as temperature, and substrate type and availability, may be equally significant and thus a weaker match with the GB Lake Typology may be found than that observed for diatoms.

Figure 2.3 PCA biplot (axis 1 and 2) of the diatom reference samples with the eight TWINSpan site end-groups shown as polygons.

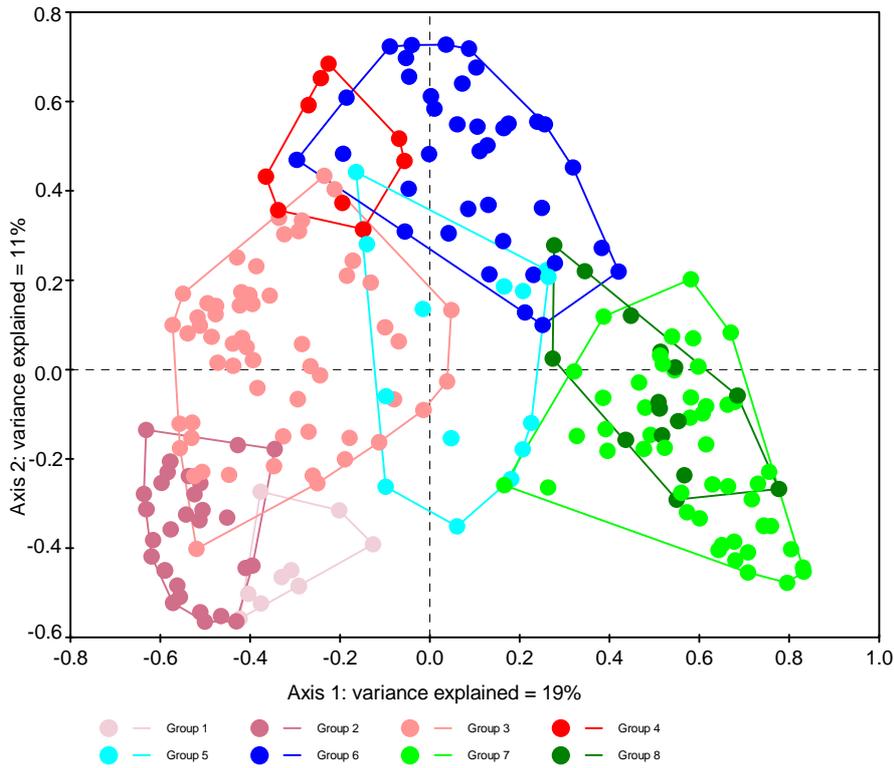
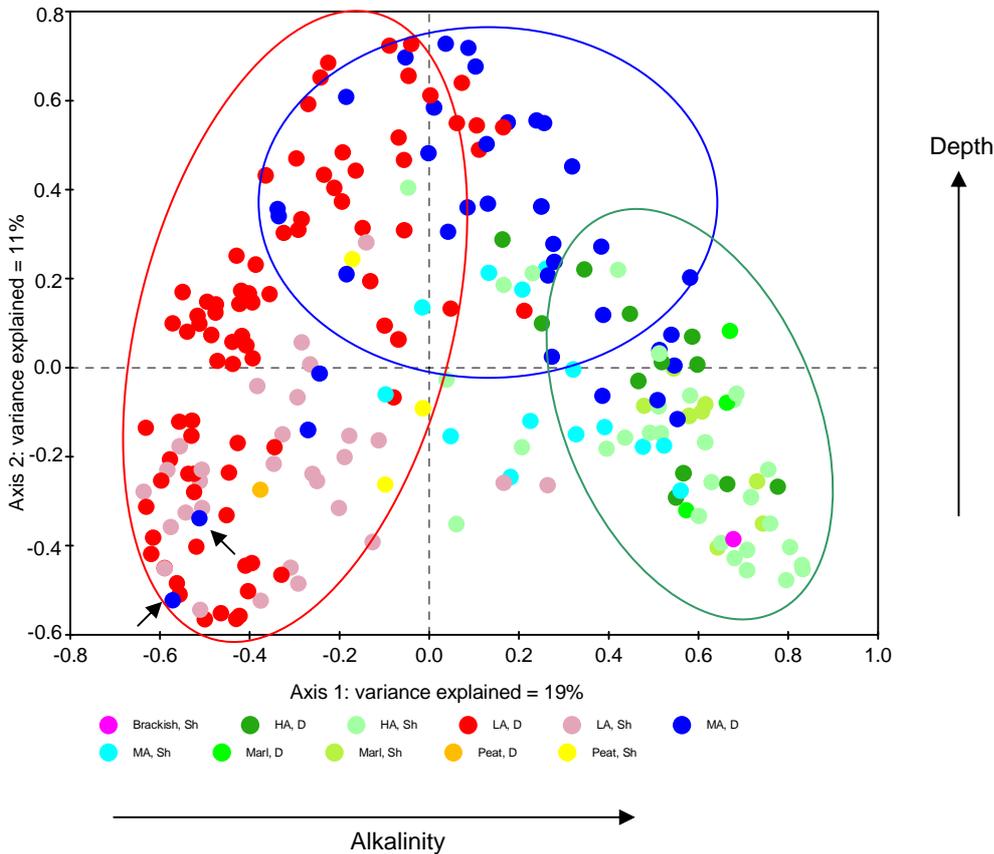


Figure 2.4 PCA biplot (axis 1 and 2) of the diatom reference samples, classified according to the GB Lake Typology. The ellipses indicate the main groups: low alkalinity (red, pink), medium alkalinity (blue) and high alkalinity (green); examples of misclassified lakes are indicated by arrows.



Floristic change

The squared chord distance dissimilarity scores calculated between the core top and reference samples of the 219 lakes range from 0.13 to 1.77, with 79 lakes experiencing low floristic change ($<0.475 = 5^{\text{th}}$ percentile). The scores for each lake are given in Appendix 4. Figure 2.5 presents the results for each lake type as a series of histograms. Here, the three lakes identified as having been misclassified by the GB Lake Typology scheme (Loch Enoch, Loch Bad an Losguinn and Llyn Hir) have been reallocated to their correct type.

None of the four lakes in the Peat group have a score below the critical value at the 5^{th} percentile, indicating that they have all experienced significant floristic change (Figure 2.5a). Llyn Fach has the least change with a score of 0.58.

Of the 84 low alkalinity, deep lakes, 37 have a score below the critical value at the 5^{th} percentile (Figure 2.5b). Examples of “reference lakes” in this group include Loch Maree and Loch Lubnaig in Scotland, Crummock Water and Wast Water in England, and Llyn y Fan Fawr and Llyn Idwal in Wales. Many of the lakes with significant floristic change have experienced increases in acidic taxa indicative of acidification (e.g. Round Loch of Glenhead, Loch Grannoch). These are lakes in areas of acid sensitive geology with little buffering capacity. In contrast, a number of lakes have seen a rise in taxa associated with productive systems, suggesting that enrichment has occurred (e.g. Loweswater and Lake Bala). These sites are in predominantly lowland, agricultural catchments with a variety of potential nutrient inputs. Therefore, both acidification and eutrophication pressures have impacted upon the low alkalinity waters. Of the 30 low alkalinity, shallow lakes, 12 have a score below the critical value at the 5^{th} percentile (Figure 2.5c). Examples of “reference lakes” in this group include Loch na Beiste and Llyn Cwm Mynach. As for the low alkalinity, deep lakes, many of the sites that have undergone significant floristic change are situated on base-poor bedrock and have been subject to acidification.

Of the 34 medium alkalinity, deep lakes, 11 have a score below the critical value at the 5^{th} percentile (Figure 2.5d). Examples of “reference lakes” in this group include Loch Lonachan on the Isle of Skye, Loch Lossit on Islay, and Ullswater in Cumbria. Of the 14 medium alkalinity, shallow lakes, three have a score below the critical value at the 5^{th} percentile (Figure 2.5e). Loch Cill Chriosd, Loch Kinord and Little Sea Mere, therefore, appear to be good examples of “reference lakes” for the medium alkalinity, shallow lake type. All of the medium alkalinity lakes with significant floristic change exhibit an increase in taxa indicative of enrichment. They are situated in predominantly agricultural, lowland catchments (e.g. the Lunan Burn chain of lochs in Perthshire, and the loughs of County Fermanagh in Northern Ireland). Eutrophication, therefore, appears to be the dominant pressure on the mid-alkalinity systems.

Of the 12 high alkalinity, deep lakes, four have a score below the critical value at the 5^{th} percentile (Figure 2.5f). Tatton Mere, Llyn yr Wyth Eidion, Loch Achnacloch and Macnean Upper Lough therefore, appear to be good examples of “reference lakes” for this lake type, although Llyn yr Wyth Eidion may be better placed in the Marl group. Furthermore, poor diatom preservation prevented analysis below the 10 cm sample in the Llyn yr Wyth Eidion core and it is unlikely, therefore, that the “reference” sample extends back more than a few decades. Of the 29 high alkalinity, shallow lakes, ten have a score below the critical value at the 5^{th} percentile (Figure 2.5g). Examples of “reference lakes” in this group include Frensham Great Pond and Burton Mill Pond in England, Oxwich Pool and Llyn Llygeirian in Wales, and Loch Watston and Loch Watten in Scotland. These sites presently have diverse and abundant plant macrophytes. In contrast many of the high alkalinity lakes that have experienced significant changes in the diatom assemblages have become plankton dominated, turbid systems as a result of eutrophication (e.g. the Norfolk Broads, the Cheshire-Shropshire meres, Loch Leven).

Of the three marl, deep lakes, only Semer Water has a score below the critical value at the 5^{th} percentile (Figure 2.5h). As for Llyn yr Wyth Eidion, poor diatom preservation prevented analysis below the 10 cm sample in the Semer Water core and it is unlikely that the “reference” sample extends back beyond ~1950 AD. Loch Borrallie and Hawes Water have both undergone significant floristic change indicative of enrichment. Of the eight marl, shallow lakes, only Bosherton Lake

Upper has a score below the critical value at the 5th percentile (Figure 2.5h). Similarly to the deep waters, the other lakes in the shallow group exhibit changes in the diatom flora suggestive of eutrophication. However, caution must be exercised when interpreting the diatom records from the marl systems as all are affected by dissolution of the diatom silica in the lower parts of the sediment cores. Martham South Broad provides the only example of a brackish, shallow lake (Figure 2.5h) and has a score of 0.71.

Figure 2.6 presents a summary of the distribution of distance scores for each lake type. In the low alkalinity group, there are many examples of lakes with low floristic change (~40% of lakes with a score <0.475). Therefore, good examples of reference lakes are available for these lake types. Nevertheless, many low alkalinity lakes have experienced floristic change, mostly in response to acidification. In the medium alkalinity and high alkalinity groups, ~30% of lakes have a score of <0.475, suggesting that there are examples of reference lakes for these types in the current dataset. Nonetheless a large proportion of lakes in these groups exhibit large floristic change. These are lowland sites in relatively productive catchments and hence are impacted by eutrophication.

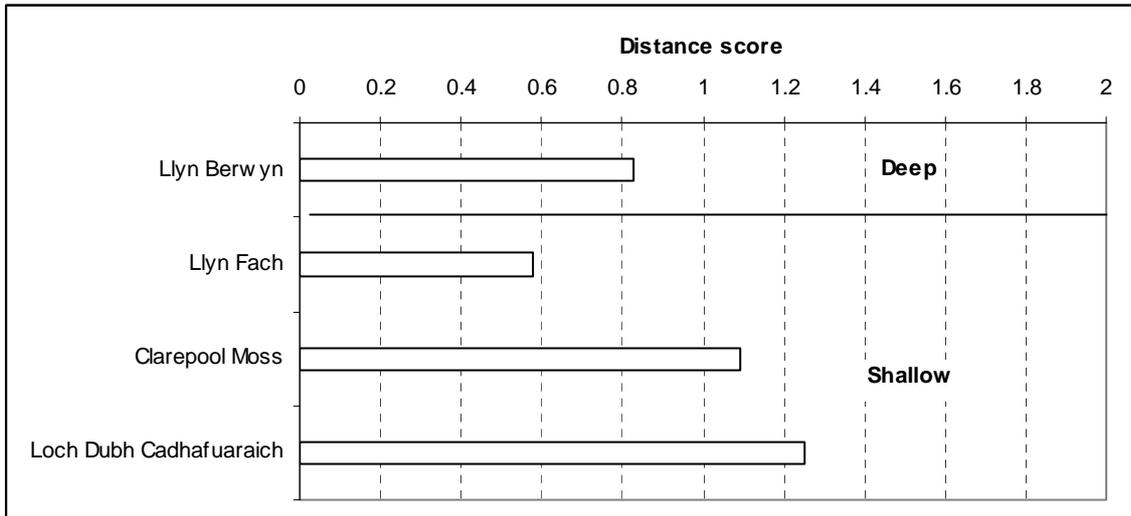
The squared chord distance dissimilarity measure is a useful tool for assessing whether lakes have experienced significant floristic change, but it is very difficult to decide how much change is acceptable for a lake to be considered as a reference lake (High status). The 5th percentile is used here to define sites with low floristic change between the reference and surface sample, and hence to provide a list of lakes considered to be minimally impacted, at least in terms of their diatom composition. Approximately 36% of lakes in the existing dataset can, therefore, be described as reference lakes. A question remains over where one should set the boundaries for defining Good and Moderate status whilst allowing for an element of natural change? If the 5th percentile (score of 0.475) is selected to define the High/Good boundary then we might logically select the 10th percentile (score of 0.58) to define the Good/Moderate boundary. Using these criteria, approximately 50% of lakes in the existing dataset fail to meet Good status (Figure 2.6). It should be noted that whilst the squared chord distance dissimilarity score is a useful tool, it does not provide any information on the nature or timing of the species shifts. In chapter 3, we examine the diatom records of 31 of the lakes in more detail to further inform selection of reference lakes and to assess the driving pressures of any observed changes.

2.4 Summary of findings

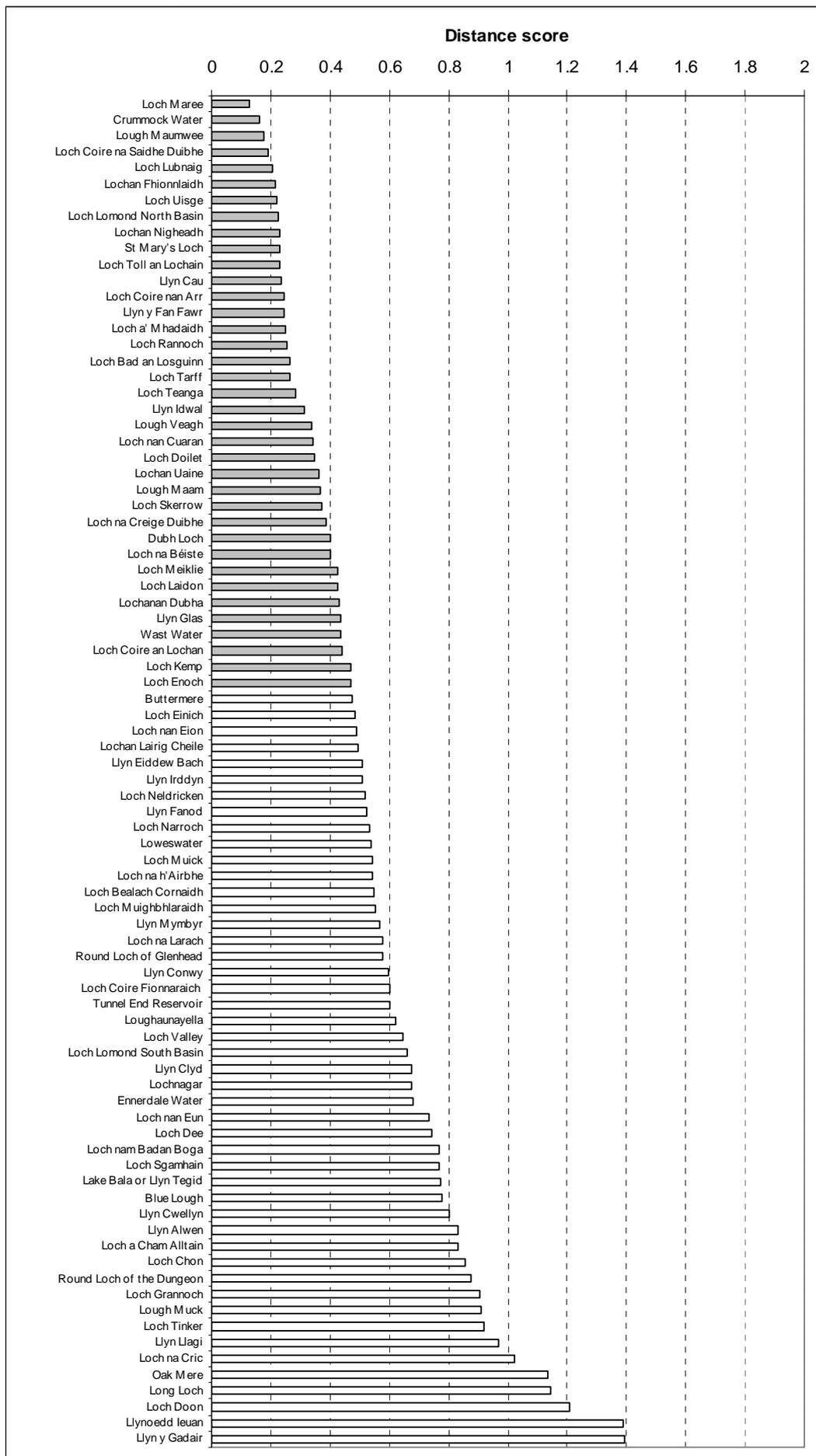
1. The diatom classification of the reference samples from 219 lakes shows good agreement with the GB Lake Typology scheme, indicating that the latter has ecological relevance. Geology (reflecting alkalinity) and, to a lesser extent, lake depth are important in explaining the diatom distributions. However, it is advised that the GB Lake Typology scheme is further validated using other biological groups such as chironomids and cladocera.
2. The diatom reference conditions are described for the main lake types.
3. Approximately 36% of lakes in the existing dataset exhibit low floristic change (squared chord distance dissimilarity score of <0.475) and examples of reference lakes are given for the main lake types.
4. Approximately 50% of lakes in the existing dataset exhibit considerable floristic change with squared chord distance dissimilarity scores of >0.58. In the low alkalinity lakes, these changes appear to largely reflect acidification, whereas in the medium alkalinity, high alkalinity and marl groups, the diatom changes are indicative of eutrophication.
5. The squared chord distance dissimilarity score is a useful tool for assessing degree of floristic change. However, it does not provide any information on the nature or timing of the species shifts, and should therefore be used in combination with other methods for assessing reference sites.

Figure 2.5 Histograms of the squared chord distance dissimilarity scores for each lake type. Sites where the scores are below the critical value at the 5th percentile (<0.475) are shown as shaded bars. (For each lake type, sites are arranged in order of increasing score).

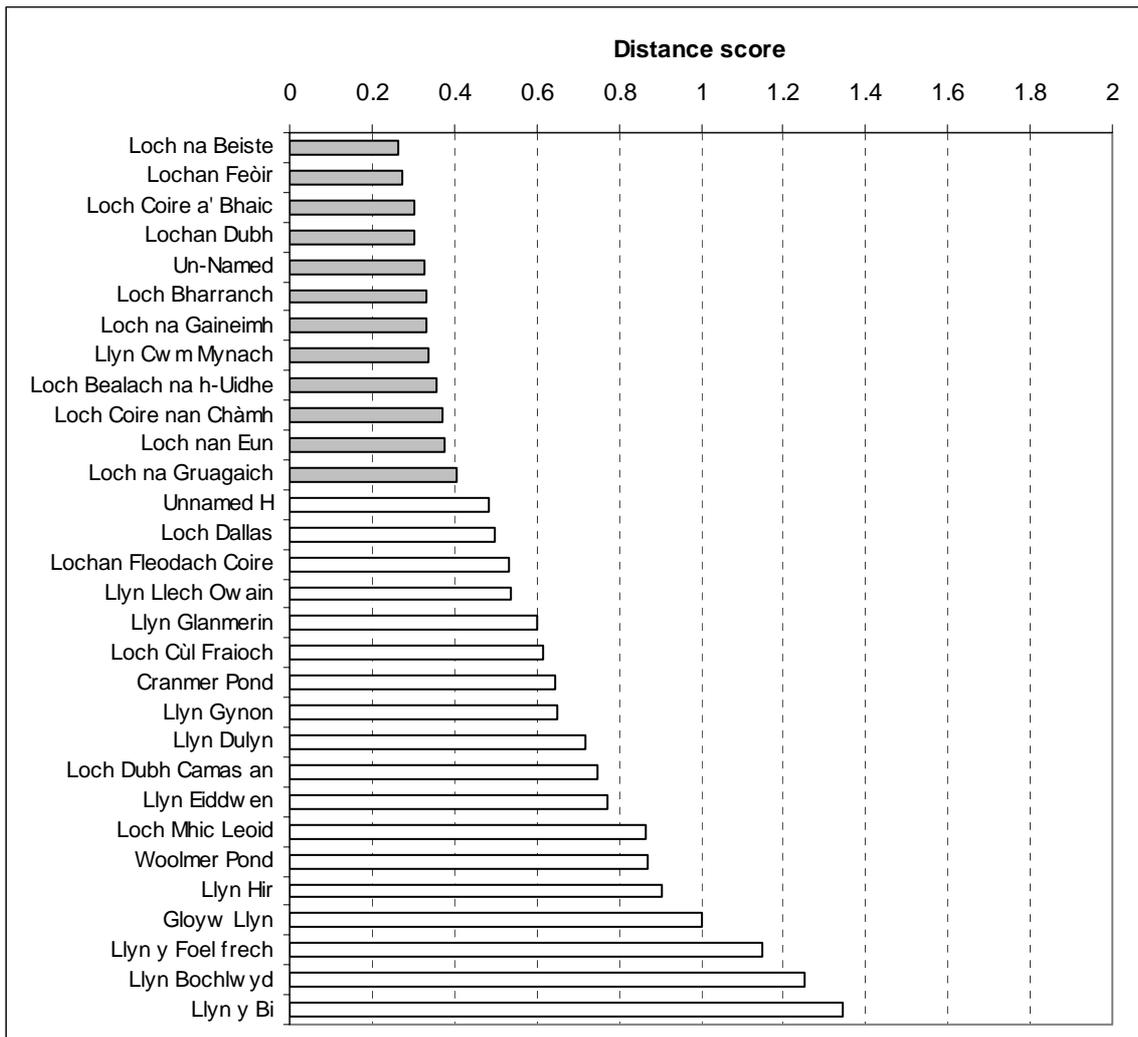
a) Peat lakes, deep and shallow



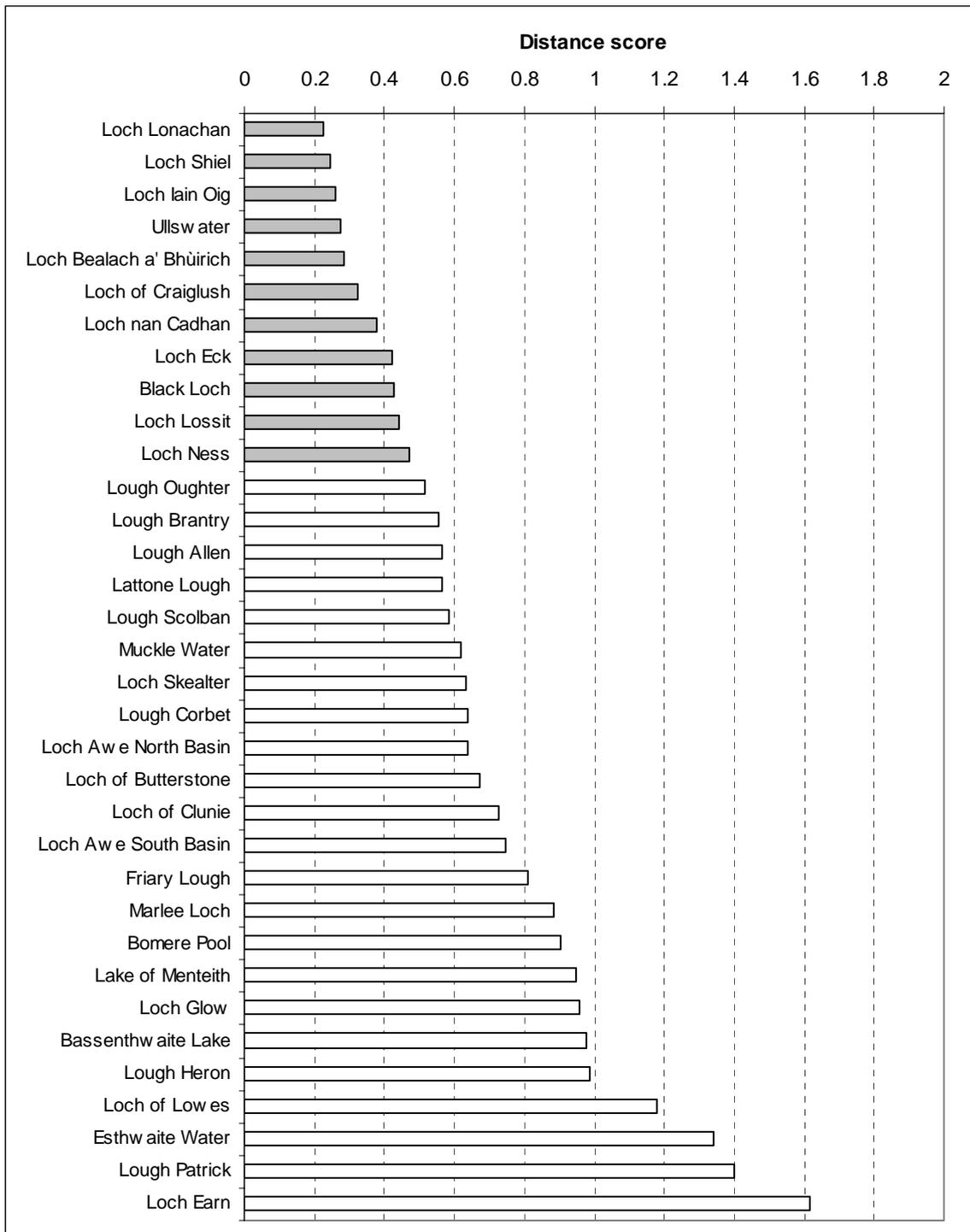
b) Low alkalinity, deep lakes



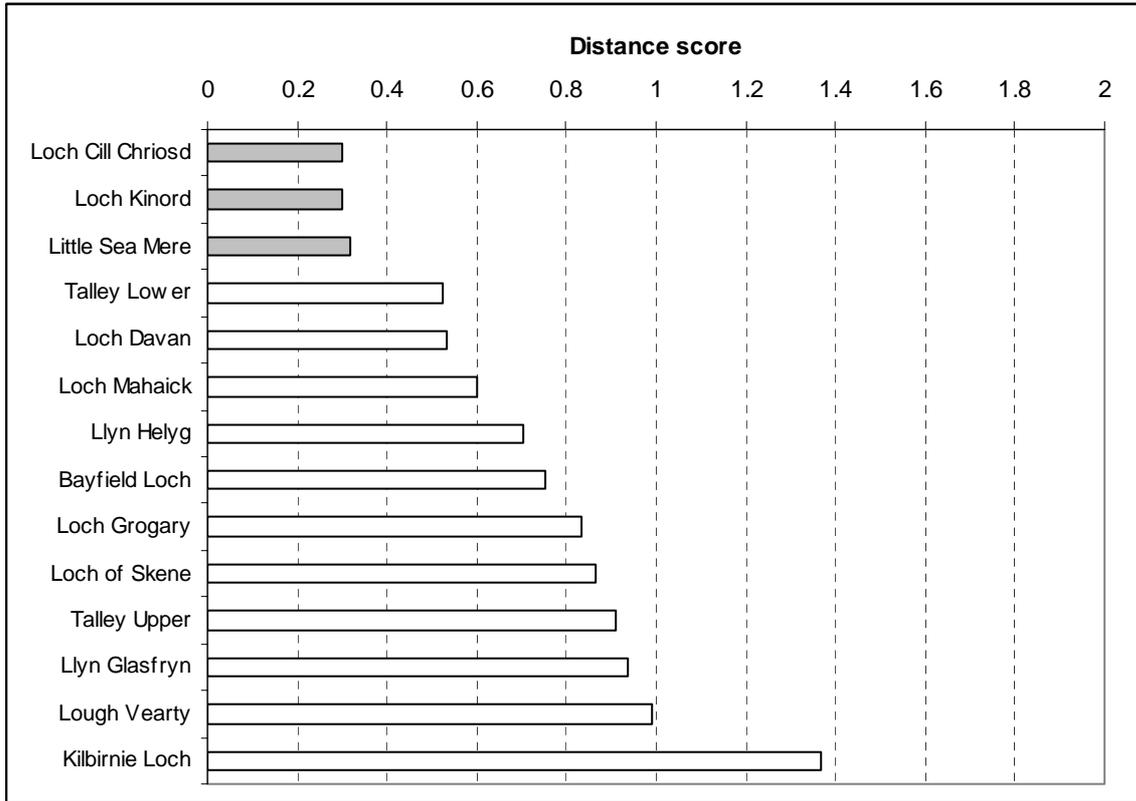
c) Low alkalinity, shallow lakes



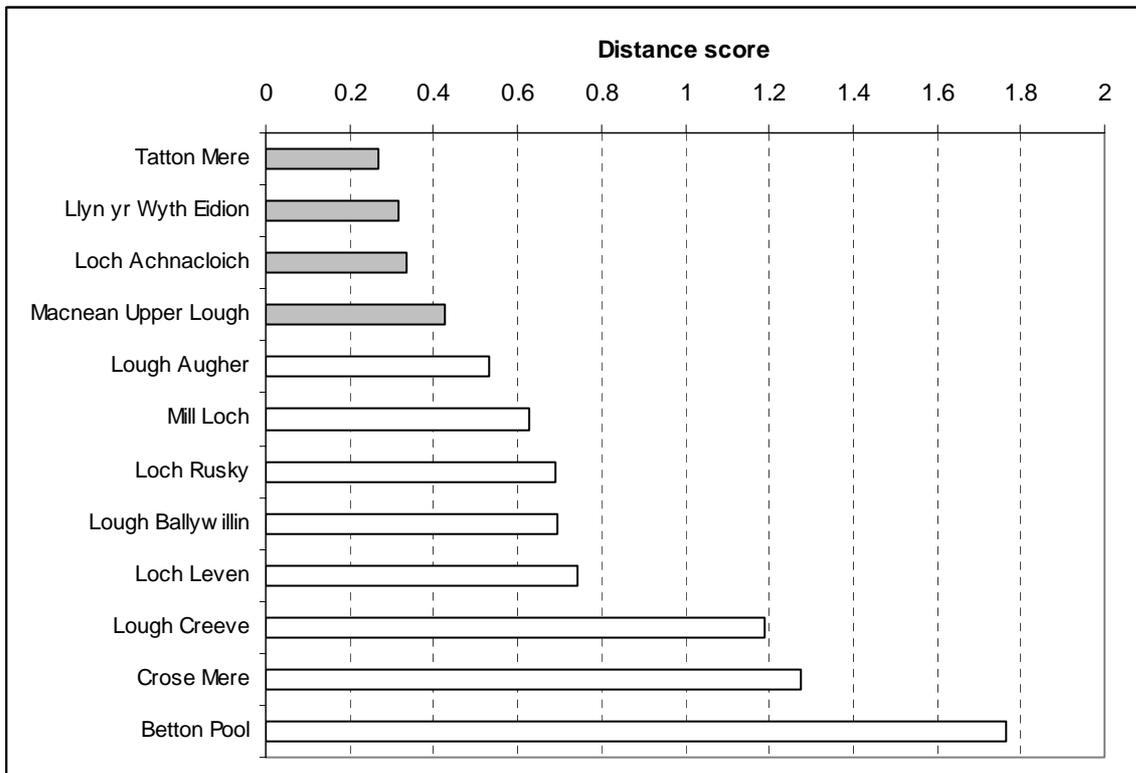
d) Medium alkalinity, deep lakes



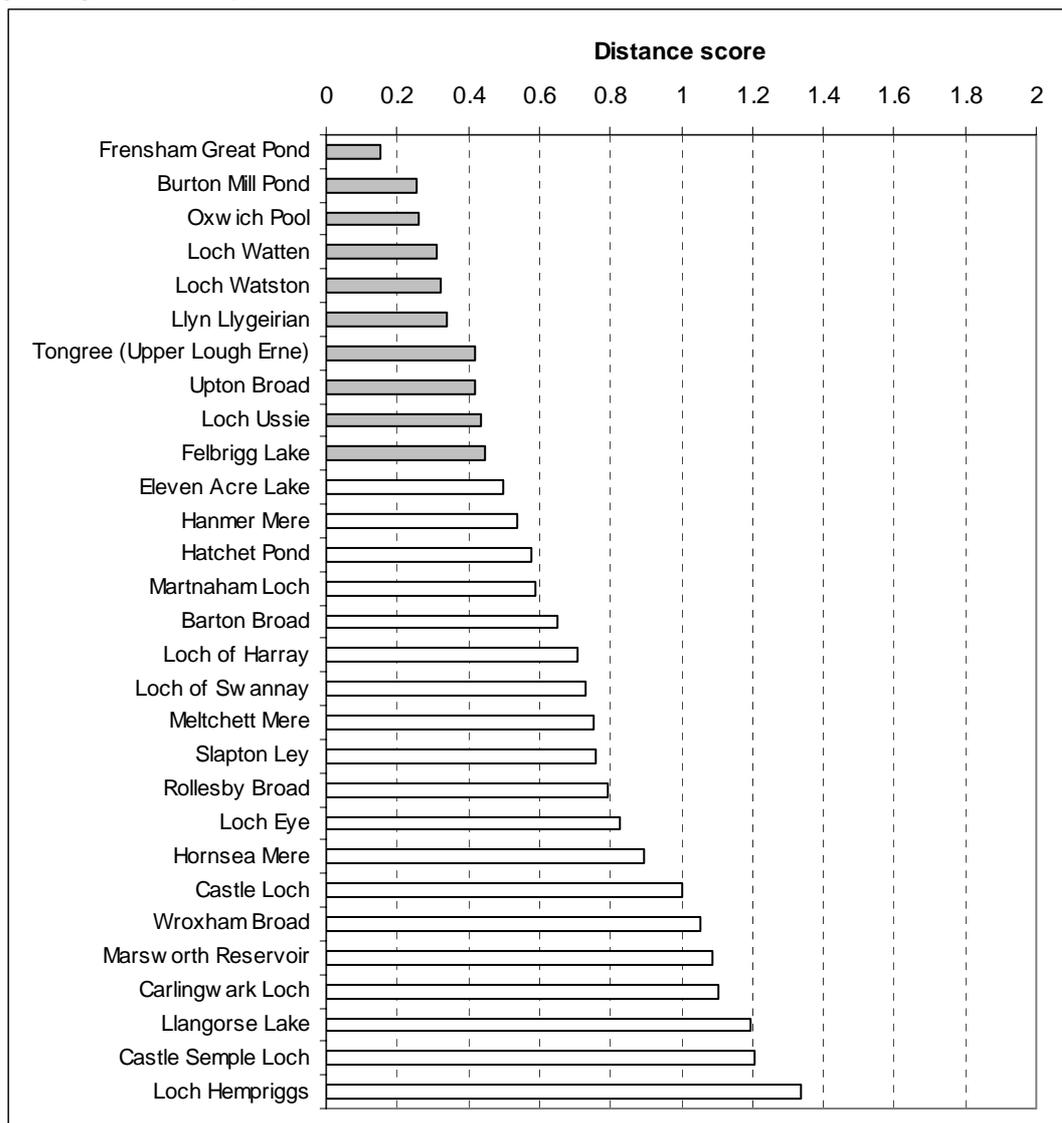
e) Medium alkalinity, shallow lakes



f) High alkalinity, deep lakes



g) High alkalinity, shallow lakes



h) Marl, deep and shallow lakes; Brackish, shallow lakes

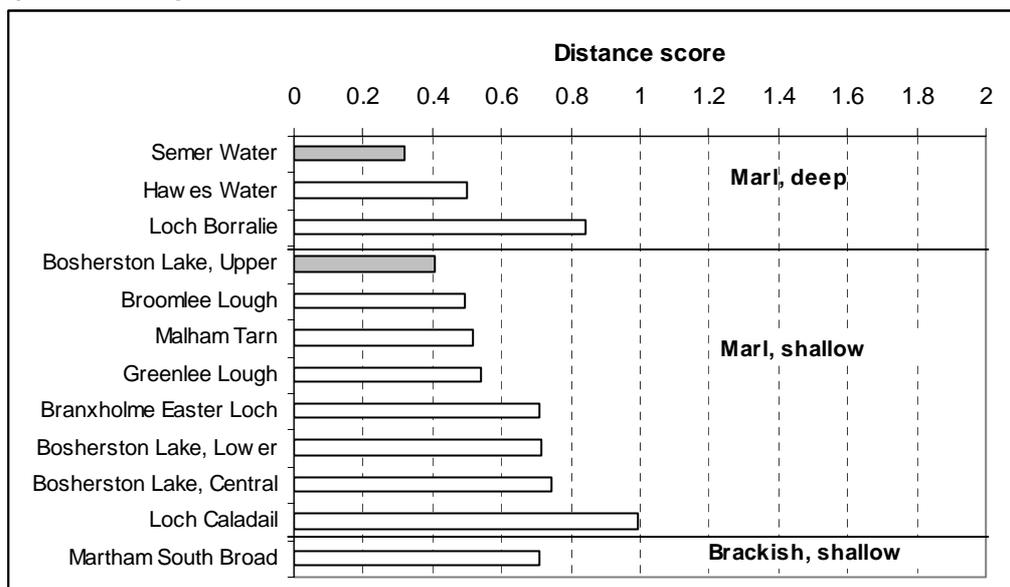
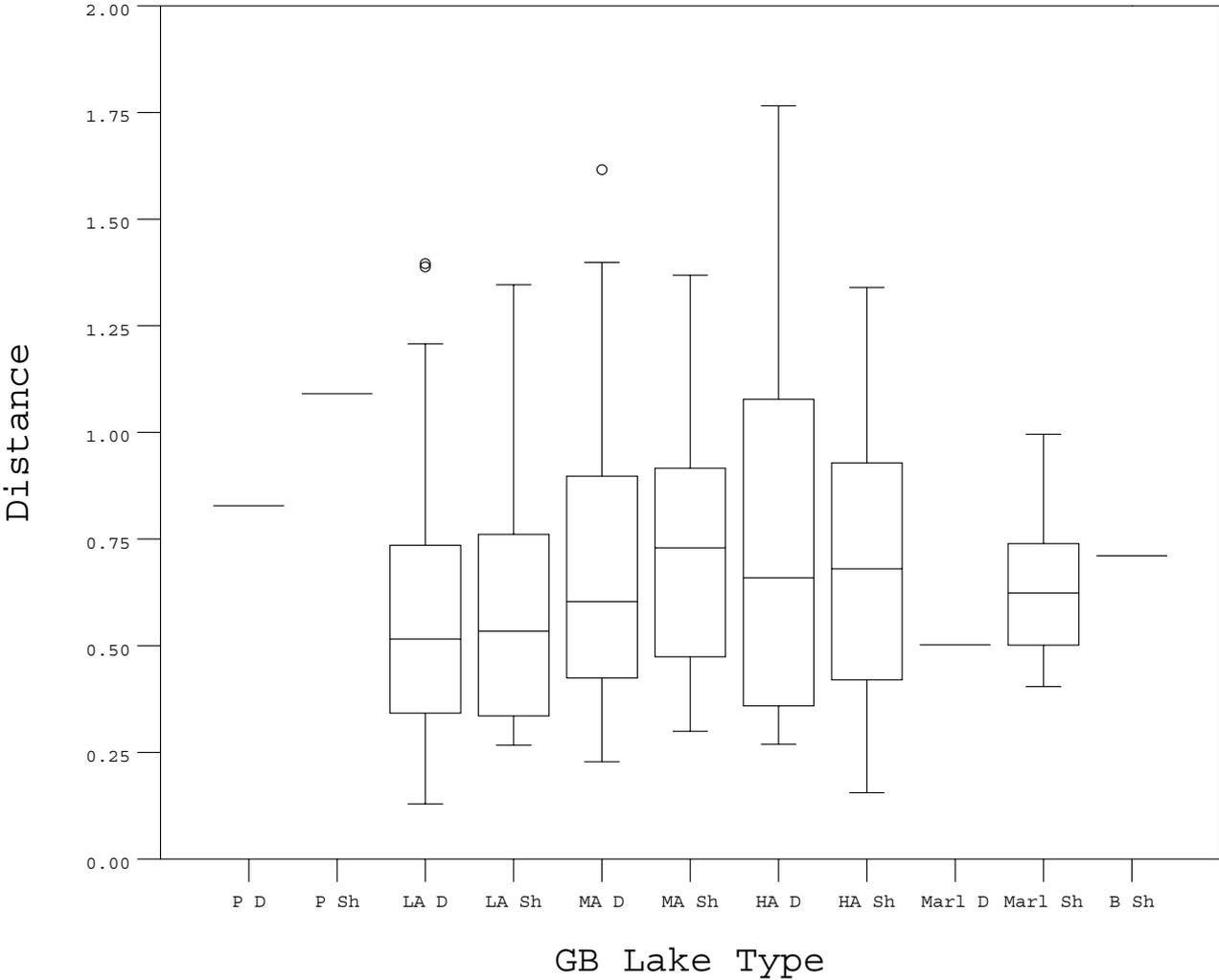


Figure 2.6 Boxplot of the squared chord distance dissimilarity scores for the range of GB lake types.



3. WORK PACKAGE 2: IDENTIFICATION AND CHARACTERISATION OF A SET OF LAKES CURRENTLY AT REFERENCE CONDITION

3.1 Objectives

The aim of work package 2 is to identify a set of reference lakes for each ecotype based on analysis of diatom assemblages preserved in lake sediment cores. In particular, the work package aims to provide data for medium to high alkalinity lakes that are poorly represented in the existing diatom dataset (Figure 2.1). Whilst work package 2 involves the analysis of 5-6 samples per core, the data for the top and bottom samples are also analysed within work package 1 and are thus incorporated into the classification. A further objective of work package 2 is to explore simple methods for characterising the ecological status of lakes including measures of floristic change, ordination and transfer functions.

3.2 Methods

Site selection

A total of 34 lakes were selected for work package 2 (Scotland=16, England=10, Wales=5, Northern Ireland=3, see Table 3.1). These lakes were chosen to represent good examples of their type (i.e. low pressure, good ecological quality) based on data held within the GB Lakes Inventory and expert judgement. Work package 2 focused on medium to high alkalinity waters as these were the types with the least examples of lakes at reference condition in the existing dataset, as shown by the analysis undertaken in work package 1.

Field and laboratory methods

A sediment core was taken in summer 2002 from the deepest part of each lake using either a mini-Mackereth piston corer (Mackereth 1969) or a wide-diameter, piston corer at shallow sites, or a Glew gravity corer (Glew 1991) at deeper sites. All cores were extruded in the laboratory at either 0.5 cm or 1.0 cm intervals (depending on expected sediment accumulation rate) from 0-50 cm and thereafter at 1.0 cm intervals. The main characteristics of the sediment and any stratigraphic changes were noted. The percentage dry weight (%DW) which gives a measure of the water content of the sediment, and percentage loss on ignition (%LOI) which gives a measure of the organic matter content, were determined by standard techniques (Dean 1974) (data shown in Appendix 5).

Slides for diatom analysis were prepared from selected levels of each core (approximately 5-6 per core), expected to represent the last 150 to 200 years, using standard methods (Battarbee *et al.* 2001). Screening of the slides revealed that three sites, Birkdale Tarn, Aqualate Mere and Llyn Cadarn, have extremely poor diatom preservation. Therefore, analysis was subsequently carried out at 31 lakes. At least 300 valves (siliceous component of the cell wall bearing the taxonomic features) were counted from each sample using a Leitz research microscope with a 100x oil immersion objective and phase contrast. Principal floras used in identification were Krammer & Lange-Bertalot (1986-1991). Four to five samples per core were analysed to allow the reference condition and general trend in water quality to be determined. In the absence of funding to establish a chronology for each core, samples spanning the complete core length were analysed. For the deeper, less productive sites, core lengths are generally in the range 25-35 cm. The database of core chronologies for UK lakes held at the University of Liverpool (P. G. Appleby, pers. comm.) indicates that a sediment accumulation rate of $\sim 0.2 \text{ cm yr}^{-1}$ is typical for such sites. For the shallow, more productive waters, core lengths are typically 50-70 cm (in a few cases $\sim 100 \text{ cm}$). The University of Liverpool database suggests that an average sediment accumulation rate of 0.4 to 0.5 cm yr^{-1} is typical for such sites. It is expected, therefore, that the sediment records extend back at least 100-150 years and that the bottom-most sample can be taken to represent reference condition. All slides are archived at the ECRC and the data are stored in the Amphora database.

Data analysis

The diatom data were expressed as percentage relative abundances in all analyses. The full dataset for the 31 cores was comprised of 147 samples and 433 diatom taxa. Summary diagrams

of the diatom changes (showing only those taxa present with a relative abundance of >3% in at least 2 samples) were produced for each site, grouped by lake type, using C² (Juggins 2003).

The degree of floristic change between the bottom sample and each of the other samples analysed in each core was assessed using the squared chord distance dissimilarity coefficient (Overpeck *et al.* 1985) implemented in the statistical software R (R Development Core Team 2004), as for work package 1. Only those 191 taxa present with a maximum relative abundance of > 1% in > 5 samples in the overall dataset were included in the analyses. The scores are plotted for each lake, grouped by lake type (Figure 3.6), to show at what point in the core any floristic change took place. As in work package 1, the 5th percentile (score < 0.475) is used to define sites with low floristic change between the bottom (reference) sample and the upper samples.

Detrended correspondence analysis (DCA) (Hill & Gauch 1980) was performed using CANOCO version 4.5 (ter Braak & Smilauer 2002) to assess the direction and magnitude of floristic change at each site. Analysis was carried out on subsets of the data according to lake type and only taxa present with a relative abundance of >1% in at least two samples in each subset were included. The results for each lake type are presented as biplots of axis 1 and 2 sample scores and species scores. Samples with similar scores on the two axes lie in close proximity, reflecting similar diatom composition. For each core, lines connect the samples in a series from core bottom to core top. The direction of the line indicates the direction of floristic change and its length is a measure of species turnover in Hill's standard deviation units (Hill & Gauch 1980).

Diatom transfer functions

The technique of weighted averaging (WA) regression and calibration (ter Braak & van Dam 1989) has become a standard technique in palaeolimnology for reconstructing past environmental variables. 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 infer lake pH (e.g. Birks *et al.* 1990) and total phosphorus (TP) concentrations (Hall & Smol 1999), whereby modern diatom pH and TP optima and tolerances are calculated for each taxon based on their distribution in the training set, and then past pH and TP concentrations are derived from the weighted average of the optima of all diatoms present in a given fossil sample. The methodology and the advantages of WA over other methods of regression and calibration are well documented (e.g. ter Braak & van Dam 1989).

Diatom transfer functions were applied to the diatom data for each core, following taxonomic harmonisation between the training sets and the fossil data. Only the 224 taxa present with a relative abundance of >1% in at least two samples in the overall dataset were included. Reconstructions of diatom-inferred TP (DI-TP) were produced using either a Northwest European training set of 152 relatively 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 0.21 log₁₀ µg TP l⁻¹ for the weighted averaging partial least squares two-component (WA-PLS2) model (Bennion *et al.* 1996), or a recently developed model based on a training set of 56 relatively large, deep lakes (> 10 m maximum depth) from Scotland, Northern Ireland, Cumbria, southern Norway and central Europe, with a median value for the dataset of 22 µg TP l⁻¹ (Bennion & Anderson unpublished). For this dataset, the best model was generated with simple WA and inverse deshrinking (RMSEP of 0.25 log₁₀ µg TP l⁻¹); For each core, the training set containing the greatest percentage of the taxa present in the fossil sample was selected (see Appendix 6). Reconstructions of diatom-inferred pH (DI-pH) were produced for the low alkalinity sites only using the Surface Water Acidification Programme (SWAP) training set of 167 lakes from largely acid-sensitive, upland regions of the UK, Norway and Sweden (Stevenson *et al.* 1991). The model is based on simple WA with classical deshrinking (Line *et al.* 1994). The median value for the dataset is pH 5.3 and the model has a RMSEP of 0.32 pH units. The RMSEP values were calculated using the jack-knife, or 'leave-one-out', cross validation method which better estimates the true predictive ability of the model (ter Braak & Juggins 1993). All reconstructions were implemented using C² (Juggins 2003).

Table 3.1 List of 34 lakes sampled as part of Work Package 2

WBID	OSNAME	Amphora site/core code	Grid ref	Map no	DOM FWS ¹	Max Depth (m) (coring location)	Est mean depth (m)	Alt (m)	Area (ha)	Sampling date	Core length (cm) & [Type ²]	pH (summer 2002)	Cond $\mu\text{S cm}^{-1}$ (summer 2002)	Revised typology based on data
SCOTLAND														
1674	Muckle Water	MUCL/ MUCL1	HY 395 300	6	3	5.1	>3	98	14.4	20-Jun-02	24 [GLE]	6.7	150	MA,D
14935	Loch Skealtar (Sgealtair)	SKEA/SKEA1	NF 897 686	18	1	11	>3	4	49.5	26-Jun-02	38 [GLE]	5.42	300	MA,D
20197	Loch Lonachan	LONA/LONA1	NG 626 189	32	4	9.7	>3	155	13.8	25-Jun-02	30 [GLE]	7.03	120	MA,D
24998	Black Loch	BLAL/ BLAL1	NT 075 961	58	4	6.2	>3	288	3.9	28-Jun-02	69 [MAC]	7.52	110	MA,D
25000	Loch Glow	GLOW/ GLOW1	NT 087 957	58	4	11	>3	277	50.9	28-Jun-02	38 [MAC]	6.46	63	MA,D
14677	Loch Grogary (Croghearraidh)	GROG/GROG1	NF 716 711	18	1	2	<3	3	8.5	26-Jun-02	117 [FAT]	7.23	300	MA,Sh
20108	Loch Cill Chriosd	CCHR/ CCHR1	NG 611 205	32	4	1.3	<3	24	20.8	24-Jun-02	93 [FAT]	6.96	140	MA,Sh
24742	Loch Mahaick	MAHA/ MAHA1	NN 706 068	57	5	2.1	<3	204	11.8	29-Jun-02	32 [GLE]	6.5	92	MA,Sh
14403	Loch Achnacloich	ACHN/ ACHN1	NH 665 736	21	3	7.3	>3	117	6.6	24-Jun-02	56 [MAC]	7.7	215	HA,D
24851	Loch Rusky	RUSK/RUSK1	NN 615 034	57	4	13	>3	138	23.0	27-Jun-02	57 [MAC]			HA,D
1678	Loch of Swannay	SWAN/SWAN1	HY 304 293	6	4	4.3	<3	43	233.4	19-Jun-02	27 [GLE]	8.6	240	HA,Sh
24933	Loch Watston	WATO/ WATO1	NN 711 003	57	5	3.6	<3	44	6.6	29-Jun-02	63 [MAC]	8.11	210	HA,Sh
2712	Loch Watten	WATT/ WATT1	ND 229 561	12	5	3.2	<3	17	372.8	21-Jun-02	28 [GLE]	8.6	255	HA,Sh
4444	Loch Hempriggs	HEMP/ HEMP1	ND 343 471	12	5	2.3	<3	45	88.1	22-Jun-02	103 [FAT]	7.5	245	HA,Sh
2161	Loch Borralie	BORR/ BORR1	NC 381 668	9	5	17	>3	17	36.7	23-Jun-02	66 [MAC]	8.2	305	Marl,D
2176	Loch Caladail	CALA/ CALA1	NC 396 666	9	5	2.5	<3	36	25.4	23-Jun-02	62 [MAC]	8.5	290	Marl,Sh
ENGLAND														
29000	Crummock Water	CRUM/CRUM1	NY157188	89	2	42	>3	96	249.7	01-Jul-02	37 [GLE]	6.02		LA,D
29052	Buttermere	BUTM/BUTM1	NY182157	89	3	27	>3	103	90.9	01-Jul-02	25 [GLE]	5.76		LA,D
28955	Ullswater (North Basin)	ULLS/ULLS1	NY425204	90	3	34	>3	144	868.2	01-Jul-02	29 [GLE]	6.3		MA,D
36544	Bomere Pool	SCM28/SCM28B	SJ498080	126	4	14.5	>3	78	10.0	05-Jul-02	61 [MAC]			MA,D
46102	Little Sea Mere	LITT/LITT1	SZ029846	195	2	1.5	<3	5	31.4	23-Sep-02	56 [FAT]			MA,Sh
44031	Frensham Great Pond	FREN/FREN1	SU845401	186	2	2	<3	61	29.2	24-Sep-02	49 [FAT]			HA,Sh
45108	Burton Mill Pond	BURT/BURT1	SU974175	197	5	2	<3	16	21.9	25-Sep-02	78 [FAT]			HA,Sh
29647	Hawes Water	CZSD47/HAWE1	SD477766	97	5	12.2	>3	8	5.7	18-Sep-02	33 [GLE]			Marl,D
29250	Birkdale Tarn	EN02/BIRK1	NY851018	91	3	1.5	<3	487	7.3	04-Jul-02	56 [FAT]			P,Sh
35724	Aqualate Mere	AQUA/AQUA1	SJ772204	127	5	1.1	<3	67	75.3	05-Jul-02	111 [FAT]			HA,Sh
WALES														
36182	Llyn y Gadair	CZSH71/GADA1	SH707135	124	1	15	>3	559	4.4	09-Jul-02	30 [GLE]			LA,D
33861	Llyn y Foel-frech	CL30B/FOEL1	SH919593	116	4	4	<3	398	2.0	06-Jul-02	33 [GLE]			LA,Sh
33862	Llyn Bochlywd	VSH6508/BLWY1	SH654593	115	1	5.7	<3	555	4.2	06-Jul-02	31 [GLE]			LA,Sh
32435	Llyn Llygeirian	CZSH38/LLYG1	SH346898	114	5	1	<3	45	11.1	08-Jul-02	31 [FAT]			HA,Sh
32792	Llyn Cadarn	CADA/CADA1	SH492811	115	5	6.7	>3	77	1.2	08-Jul-02	36 [GLE]			Marl,D

Table 3.1 (continued)

OSNAME	Amphora site/core code	Grid ref	Map no	Area (ha)	Alt (m)	Geol	Sampling date	Core length (cm) & [Type ²]	Chl a ($\mu\text{g L}^{-1}$)	Cond ($\mu\text{S cm}^{-1}$)	Secchi depth (m) (Aug 02)	Max depth (m)	Est mean depth (m)	Type
N IRELAND														
Lattone Lough	LATT/LATT1	H001455	17	30	75	Sil	30-Aug-02	90 [MAC]	na	135	1.60	12.5	>3	MA,D
Lough Scolban	SCOL/SCOL1	G995605	17	64	50	Calc	30-Aug-02	57 [MAC]	4	110	1.80	18.5	>3	MA,D
Lough Vearty	VEAR/VEAR1	G994658	17	47	110	Sil	30-Aug-02	90 [MAC]	3	108	2.00	5.2	<3	MA,Sh

1 - Dominant Freshwater Sensitivity Class where 1=very sensitive to acidification and 5=not sensitive to acidification (data taken from the GB Lakes Inventory).

2 - FAT=wide-diameter, fat piston core, GLE = Glew core, MAC=Mackereth core

Figure 3.1 Summary diagram of diatom changes (% relative abundance) in cores from the Low Alkalinity, Deep and Shallow lake types

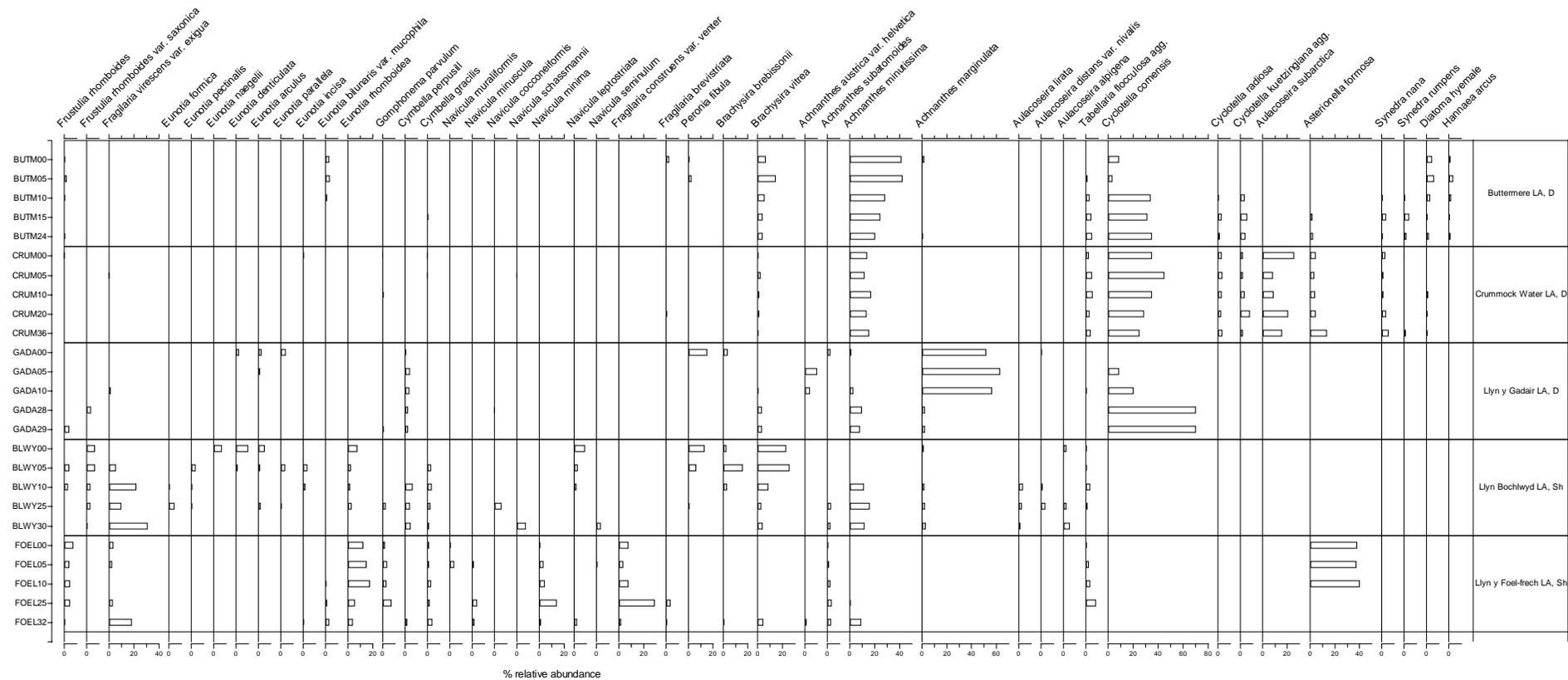


Figure 3.2 Summary diagram of diatom changes (% relative abundance) in cores from the Medium Alkalinity, Deep lake types

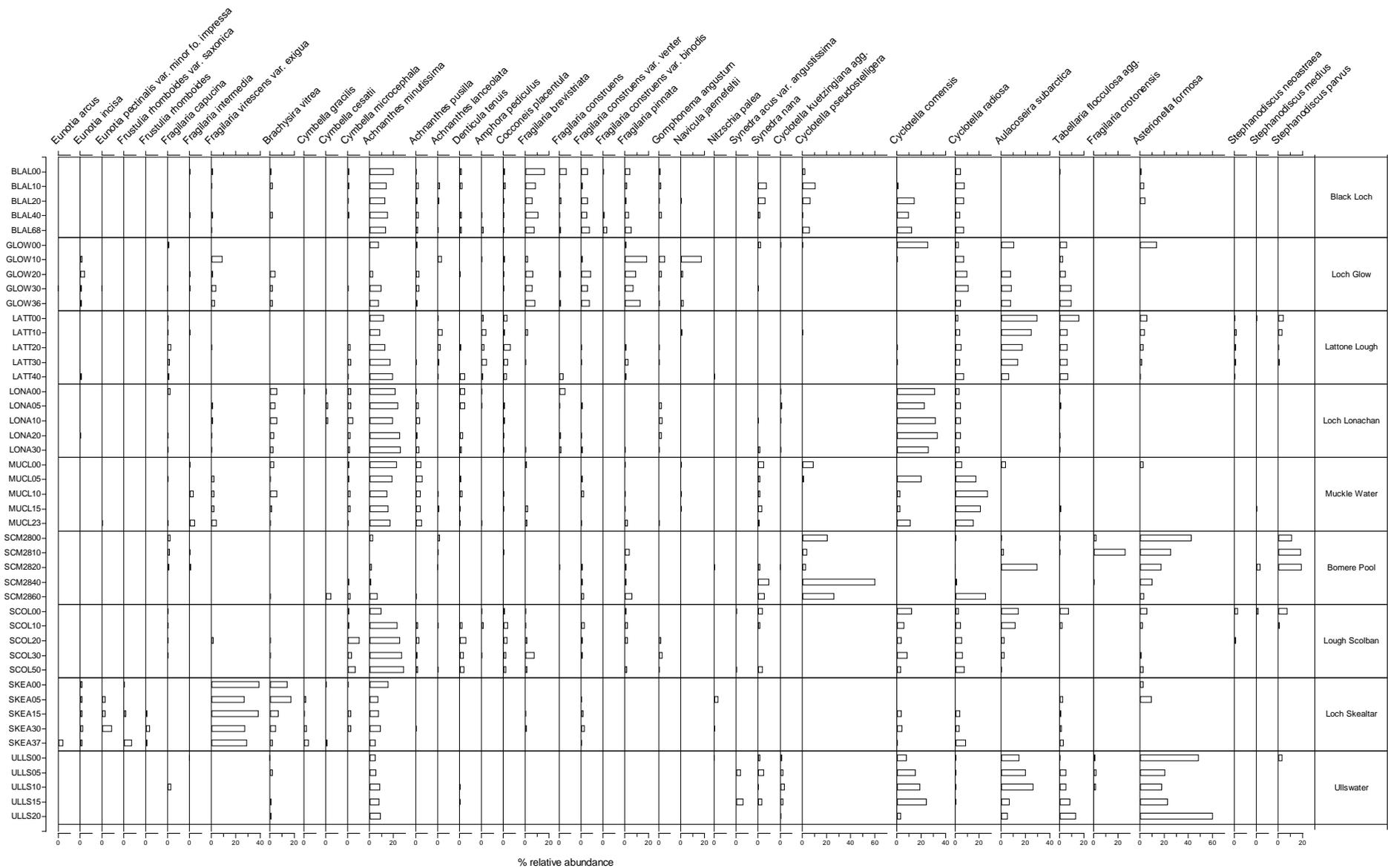


Figure 3.3 Summary diagram of diatom changes (% relative abundance) in cores from the Medium Alkalinity, Shallow lake types

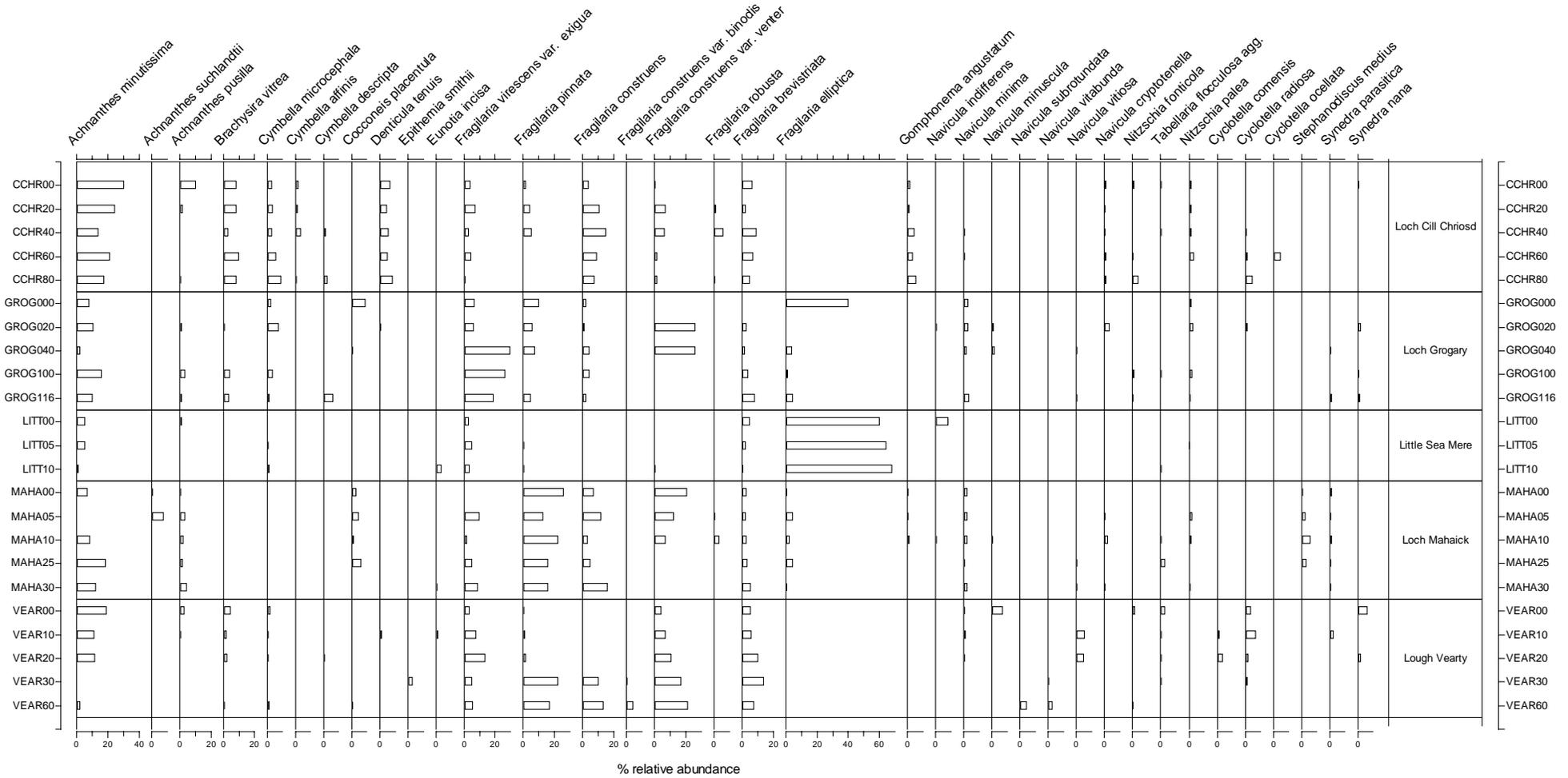


Figure 3.4 Summary diagram of diatom changes (% relative abundance) in cores from the High Alkalinity, Deep and Shallow lake types

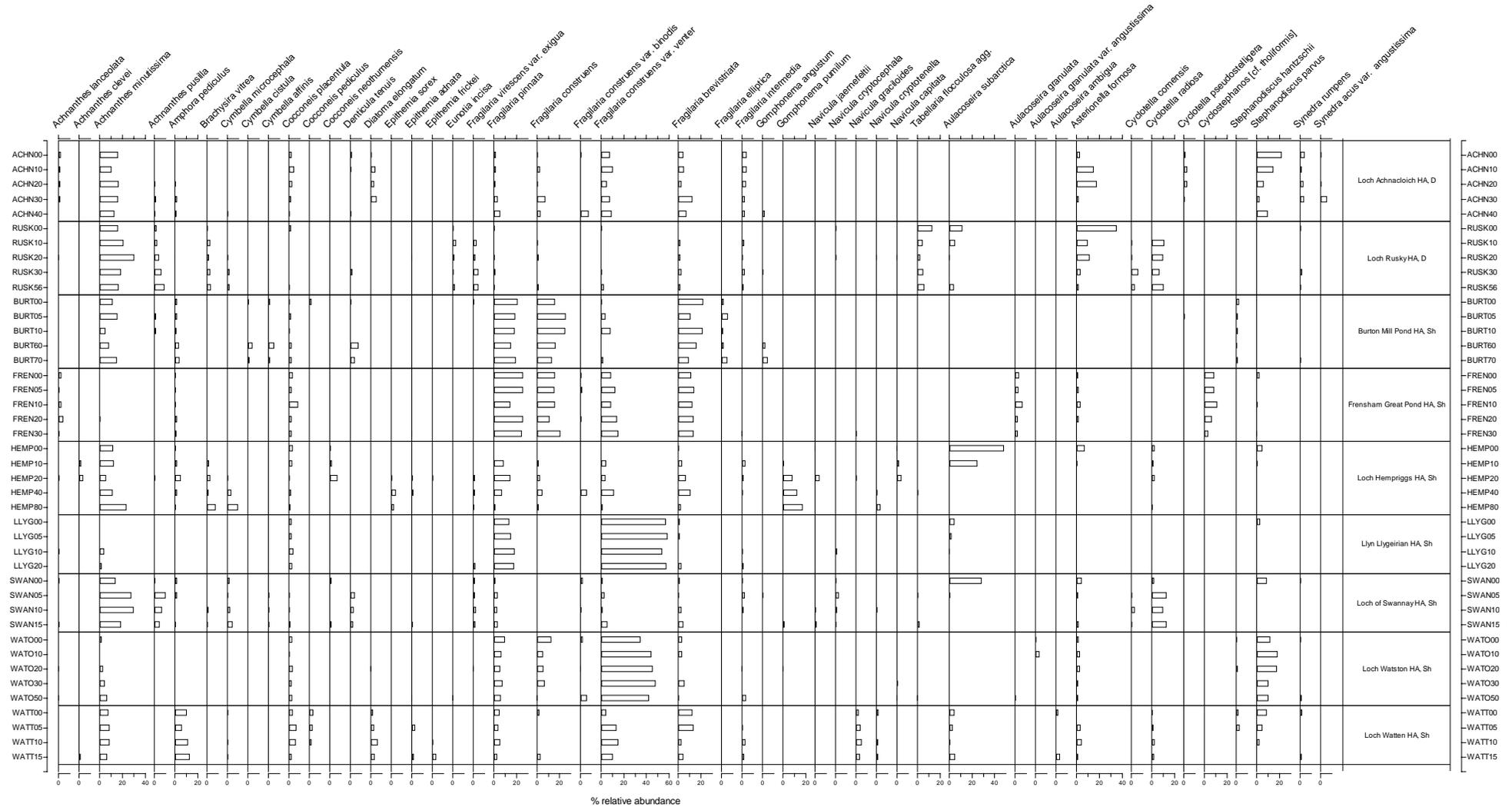
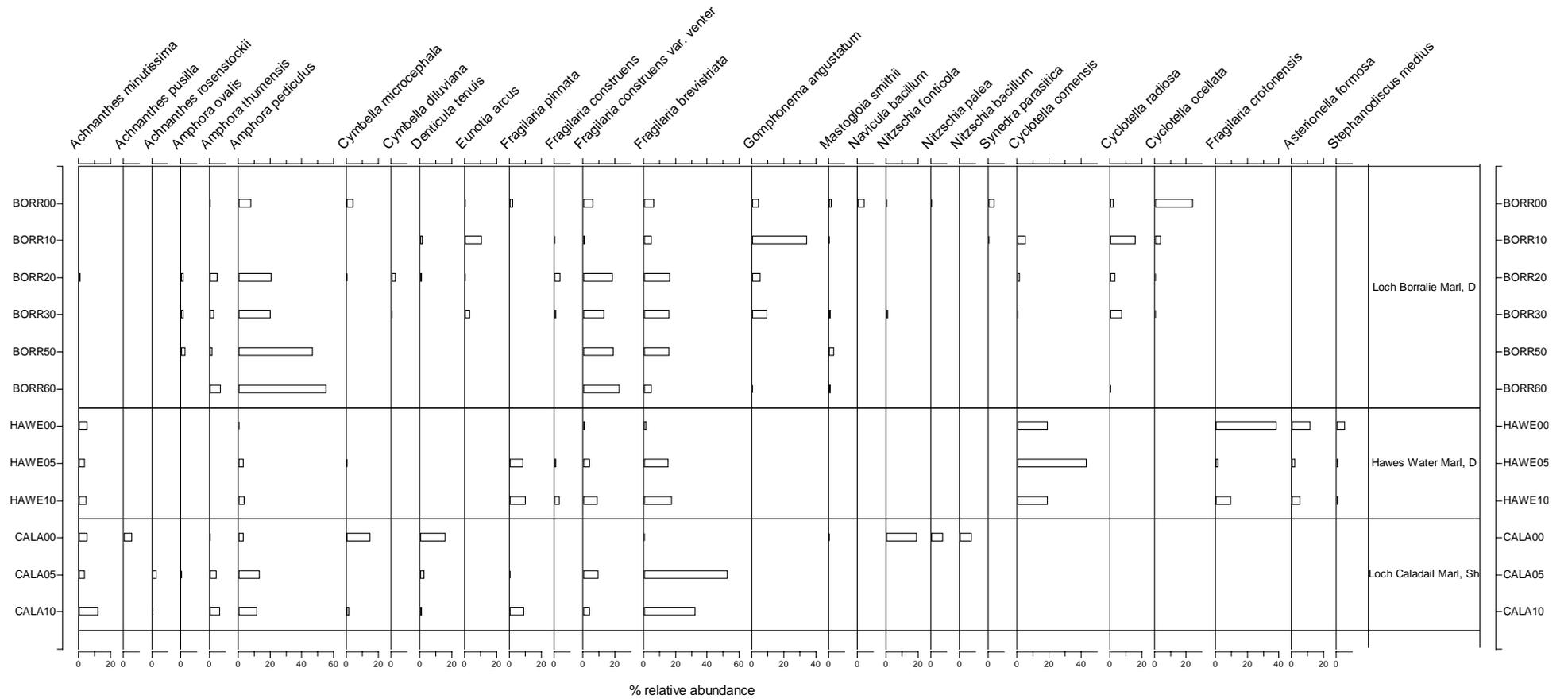


Figure 3.5 Summary diagram of diatom changes (% relative abundance) in cores from the Marl, Deep and Shallow lake types



3.3 Results and discussion

The 31 lakes represent a broad range of types with both deep (D) and shallow (Sh) examples of low alkalinity (LA), medium alkalinity (MA), high alkalinity (HA) and marl (Marl) systems.

A summary of the diatom assemblages in the cores from each site is shown in Figures 3.1 to 3.5. The squared chord distance dissimilarity scores are presented in Figure 3.6 and the DCA results are plotted in Figure 3.7. The diatom based reconstructions of pH (for the low alkalinity lakes only) and total phosphorus are shown as line graphs in Figure 3.8 (see Appendix 6 for tabulated transfer function results). The following section describes the results for each of the lake types.

3.3.1 Low alkalinity lakes

Deep lakes

Of the three low alkalinity, deep lakes, Buttermere and Crummock Water (neighbouring lakes in the English Lake District) provide good examples of reference sites. All five samples analysed from each core are in close proximity in Figure 3.7a, reflecting similar species composition throughout the diatom records. Buttermere is comprised of a mixed community of planktonic and non-planktonic forms with high relative abundances of acidophilous to circumneutral, oligotrophic taxa, such as *Cyclotella comensis*, *Brachysira vitrea* and *Achnanthes minutissima* (Figure 3.1). Crummock Water has a more plankton dominated community comprised of oligotrophic *Cyclotella* spp. as well as a number of taxa indicative of slightly more productive waters, e.g. *Aulacoseira subarctica* and *Asterionella formosa* (Figure 3.1). The squared chord distance dissimilarity scores between the bottom sample and all upper samples in the Crummock Water core are < 0.475, and likewise in the Buttermere core, with the exception of the 5 cm sample where the score is slightly higher (0.58) owing to a decline in the *Cyclotella* spp. and an increase in acidophilous non-planktonic species (Figure 3.6a). These sites, therefore, exhibit low floristic change throughout the period represented by the sediment cores. This is reflected by the diatom-inferred pH and TP reconstructions. In Crummock Water, the DI-pH values are stable throughout the core and the DI-TP concentrations are in the oligotrophic range (8-12 $\mu\text{g l}^{-1}$) with no upward trend (Figure 3.8a). In Buttermere, the results suggest recent, though slight, acidification (DI-pH values decreasing from 7.1 to 6.7 pH units) and no change in DI-TP ($\sim 7\text{-}8 \mu\text{g l}^{-1}$) (Figure 3.8a). In contrast, the third low alkalinity, deep lake, Llyn y Gadair (Snowdonia, Wales) has experienced significant floristic change. This is shown by the high squared chord distance dissimilarity scores between the lower samples and the three upper samples in the core (Figure 3.6a) and the wide spread of the data points in the DCA biplot (Figure 3.7a). There has been a marked shift from a *Cyclotella* dominated flora, typical of circumneutral waters to one comprised of non-planktonic, acid-tolerant species, principally *Achnanthes marginulata*, *Peronia fibula* and *Eunotia* spp. (Figure 3.1). The move toward more acidic conditions is shown by the DI-pH reconstruction whereby values steadily decline from 7.2 to 5.0 pH units (Figure 3.8a). Llyn y Gadair has clearly been impacted by acidification and does not, therefore, provide an example of a reference site for this lake type.

Shallow lakes

Both of the low alkalinity, shallow lakes, Llyn Bochlywd and Llyn y Foel-frech (Wales), have experienced significant floristic change. In the Llyn Bochlywd core, the assemblages in the two upper samples are markedly different from those in the lower samples (Figure 3.6b). There is a shift from a mixed community of planktonic taxa (*Aulacoseira* spp.) and acidophilous-circumneutral non-planktonic species (e.g. *Achnanthes minutissima*, *Fragilaria virescens* var. *exigua*) to a non-planktonic flora dominated by taxa tolerant of more acidic conditions (e.g. *Brachysira* spp., *Eunotia* spp., *Peronia fibula*) (Figure 3.1, Figure 3.7a). The DI-pH reconstruction indicates a steady decline in pH from ~ 5.9 to 5.2 pH units (Figure 3.8b). Whilst Llyn Bochlywd is a naturally acid lake, it has experienced marked acidification over the time period represented by the sediment core and cannot be considered as a reference site. In the Llyn y Foel-frech core, the squared chord distance dissimilarity scores between the bottom sample and all upper samples are high (Figure 3.6a) and the DCA plot clearly shows the position of the bottom sample at a distance from all of the upper samples reflecting its different species composition (Figure 3.7a). The diatom flora in the bottom-most sample is non-planktonic and acidophilous with taxa typical of low alkalinity, upland systems (e.g. *Brachysira vitrea*, *Fragilaria virescens* var. *exigua*) (Figure 3.1). This changes initially to a non-planktonic assemblage comprised of taxa associated with circumneutral-alkaline waters (e.g.

Fragilaria construens var. *venter*, *Gomphonema parvulum*) and then to an assemblage dominated by the planktonic diatom *Asterionella formosa*, which is commonly found in relatively productive waters and frequently appears in formerly oligotrophic lakes as a sign of enrichment (Figure 3.1). However, taxa typical of slightly acidic conditions continue to be present (e.g. *Eunotia rhomboidea*, *Frustulia rhomboides*). The shift towards more circumneutral, productive taxa is reflected by the DI-pH and DI-TP reconstructions, with markedly higher values for the four upper samples than for the bottom sample (Figure 3.8b). The lake, therefore, appears to have experienced eutrophication and/or alkalisation and does not provide an example of a reference site for this lake type.

3.3.2 Medium alkalinity lakes

Deep lakes

Of the nine medium alkalinity, deep lakes, Loch Lonachan (Isle of Skye), Black Loch (Fife) and Ullswater (Cumbria) provide the best examples of reference sites. The squared chord distance dissimilarity scores between the bottom sample and all upper samples in the cores are < 0.475 (Figure 3.6c), and all five samples analysed from each core are in close proximity in Figure 3.7b, reflecting similar species composition throughout the diatom records. Loch Lonachan appears to be the least productive of the three sites with a classic oligotrophic *Cyclotella-Achnanthes minutissima* assemblage. Black Loch and Ullswater are slightly more productive with a number of planktonic taxa associated with intermediate nutrient concentrations (e.g. *Asterionella formosa*) (Figure 3.2). The relatively low degree of floristic change is reflected by the DI-TP results, whereby concentrations in Loch Lonachan are stable at $\sim 8 \mu\text{g l}^{-1}$, and values increase only slightly from 18-21 $\mu\text{g l}^{-1}$ and 11-15 $\mu\text{g l}^{-1}$ in Black Loch and Ullswater, respectively, indicating a small amount of enrichment (Figure 3.8c). Muckle Water (Orkney) and Lough Scolban (Northern Ireland) are also relatively good examples of minimally impacted lakes for this type, with only the surface sediment sample differing slightly from the rest of the core (Figure 3.6c). In Muckle Water, a number of planktonic taxa indicative of mesotrophic conditions (e.g. *Asterionella formosa*, *Cyclotella pseudostelligera*) appear in the surface sample only, albeit in small amounts (Figure 3.2) and in Lough Scolban several *Stephanodiscus* species with a preference for nutrient rich waters are present in the upper sediments. This slight enrichment is indicated by the DI-TP reconstructions but nevertheless concentrations never exceed 17 $\mu\text{g l}^{-1}$ at Muckle Water or 26 $\mu\text{g l}^{-1}$ at Lough Scolban and are, therefore, within the mesotrophic range. Similarly, Lough Lattone (Northern Ireland) and Loch Skealtar (North Uist) are reasonable examples of minimally impacted lakes, exhibiting slight floristic change in the upper two samples (Figure 3.6c, Figure 3.7b). At Lough Lattone, the relative abundance of *Stephanodiscus parvus* increases and at Loch Skealtar, *Asterionella formosa* arrives (Figure 3.2). In both cases, the species shifts are indicative of mild enrichment. The DI-TP increases are relatively small with values rising from 16 to 22 $\mu\text{g l}^{-1}$ and 10 to 12 $\mu\text{g l}^{-1}$ at Lough Lattone and Loch Skealtar, respectively (Figure 3.8c).

Two of the medium alkalinity, deep lakes, Loch Glow (Fife) and Bomere Pool (Shropshire), experienced significant floristic change (Figure 3.6c). The data for Loch Glow should be interpreted with caution, however, owing to extremely poor preservation in the middle section of the core. The 10-11 cm sample was particularly badly affected and only ~ 200 valves were counted. Nevertheless the surface sample contains very different taxa from the lower portion of the core with relatively high abundances of two planktonic forms, *Asterionella formosa* and *Cyclotella comensis*, not previously observed in the diatom record (Figure 3.2). The relative abundance of non-planktonic taxa consequently declines. It is difficult to determine the driver of the changes as *Asterionella formosa* is associated with intermediate nutrient levels and *Cyclotella comensis* is commonly found in oligotrophic waters. The relatively high abundance of the latter in the surface sample results in a decrease in DI-TP (Figure 3.8c) and suggests that enrichment is not necessarily the cause of the species shifts. It is possible that alterations in the physical environment (e.g. light, temperature, substrate) or in other biological elements of the system (e.g. top down control) may explain the observed diatom changes but a more detailed study would be required to establish this. The diatom assemblages in Bomere Pool change continually throughout the sediment sequence with a succession of planktonic species from *Cyclotella* spp., to *Aulacoseira subarctica*, to *Fragilaria crotonensis*, and finally to *Asterionella formosa* and *Stephanodiscus parvus* (Figure 3.2). The floristic change is indicated by high squared chord distance dissimilarity scores between the bottom sample and all upper samples (Figure 3.6c). The dissimilarity of the samples is also shown

by the wide spread of the data points in the DCA biplot (Figure 3.7b). The data series (core bottom to top) broadly moves in the direction from right to left of the plot reflecting the increase in nutrient-rich taxa. There is a slight reversal between the 10 cm sample and the surface sediment as *Cyclotella pseudostelligera* increases once more and the relative abundance of *Stephanodiscus parvus* declines. This is reflected in the DI-TP results whereby values rise in the lower part of the core and then decline toward the top (Figure 3.8c). The diatom data indicate that Bomere Pool is a naturally nutrient-rich lake with taxa commonly found in productive waters occurring throughout the whole diatom record, including the bottom sample. Nevertheless the lake has gone through a series of changes which are most likely the result of enrichment, perhaps with a degree of recovery in recent years. A higher resolution study would be necessary, however, to fully examine the dynamics of the diatom flora and to assess possible causes for the observed shifts.

Shallow lakes

Of the five medium alkalinity, shallow lakes, Loch Cill Chriosd (Isle of Skye) and Little Sea Mere (Dorset) provide the best examples of reference lakes. The squared chord distance dissimilarity scores between the bottom sample and all upper samples in the cores are < 0.475 (Figure 3.6d), and all samples analysed from each core are in close proximity in Figure 3.7c, reflecting similar species composition throughout the diatom records. The assemblages of Loch Cill Chriosd are dominated by non-planktonic forms with high relative abundances of circumneutral to alkaline taxa, such as *Achnanthes minutissima*, *Brachysira vitrea*, *Cymbella* spp., and *Fragilaria* spp. (Figure 3.3). The assemblages of Little Sea Mere are dominated by the non-planktonic, alkaline taxon, *Fragilaria elliptica* (~60% of the total assemblage). However, diatoms were badly preserved throughout the core and it is possible that many other less well silicified taxa may have dissolved. The DI-TP reconstruction gives values of $\sim 20 \mu\text{g l}^{-1}$ for all samples in the Loch Cill Chriosd core with the exception of sample 40-41 cm which has a value of $36 \mu\text{g l}^{-1}$ (Figure 3.8d) This arises because of the slightly higher abundance of the *Fragilaria* spp. relative to the less productive taxa in the sample (Figure 3.3). This could be an artefact of the counting strategy as *Fragilaria* spp. commonly occur in chains and, therefore, can be overestimated in counts of ~ 300 valves if a number of chains are encountered during analysis. In any case, the return to DI-TP values of $\sim 20 \mu\text{g l}^{-1}$ in the two upper samples suggests that, if any enrichment did occur, it was relatively short-lived. The DI-TP reconstruction for Little Sea Mere shows that concentrations were relatively stable at $\sim 40 \mu\text{g l}^{-1}$. Loch Mahaick is another relatively good example of a minimally impacted lake for this type, exhibiting only minor floristic change (Figure 3.6d, Figure 3.7c). The assemblages are dominated by the non-planktonic *Fragilaria* taxa throughout the core with slight variation in the dominant species. The DI-TP indicates only minor enrichment with concentrations of $20\text{-}30 \mu\text{g l}^{-1}$ (Figure 3.8d).

The remaining medium alkalinity, shallow lakes, Loch Grogary (North Uist) and Lough Vearty (Northern Ireland), have both experienced significant floristic change with high squared chord distance dissimilarity scores between the bottom sample and the three upper samples in each core (Figure 3.6d) and widely spread data points in the DCA biplot (Figure 3.7c). However, both sites suffer from poor diatom preservation in sections of the sequence which may influence the data. In Loch Grogary, preservation was a particular problem in the central section from $\sim 40\text{-}60$ cm, and in Lough Vearty in the upper section from $\sim 10\text{-}20$ cm. The diatom assemblages in Loch Grogary are dominated by the non-planktonic *Fragilaria* taxa, observed in other lakes of this type (Figure 3.3) and, much like Loch Mahaick, most of the floristic change can be attributed to variations in the dominant species (e.g. *F. virescens* var. *exigua* is dominant in the lower section, *F. construens* var. *venter* in the middle, and *F. elliptica* in the top). These shifts result in a rise in DI-TP values from ~ 15 to $56 \mu\text{g l}^{-1}$ suggesting that the lake has experienced eutrophication (Figure 3.8d). Whilst *F. virescens* var. *exigua* is typically found in less productive waters than *F. construens* var. *venter* and *F. elliptica*, little is known of the ecology of these taxa, and it is possible that habitat shifts may be as important as nutrient pressures in explaining the diatom changes. The diatom record of Lough Vearty is also difficult to interpret. The assemblages in the lower core are dominated by the non-planktonic *Fragilaria* taxa seen in the other lakes, whilst the upper samples have higher abundances of *Achnanthes minutissima* and the planktonic diatom, *Cyclotella radiosa*, which tends to occur in lakes with intermediate nutrient levels (Figure 3.3). The DI-TP reconstruction suggests that a dramatic decline in concentrations from ~ 85 to $20 \mu\text{g l}^{-1}$ has occurred in the upper core

section (Figure 3.8d). This is caused by the decrease in *Fragilaria* spp. relative to *Achnanthes minutissima* as the former have high TP optima in the training set whilst the optimum of the latter is low. Given the preservation problems in the upper core, it is uncertain whether the diatom record provides a true reflection of changes occurring in the diatom community and hence whether there has been a real decline in nutrient levels. In light of the data interpretation problems for the Loch Grogary and Lough Vearty cores, it is advised that the results are used with caution.

3.3.3 High alkalinity lakes

Deep lakes

Of the two high alkalinity, deep lakes, Loch Achnacloich (near Dingwall) provides a good example of a reference lake. The squared chord distance dissimilarity scores between the bottom sample and all upper samples in the core are relatively low (< 0.57) (Figure 3.6e), and all samples are in close proximity in Figure 3.7d, reflecting similar species composition throughout the diatom record. The assemblages are comprised of both non-planktonic, circumneutral to alkaline taxa (e.g. *Achnanthes minutissima*, *Cocconeis placentula*, *Fragilaria* spp.) and planktonic forms typical of alkaline, productive waters (e.g. *Asterionella formosa*, *Stephanodiscus parvus*) (Figure 3.4). The presence of *Stephanodiscus parvus* throughout the sequence, including the bottom-most sample, suggests that the loch is naturally nutrient-rich. The DI-TP reconstruction is relatively stable with concentrations of $\sim 25 \mu\text{g l}^{-1}$ (Figure 3.8e). The other lake in this group, Loch Rusky (near Aberfoyle), appears to have experienced recent floristic change. The squared chord distance dissimilarity scores between the bottom sample and the three subsequent upper samples in the core are low (< 0.475) but the score for the upper-most is considerably higher at 0.66 (Figure 3.6e). The data point for the surface sample is located at a distance from the other samples in the core in the DCA biplot (Figure 3.7d) highlighting its dissimilarity. The lower samples in the core have a diverse, mixed assemblage comprised of circumneutral, relatively nutrient poor taxa (e.g. *Achnanthes minutissima*, *Eunotia incisa*, *Brachysira vitrea*, *Cyclotella comensis*) and the mesotrophic taxon, *Cyclotella radiosa*. The surface sample, however, sees the disappearance of many of these taxa, a marked rise in *Asterionella formosa* and increases in *Aulacoseira subarctica* and *Tabellaria flocculosa*, all planktonic species commonly observed in mesotrophic waters (Figure 3.4). This is reflected in the DI-TP results where values increase from 16 to $28 \mu\text{g l}^{-1}$ (Figure 3.8e). It appears, therefore, that Loch Rusky has experienced recent enrichment. The expansion of the planktonic diatom forms at the expense of the attached diatom species may arise from reduced light penetration and hence fewer habitats (plants and sediment surfaces) for the latter. It is recommended that Loch Rusky is not selected as a reference lake.

Shallow lakes

Of the seven high alkalinity, shallow lakes, five provide good examples of reference sites: Burton Mill Pond (Sussex), Frensham Great Pond (Hampshire), Llyn Llygeirian (Anglesey), Loch Watston (near Stirling) and Loch Watten (near Wick). The squared chord distance dissimilarity scores between the bottom sample and all upper samples in the cores are < 0.475 (Figure 3.6f), and all samples analysed from each core are in close proximity in Figure 3.7d, reflecting similar species composition throughout the diatom records. The assemblages of all these lakes are dominated by non-planktonic taxa including the *Fragilaria* taxa seen in the medium alkalinity waters, *Amphora pediculus* and *Cocconeis placentula* (taxa commonly observed attached to plants in alkaline waters), *Cymbella* spp. and *Navicula* spp. (Figure 3.4). The assemblages in three of these lakes also have a considerable planktonic component, suggesting that they are perhaps naturally more productive than the other two sites. For instance, Frensham Great Pond has a relatively high abundance of *Cyclostephanos* [cf. *tholiformis*] throughout the core, and Loch Watston and Loch Watten have continual presence of *Stephanodiscus parvus*. The stability of the diatom assemblages in these lakes is reflected by the DI-TP results which show negligible change with concentrations of $\sim 30\text{-}40 \mu\text{g l}^{-1}$ (Figure 3.8f).

These very shallow sites currently support a diverse macrophyte flora with clear-water conditions. Macrophytes are likely to play a role in maintaining good water quality through uptake of nutrients and provision of refuges for phytoplankton grazers. The relatively low percentage of planktonic diatoms in the recent assemblages of these five lakes suggests that they have not switched to

algal-dominated, turbid conditions (cf. the alternative stable states theory of Scheffer *et al.* 1993). Nevertheless, it is worth noting that the planktonic diatom, *Stephanodiscus parvus*, an indicator of enrichment, appears in small amounts in the surface samples of Llyn Llygeirian and Frensham Great Pond, having not been observed in the lower core sections, perhaps providing an early warning that an ecologically important threshold has been crossed. Additionally, it should be noted that the non-planktonic *Fragilaria* spp. which typically dominate the diatom assemblages of nutrient-rich, alkaline waters, such as those observed here, are cosmopolitan taxa and are relatively insensitive to changes in water chemistry. Their high abundance throughout the diatom records of the high alkalinity, shallow lakes results in low floristic change measures and hence determination of reference lake status. We advise that additional biological groups, which may be more sensitive to changes in water quality (e.g. chironomids, cladocera, plant macrofossils), are analysed to confirm reference lake status for this lake type.

The other two lakes in this group, Loch of Swannay (Orkney) and Loch Hempriggs (near Wick) both exhibit floristic change. It is only the surface sample of Loch of Swannay that is significantly different from the bottom sample (Figure 3.6f, Figure 3.7d). The assemblages in the lower part of the core are comprised of a mixed planktonic and non-planktonic flora with common taxa including *Achnanthes minutissima* and *Cyclotella radiosa*. The surface sample, however, is markedly different and sees an expansion of *Aulacoseira subarctica* and the appearance of *Stephanodiscus parvus* (Figure 3.4). The DI-TP reconstruction indicates an increase in concentrations from ~25 to ~40 $\mu\text{g l}^{-1}$ (Figure 3.8f) and it appears that the lake has become more nutrient-rich. A much larger degree of floristic change is observed at Loch Hempriggs. The squared chord distance dissimilarity scores between the bottom sample and the upper samples increase gradually up the core and are as high as 1.3 for the surface sample (Figure 3.6f). The gradual shift away from the composition of the bottom sample is illustrated in the DCA biplot where the data series moves from the bottom to the top of the plot, towards more nutrient-rich taxa (Figure 3.7d). The assemblages in the lower part of the core are non-planktonic and are typical of a relatively unproductive, circumneutral system (e.g. *Achnanthes minutissima*, *Cymbella* spp.). There follows an increase in the non-planktonic *Fragilaria* taxa, which are subsequently replaced by planktonic species, *Aulacoseira subarctica* and *Asterionella formosa*, and in the uppermost sample *Stephanodiscus parvus* appears (Figure 3.4). The DI-TP reconstruction indicates an increase in concentrations in the middle section of the core from 20 to 70 $\mu\text{g l}^{-1}$ followed by a decrease to 35 $\mu\text{g l}^{-1}$ at the surface (Figure 3.8f). This is caused principally by the increase in *Aulacoseira subarctica* which has a much lower TP optimum in the Northwest European dataset than the *Fragilaria* taxa that dominate the lower samples. These *Fragilaria* taxa are common in shallow, alkaline lakes but are poor indicators of lake trophic status as their distributions are not related directly to epilimnetic chemistry but rather to habitat availability (see above). Consequently they cause problems with diatom reconstructions and these have been reported in a number of shallow lake studies (e.g. Bennion *et al.* 2001a, Sayer 2001). It is unlikely that the species shifts observed in the Loch Hempriggs core reflect a recent decline in nutrient concentrations in the lake but rather a change in habitat availability arising from eutrophication. Neither Loch of Swannay nor Loch Hempriggs are recommended as reference lakes.

3.3.4 Marl lakes

Deep lakes

Of the two deep, marl lakes, Hawes Water (Silverdale, Lancashire) exhibits the least change. However, the data must be interpreted with caution as poor diatom preservation prevented analysis beyond a depth of 10 cm downcore, and the 10 cm sample may not represent pre-impact conditions. Even in the short sequence analysed, there is some floristic change with the surface sample being slightly different from the two lower samples (Figure 3.6g, Figure 3.7e). The lower assemblages are a mixed community comprised principally of the planktonic diatom *Cyclotella comensis*, typically found in nutrient-poor waters, and the non-planktonic *Fragilaria* taxa. The surface sample, however, sees a marked increase in three planktonic taxa, *Fragilaria crotonensis*, *Asterionella formosa* and *Stephanodiscus medius*, all associated with more mesotrophic conditions (Figure 3.5). Loch Borralie (Durness) exhibits greater change than Hawes Water most notably in the two upper samples which are significantly different from the assemblages in the lower core (Figure 3.6g, Figure 3.7e). The latter are dominated by non-planktonic taxa such as the *Fragilaria*

spp. and *Amphora pediculus* which frequently occurs as an epiphyte attached to plant surfaces (Figure 3.5). The assemblage in the 10 cm sample is markedly different; the relative abundances of *Gomphonema angustatum* and three species of *Cyclotella* (*C. comensis*, *C. radiosa* and *C. ocellata*) increase at the expense of the formerly important taxa. *Cyclotella ocellata*, a diatom associated with high alkalinity waters continues to increase in the surface sample.

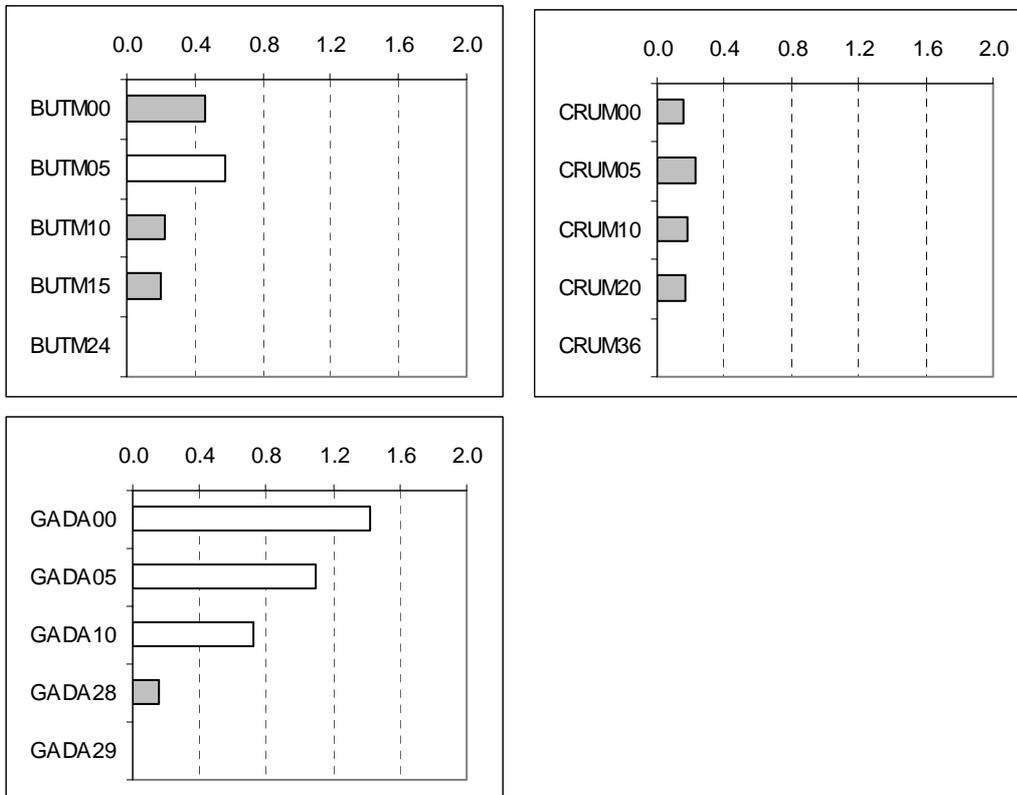
Shallow lakes

Loch Caladail (Durness) provides the only example of a shallow, marl lake in the dataset. Unfortunately, diatom preservation was exceptionally poor in this site and, as for Hawes Water, analysis could not be undertaken beyond a depth of 10 cm downcore. There is some floristic change even in the upper 10 cm section with the surface sample being markedly different from the two lower samples (Figure 3.6h, Figure 3.7e). The assemblages in the lower core section are dominated by non-planktonic taxa including *Fragilaria* spp., *Achnanthes minutissima* and *Amphora* spp. (Figure 3.5) The surface sample is also non-plankton dominated but the species composition is quite different with relatively high abundances of *Cymbella microcephala*, *Denticula tenuis* and three species of *Nitzschia* (*N. fonticola*, *N. palea*, *N. bacillum*), and a notable disappearance of the *Fragilaria* taxa. The causes of such species shifts are unclear and it is possible that bottom up (e.g. higher alkalinity or elevated nutrients) and/or top down controls (e.g. changes in grazing pressure) may be important.

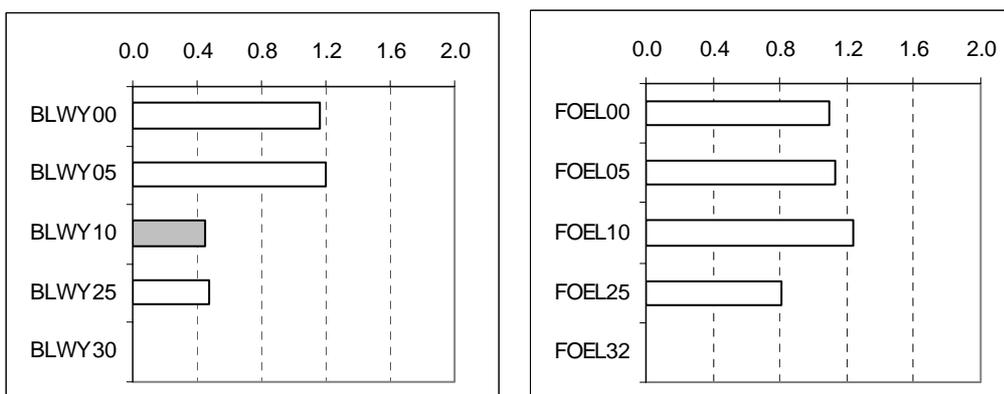
It is difficult to interpret the species shifts observed in the marl lakes in terms of water quality changes, particularly as few diatom studies have been undertaken in marl systems. Furthermore, there are no marl lakes in the diatom-phosphorus training sets and it is, therefore, unlikely that the DI-TP reconstructions are reliable for these systems. Indeed the results for all three sites suggest a general decline in trophic status (Figure 3.8g, h) whereas a qualitative interpretation of the diatom data based on ecological information may lead us to conclude that the lakes have experienced a degree of enrichment. In light of the uncertainties surrounding the data, we recommend that further work is carried out on a greater number of lakes using indicators other than diatoms to identify appropriate reference sites for marl systems. Chironomids, cladocera and ostracods are likely to be more useful biological groups for assessing ecological status in these systems.

Figure 3.6 Histograms of the squared chord distance dissimilarity scores between the bottom sample and each of the upper samples in the 31 cores. Samples where the scores are below the critical value at the 5th percentile (<0.475) are shown as shaded bars. (Sites are arranged by lake type).

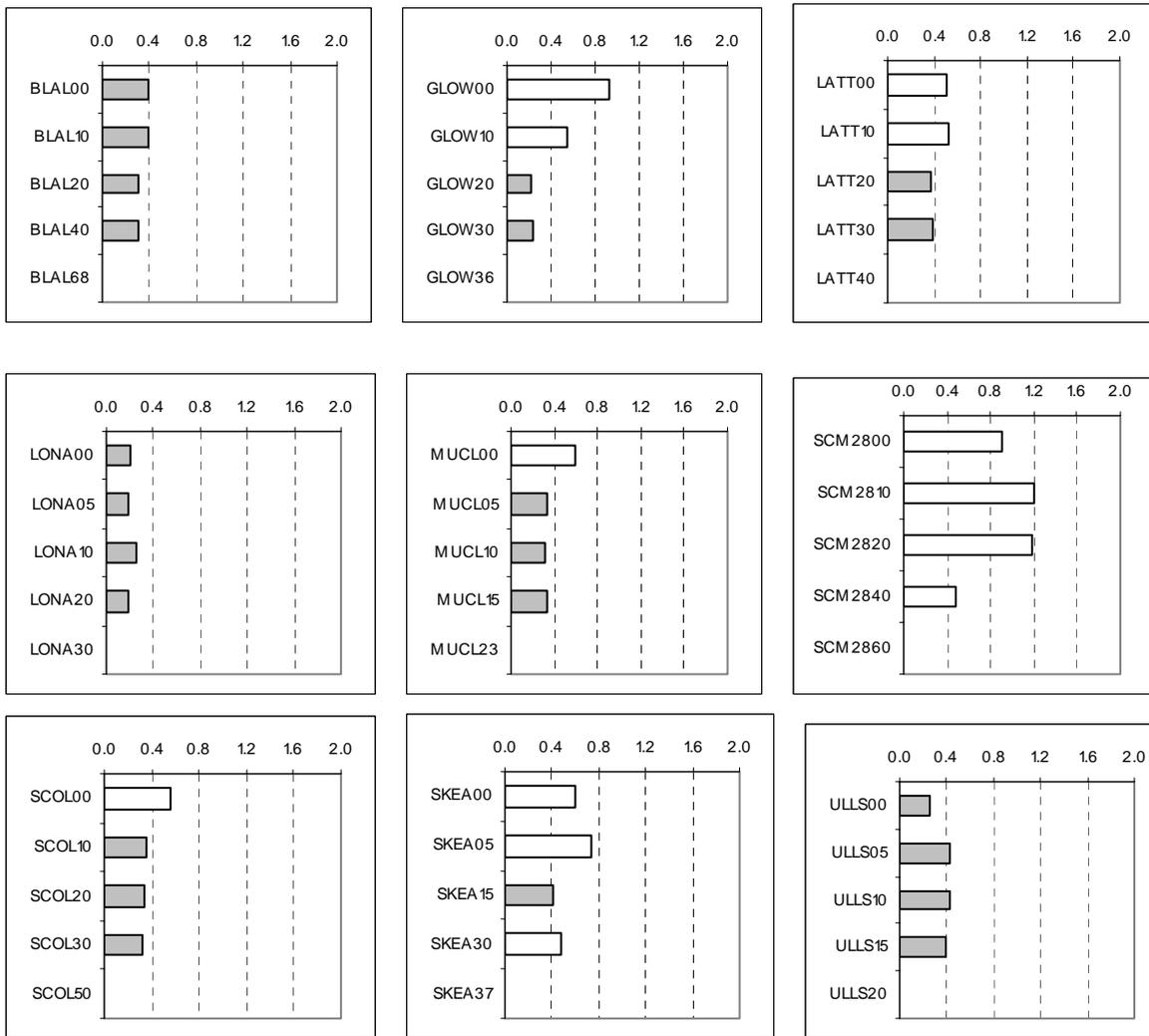
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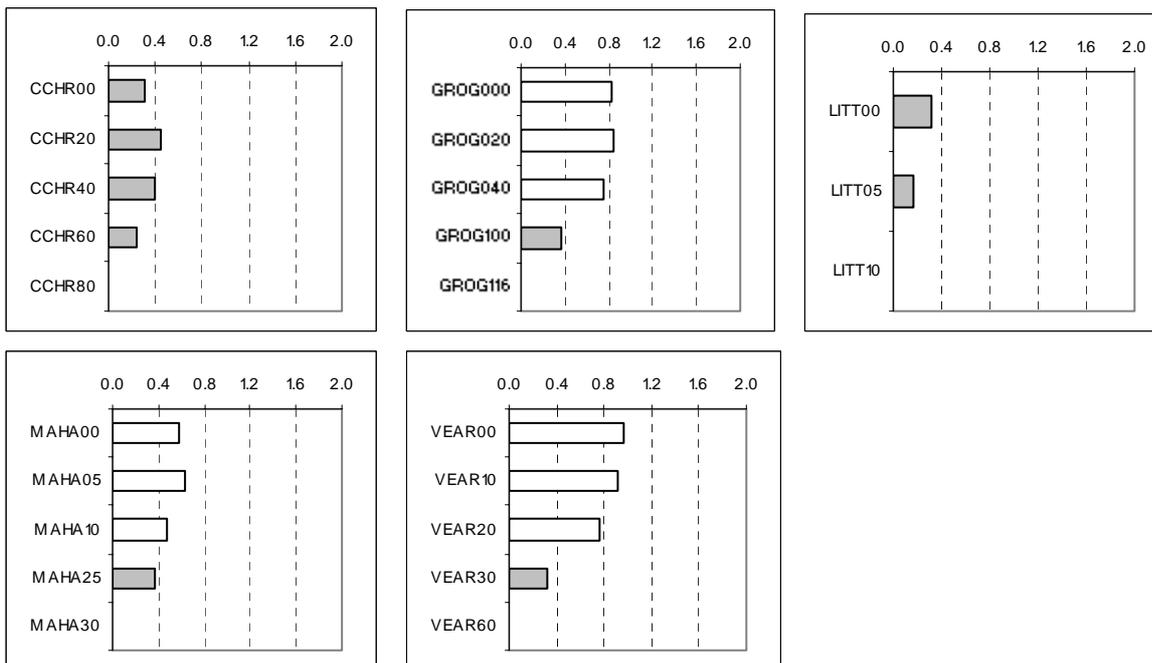
b) Low alkalinity, shallow lakes



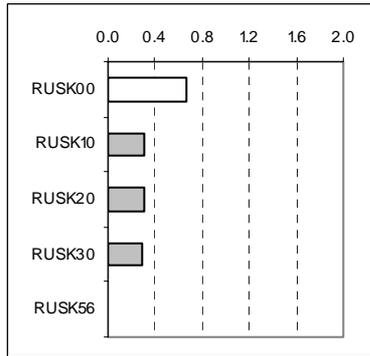
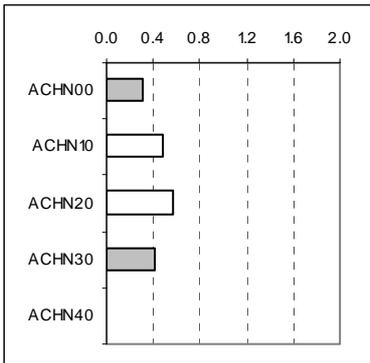
c) Medium alkalinity, deep lakes



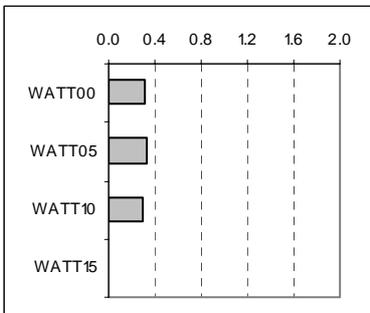
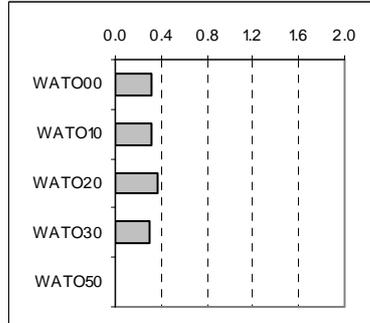
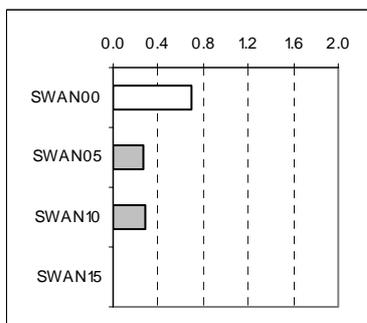
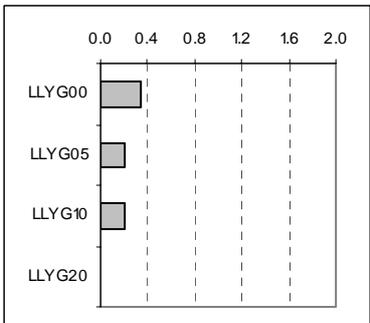
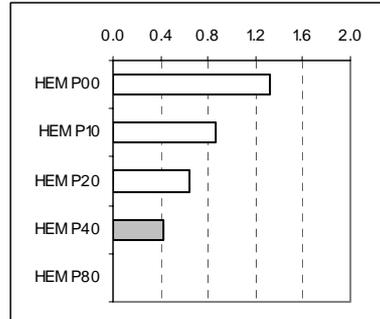
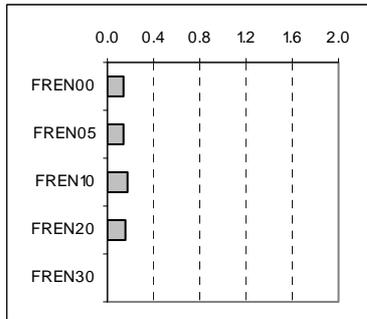
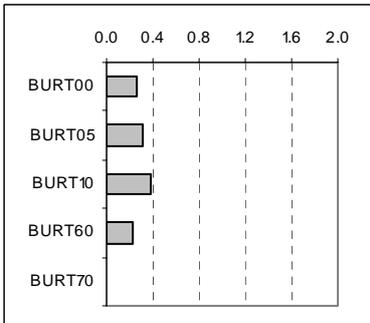
d) Medium alkalinity, shallow lakes



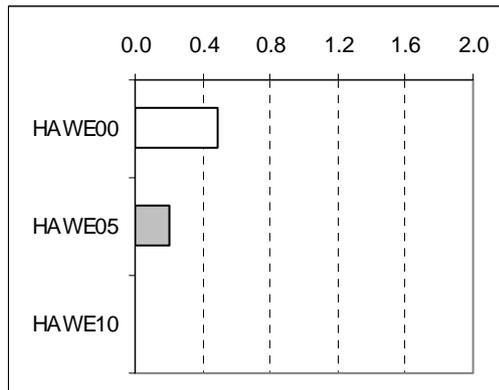
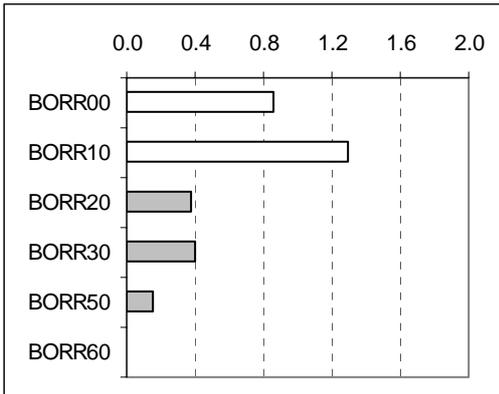
e) High alkalinity, deep lakes



f) High alkalinity, shallow lakes



g) Marl, deep lakes



h) Marl, shallow lakes

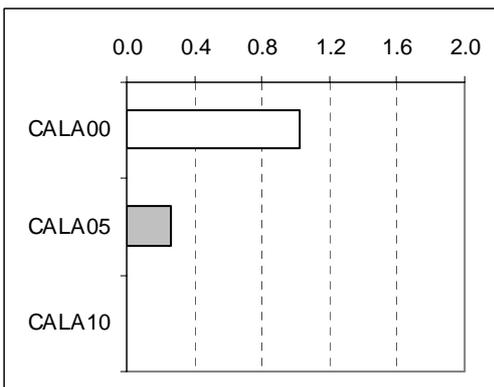
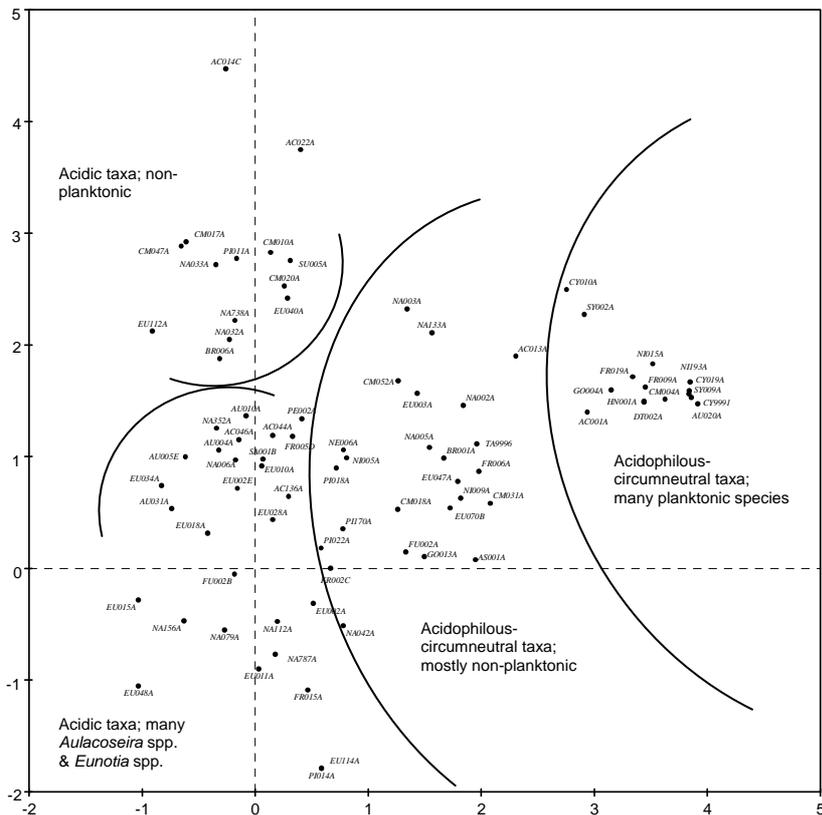
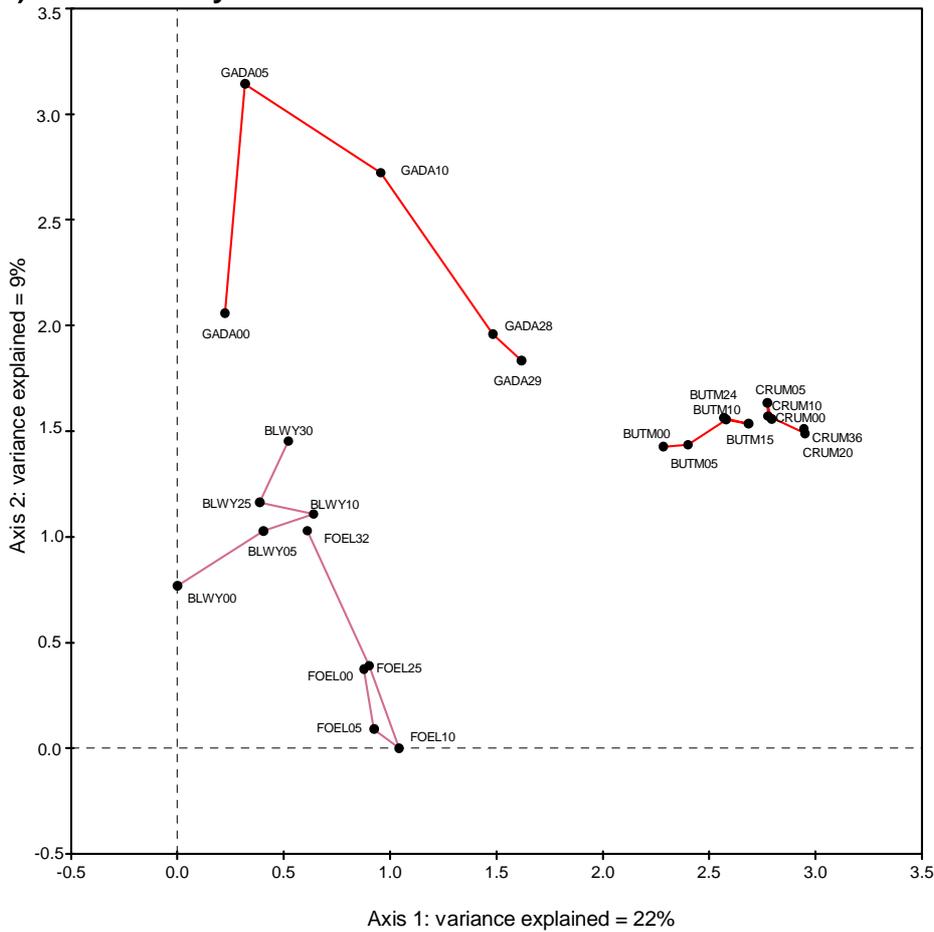
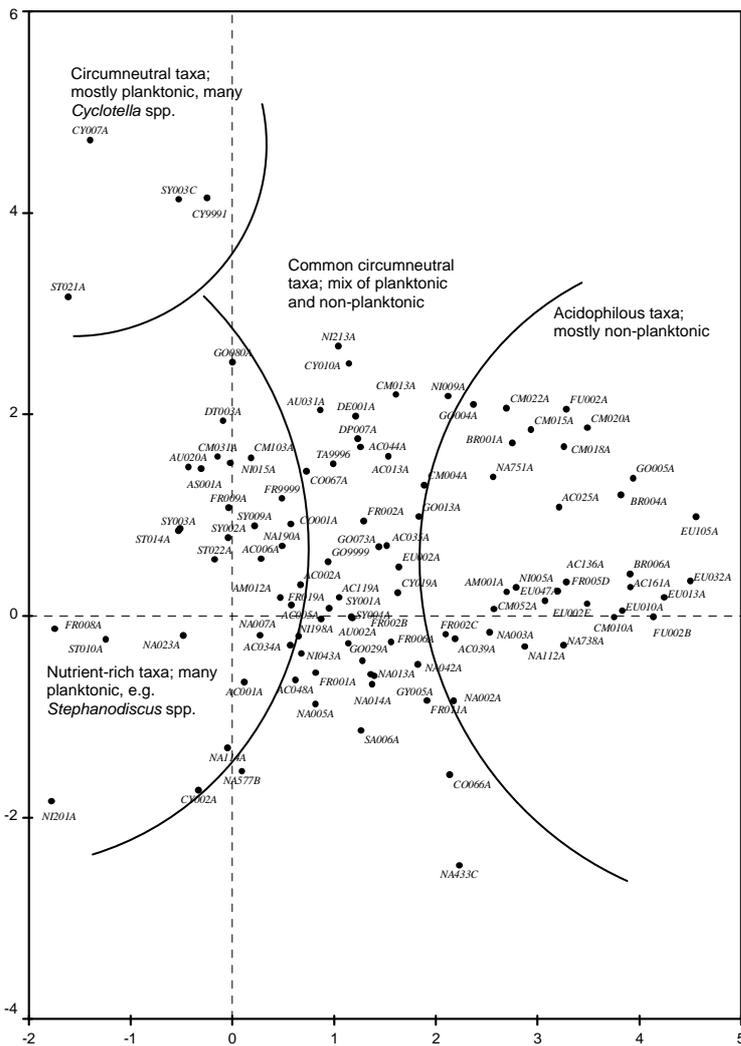
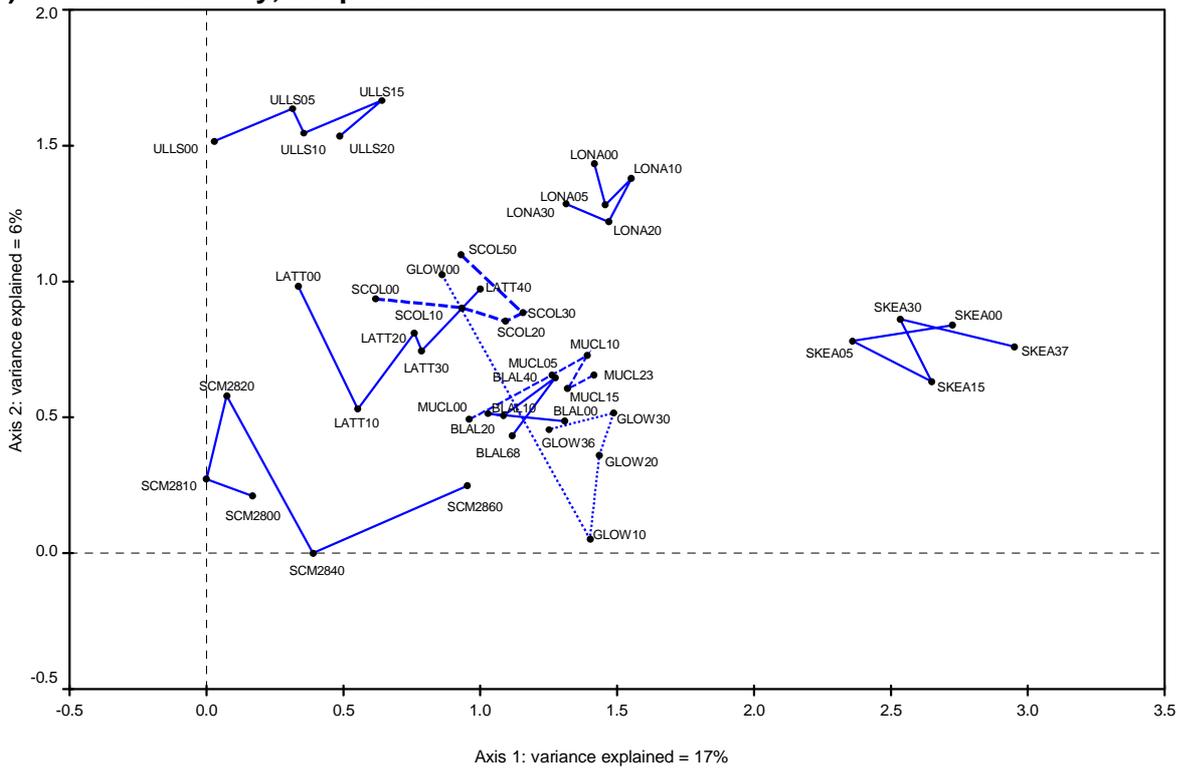


Figure 3.7 DCA biplots (axis 1 and 2) of the sample scores and species scores for the 31 lakes in work package 2

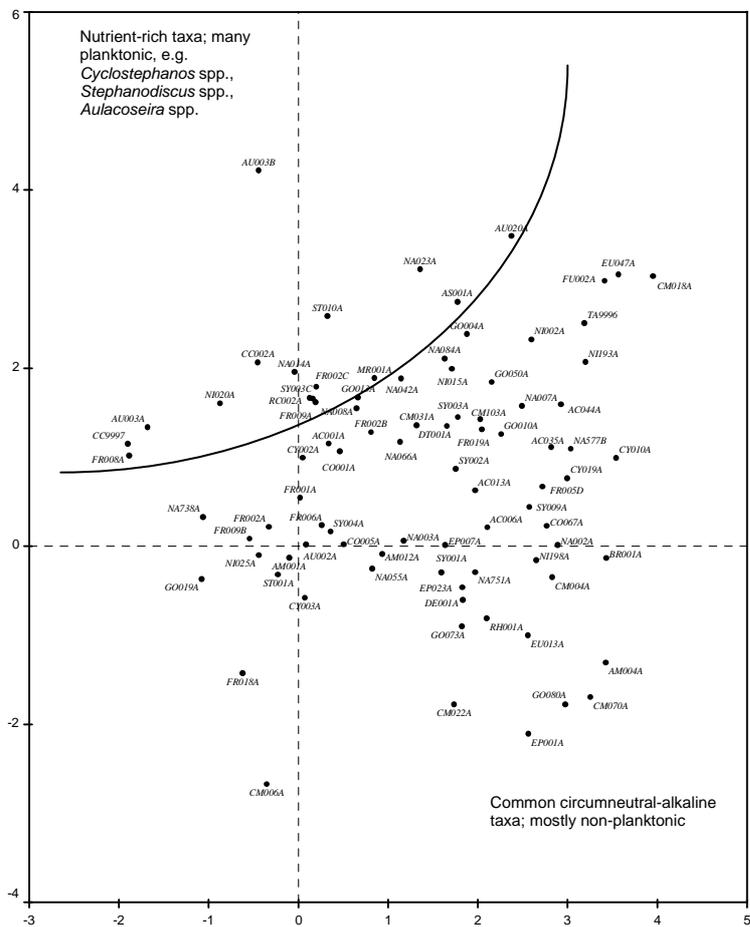
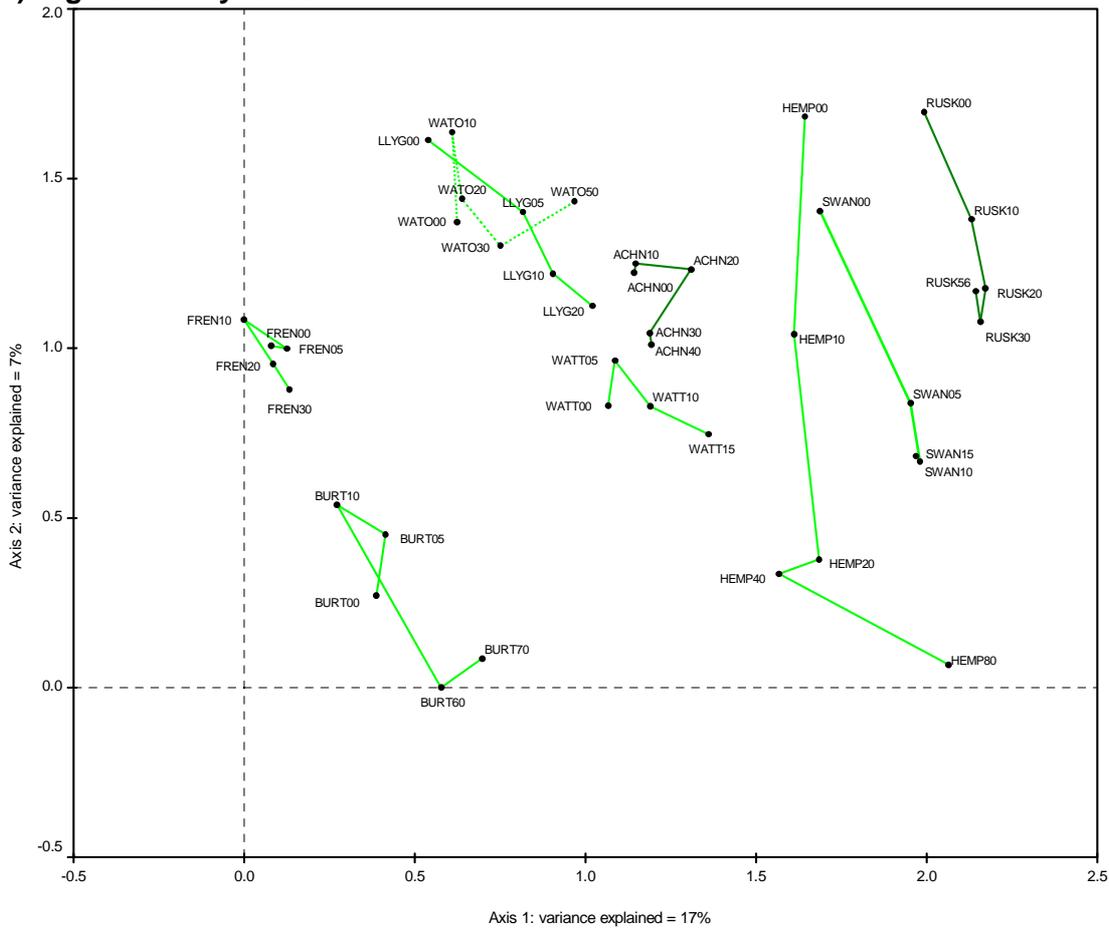
a) Low alkalinity lakes



b) Medium alkalinity, deep lakes



d) High alkalinity lakes



e) Marl lakes

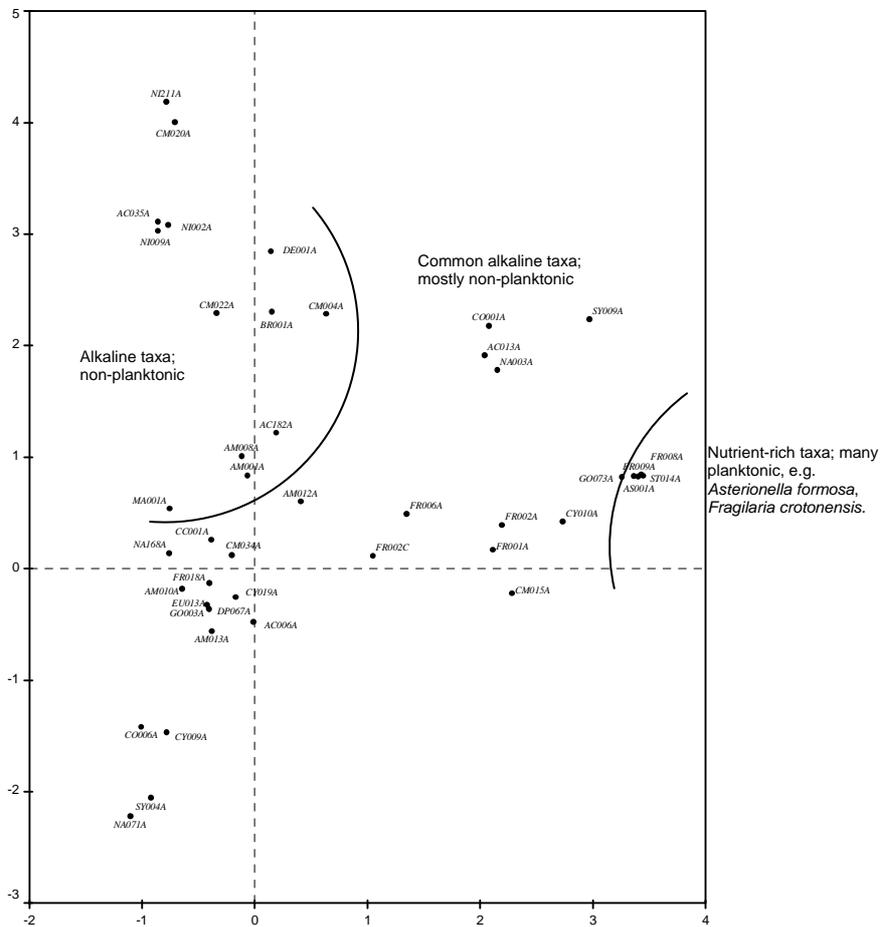
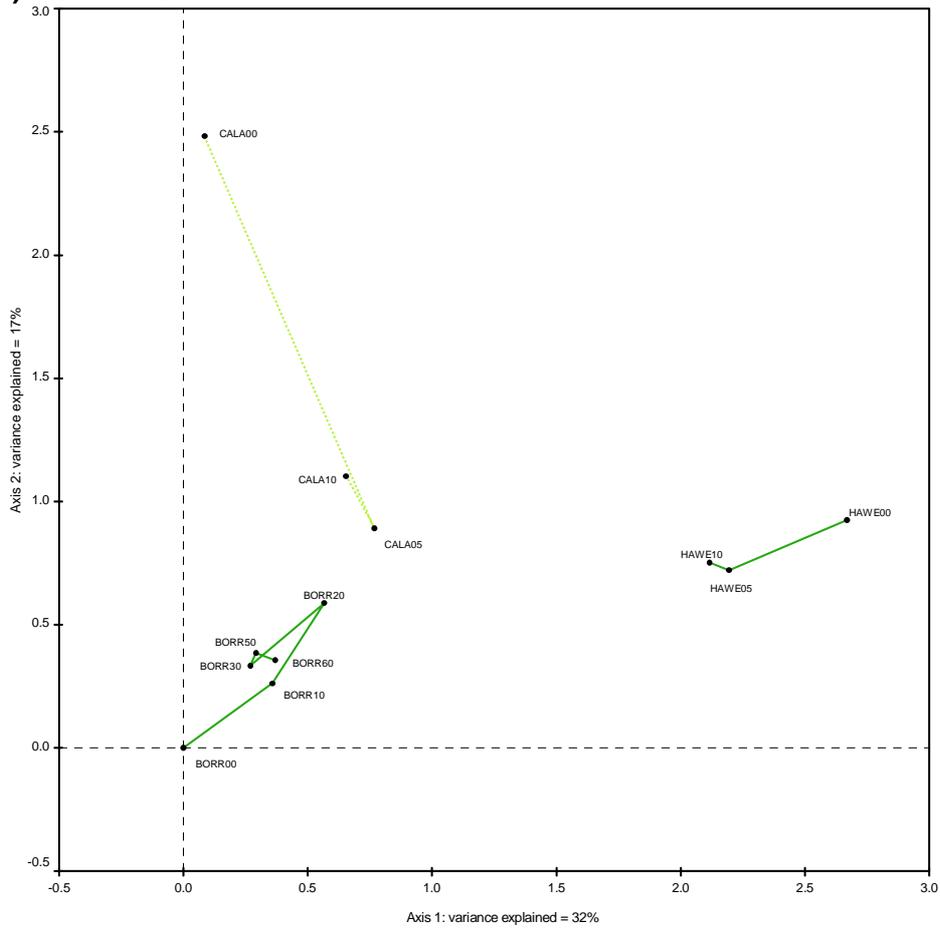
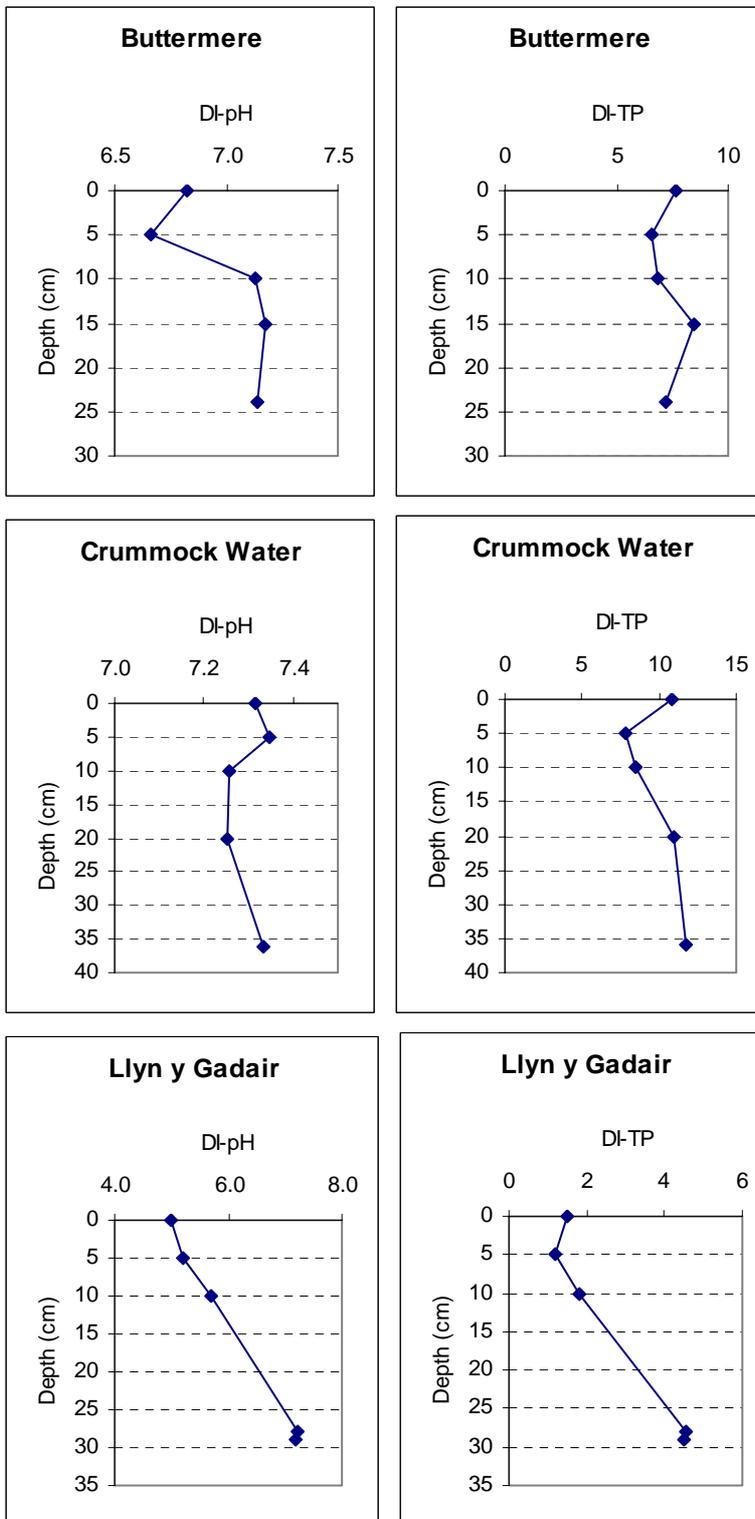
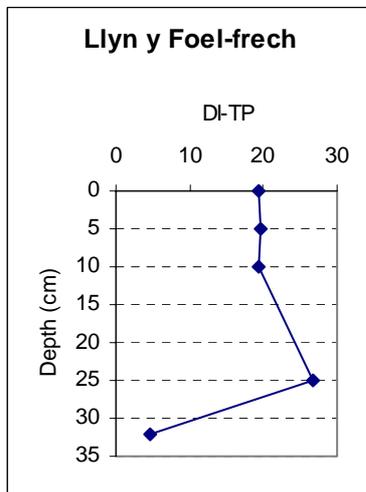
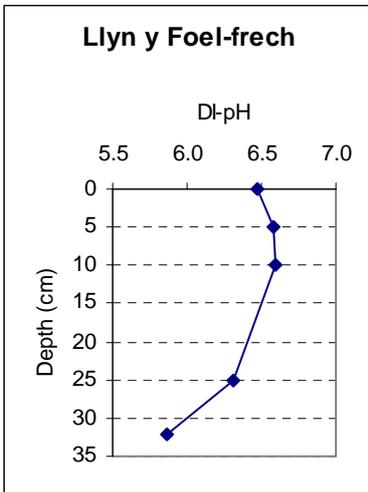
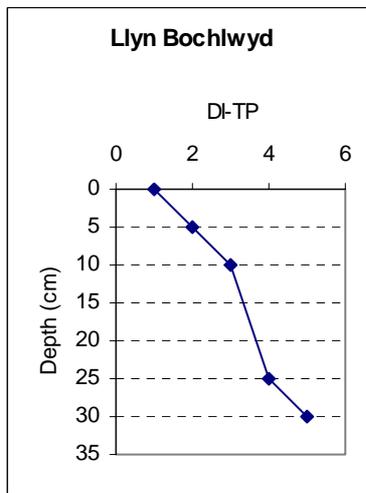
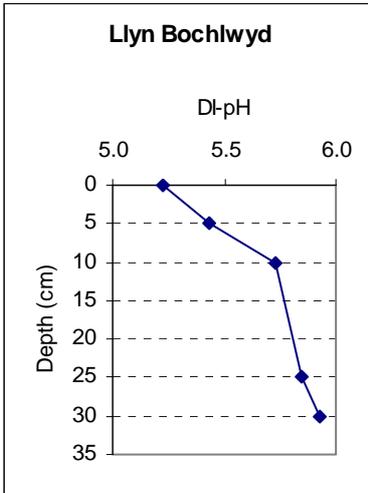


Figure 3.8 Diatom inferred pH (DI-pH) (for Low alkalinity lakes only) and total phosphorus (DI-TP $\mu\text{g l}^{-1}$) for the lakes in work package 2. Lakes are grouped by lake type.

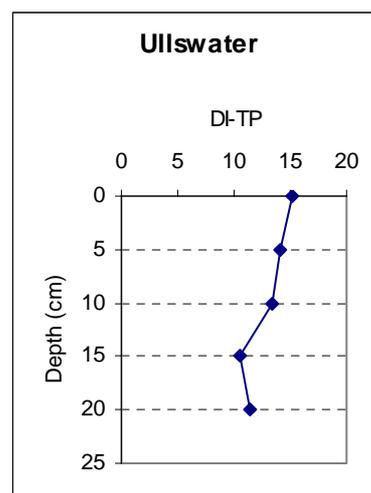
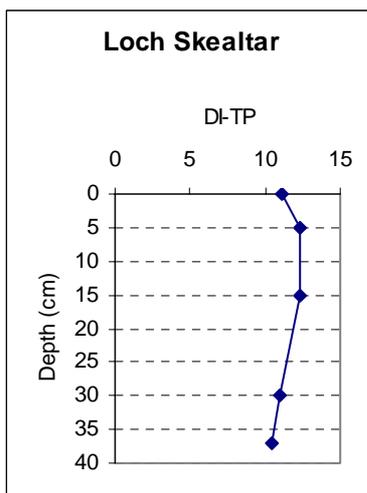
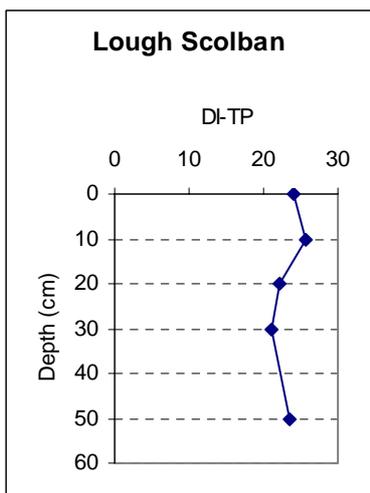
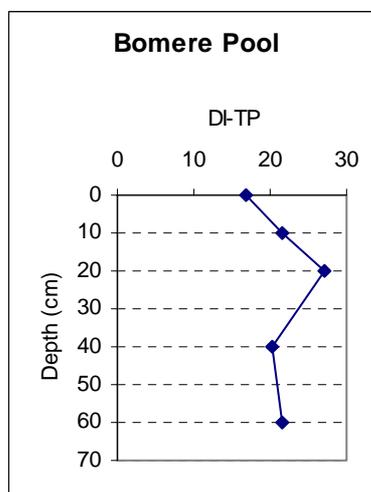
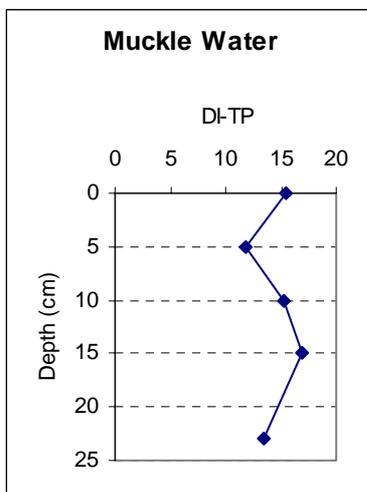
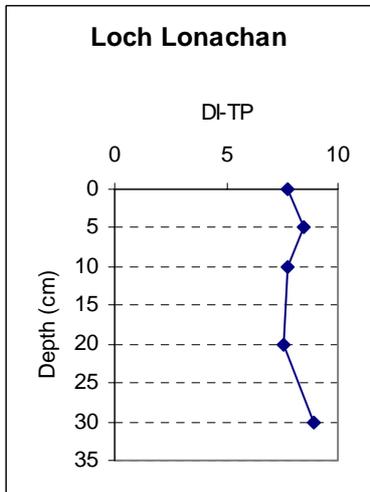
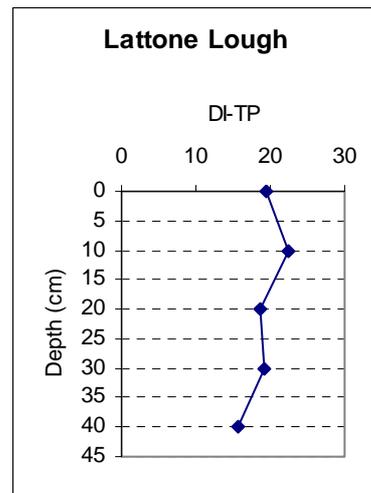
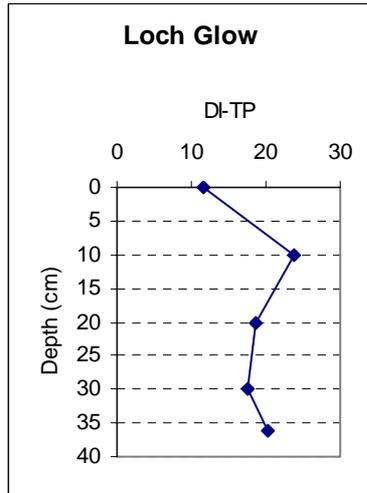
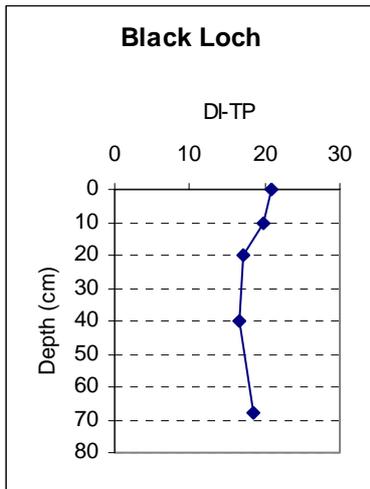
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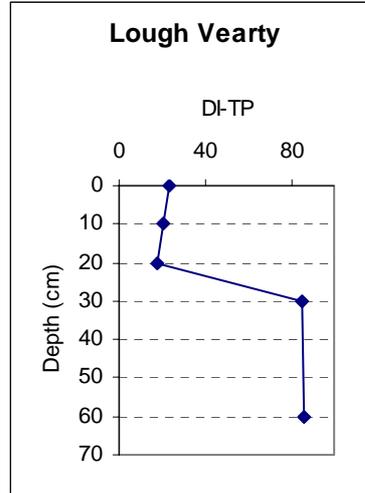
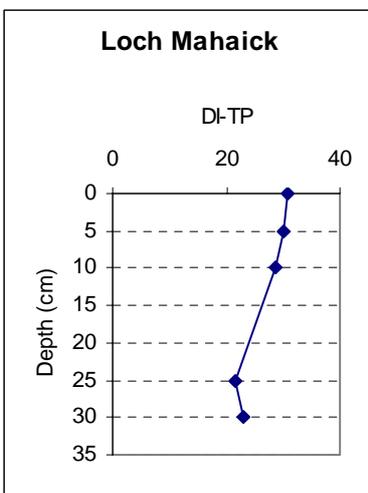
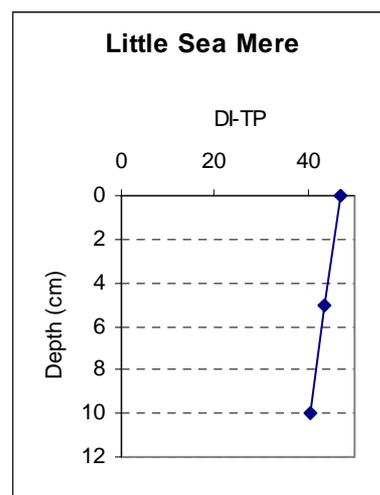
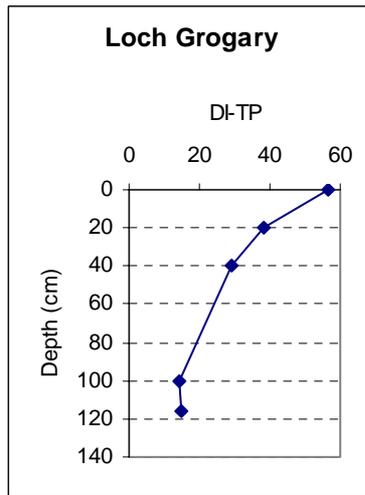
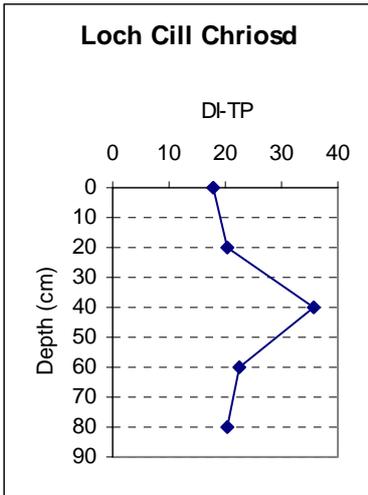
b) Low alkalinity, shallow lakes



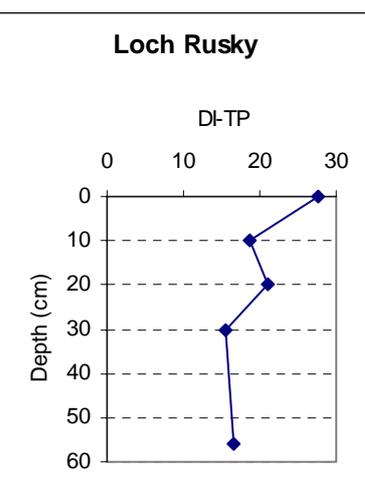
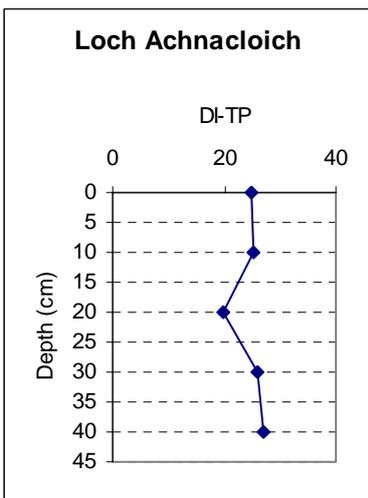
c) Medium alkalinity, deep lakes



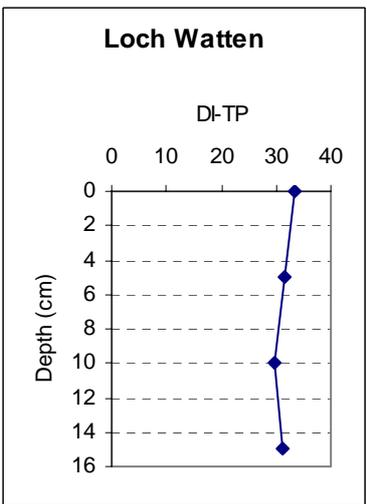
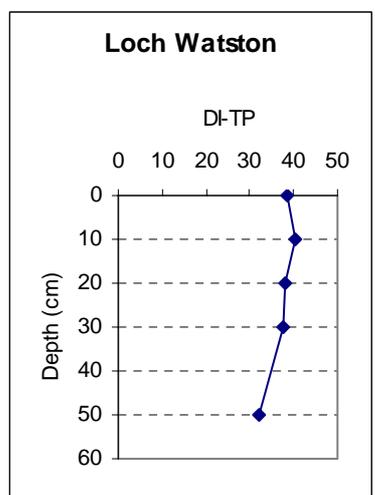
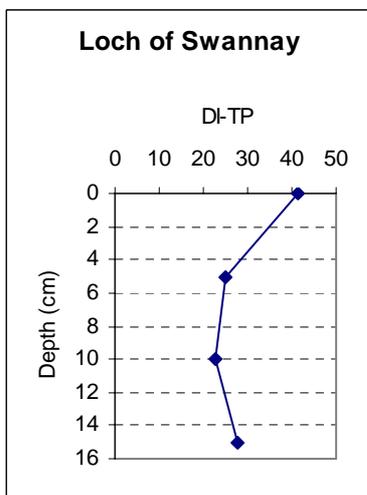
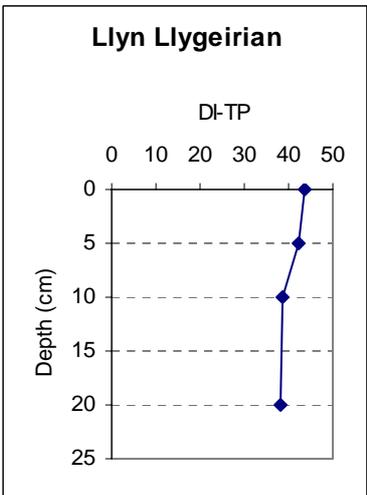
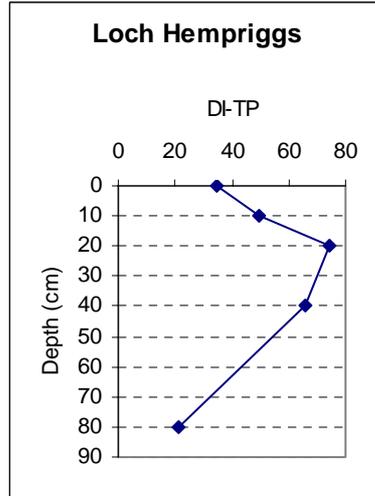
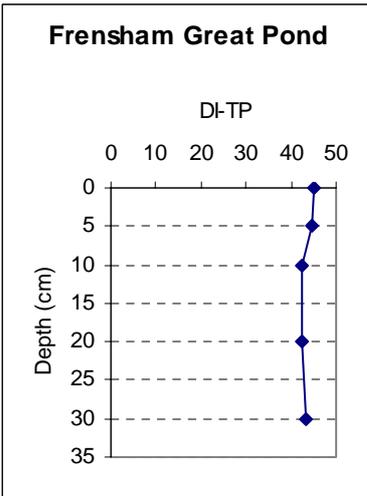
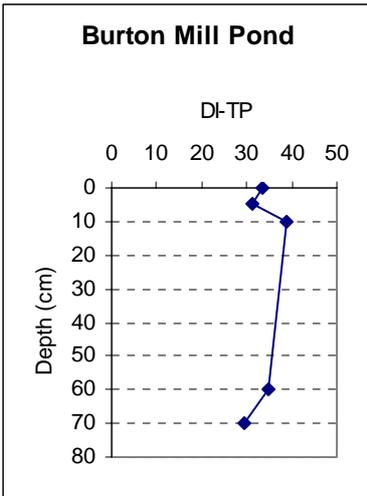
d) Medium alkalinity, shallow lakes



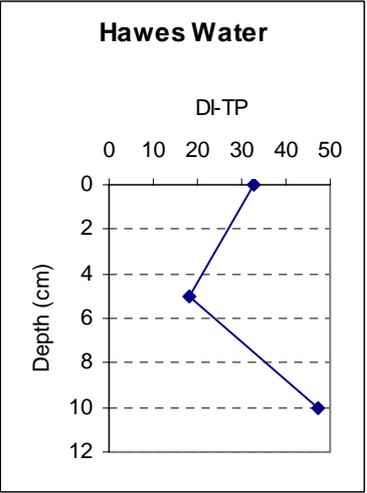
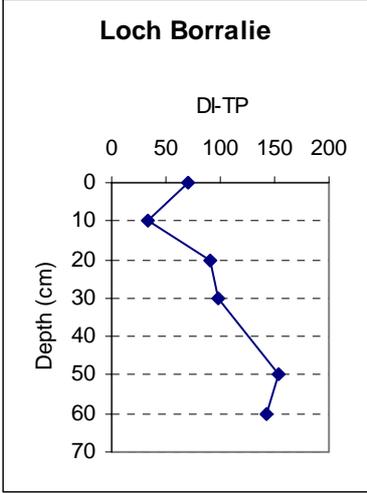
e) High alkalinity, deep lakes



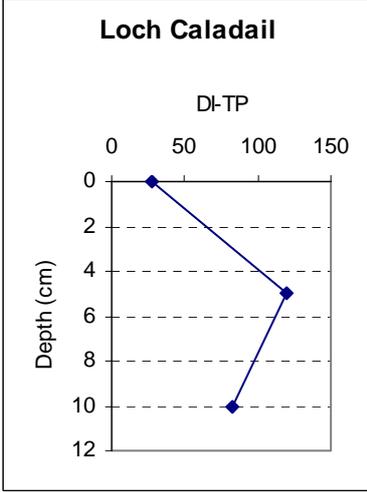
f) High alkalinity, shallow lakes



g) Marl, deep lakes



h) Marl, shallow lakes



3.4 Summary of findings

A set of reference lakes are identified for a number of the main lake types based on analysis of diatom assemblages preserved in 31 lake sediment cores. The following sites provide good examples of reference lakes based on the low degree of floristic change observed throughout the sediment record:

Low alkalinity, deep: Buttermere and Crummock Water.

Medium alkalinity, deep: Loch Lonachan, Black Loch and Ullswater.

Medium alkalinity, shallow: Loch Cill Chrìosd and Little Sea Mere.

High alkalinity, deep: Loch Achnaclòich.

High alkalinity, shallow: Burton Mill Pond, Frensham Great Pond, Llyn Llygeirian, Loch Watston and Loch Watten.

A further set of lakes exhibit only slight deviation from the assemblages in the bottom of the cores and could, therefore, be described as good status:

Medium alkalinity, deep: Muckle Water, Loch Skealtar, Lough Lattone and Lough Scolban.

Medium alkalinity, shallow: Loch Mahaick.

Only two examples of low alkalinity, shallow lakes are available in the dataset (Llyn Bochlwyd and Llyn y Foel-frech) but both of these have experienced significant floristic change and, therefore, reference lakes are not identified for this type. However, the bigger dataset of 219 lakes includes a number of low alkalinity, shallow sites that exhibit low floristic change based on the top and bottom analysis, and hence these could act as reference sites for this lake type.

Analysis of the three marl lakes highlights the difficulties of using diatoms to assess floristic change in these systems. Dissolution of the silica hindered data interpretation particularly at Hawes Water and Loch Caladail. Consequently, reference lakes are not identified for the marl lakes. A separate study is recommended that focuses specifically on marl systems using indicators other than diatoms to identify appropriate reference sites for this lake type (e.g. ostracods, cladocera, chironomids).

In summary, of the 31 cores analysed, thirteen could be classified as reference lakes with low floristic change, five lakes could be classified as good status with only slight shifts from the lower core assemblages, and thirteen exhibit considerable changes in the diatom assemblages and are thus considered to be at less than good status. These findings concord with those in work package 1 in that the same sites are identified as reference lakes using the top and bottom approach (work package 1) and the higher resolution five sample approach (work package 2). The latter provides a more robust assessment of floristic change and it is therefore encouraging that the results are in agreement with those produced by the top and bottom method. Given the high abundance of non-planktonic *Fragilaria* spp. in the high alkalinity, shallow lake diatom records and the low sensitivity of these taxa to water quality shifts, we recommend that further biological groups (e.g. chironomids, cladocera, plant macrofossils) are analysed to confirm reference lake status for this lake type.

In one of the low alkalinity, deep lakes (Llyn y Gadair) and one of the low alkalinity, shallow lakes (Loch Bochlwyd) acidification appears to be the main driver of the change. In one low alkalinity, shallow lake (Llyn y Foel-frech), one medium alkalinity, deep lake (Bomere Pool), one high alkalinity, deep lake (Loch Rusky) and two high alkalinity, shallow lakes (Loch of Swannay and Loch Hempriggs), eutrophication is the most likely explanation for the observed diatom changes. In a number of sites, however, (Loch Glow, Loch Grogary, Lough Vearty, and the three marl lakes) the species shifts are less easy to interpret and may not be caused directly by changes in water chemistry but by a host of factors (some of which may indirectly be related to nutrient enrichment), including habitat availability and top down controls. Analysis of the fuller palaeoecological record (as employed in work package 3) would enable food-web alterations and interactions between the various components of the ecosystem to be assessed and thus the causes of the ecological shifts to be explored more fully.

Application of the diatom transfer functions to the fossil diatom assemblages in the 31 cores enabled typical ranges of 'reference' total phosphorus (TP) concentrations to be determined for the main lake types. The DI-TP values were in the same range as those produced for the work package 1 dataset (Bennion, unpublished), as follows: Low alkalinity lakes: $< 10 \mu\text{g l}^{-1}$, Medium alkalinity lakes: $10\text{-}20 \mu\text{g l}^{-1}$, High alkalinity and Marl lakes: $20\text{-}40 \mu\text{g l}^{-1}$. These values should be used as guidelines only, because TP concentrations are clearly site specific and will depend on a range of factors.

One limitation of the present study is that the cores are not dated. It is assumed, on the basis of sediment accumulation rates established for other lakes in the UK, that the length of the sediment records collected here will extend back to at least 1850 AD. However, sediment accumulation rates are site specific and it remains uncertain whether our cores cover comparable time periods. The lack of a chronology is of less concern where the diatom assemblages remain stable throughout the core but it becomes a greater limitation when interpreting the data from sites that exhibit floristic change as we have no estimate of the time at which the changes occurred. Furthermore, poor diatom preservation at a number of sites prevented analysis of the whole core and it is possible that the bottom sample does not represent a true pre-impact assemblage. Full radiometric dating is an expensive and relatively time consuming technique and may not be appropriate for studies such as this which involve low resolution analysis of a large number of cores. However, lower resolution (skeleton) radiometric dating of four or five levels can be undertaken relatively cheaply or, alternatively, chronologies can be approximated using the spheroidal carbonaceous particle (SCP) dating method (Rose 1994). The start of the SCP record occurs at ~ 1850 , with a rapid increase in concentrations at ~ 1950 , and a concentration peak at ~ 1970 , and these features can be used to provide an approximate chronology for each core (Rose *et al.* 1995). This approach is being taken in a similar project, 'Identification of reference-status for Irish lake typologies using palaeolimnological methods and techniques (IN-SIGHT)', as part of the ERTDI Programme funded by the Irish Environment Protection Agency. In the IN-SIGHT project, five samples from each core, taken at roughly equidistant levels from the sediment surface to the core base, have been analysed to provide a broad estimate of sediment chronology.

On the basis of the work package 2 study, the following methodology is recommended for identifying reference lakes using palaeolimnological approaches:

1. Select four to five samples at roughly equidistant intervals throughout the sediment record for diatom analysis at each site.
2. Calculate the squared chord distance dissimilarity coefficient between the bottom (reference) sample and the upper samples to assess degree of change. The 5th percentile (score < 0.475) is used to define sites with low floristic change between the bottom sample and the upper samples.
3. Perform detrended correspondence analysis (DCA) on the samples from each core to assess nature and direction of floristic change.
4. Apply diatom transfer functions to identify the key pressures and assess chemical reference conditions.
5. Ideally, a chronology should be approximated for each core using low resolution radiometric dating or the spheroidal carbonaceous particle (SCP) dating method. Analysis of five samples, taken at roughly equidistant levels from the sediment surface to the core base is recommended.
6. Repeat the above, where possible, using other suitable biological groups such as chironomids, cladocera and plant macrofossils.

4. WORK PACKAGE 3: DEMONSTRATION OF THE MULTI-PROXY APPROACH FOR DEFINING SITE SPECIFIC REFERENCE CONDITION

4.1. Objectives

The aim of work package 3 is to demonstrate the value of the multi-indicator palaeoecological record for defining site-specific ecological reference conditions at lake types where reference sites cannot easily be found in the current UK lake population.

The sediment record contains the remains of a range of food-web components which can be examined to assess the broader ecosystem structure. For example, analysis of plant macrofossils (fruits, seeds, spores and vegetative fragments) provides a technique for determining the past composition, structure and dynamics of in-lake macrophyte communities (e.g. Brodersen *et al.* 2001, Odgaard and Rasmussen 2001). Other components of the food-web commonly preserved in lake sediments include diatoms (phytoplankton and periphyton), chironomids (invertebrates), and cladoceran (zooplankton). Numerous palaeoecological studies have examined one or more of these fossil groups to assess ecological response to pressures such as eutrophication (e.g. Leavitt *et al.* 1994; Sayer *et al.*, 1999; Brooks *et al.* 2001) but the potential of the fuller sediment record for providing an integrated basin wide assessment of reference condition has not been fully explored.

The objective of this work package is to examine five groups of remains (diatoms, cladocera, chironomids, aquatic pollen and plant macrofossils, and non-plant macrofossils) representative of the key elements required by the WFD, in cores retrieved from two case study lakes, Lake of Menteith in Scotland and Llangorse Lake in Wales, to provide an integrated basin wide assessment of reference condition for each lake.

4.2 Methods

4.2.1 Field methods

Three cores, one from the open water in the profundal zone and two from the littoral zone, were taken from each of the two sites in September 2002 (details given below). The cores were extruded in the field at 1 cm intervals from 0-50 cm and thereafter at 2 cm intervals to the core base.

4.2.2 Laboratory Methods

Sediment characterisation

The main characteristics of the sediment and any visual stratigraphic changes were noted. The percentage dry weight (%DW) which gives a measure of the water content of the sediment, and percentage loss on ignition (%LOI) which gives a measure of the organic matter content, were determined using standard techniques (Dean 1974).

Dating

All sediment cores were analysed for spheroidal carbonaceous particles (SCPs) using the method described in Rose (1994) in order to provide an approximate chronology. Concentrations of SCPs are expressed as number of SCPs per gram dry mass of sediment (or gDM^{-1}). The concentration peak which is expected to occur at ~1970 and the start of the record which occurs at ~1850 were used to provide an approximate chronology for each core (Rose *et al.* 1995). There are reasonably large errors associated with a chronology based on analysis of a low number of samples. However, the data were sufficient to provide an estimate of ~1850 for each core and the sample representative of this date was taken as the 'reference sample'. The 'reference samples' and the surface sediment samples (i.e. representative of current conditions) were prepared for a range of biological analyses.

Diatoms

Diatoms are siliceous, unicellular algae and represent elements of both the phytoplankton and phytobenthos. They are sensitive to lake pH, nutrients and habitat. The surface and reference samples of each core were prepared and analysed for diatoms using standard methods (Battarbee

et al. 2001). At least 300 valves were counted from each sample using a Leitz research microscope with a 100x oil immersion objective and phase contrast. Principal floras used in identification were Krammer & Lange-Bertalot (1986-1991). All slides are archived at the ECRC and the data are stored in the ECRC's Amphora database.

Chironomids

Chironomids (Diptera) are non-biting midges whose larval head capsules are preserved in lake sediments. They represent the benthic-epiphytic invertebrate community and are sensitive to oxygen, nutrients, temperature, and habitat shifts. Sediments from the surface and reference samples of each core were deflocculated in 10% KOH warmed to 70°C for five minutes and washed through a 212 µm and 90 µm sieve. The sievings were then transferred to a grooved sorting tray and the chironomid larval head capsules were picked out by hand using fine forceps under a 25-40 x binocular microscope and stored in 80% ethanol. A minimum of 50 head capsules per sample were picked since this has been shown to be the minimum required to produce consistent results (Quinlan & Smol 2001, Heiri & Lotter 2001, Larocque 2001). After being dehydrated in 100% ethanol for five minutes, the head capsules were slide mounted, two per 6 mm coverslip, ventral side uppermost, in Euparal. The larval head capsules were identified by reference to Wiederholm (1983) and the national collection of Chironomidae at The Natural History Museum, London. Total phosphorus (TP) was inferred using a weighted average (WA) chironomid-TP inference model developed by Brooks *et al.* (2001). Because the count size was different in each sample it was not possible to compare directly the species diversity between samples. Therefore rarefaction and Chao estimates of species richness (e.g. Simberloff 1978, Chao 1987) were calculated based on the smallest sample using the rarefaction calculator: (Brzustowski, www.biology.ualberta.ca/jbrzusto/rarefact.php).

Cladocera

Cladocera are microscopic crustaceans (zooplankton) and are represented in lake sediments by a variety of body parts. They can be used to infer changes in fish population density and shifts in habitat structure (i.e. macrophytes), particularly in shallow lakes (e.g. Jeppesen *et al.*, 1996, 2001). Sediments from the surface and reference samples of each core 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 shallow lakes in Denmark (Jeppesen *et al.* 1996, Jeppesen 1998). For each sample at least 5 cm³ of sediment was heated in a deflocculating agent (10% potassium hydroxide, KOH) and sieved at 150 µm and 50 µm. The retents of the two sieves were then washed into separate pots and safranin stain was added. A sub-sample (of known volume) of each was analysed 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. At least 500 individuals were counted from each sub-sample. Data are expressed here as percentage relative abundance.

Pollen

The terrestrial pollen record can give an indication of vegetation changes in the lake catchment and the aquatic pollen remains can be used to reconstruct changes in the aquatic macrophyte flora of the lake. The surface and reference samples from each core were prepared using a standard chemical procedure (Berglund & Ralska-Jasiewiczowa 1986), including heating with hydrofluoric acid, and the residues suspended in 2000 cs silicone oil. Whole slides were counted at equally-spaced traverses at a magnification of 400x (bright field) until a total of at least 500 pollen and spores of terrestrial taxa was reached in each sample. Critical examinations were made at a magnification of 1000x using an oil immersion objective. Identifications were made using keys and a modern pollen reference collection. The results are shown as percentages of selected taxa. Terrestrial pollen and spore taxa are presented as percentages of the total terrestrial pollen and spores (ΣP). Obligate aquatics are calculated as percentages of $\Sigma P + \Sigma$ aquatics, and *Sphagnum* spores as percentages of $\Sigma P + Sphagnum$.

Macrofossils

The surface and reference samples of each core were prepared and analysed for plant and non-plant macrofossils. The former can be used to assess changes in the aquatic macrophytes and the latter may be useful for determining changes in the broader ecological structure of a lake. Sediment sample sizes were determined both by mass and volume, and samples were washed through 350 μm and 125 μm sieves. The entire retent of the 350 μm was examined using a stereomicroscope at 10-40x magnification and identifiable remains enumerated. This fraction contained the larger macrofossils including the majority of plant reproductive remains and cladoceran ephippia. A sub-sample, approximately a fifth of the total sample, from the 125 μm sieve was analysed at a higher magnification for smaller vegetative fossils including *Nymphaeaceae* leaf trichosclereids. Plant macrofossils were identified by comparison with herbarium documented reference material. Both the plant macrofossil data and the cladoceran ephippia data are expressed as numbers of fossils per 100 cm^3 . Very few remains of other non-plant macrofossils were found in the samples analysed and therefore only cladoceran ephippia data are presented here.

4.3 Case study sites

Two lakes were selected as case study sites:

Lake of Menteith (NN 57261 00708) is situated near to Aberfoyle in central Scotland. It is a large (252 ha), lowland (18 m), relatively shallow (mean depth 6 m) loch with one deep basin (max depth 23.5 m). It is classified as a medium alkalinity, deep lake (MA, D) in the GB Lake Typology scheme. The catchment is a mix of improved grassland and scrub with ~10% coniferous plantation and a small proportion of arable. The lake is currently mesotrophic with a mean total phosphorus concentration of ~20 $\mu\text{g l}^{-1}$ but palaeolimnological data suggest that eutrophication has taken place since the early twentieth century with the most marked enrichment from ~ 1980 (Bennion *et al.* 2001b). The latter is supported by reports of algal blooms on the lake from the early 1980s (Fozzard & Marsden 1990). A bloom was present during sampling in 2002 and the Secchi depth was 1.5 m. Potential nutrient sources include a trout fishery which has operated at the site for approximately the last twenty years, increased point sources from sewage and P detergents, diffuse agricultural runoff, and afforestation in the last two decades (Marsden *et al.* 1995).

Llangorse Lake (SO 13922 26200) is situated in the Brecon Beacons National Park in south Wales. It is a large (140 ha), lowland (156 m), shallow (mean depth 2 m) lake with two deeper basins (max depth 7.5 m). It is classified as a high alkalinity, shallow (HA, Sh) lake in the GB Lake Typology scheme. The catchment is primarily agricultural and the lake itself is used for recreational activities. The lake is currently eutrophic with a mean total phosphorus concentration of ~100 $\mu\text{g l}^{-1}$. The Secchi depth measured in September 2002 was 1.2 m. Palaeolimnological and monitoring data indicate enrichment from ~1950 with a shift to planktonic, nutrient-rich diatom taxa in the 1950s, summer hypolimnetic deoxygenation, an increase in frequency of algal blooms in the 1960s and 1970s, and a eutrophic macrophyte flora (Bennion & Appleby 1999, Duigan *et al.* 1999). Increased use of fertilisers, agricultural intensification, afforestation and development of tourism and recreation have all been suggested as possible causes of eutrophication. Sewage diversions were introduced in 1981 and 1992 and the return of a number of mesotrophic diatom taxa has been observed since 1985, along with improved oxygen conditions and recovery of the submerged macrophyte flora (Bennion & Appleby 1999).

4.4. Results and discussion

4.4.1 Lake of Menteith

Core descriptions

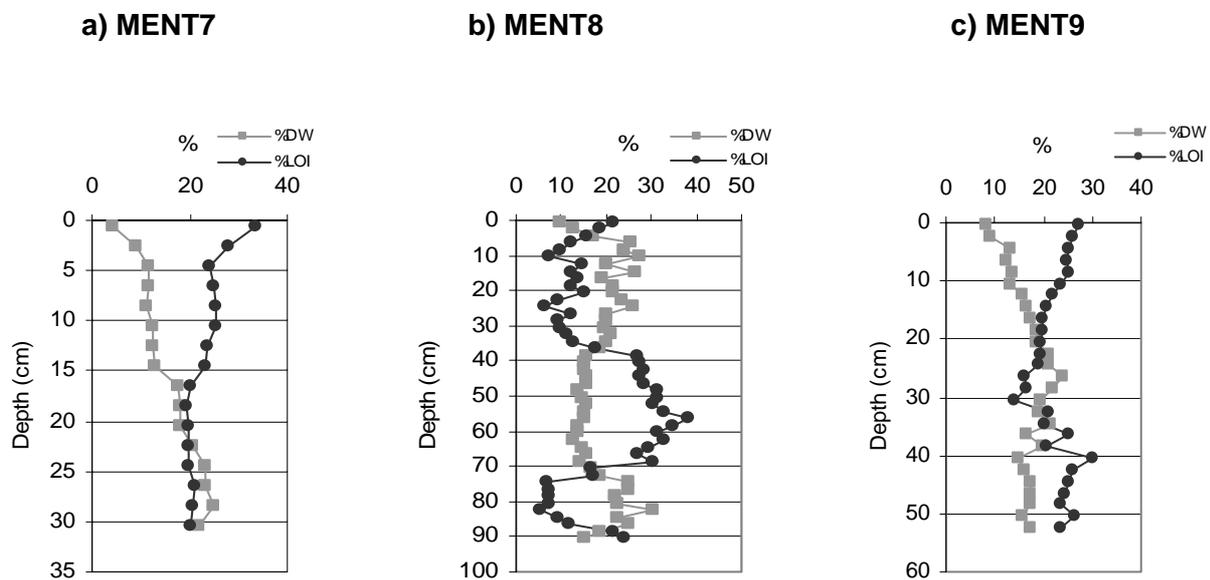
Three sediment cores were taken from the lake on 17 September 2002 as follows:

MENT7 (NN 57261 00708), a Glew gravity core taken in open water in the main deep basin (core length 31 cm, water depth 23 m). The upper 20 cm were a black, soft, organic (~25-30%) lake mud with a stiffer, more consolidated, brown, less organic (~20%) sediment below (Figure 4.1a).

MENT8 (NN 57975 01036), a fat piston core taken in shallow water, close to reed beds, along the northern shore (core length 92 cm, water depth 2.4 m). There were marked stratigraphic changes in this core which were not seen in either MENT7 or MENT9. The upper 20 cm were a dark brown, relatively inorganic (~15%) lake mud. From 20-40 cm, the sediment was a grey marl with very low organic content (~10%). The sediment changed abruptly to a light brown, organic (~30-35%) material from 40-70 cm before returning to a grey, marl from 70-88 cm. The lowermost section was light brown and relatively organic (~20-25%) (Figure 4.1b).

MENT9 (NN 56736 00725), a fat piston core taken in shallow water, close to *Nymphaea alba* and *Persicaria amphibia* beds, along the western shore (core length 60 cm, water depth 2.6 m). This littoral core resembled the open water core (MENT7) more closely than the other littoral core (MENT8). The upper ~25 cm were a black, soft, organic (~20-25%) lake mud below which was a stiffer brown, less organic (~15%) layer from ~25-30 cm. There were no further colour changes but organic matter increased to ~25-30% in the lowermost section (> 30 cm) (Figure 4.1c).

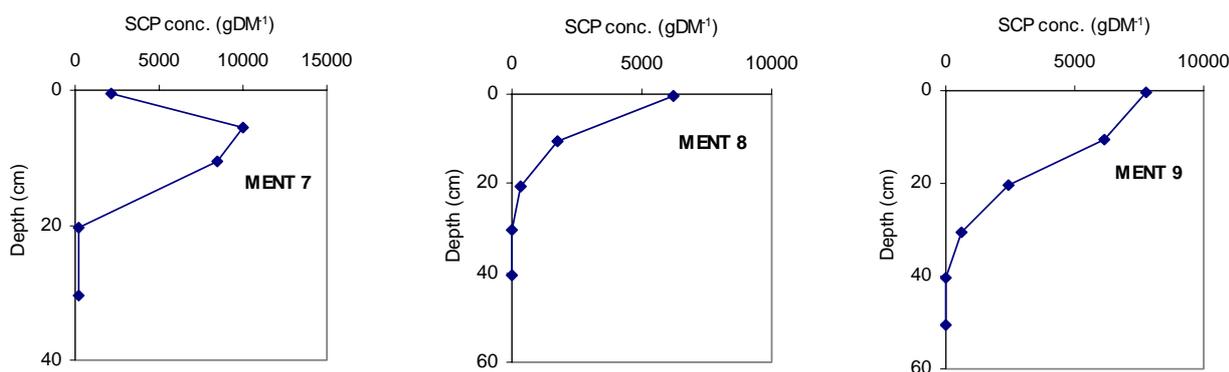
Figure 4.1 Dry weight and organic matter profiles for the Lake of Menteith cores



Spheroidal carbonaceous particles (SCPs)

The SCP concentration profiles are shown in Figure 4.2. First presence of SCPs is at approximately 30, 30 and 40 cm for MENT7, 8 and 9, respectively. These depths were, therefore, taken to represent the reference samples. The SCP data for MENT7 agree with the full radiometric dating results for MENT2, an open water core taken in the same location as MENT7, which also placed ~1850 at ~30 cm (Bennion *et al.* 2001b).

Figure 4.2 Spheroidal carbonaceous particle concentration profiles for Lake of Menteith cores



Figures 4.3 to 4.9 illustrate the results for each of the biological indicator groups. In each case the samples are presented on the y axis and are labelled according to their core code and sample depth (e.g. MENT7 0 is the surface sample for core MENT7, and MENT9 40 is the 40 cm sample for core MENT9).

Diatoms

Diatom preservation was good in both the open water and littoral cores from the Lake of Menteith. A total of 111 taxa were observed in the six samples analysed, 24 of which were present with a relative abundance of > 2% (Figure 4.3). All three cores show a shift from a diverse, mixed planktonic and non-planktonic assemblage comprised of taxa associated with oligotrophic-mesotrophic conditions (e.g. *Cyclotella comensis*, *Cyclotella radiosa*, *Achnanthes minutissima*, *Achnanthes pusilla*, *Cymbella* spp., *Brachysira vitrea*, *Gomphonema* spp.) to an assemblage comprised of taxa more typically found in meso-eutrophic waters (*Stephanodiscus parvus*, *Asterionella formosa*, *Fragilaria crotonensis*, *Aulacoseira subarctica*, non-planktonic *Fragilaria* spp.). As expected, the littoral cores contain a higher relative abundance of non-planktonic taxa than the open water core. The latter shows a marked shift to a plankton dominated assemblage. The diatom changes in all cores provide clear evidence of enrichment. The diatom-inferred TP value for the reference sample of the open water core was ~10 $\mu\text{g l}^{-1}$ compared to a value for the surface sample of ~25 $\mu\text{g l}^{-1}$. The major species shifts are similar to those observed in the MENT2 open water core analysed at a higher resolution (Bennion *et al.* 2001b).

Chironomids

The summary diagram of chironomid taxa in the Lake of Menteith core samples is shown in Figure 4.4 with data expressed as percentage relative abundance. The total number of head capsules counted in each sample is also shown. Samples from deep, open water are likely to be representative of the entire chironomid fauna of the lake because they include littoral and profundal taxa and should, therefore, reflect general lake conditions. A sample from the littoral is unlikely to provide a good representation of deep water taxa and is more likely to reflect local conditions. The core bottoms had higher rarefaction and taxon richness values than the core tops (Table 4.1). The decline in species richness may be in response to increasing nutrient levels. The Orthocladiinae,

which are intolerant of eutrophic conditions, are generally less abundant in the top samples of all cores suggesting that enrichment has taken place. They have not been replaced by Chironomini, however, perhaps because nutrient levels are still lower than optimum thresholds for these taxa. The chironomid inferred TP (CI-TP) values for all three reference samples were very similar (~20 $\mu\text{g l}^{-1}$). The CI-TP values for the surface of the littoral cores were ~60 $\mu\text{g l}^{-1}$ indicating enrichment in the littoral zone. However, the CI-TP value for the surface of the open water core was only 20 $\mu\text{g l}^{-1}$ indicating little change in the productivity of the profundal zone. In summary, while there was some spatial variation in the chironomid data, the temporal patterns were broadly consistent across all three cores with slight shifts in the fauna in response to enrichment.

Table 4.1 Rarefaction and Chao taxon richness scores for the Lake of Menteith samples

	Rarefaction	Chao
MENT7 TOP	19.8	31
MENT7 BOTTOM	23.1	51.5
MENT8 TOP	18.3	25.6
MENT8 BOTTOM	24.5	43.1
MENT9 TOP	17.6	38.7
MENT9 BOTTOM	20.2	40.1

Cladocera

The summary diagram of cladocera chitinous remains in the Lake of Menteith sediment samples is shown in Figure 4.5. Data are expressed as percentage relative abundance. Very few remains were found in the MENT8 core and therefore data are presented for MENT7 and MENT9 only. There was a spatial pattern in the data with the planktonic taxon, *Bosmina longirostris*, dominating the open water core samples, and benthic and plant-associated taxa being more abundant in the littoral core. There were also a number of temporal shifts. *Leptadora kindtii* occurred in the surface samples of both cores but was not present in the reference samples. This is a large bodied predatory cladoceran which would be subject to fish predation and its increase may indicate a change in food web structure or a habitat shift. A number of plant-associated taxa, e.g. *Pleuroxus* spp. and *Camptocercus rectirostris*, were more abundant (albeit in relatively low numbers) in the reference samples than the surface samples, suggesting a shift from benthic/epiphytic to pelagic production. The changes observed were relatively subtle and the data suggest that the lake currently has a healthy, diverse Cladocera community.

Macrofossils

The summary plant macrofossil diagram for the Lake of Menteith samples is shown in Figure 4.6. Data are expressed as numbers of fossils per 100 cm^3 . Plant macrofossils were much less abundant in the open water core than in the two littoral cores. This has been seen in other multi-core studies and indicates that heavy remains tend not to be transported far from the source plant. The data show a number of marked temporal changes. Aquatic moss, *Chara* and *Isoetes* remains were more abundant in the reference samples than the surface samples and *Isoetes echinospora* was observed in only the MENT8 reference sample. The littoral cores suggest a shift in the stonewort community from *Chara* to *Nitella*. There were remains from a greater number of plants in the reference samples than the surface samples with *Potamogeton*, *Najas flexilis* and *Nymphaea alba* fossils all present in the former. *Cladophora* was found only in the surface samples although this may be a function of preservation. An increase in *Callitriche* spp. was evident in both littoral cores. In summary the plant macrofossil data suggest that there was greater plant coverage and diversity in the open water in the past and there has been a general shift away from the isoetids to more nutrient tolerant plants such as *Callitriche*.

The summary zooplankton ephippia diagram is shown in Figure 4.7. Data are expressed as numbers of fossils per 100 cm^3 . As for the chitinous cladocera remains, very few ephippia were found in the MENT8 core and therefore data are presented for MENT7 and MENT9 only. The remains in the open water and littoral cores were markedly different. The open water core

reference sample contained very large numbers of the planktonic taxon, *Daphnia pulex*, along with plant obligate species such as *Simocephalus*, *Camptocercus rectirostris* and *Chydoridae*. None of these taxa were found in the surface sample where only small numbers of *Daphnia hyalina* ephippia were present. *Daphnia hyalina* remains were also present in the surface sample of the littoral core along with *Simocephalus* ephippia. The decline in plant associated taxa in the open water core supports the changes seen in the plant macrofossil record, both sets of data suggesting an overall decrease in plant abundance. The littoral zone, however, still supports plant associated zooplankton. The zooplankton data suggest that broader alterations in the food web structure may have occurred, for example the switch in *Daphnia* species away from the larger *D. pulex* could mark a change in predation pressure by either fish or invertebrates. As for the plant macrofossils, cores from different parts of the lake are required to establish a broad picture of ecological change.

Pollen

The summary pollen diagrams for terrestrial and aquatic taxa are shown in Figures 4.8 and 4.9, respectively. The pollen assemblages of the terrestrial taxa showed a decrease in deciduous woodland in the Lake of Menteith catchment since ~1850 including trees and shrubs, *Alnus glutinosa*, *Betula*, and *Corylus avellana*, and fern taxa, *Dryopteris*-type, *Polypodium vulgare* agg., and *Pteridium aquilinum*. There were increases in *Pinus sylvestris* and *Fagus sylvatica* pollen, together with the appearance of *Picea* pollen, all tree taxa which have probably been planted within the catchment during the last 150 years. Increases in Gramineae (grasses), *Solidago*-type, Compositae (Cichorioideae), *Urtica*, and other herbs, suggest increased clearance of woodland and the development of increased pasture around the lake.

The most striking changes in the aquatic pollen assemblages between the ~1850 samples and those of the present-day, were the decreases in *Isoetes lacustris* spores, *Potamogeton* (Eupotamogeton) (includes all *Potamogeton* taxa except *P. pectinatus* and *P. filiformis*), and *Nymphaea* pollen, and the absence of the pollen of *Nuphar lutea*, *Myriophyllum* (both *M. alterniflorum* and *M. spicatum*) in the latter. Furthermore, *Callitriche*, *Menyanthes trifoliata*, and *Glyceria*-type pollen, were found only in the present-day samples, and there was an increase in cf. *Phragmites australis* pollen suggesting more reedswamp and wet meadows around the lake at the present-day. The shift towards more nutrient tolerant plants and an overall decline in the number of taxa represented in the pollen record agrees well with the plant macrofossil data. The pollen and plant macrofossils provide complementary evidence about the past flora, the former adding data on the *Myriophyllum* taxa and the latter providing information on changes in the stonewort community.

Figure 4.3 Summary diagram of the diatom assemblages in Lake of Menteith

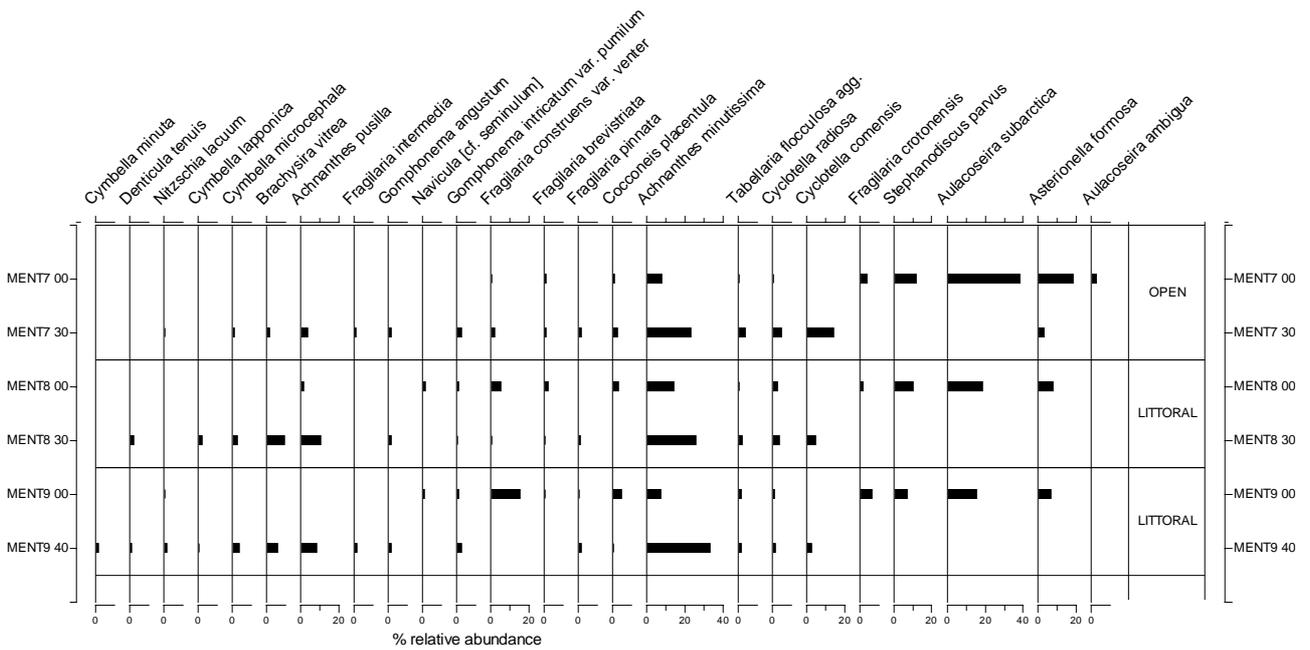


Figure 4.4 Summary diagram of Chironomidae in Lake of Menteith

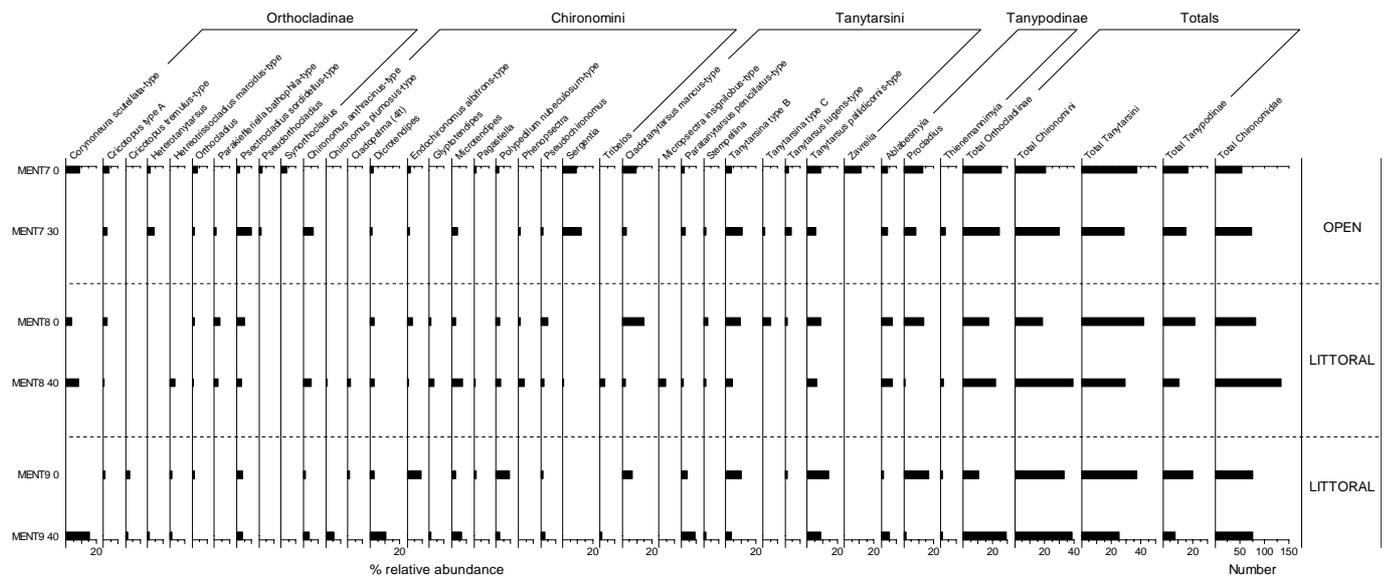


Figure 4.5 Summary diagram of Cladocera chitinous remains in Lake of Menteth

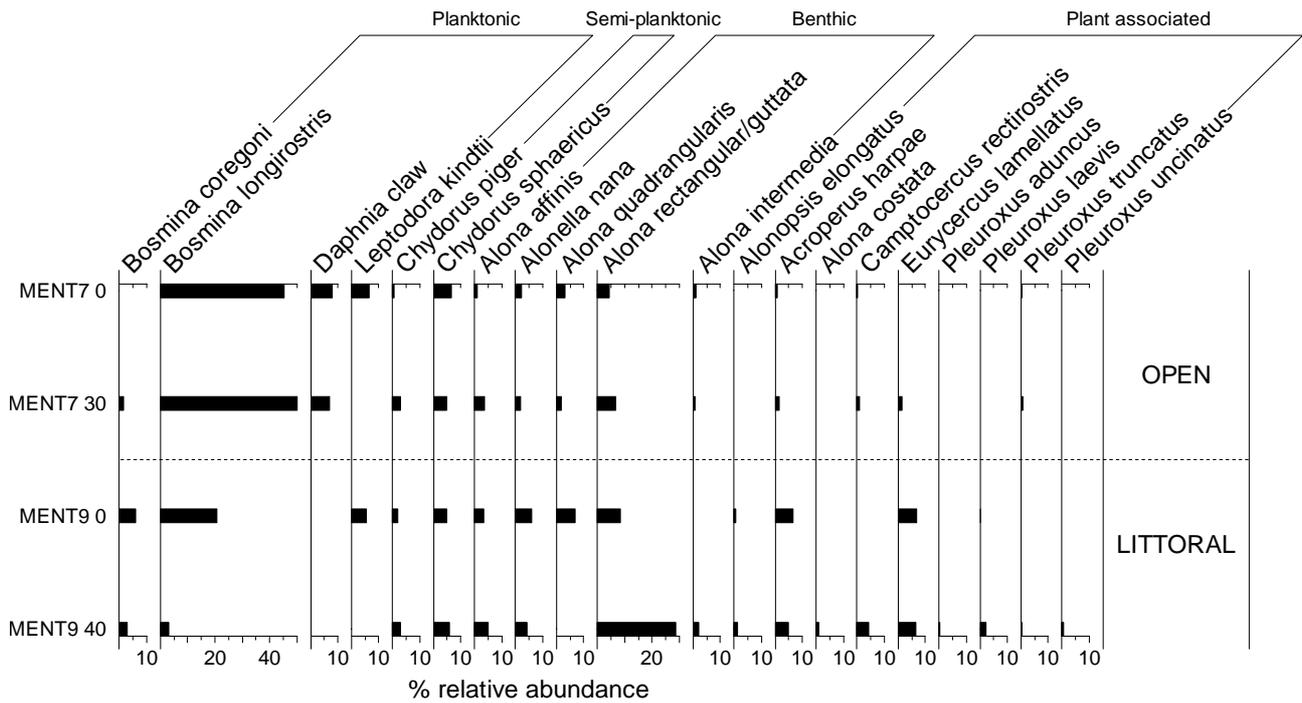


Figure 4.6 Summary diagram of plant macrofossils in Lake of Menteth

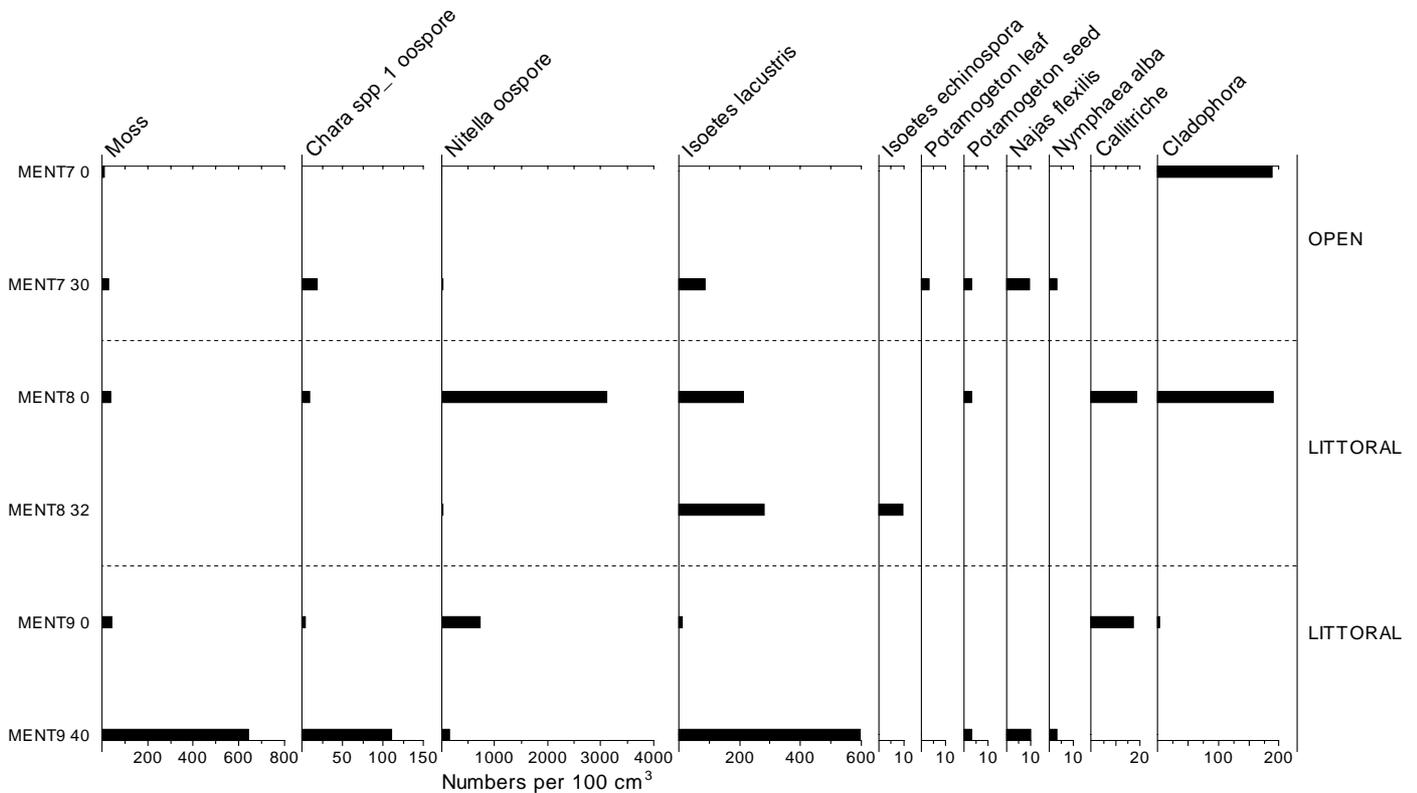
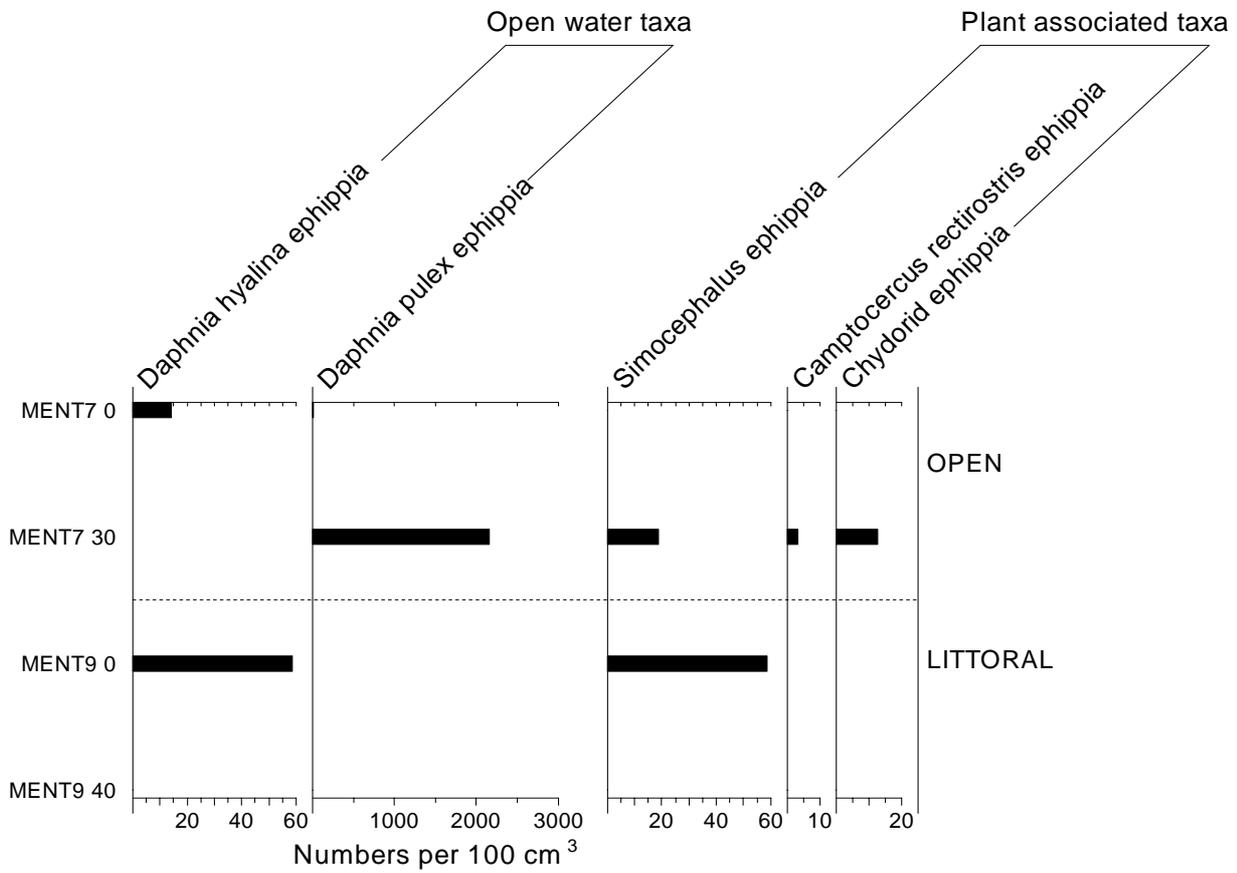


Figure 4.7 Summary diagram of zooplankton ephippia in Lake of Menteith



4.4.2 Llangorse Lake

Core descriptions

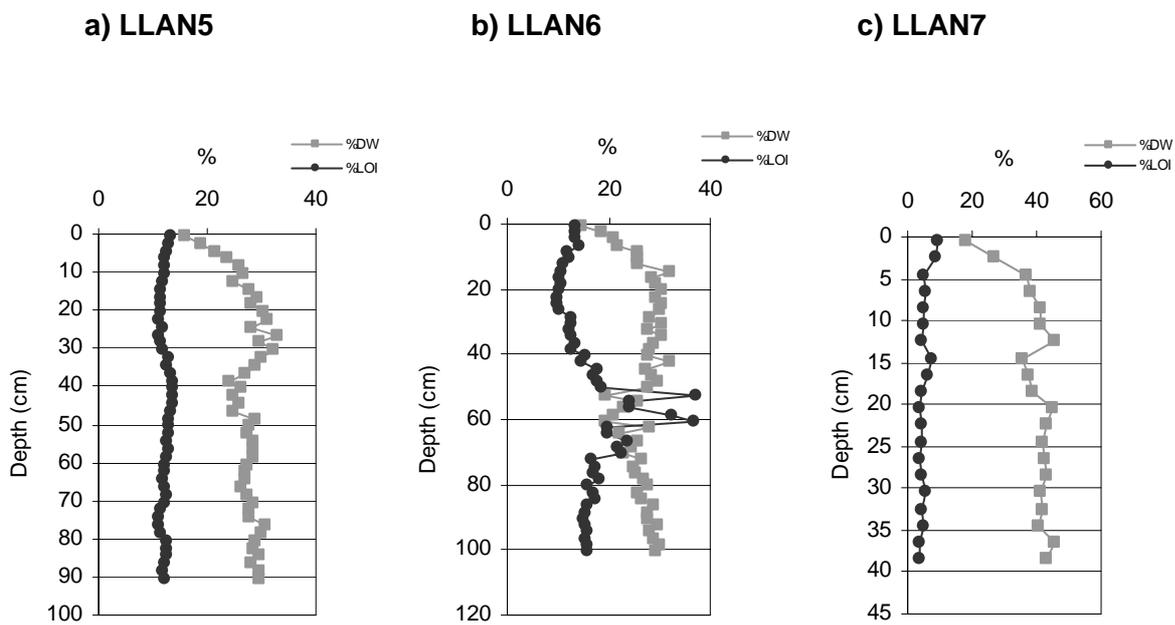
Three sediment cores were taken from the lake on 19 September 2002 as follows:

LLAN5 (SO 13922 26200), a tapper core taken in open water in the easterly deep basin (core length 92 cm, water depth 6.5 m). The core was very similar throughout. It was dark brown in colour and relatively consolidated with ~10-15% organic matter content (Figure 4.10a).

LLAN6 (SO 13775 25891), a fat piston core taken in shallow water, approximately 20 cm offshore adjacent to *Phragmites* and *Typha* dominated reed beds and *Elodea canadensis* and *Nuphar lutea* plant beds, at the south east end of the lake (core length 101 cm, water depth 2.1 m). The upper ~60 cm were a homogenous light brown, relatively inorganic (~15%) lake mud. Large woody remains were present at ~55-60 cm causing peaks in the %LOI data (Figure 4.10b). Below 60 cm, the sediment was similar in colour and organic matter content to the upper part but was more consolidated.

LLAN7 (N/A), a fat piston core taken in shallow water, approximately 50 m offshore close to *Phragmites* beds and *Nymphaea alba*, *Nuphar lutea*, *Elodea canadensis* and *Lemna trisulca* plant beds, along the southern edge of the broader shallow basin (core length 39 cm, water depth 0.9 m). This core was very different from the littoral core LLAN6. The upper ~15 cm were a light brown, inorganic (~5-10%) lake mud below which was a grey marl (~4% LOI) with abundant calcareous remains (Figure 4.10c).

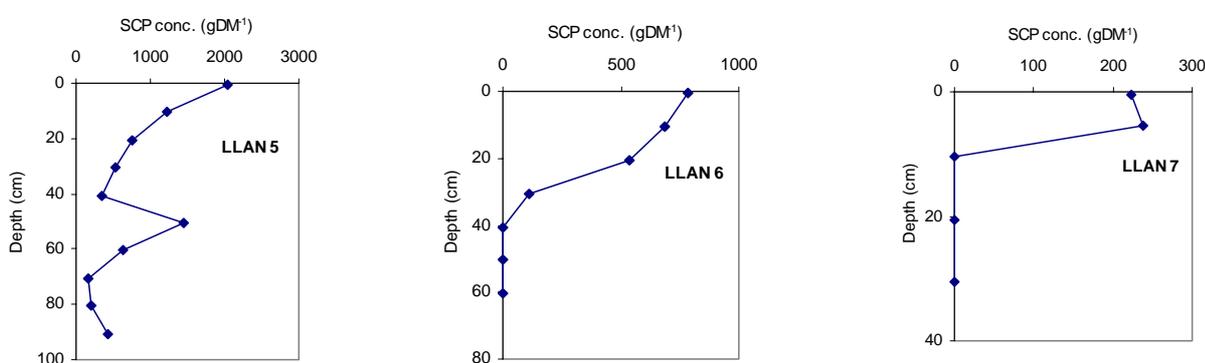
Figure 4.10 Dry weight and organic matter profiles for the Llangorse Lake cores



Spheroidal carbonaceous particles (SCPs)

The SCP concentration profiles are shown in Figure 4.11. First presence of SCPs is at approximately 40 and 10 cm for the littoral cores LLAN6 and 7, respectively. These depths were, therefore, taken to represent the reference samples. Whilst concentrations were relatively low, SCPs were still present at the bottom of the LLAN5 open water core suggesting that the 92 cm sediment record does not quite extend back to ~1850. A radiometrically dated sediment core, taken in 1996 from approximately the same location, also showed that sediment accumulation rates in the Llangorse Lake main basin were high, with a mean post-1960 rate of ~1.3 cm yr⁻¹ (Bennion & Appleby 1999). The 90 cm sample in the 1996 core extended back to ~1890. The bottom sample of the LLAN5 core was taken to represent the reference sample.

Figure 4.11 Spheroidal carbonaceous particle concentration profiles for Llangorse Lake cores



Figures 4.12 to 4.18 illustrate the results for each of the biological indicator groups. In each case the samples are presented on the y axis and are labelled according to their core code and sample depth (e.g. LLAN5 0 is the surface sample for core LLAN5, and LLAN7 10 is the 10 cm sample for core LLAN7).

Diatoms

Diatom preservation was poor in the surface and reference samples from the open water and littoral cores of Llangorse Lake. Only LLAN5, the open water core, had sufficient preservation in the reference sample for analysis. A total of 83 taxa were observed in the four samples analysed, 15 of which were present with a relative abundance of > 2% (Figure 4.12). All three cores have a similar assemblage in the surface samples with a plankton dominated flora comprised of taxa associated with eutrophic waters (e.g. *Cyclostephanos dubius*, *Stephanodiscus parvus*, *Cyclotella radiosa*, *Aulacoseira alpigena*, *Aulacoseira granulata*). Non-planktonic *Fragilaria* taxa were also relatively numerous in the tops of all three cores, particularly the littoral cores. In the latter, *Cocconeis placentula* and *Amphora pediculus*, taxa typically found attached to plant surfaces, were also present reflecting the close proximity of the littoral cores to dense macrophyte beds. The reference sample from the open water core was a mixed assemblage with abundant non-planktonic *Fragilaria* taxa and *Amphora pediculus*, and planktonic diatoms including *Cyclostephanos dubius*, *Aulacoseira granulata*, *Cyclotella radiosa*, and *Stephanodiscus parvus*. Major differences between the reference and surface samples include an increase in the abundance of planktonic taxa relative to the attached forms, and the appearance of *Aulacoseira alpigena*. The diatom data indicate that the lake has always been relatively productive and has supported a planktonic diatom community since at least ~1850 AD, but that the planktonic forms have expanded at the expense of the plant-associated and bottom-dwelling taxa. These changes appear to reflect a loss of habitat for the attached forms through a decline in plant cover or reduced light climate in the open water, most likely brought about through eutrophication. Similar species shifts were observed in the deep, open water core taken in 1996 (Bennion & Appleby 1999).

Chironomids

The summary diagram of chironomid taxa in the Llangorse Lake core samples is shown in Figure 4.13 with data expressed as percentage relative abundance. The total number of head capsules counted in each sample is also shown. Rarefaction and taxon richness were higher in the core tops than core bottoms of Llangorse Lake (Table 4.2). The increase in species richness may be in response to increasing nutrient levels as new taxa become established in the fauna. There was greater abundance of the Chironomini taxa relative to the Tanytarsini taxa in the surface samples than in the reference samples. The Chironomini generally favour more eutrophic conditions suggesting that the shifts are in response to nutrient enrichment. The greatest changes occurred in the littoral core LLAN7. Some of the taxa present only in the core top are associated with aquatic macrophytes while those taxa present only in the bottom sample do not have such an association. It is possible that macrophytes have developed close to the sampling site as the lake has become more productive. Indeed *Nymphaea alba*, *Nuphar lutea*, *Elodea canadensis* and *Lemna trisulca* were all present adjacent to the coring site at the time of sampling. There was marked spatial variability in the chironomid data which makes the CI-TP results difficult to interpret. Both LLAN5 and LLAN7 have a lower CI-TP for the reference sample than the surface sample suggesting enrichment but the opposite was true for LLAN6 which had a very high CI-TP for the reference sample. The species composition of the LLAN6 reference sample was quite different from that of the other littoral core LLAN7. The former was less diverse and contained more eutrophic tolerant taxa. Given that this core was taken close to the inflow where substrates are muddier, it is possible that this part of the lake has always been more productive having received nutrient and sediment inputs from the catchment. In summary, while there was spatial variation in the chironomid data, the temporal patterns indicate a general shift towards a more nutrient tolerant fauna.

Table 4.2 Rarefaction and Chao taxon richness scores for the Llangorse Lake samples

	Rarefaction	Chao
LLAN5 TOP	16.2	30.3
LLAN5 BOTTOM	13	15.7
LLAN6 TOP	16	38
LLAN6 BOTTOM	10.8	17.5
LLAN7 TOP	14.7	28.5
LLAN7 BOTTOM	13	23

Cladocera

The summary diagram of cladocera chitinous remains in the Llangorse Lake sediment samples is shown in Figure 4.14. Data are expressed as percentage relative abundance. There are differences between the open water and littoral cores with higher numbers of benthic and plant associated taxa in the latter. However, chitinous remains are much more easily transported from other areas of the lake than macrofossils and therefore the differences between littoral and open water cores are likely to be less than those seen in the plant macrofossil and zooplankton ephippia records. The open water core was dominated by remains of the planktonic taxon *Bosmina longirostris* in both the reference and surface samples. A number of temporal patterns were seen in all cores. There were a number of taxa typically associated with plants, such as *Camptocercus recti*, *Alona costata*, and *Pleuroxus trigonellus*, which were found in only the bottom of the cores, albeit in very small numbers. Additionally there was an increase in the more opportunistic species such as *Alona affinis* and *Alona quadrangularis*, whose numbers tend to increase when water quality deteriorates. The data appear to indicate a decline in plant abundance. *Daphnia* remains were greater in the surface samples than the reference samples and may complement other data types by suggesting an increase in the open water habitat.

Macrofossils

The summary plant macrofossil diagram for the Llangorse Lake samples is shown in Figure 4.15. Data are expressed as numbers of fossils per 100 cm³. Plant macrofossils were less abundant in the open water core than in the two littoral cores. There were a number of marked differences

between the reference and surface samples. There were fewer remains of aquatic moss, *Nitella* and *Potamogeton praelongus* in the open water core surface sample compared to the reference sample. This was mirrored by the littoral cores which showed lower abundances of moss, *Nitella* and *Chara* spp. remains in the surface samples. These taxa are generally associated with relatively nutrient poor waters. In contrast, remains of nutrient tolerant plants, *Zannichellia* and *Ceratophyllum demersum*, were present only in the surface samples of the littoral cores. Remains of fine leaved *Potamogeton* spp. (e.g. *P. pusillus*) were found in the surface sample of LLAN7. The *Potamogeton* seeds found in the reference sample of LLAN6 have not been identified to species level. The plant macrofossil record indicates that the lake has not supported isoetids for at least the last 150 years (cf. Lake of Menteith) most likely because it was too productive. The shifts observed in the record are consistent with a move towards more eutrophic conditions.

The summary zooplankton ephippia diagram is shown in Figure 4.16. Data are expressed as numbers of fossils per 100 cm³. The open water core has greater numbers of *Daphnia* remains in the surface sample compared to the reference sample, and has remains of *Simocephalus* only in the reference sample. *Daphnia* prefer the pelagic environment whilst *Simocephalus* is a plant obligate. The littoral cores also have higher abundance of *Daphnia* remains in the surface samples. *Camptocercus rectirostris* and *Chydoridae* were present only in the reference sample of LLAN6 which suggests a change in plant abundance or structure. The general pattern of an increase in the abundance of pelagic species and a decrease in plant associated taxa indicates a habitat shift. Zooplankton populations are controlled by a multitude of factors, many of which interact, including fish predation, habitat availability and food source, and therefore it is difficult to be certain of the mechanisms responsible for the observed changes. Plant abundance can influence predation pressure and competition. In summary, the macrofossil data indicate a decline in the areal coverage of plants, a change in plant composition and a general shift from a littoral, plant dominated system to a more pelagic system since ~1850.

Pollen

The summary pollen diagrams for terrestrial and aquatic taxa are shown in Figures 4.17 and 4.18, respectively. The ~1850 samples had high values of tree pollen including *Corylus avellana*, *Alnus glutinosa*, *Betula*, *Quercus* and *Ulmus*, suggesting that the lake catchment contained deciduous woodland at that time. Abundant pollen of Gramineae (grasses) and other herbs, for example *Solidago*-type (including *Bellis*, *Eupatorium*, *Senecio*, and many other tubuliflorate Compositae), *Plantago lanceolata*, Compositae (Cichorioideae) (including *Taraxacum*, *Leontodon*, *Hieracium*), and *Ranunculus acris*-type, were present in the reference samples. These taxa are characteristic of meadows and pastures. The surface samples had increased values of the trees *Alnus glutinosus* and *Fraxinus excelsior* suggesting some increase in fen woodland immediately around the lake. However, the largest increases were in Gramineae, along with Juncaceae, *Mentha*-type, *Rumex crispus*-type, and *Urtica*, suggesting an increase in pasture and water meadows around the lake since ~1850. Decreases in *Solidago*-type, *Plantago lanceolata*, Cyperaceae, and other herbs, may suggest some improvement of pastureland with fewer species than in the past. The amount of arable land within in lake catchment appears little changed from ~1850, with similar amounts of cereal pollen in both sets of samples (Cerealia undiff., *Avena/Triticum*-type, *Hordeum*-type).

A wide range of aquatic taxa were identified in the pollen record, particularly in the present-day samples, showing a general increase in taxa associated with reedswamp (e.g. *Alisma*-type, *Glyceria*-type, *Scirpus lacustris*-type, cf. *Phragmites australis*) compared with the samples representing ~1850. There was evidence for a slight increase in floating-leaved aquatics, including *Nuphar lutea*, *Nymphaea*, *Nymphoides peltata* (known to have invaded 1936 A.D., probably introduced), *Lemna*, and *Ranunculus trichophyllus*-type. There was also an increase in vegetative parts of the Nymphaeaceae (*Nymphaea*, *Nuphar*) including basal cells of hairs found growing on the undersides of the leaves, and trichosclereids, the supporting cells found in the leaves. A number of changes indicative of enrichment were observed. *Myriophyllum alterniflorum* and *Potamogeton* (Eupotamogeton) (includes all *Potamogeton* taxa except *P. pectinatus* and *P. filiformis*) were found only in the reference sample of the open water core, *Callitriche* was present only in the surface sample of the open water core, and *Ceratophyllum* spines were more abundant in the present-day samples of the littoral cores than the ~1850 samples. There were slight differences between the open

water core (LLAN5) and the littoral cores (LLAN6 and 7) with the open water core having less *Potamogeton* (Eupotamogeton), greater abundance of *Glyceria*-type pollen, and more taxa overall. Several grains of *Cladium mariscus* pollen were found in the ~1850 sample of LLAN6.

In summary, the aquatic pollen record is quite complex and is more difficult to interpret than the plant macrofossil record. Nevertheless, both sets of data indicate that the lake has not supported an isoetid community for at least the last 150 years. In combination the pollen and plant macrofossil data provide a valuable record of the past flora, indicating a shift away from charophytes towards more nutrient-tolerant plants (e.g. *Ceratophyllum*, *Callitriche*, *Zannichellia*) with evidence of changes in the *Potamogeton* community. The records indicate that the lake has supported a relatively diverse floating-leaved community both past and present, and indeed historical macrophyte surveys show that the distribution of the floating-leaved community remained fairly constant from 1961 to 1992 (Max Wade, *pers. comm.*). One reason for the data being more difficult to interpret than those from Lake of Menteith is that the submerged plant community of Llangorse Lake has shown signs of recovery since 1985 so we may be seeing the return of taxa that were lost during the major phase of eutrophication in the 1970s and early 1980s.

Figure 4.12 Summary diagram of the diatom assemblages in Llangorse Lake

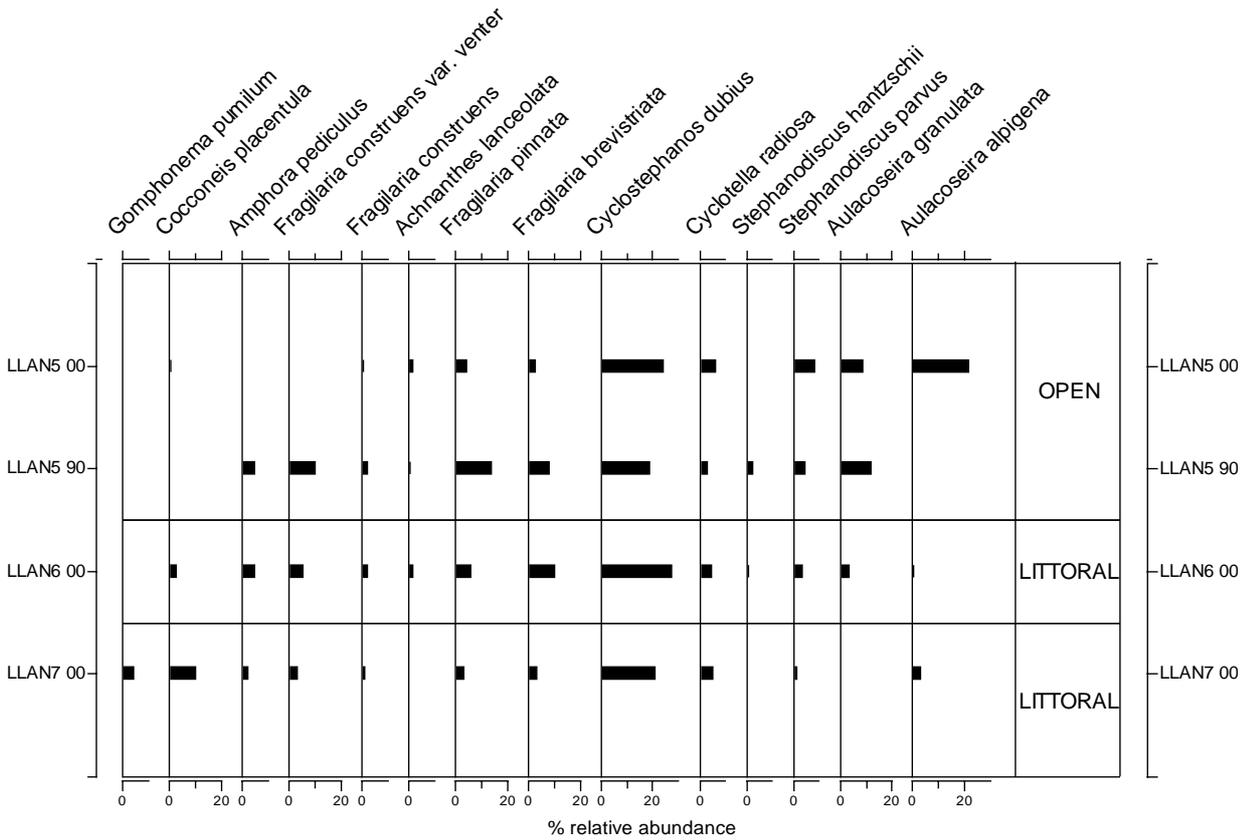


Figure 4.13 Summary diagram of Chironomidae in Llangorse Lake

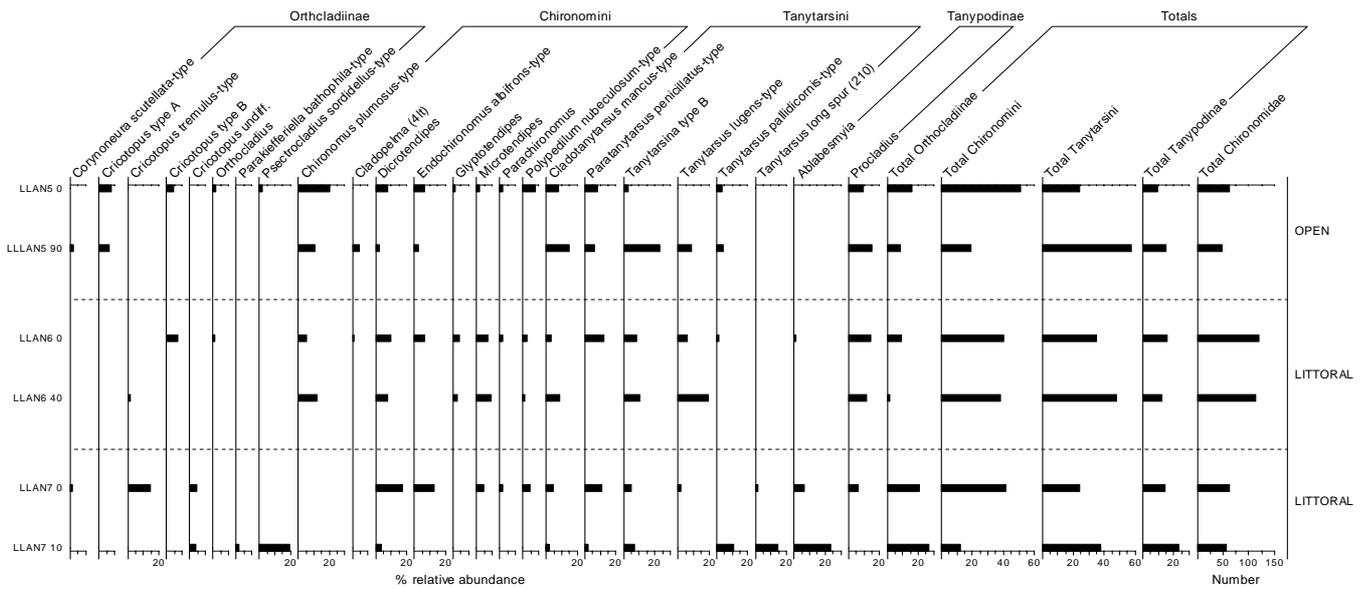


Figure 4.14 Summary diagram of Cladocera chitinous remains in Llangorse Lake

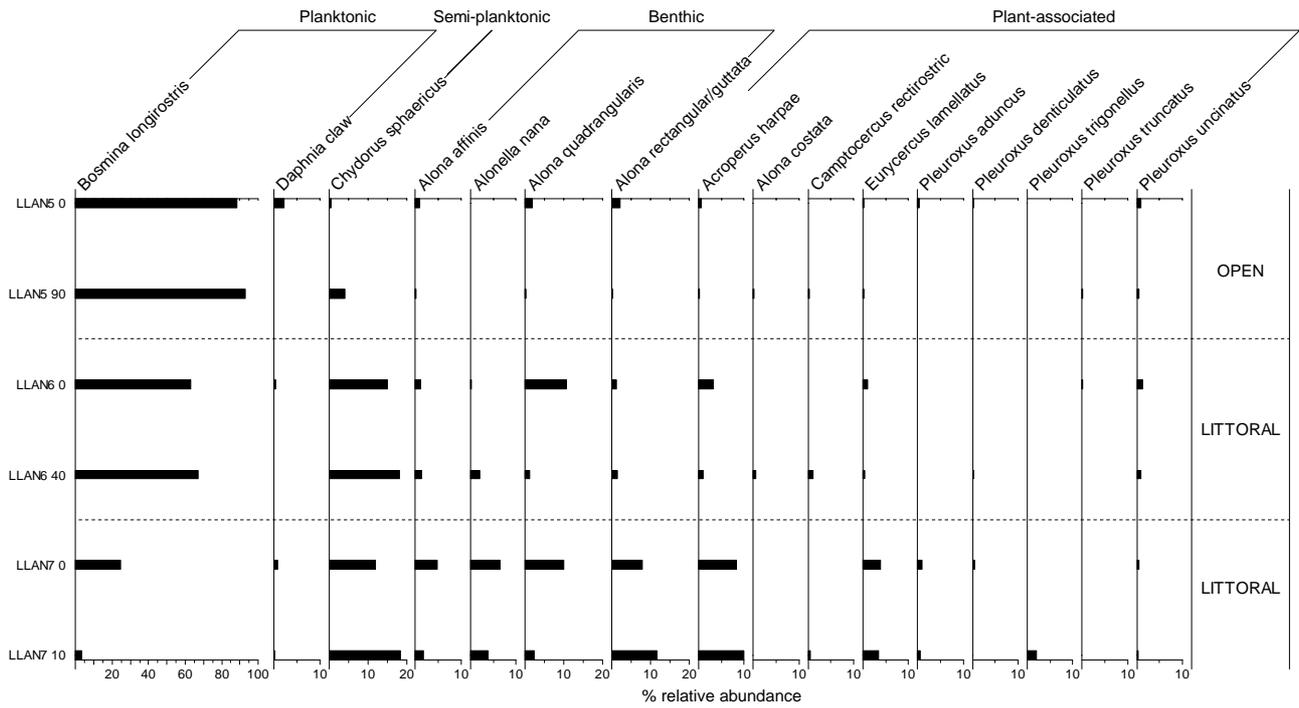


Figure 4.15 Summary diagram of plant macrofossils in Llangorse Lake

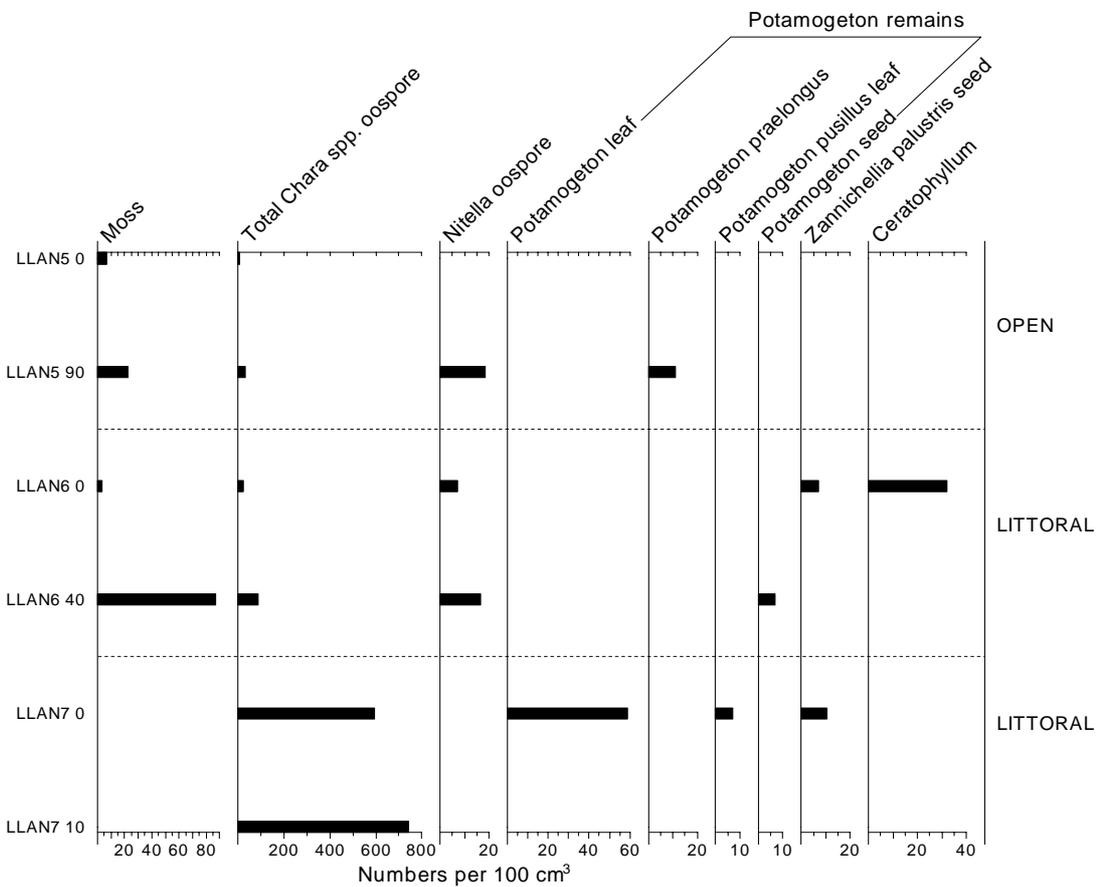


Figure 4.16 Summary diagram of zooplankton ephippia in Llangorse Lake

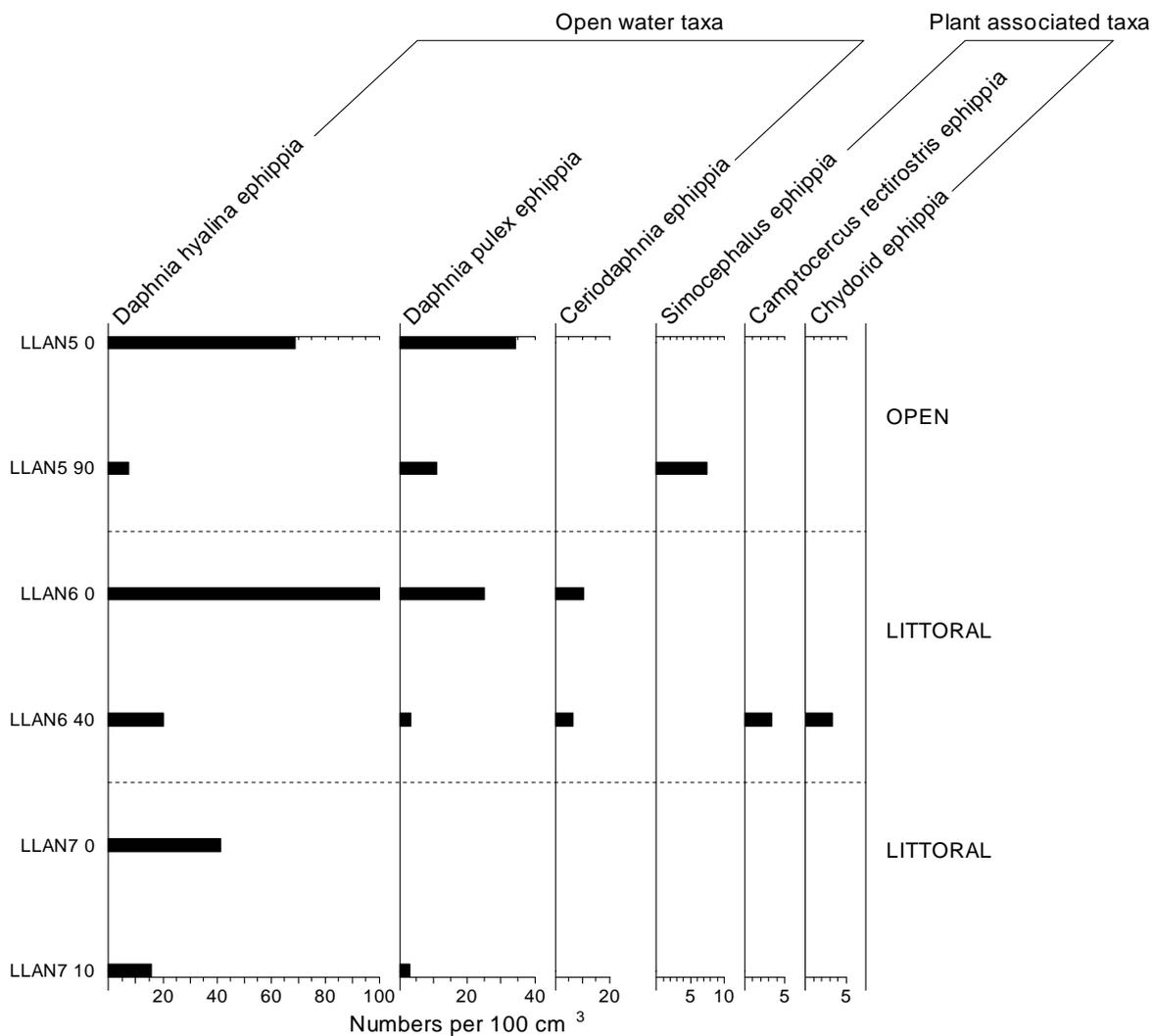


Figure 4.17 Summary diagram of terrestrial pollen in Llangorse Lake

(Note different scaling to highlight less abundant taxa)

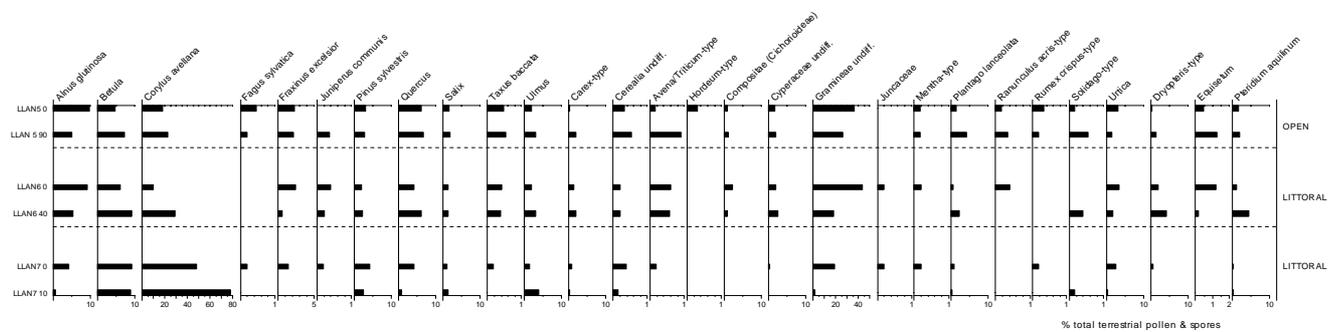
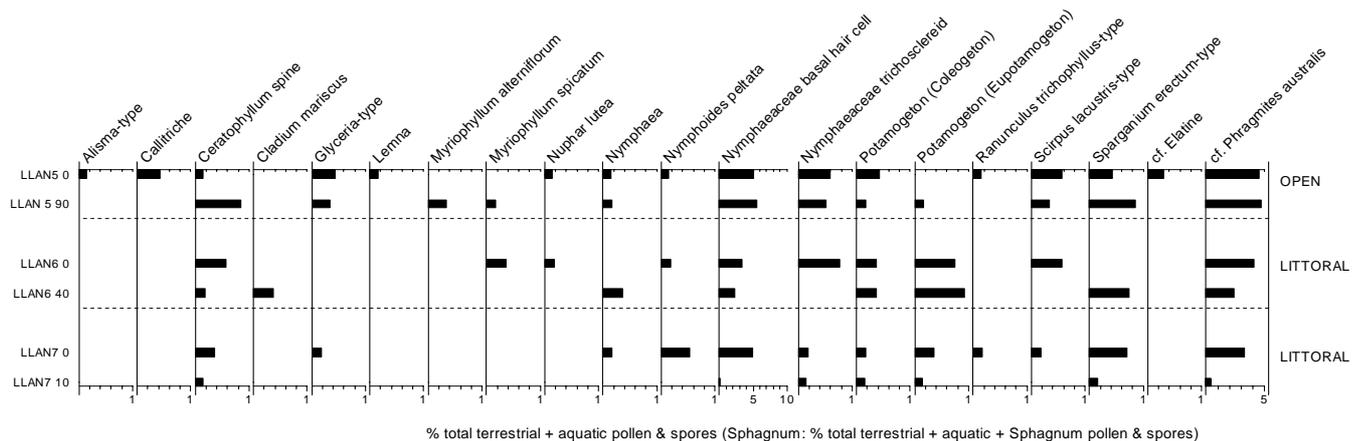


Figure 4.18 Summary diagram of aquatic pollen in Llangorse Lake

(Note different scaling to highlight less abundant taxa)



4.5 Summary of findings

The following section provides a summary description of the past and present ecological status of the two lakes based on interpretation of the multi-proxy data. An integrated basin wide assessment of reference condition is made.

4.5.1 Lake of Menteith

Reference conditions:

The multi-proxy data for the reference samples of the Lake of Menteith cores indicate a healthy ecosystem with diverse communities of diatoms, chironomids, cladocera and aquatic macrophytes. The assemblages are typical of a relatively nutrient poor, circumneutral system.

Diatoms: A mixed planktonic and non-planktonic assemblage comprised of taxa associated with oligotrophic-mesotrophic conditions, namely *Cyclotella comensis*, *Cyclotella radiosa*, *Achnanthes minutissima*, *Achnanthes pusilla*, *Cymbella* spp., *Brachysira vitrea*, *Gomphonema* spp. The diatom-inferred TP value for the reference sample of the open water core was $\sim 10 \mu\text{g l}^{-1}$.

Chironomids: A diverse assemblage including the Chironomini, Tanytarsini, Tanypodinae, and Orthoclaadiinae, the latter being intolerant of eutrophic conditions and thus suggesting relatively low trophic status. The chironomid inferred TP values for all three reference samples were very similar at $\sim 20 \mu\text{g l}^{-1}$.

Cladocera: The chitinous remains indicate a diverse Cladocera community, including planktonic (*Bosmina* spp.), semi-planktonic (*Chydorus* spp.), benthic (*Alona* spp.), and a number of plant-associated taxa (e.g. *Pleuroxus* spp. and *Camptocercus rectirostris*). The ephippia add further information indicating the presence of the planktonic taxon, *Daphnia pulex*, along with plant obligate species such as *Simocephalus* and *Chydoridae*.

Plant macrofossils: The data suggest high plant coverage and diversity in the open water with presence of aquatic moss, *Chara*, *Isoetes* (e.g. *Isoetes lacustris* and *Isoetes echinospora*), *Potamogeton*, *Najas flexilis* and *Nymphaea alba*.

Pollen: The terrestrial taxa indicate presence of deciduous woodland in the Lake of Menteith catchment (e.g. *Alnus glutinosa*, *Betula*, and *Corylus avellana*). The aquatic pollen assemblages indicate the presence of *Isoetes lacustris*, *Myriophyllum* (both *M. alterniflorum* and *M. spicatum*), *Potamogeton* (includes all *Potamogeton* taxa except *P. pectinatus* and *P. filiformis*), and *Nymphaea*.

Current conditions:

The multi-proxy data for the surface samples of the Lake of Menteith cores indicate a relatively healthy ecosystem but with lower diversity in communities of diatoms, chironomids, cladocera and aquatic macrophytes than in the past. The assemblages are typical of a mesotrophic, circumneutral system.

Diatoms: A plankton dominated assemblage comprised of meso-eutrophic taxa, namely *Stephanodiscus parvus*, *Asterionella formosa*, *Fragilaria crotonensis*, *Aulacoseira subarctica*, and non-planktonic *Fragilaria* spp.

Chironomids: The assemblage remains diverse but there is lower species richness than in the reference samples. The greatest change has occurred in the littoral samples where increases in *Cladotanytarsus*, *Endochironomus* and *Polypedium* suggest nutrient enrichment (chironomid-inferred TP values increased to $\sim 60 \mu\text{g l}^{-1}$) and possibly an increase in macrophytes. The latter may also account for the relative decline in silt-associated taxa such as *Chironomus* and *Microtendipes*. The findings are in agreement with chironomid samples collected in the early 1980s in which Tanytarsini and Chironomini were most abundant (Fozzard & Marsden 1990).

Cladocera: The chitinous remains indicate a diverse Cladocera community but *Leptadora kindtii*, a large bodied predatory species normally subject to fish predation, is present which was not seen in the reference samples. This suggests a change in food web structure to a more pelagic system. There are fewer plant associated species than in the reference sample. The ephippia also indicate a loss of the plant obligate species such as *Simocephalus*, *Camptocercus rectirostris* and *Chydoridae* in the open water. Indeed the only ephippia in the open water core are *Daphnia hyaline*. The data, therefore, indicate a decline in plant cover in the open water zone. Zooplankton data collected in the early 1980s identified *Daphnia* spp. as one of the dominant genera (Fozzard & Marsden 1990). The littoral zone, however, still supports plant associated zooplankton (*Simocephalus*). The zooplankton data suggest that broader alterations in the food web structure may have occurred, for example the switch in *Daphnia* species away from the larger *D. pulex* could mark a change in predation pressure by either fish or invertebrates.

Plant macrofossils: The data suggest a change in the stonewort community from *Chara* dominance to *Nitella* dominance, and a general shift away from the isoetids to more nutrient tolerant plants such as *Callitriche*. *Cladophora* remains are also present.

Pollen: The terrestrial taxa indicate planting of *Pinus sylvestris*, *Fagus sylvatica* and *Picea*. Pollen of Gramineae (grasses), *Solidago*-type, Compositae (Cichorioideae), *Urtica*, and other herbs, suggest clearance of woodland and the development of increased pasture around the lake. The aquatic pollen assemblages are absent of *Nuphar lutea*, *Myriophyllum* (both *M. alterniflorum* and *M. spicatum*), taxa that were found in the reference samples and there is an overall decline in the number of taxa represented in the pollen record. The modern assemblages are comprised of *Callitriche*, *Menyanthes trifoliata*, and *Glyceria*-type pollen. Higher abundance of cf. *Phragmites australis* pollen suggests more reedswamp and wet meadow around the lake at the present-day.

In summary, the multi-proxy palaeoecological data for Lake of Menteith support the previously published fossil diatom records (Bennion *et al.* 2001b, 2004) and recent observations in demonstrating that the lake has undergone enrichment (Fozzard & Marsden 1990). There appears to have been a cascading effect through the whole system (e.g. Carpenter *et al.* 1985). The plant macrofossil and aquatic pollen records suggest an overall decrease in plant abundance and a shift towards more nutrient tolerant plants. This is reflected in the cladocera community where a decline in plant associated taxa in the open water was observed. The system is now more plankton dominated with greater abundance of planktonic cladocera and diatoms, and a less diverse chironomid community. Eutrophication may have brought about alterations in the food web structure. For instance, fewer *Daphnia pulex* and appearance of *Leptadora kindtii* could mark a change in predation pressure by either fish or invertebrates. The data suggest that the littoral zone still supports plant associated zooplankton and that a diverse Cladocera community is still present. The lake is currently mesotrophic with a mean total phosphorus concentration of $\sim 20 \mu\text{g l}^{-1}$.

4.5.2 Llangorse Lake

Reference conditions:

The multi-proxy data for the reference samples of the Llangorse Lake cores indicate a healthy ecosystem with diverse communities of diatoms, chironomids, cladocera and aquatic macrophytes. Numerous plant-associated cladocera taxa and attached forms of diatom suggest that macrophytes were present in the lake. The assemblages are typical of an alkaline system of intermediate trophic status

Diatoms: A mixed assemblage with abundant non-planktonic *Fragilaria* taxa and *Amphora pediculus*, and planktonic diatoms typically found in nutrient-rich lakes including *Cyclostephanos dubius*, *Aulacoseira granulata*, *Cyclotella radiosa*, and *Stephanodiscus parvus*.

Chironomids: A diverse assemblage including the Chironomini, Orthoclaadiinae and Tanyptodinae, and Tanytarsini particularly well represented.

Cladocera: The chitinous remains indicate a diverse Cladocera community with a number of taxa typically associated with plants, such as *Camptocercus recti*, *Alona costata*, and *Pleuroxus trigonellus*. The planktonic taxon, *Bosmina longirostris*, dominates the open water. The ehippia data indicate that *Daphnia* spp. are an important part of the community, and plant associated taxa, *Simocephalus*, *Camptocercus rectirostris* and *Chydoridae*, are also present.

Plant macrofossils: The data indicate presence of plants generally associated with relatively nutrient poor waters, namely aquatic moss, *Chara* spp., *Nitella* and *Potamogeton praelongus*. Early plant surveys carried out in 1698 note the presence of *Chara* species in the lake (Gunther 1945).

Pollen: The terrestrial taxa include *Corylus avellana*, *Alnus glutinosa*, *Betula*, *Quercus* and *Ulmus*, suggesting presence of deciduous woodland in the catchment. Abundant Gramineae (grasses) and other herbs indicate meadow and pastureland. The aquatic pollen assemblages indicate the presence of *Myriophyllum alterniflorum* and *spicatum*, *Potamogeton* (Eupotamogeton) (includes all *Potamogeton* taxa except *P. pectinatus* and *P. filiformis*), *Ceratophyllum* and Nymphaeaceae.

Current conditions:

The multi-proxy data for the surface samples of the Llangorse Lake cores indicate a more productive system than in the past with plankton dominated diatom and cladocera communities, chironomids associated with eutrophic waters, and the presence of nutrient-tolerant aquatic macrophytes. The assemblages are typical of a nutrient-rich, alkaline system.

Diatoms: A plankton dominated flora comprised of taxa associated with eutrophic waters (e.g. *Cyclostephanos dubius*, *Stephanodiscus parvus*, *Cyclotella radiosa*, *Aulacoseira alpigena*, *Aulacoseira granulata*). Non-planktonic *Fragilaria* taxa are also abundant.

Chironomids: An increase in diversity of Chironomini and a decline in Tanytarsini (especially *Tanytarsus lugens* which is intolerant of nutrient-rich conditions) relative to the reference samples suggests enrichment. The relatively large increase in Chironomini in the open water sample probably reflects oxygen stress since they are able to tolerate low oxygen concentrations by virtue of possessing haemoglobin. Taxa associated with macrophytes such as *Cricotopus*, *Dicrotendipes*, *Endochironomus*, *Polypedilum* and *Paratanytarsus* are present in higher amounts than in the reference samples of the open water and littoral cores.

Cladocera: The chitinous remains indicate a diverse community including taxa from all habitats. The planktonic taxon, *Bosmina longirostris*, dominates the open water and *Daphnia* spp. are also present. Opportunistic species such as *Alona affinis* and *Alona quadrangularis*, whose numbers tend to increase when water quality deteriorates, are present. Open water *Daphnia* spp. dominate the ehippia remains and plant associated taxa are absent.

Plant macrofossils: The data indicate presence of *Chara* spp., *Nitella*, a fine leaved *Potamogeton* spp. (e.g. *P. pusillus*) and nutrient tolerant plants, *Zannichellia palustris* and *Ceratophyllum demersum*. All of these plants have been recorded in recent macrophyte surveys (Duigan *et al.* 1999). Indeed *Zannichellia palustris* along with *Potamogeton pectinatus* were recorded as the most abundant species in the 1970s whilst *Myriophyllum spicatum* had become rare (e.g. Britton & Britton 1973). Both of the former species are characteristic of eutrophic conditions.

Pollen: The terrestrial taxa include abundant remains of Gramineae, along with Juncaceae, *Mentha*-type, *Rumex crispus*-type, and *Urtica*, suggesting presence of pasture and water meadows around the lake. The aquatic pollen assemblages indicate the presence of reedswamp (e.g. *Alisma*-type, *Glyceria*-type, *Scirpus lacustris*-type, cf. *Phragmites australis*). Pollen of the floating-leaved aquatics including *Nuphar lutea*, *Nymphaea*, *Nymphoides*, *Lemna*, and *Ranunculus trichophyllum*-type, are more abundant than in the reference samples. *Callitriche* was present only in the surface sample of the open water core, and *Ceratophyllum* spines are more abundant in the littoral cores than in the reference samples. *Myriophyllum spicatum* pollen was observed in the surface sample of one littoral core and *Potamogeton* taxa were present in all cores. This species list agrees well with current macrophyte data (Duigan *et al.* 1999)

In summary, the findings of the study indicate enrichment of the lake and are, therefore, in agreement with previous diatom based palaeoecological work and monitoring data (Bennion & Appleby 1999, Duigan *et al.* 1999). As for Lake of Menteith, all components of the ecosystem have been affected. The data indicate a decline in the areal coverage of plants and a change in plant composition away from charophytes toward more nutrient-tolerant species. A general shift from a littoral, plant dominated system to a more pelagic system has occurred with the planktonic diatoms and pelagic cladocera expanding at the expense of the plant-associated and bottom-dwelling taxa. A general shift towards a more nutrient tolerant chironomid fauna was also observed. The data indicate that the lake has always been relatively nutrient-rich, having supported a planktonic diatom community since at least ~1850 AD. The plant macrofossil record and pollen data indicate that, unlike Lake of Menteith, the lake has not supported isoetids for at least the last 150 years, most likely because it has been too productive. In general, the data are more difficult to interpret than those for Lake of Menteith. This may in part be because the submerged plant community of the lake has shown signs of recovery since 1985 and our surface samples post-date the major phase of eutrophication in the 1970s and early 1980s.

4.5.3 Recommendations for using multi-proxy palaeoecological methods for defining site-specific ecological reference conditions in lakes.

The study has demonstrated the potential of multi-proxy palaeoecological methods for defining ecological reference conditions for lakes. Here we make a number of methodological recommendations with regard to defining reference conditions for WFD purposes.

The analysis of a single open water core is recommended for diatoms and chironomids. Sediment samples from deep, open water zones generally represent the entire chironomid fauna and diatom flora of the lake. They incorporate both littoral and profundal taxa and should, therefore, reflect general lake conditions. Little is gained from analyses of littoral cores. Indeed samples from the littoral zone are more likely to reflect local conditions.

The analysis of littoral cores is essential for plant macrofossils. Plant macrofossils were much less abundant in the open water cores than in the littoral cores of the two study lakes. This has been seen in other multi-core studies (e.g. Davidson *et al.* in review). Plant macrofossils are generally large and relatively heavy and, therefore, tend not to be transported far from the source plant. In this top and bottom study, differences were observed in the littoral cores from within a single site. However, higher resolution analysis of plant macrofossils in multiple cores from other sites has shown that one littoral core adequately provides a picture of broad changes in the aquatic vegetation (Davidson *et al.* in review). For the top and bottom approach, where reliance is placed on interpretation of only two samples per core, we therefore recommend that at least two littoral cores, but ideally more, should be collected and that the reference samples are subsequently pooled prior to plant macrofossil analysis and likewise for the surface samples. This provides a spatially integrated sample for both the reference and current assemblages and reduces the possibility of mis-interpretation that may arise from one atypical sample. In large lakes it may be necessary to collect cores from a number of bays representative of the various lake habitats.

Comparison of the plant macrofossil and pollen records of the Llangorse Lake cores with contemporary macrophyte surveys of the lake shows good agreement between the two sets of data. However, a number of species recorded by recent surveys were not found in the fossil data, most notably a number of *Potamogeton* taxa (not recorded by plant macrofossils) and *Elodea canadensis*. The latter species does not produce seeds, and leaf fragments tend not to be preserved. Studies comparing contemporary plant populations with surface sediment assemblages found *Potamogeton* remains to be relatively rare, even where abundant and diverse extant populations were present (Kautsky 1990). Therefore, the palaeo-record tends to underestimate past species richness. The pollen and plant macrofossil records provide complementary evidence about the past flora of the study lakes, e.g. the former adding data on the *Myriophyllum* taxa and the latter providing information on changes in the stonewort community. Therefore, pollen and macrofossil data combined provide a more complete record of change in the aquatic flora. It is

recommended that both plant macrofossils and pollen remains are analysed in order to provide as complete a vegetation history as possible.

The analysis of zooplankton ephippia from a single open water core is likely to provide sufficient information but nevertheless, additional analysis of a littoral core is desirable to capture any spatial variability. Chitinous cladocera remains, however, are more easily transported from other areas of the lake than macrofossils and thus the differences between littoral and open water cores are less than those seen in the plant macrofossil and zooplankton ephippia records. It is, therefore, recommended that analysis of chitinous cladocera remains in a single open water core is sufficient.

The use of the spheroidal carbonaceous particle technique for providing an estimate of ~1850 AD for each core is essential when analysing data from a number of different cores. Alternatively, low resolution radiometric dating could be carried out. We recommend that the ~1850 AD sample is taken to represent the 'reference sample'. The present study involved the analysis of a single sample from each core in order to define the reference condition. However, it is advisable to analyse two or three additional samples in the same section of the core to improve the reliability of the data and, for plant macrofossils, to pool a number of analogous samples to provide spatially integrated data (see above).

4.5.4 Conclusion

The application of multi-proxy approaches to two test lakes has illustrated the potential of the fuller sediment record for providing an integrated basin wide assessment of reference condition. Whilst the data for Llangorse Lake were somewhat more difficult to interpret than those for Lake of Menteith, the multi-indicator data reflect a shift in the functioning of both lakes from benthic-littoral to planktonic dominated production. Given issues of spatial patchiness and preservation, it is not possible for the fossil records to provide a full species list for all taxa present at reference condition. However, the study demonstrates that the strength of the method is in its ability to provide comprehensive information on the functioning of the system.

5. WORK PACKAGE 4: DEMONSTRATION OF THE ANALOGUE MATCHING APPROACH FOR IDENTIFYING APPROPRIATE REFERENCE SITES FOR IMPACTED LAKES

5.1 Objectives

Work package 4 aims to test the value of the analogue matching approach for identifying appropriate reference sites to be used to formulate restoration targets for lakes impacted by eutrophication.

Analogue matching is a form of space for time substitution modelling. It is a statistical technique that compares degree of floristic or faunistic similarity between a fossil sample (in a sediment core) taken from an impacted lake and a range of modern (surface sediment) samples. The best modern analogues for the pre-disturbance assemblages are identified. These analogue lakes are then assumed to have similar community composition to those present in the pre-disturbance period of the impacted lake in biological groups other than those analysed in the palaeo-record (e.g. fish, benthic macroinvertebrates). The technique has to date only been developed for identifying restoration targets for acidified lakes based on diatom analogues (Flower *et al.* 1997) and more recently based on both diatoms and cladocera in 83 upland surface waters in the UK (Simpson 2001). The technique is proving a powerful one for identifying site specific ecological reference conditions in these waters but requires further development to be applicable to a wider range of UK lake types. In order to establish pre-disturbance communities in enriched lakes, the analogue matching approach must be extended to lowland waters spanning the full trophic gradient from oligotrophic to hypertrophic conditions.

The aim of this work package is to generate a 30 lake training set for demonstrating the application of the analogue matching technique to nutrient stressed systems. The surface samples from the 30 sites will be analysed for diatoms and cladocera. The method will then be tested on three impacted lakes where dated sediment cores already exist. The diatom and cladocera assemblages in the samples representative of ~1850 AD will be analysed and a squared chord distance dissimilarity measure will be employed to determine the best analogues for the 'reference' assemblages.

5.2 Methods

5.2.1 The analogue matching training set

Sediment cores were collected from a total of 34 lakes in summer 2002 as part of work package 2 (Table 3.1). An additional 15 lakes were cored in summer 2003 to increase dataset size and in particular to increase the numbers of medium and high alkalinity waters (Figure 2.1). The cores collected in 2003 were extruded in the field and subsequently analysed for % dry weight and % organic matter in the laboratory, using the same methods as for the 2002 cores (see chapter 3). Diatom slides were prepared from 4-5 selected levels of the 2003 cores and were screened to determine degree of preservation. The surface and bottom samples were counted to assess degree of floristic change, using the methods detailed in chapter 3, and the data were incorporated into work package 1. At two lakes, Loch Ardnave (Islay) and Loch Ballygrant (Islay), only the surface sediment was analysed owing to poor diatom preservation.

A total of 30 lakes were selected from the 2002 and 2003 dataset to form the analogue matching training set (Table 5.1). Sites with the least change in the diatom assemblages, representative of a broad range of lake types, were selected. The dataset is purposely bias towards medium and high alkalinity, and marl lakes as these types have fewer examples of reference lakes in the current population than low alkalinity waters, and they are the types where nutrient enrichment is generally the key pressure. Thirteen of the fifteen lakes sampled in 2003 were included. Only Loch Ballygrant (Islay) and Tatton Mere (Cheshire) were omitted, the former owing to poor preservation and a very similar surface sediment diatom assemblage to adjacent Loch nan Cadhan, and the latter because the assemblages are dominated by nutrient-rich taxa (e.g. *Stephanodiscus* spp. and *Cyclostephanos* spp.) which are not commonly observed in such high abundances in pre-impact assemblages. Some of the Shropshire-Cheshire meres are thought to be naturally nutrient-rich owing

to a phosphate-rich bedrock (Moss *et al.* 1992) and this may explain the dominance of the planktonic, centric forms throughout the 25 cm core from Tatton Mere.

Surface sediment samples of the 30 selected lakes were prepared for cladocera analyses using the same techniques as those described in section 4.2. . Body parts identified included ephippia, carapaces, head shields, post abdomens and post abdominal claws. Only the chitinous remains were used in the training set owing to the lack of ephippial remains in six of the samples.

5.2.2 The test lakes

Three lakes were selected for testing the technique: Loch Davan (Scotland), Felbrigg Lake (England), and Groby Pool (England). All three lakes have experienced ecological change in response to eutrophication. The diatom assemblages have already been analysed in dated sediment cores and the data from the 1850 samples were extracted from the Amphora database. In each of the three cores, the cladocera assemblages in the sample dated to ~1850 AD were analysed using the same preparation and counting methods as for the training set samples.

Loch Davan (NJ 442 007) is a small (0.42 km²), shallow (mean depth 1.2m, maximum depth 2.7m), lowland (165 m a.s.l.) loch situated in the Muir of Dinnet National Nature Reserve approximately 50 km west of Aberdeen in north-east Scotland. It has a volume of 0.37 x 10⁶. The catchment is relatively large (33.8 km²) and is predominantly heather scrubland (33%), with significant amounts of improved grassland (19%), coniferous plantation (18%) and arable land (14%). It is classed as medium alkalinity and shallow in the GB Lake Typology scheme. Potential nutrient sources include diffuse agricultural inputs, forestry, and one small sewage treatment works. A 95 cm sediment core (DAVA2) was taken in July 1998 in a water depth of 2 m using a mini-Mackereth piston corer (see Bennion *et al.* 2001b for details). On the basis of the ¹³⁷Cs record, the mean sedimentation rate in the core was estimated to be 0.088 g cm⁻² yr⁻¹ (0.4 cm yr⁻¹). This places ~1850 AD at approximately 70 cm sediment depth and this sample was, therefore, selected here as the “reference” sample.

The loch is mesotrophic today with clear water, and still supports a dense growth of macrophytes. The current mean TP concentration is ~25 µg TP l⁻¹ (SEPA data, 1994-2000). Nevertheless, palaeolimnological data and historical land cover data indicate a decline in water quality in the loch (Bennion *et al.* 2001b). Three taxa, *Stephanodiscus parvus*, *Fragilaria capucina* var. *mesolepta* and *Synedra pulchella*, not previously observed in the core, appeared from ~1960 and a decline in the relative abundance of many of the formerly important non-planktonic taxa, in particular *Achnanthes minutissima*, occurred. The new arrivals were present in relatively low percentages but, nevertheless, their appearance in the loch provides evidence of eutrophication. The DI-TP data indicated that TP remained relatively stable at ~10-15 µg TP l⁻¹ throughout the lower part of the core but concentrations began to increase steadily from the early 1900s to ~25 µg TP l⁻¹ and have remained high since 1960. Land cover analysis by Ferrier *et al.* (1997) of the Loch Davan catchment showed that increases in coniferous woodland, intensive arable and improved pasture since 1850, as well as intensification of agricultural practices, had resulted in increased nutrient loading to the loch.

Felbrigg Lake (TG 190388) is a very small (0.03 km²), shallow (mean depth 1 m, maximum depth 1.2 m), low-lying (50 m a.s.l.) estate lake situated in Norfolk, Eastern England. It was created through the damming of two first order streams in approximately 1780 AD. It is situated in a small (<6 km²), predominantly agricultural catchment. The lake is alkaline and eutrophic with elevated mean annual (May 1999-May 2000) TP (107 µg l⁻¹), Nitrate nitrogen (1.26 mg l⁻¹), and chlorophyll a (15 µg l⁻¹) concentrations (Sayer, unpublished data). It is classed as a high alkalinity, shallow lake in the GB Lake Typology scheme. Submerged vegetation occupies approximately 40% of the lake area and 18.5% of lake volume. The dominant species are *Zannichellia palustris*, *Potamogeton pusillus* and *Potamogeton pectinatus*. *Potamogeton crispus* and *Lemna minor* are also present. Significant growths of the filamentous algae, *Cladophora* and *Enteromorpha* sp. also occur in the lake. The dominant fish present are rudd (*Scardinius erythrophthalmus*), tench (*Tinca tinca*) and pike (*Esox lucius*) and fish density is high (5.4 individuals m²) (Sayer & Perrow, unpublished data).

A 85 cm sediment core (FELB1) was taken in 1998 using a piston corer. The ^{210}Pb record places ~1850 AD at approximately 55 cm sediment depth and this sample was, therefore, selected here as the “reference” sample.

A 250 year palaeolimnological record from Felbrigg Lake suggests that dynamic change has taken place (Sayer, unpublished). Macrofossils and pollen indicate stepped shifts between early abundances of *Myriophyllum spicatum*-*Chara*, followed by *Ranunculus-Ceratophyllum-Potamogeton crispus*, before the more recent dominance (since ~1960) of the more nutrient tolerant *Zannichellia palustris* and fine-leaved *Potamogeton* taxa. Multi-proxy palaeoecological data suggest that since 1960, the lake has experienced more frequent mid-summer reductions in plant coverage and subsequent compensatory increases in phytoplankton abundance. Cladoceran-inferred zooplanktivorous fish abundance suggests a significant reduction in the density of fish during the early- to mid-twentieth century, followed by a more recent (post 1970) increase. In summary, Felbrigg Lake has experienced reductions in macrophyte cover and stability against a background of gradual increases in nutrient loading.

Groby Pool (SK 421083) is a small (0.12 km²), shallow (mean depth <1.1m), medieval lake with a largely rural, lowland catchment (8.6km²) located in Leicestershire, England. The lake is currently alkaline (mean pH ~9.0) and eutrophic (mean ~200 µg TP l⁻¹) but remains in a clear-water, vegetated state (Sayer *et al.* 1999; Sayer 2001). It is classed as a high alkalinity, shallow lake in the GB Lake Typology scheme. Land enclosure took place in 1789 resulting in the ploughing up of large tracts of pasture for arable farming, and by 1925 approximately 30% had been converted to arable (David 1991; David and Roberts 1990). The geology, chemistry, ecology, history and palaeolimnology of the lake are documented in David and Roberts (1990), David *et al.* (1998), Sayer (1997) and Sayer *et al.* (1999). A wide diameter piston core (GROB5), 85 cm in length, was taken from the centre of the lake in a water depth of 1.3 m in July 2000 (Bennion 2001). The chronology of the core was derived using the spheroidal carbonaceous particle method (Rose 1994). This placed 1850 AD at a sediment depth of ~46 cm (Davidson *et al.*, in review) and this sample was, therefore, selected here as the “reference” sample.

Previous palaeoecological studies of the lake, combining botanical data and pollen records, have demonstrated a dynamic sequence of vegetation change over the last 250 years in response to eutrophication (Sayer *et al.* 1999). Eutrophication of Groby Pool since the mid to late nineteenth century has been attributed to the conversion of pasture to arable land (Sayer *et al.* 1999), with a more recent phase of enrichment following the arrival of sewage effluent into the lake inflow in the mid-1900s (Sayer 2001). A recent multi-proxy palaeoecological study of the lake (Bennion *et al.* unpublished) showed that the most marked changes in the biological indicators coincided with these two major events, with synchronous stratigraphic shifts in all fossil groups occurring at ~1840 and ~1940.

5.2.3 Data analysis

The squared chord distance dissimilarity coefficient (Overpeck *et al.* 1985) implemented in the statistical software R (R Development Core Team 2004), as before, was employed to determine the best analogues for the ‘reference’ assemblages of the three test lakes. The 5th percentile (score < 0.475) is used to define good analogue sites.

Three sets of data were used:

- i) the diatom data alone (a total of 280 taxa in the 30 training set samples and 3 reference samples),
- ii) the cladocera data alone (a total of 41 taxa in the 30 training set samples and 3 reference samples), and
- iii) the diatom and cladocera data combined (a total of 321 taxa in the 30 training set samples and 3 reference samples).

All data are expressed as percentage relative abundances.

5.3 Results and discussion

The diatom training set

The diatom training set is comprised of 30 samples and 266 taxa. The common taxa (>3% in at least 2 samples) are shown in Figure 5.1. The dataset has good representation of both non-planktonic and planktonic forms and includes taxa associated with oligotrophic through to eutrophic waters. The assemblages range from the *Cyclotella comensis*-*Achnanthes minutissima* communities of low alkalinity lakes, through the non-planktonic *Fragilaria* spp. dominated, medium alkalinity lakes to the more nutrient-rich flora of the high alkalinity and marl lakes comprised of non-planktonic *Fragilaria* spp. and planktonic forms such as *Stephanodiscus parvus* and *Aulacoseira ambigua*.

The cladocera training set

The cladocera training set is comprised of 30 samples and 41 taxa. The common taxa (>1% in at least 2 samples) are shown in Figure 5.2. The dataset has good representation of taxa from the full range of habitats including planktonic, semi-planktonic, benthic and plant associated species. The assemblages range from the largely planktonic dominated communities of the low alkalinity, deep lakes (e.g. *Bosmina coregoni*) through the diverse communities of the medium alkalinity waters which are comprised of numerous plant obligate and benthic species to the typically plankton and semi-plankton dominated communities of the high alkalinity and marl systems where *Bosmina longirostris* and *Chydorus sphaericus* are often abundant.

The reference assemblages in the three test lakes

The common diatom taxa (21 taxa >2%) in the reference samples of the three test lakes are shown in Figure 5.3, and all 24 cladocera taxa are shown in Figure 5.4.

The diatom assemblage of Loch Davan is dominated by non-planktonic taxa (> 90% of the whole assemblage). The most abundant species are *Achnanthes minutissima* and the small, benthic *Fragilaria* spp. The assemblages are very diverse with occurrence of a large number of taxa (58) in relatively low percentages. The planktonic component is comprised of *Cyclotella* taxa (*C. comensis*, *C. gordonensis*, *C. radiosa*) and *Tabellaria flocculosa*. The assemblage is indicative of waters with low to medium nutrient concentrations. The importance of *Achnanthes minutissima* and the benthic *Fragilaria* taxa reflects the shallow nature of loch which provides sufficient light penetration for the growth of diatoms on the surface sediments. The high percentage of taxa associated with epiphytic habitats suggests that macrophytes were present. The cladocera assemblage of Loch Davan is relatively diverse (18 taxa) being comprised of planktonic taxa, namely *Bosmina longirostris* and *Bosmina coregoni*, semi-planktonic taxa such as *Chydorus piger* and *Chydorus sphaericus*, and benthic and plant associated species (e.g. *Alonella nana* and *Acroperus harpae*, respectively). The presence of the latter indicates presence of macrophytes and is thus in agreement with the diatom data.

The diatom assemblage of Felbrigg Lake is relatively undiverse with only 19 taxa and is dominated by non-planktonic *Fragilaria* taxa (*F. construens*, *F. construens* var. *venter*, *F. construens* var. *binodis*, *F. brevistriata*, *F. pinnata*, *F. elliptica*). *Fragilaria* spp. dominated assemblages are typical of alkaline, shallow lakes of intermediate nutrient status. These species grow in situ on the surface sediments or attached to plant surfaces. The cladocera assemblage of Felbrigg Lake contains 14 taxa but it is dominated by the semi-planktonic taxon *Chydorus sphaericus* and the planktonic taxon *Bosmina longirostris*. A number of benthic and plant obligate species are present but in low relative abundances.

The diatom flora of Groby Pool is similar to that of Felbrigg Lake. It too is relatively undiverse with only 19 taxa and is dominated by small benthic *Fragilaria* spp (*F. construens* var. *venter*, *F. construens* var. *binodis*, *F. brevistriata*, *F. pinnata*). *Cyclostephanos dubius*, a small centric planktonic diatom and *Aulacoseira granulata* var. *angustissima*, another planktonic form, are also present. These latter taxa are commonly associated with alkaline, productive waters. The cladocera assemblage of Felbrigg Lake contains 19 taxa. There are three co-dominants, namely the planktonic taxon *Bosmina longirostris*, the semi-planktonic species *Chydorus sphaericus* and the benthic *Alona rectangular/guttata*. Two other benthic taxa are also present in reasonable

numbers, *Alona quadrangularis* and *Leydigia leydigii*. A number of plant associated taxa are present but at low relative abundances of <2%.

Squared chord distance dissimilarity results

Loch Davan

The squared chord distance dissimilarity scores between the Loch Davan reference sample and the training set samples are given for the diatom dataset, the cladocera dataset and the combined dataset in Table 5.2 and Figure 5.5. There are no close analogues (i.e. score <0.475) in the diatom dataset, the best matches being Black Loch (0.783), Lough Vearty (0.786), and Bayfield Loch (0.847). Like Loch Davan, these are medium alkalinity waters and contain similar species to the Loch Davan reference sample including the non-planktonic *Fragilaria* spp., *Achnanthes minutissima*, *Achnanthes pusilla*, *Cyclotella radiosa* and *Tabellaria flocculosa*. However, these samples do not contain the more oligotrophic *Cyclotella* taxa observed in Loch Davan. Work package 2 identified Black Loch as a good example of a medium alkalinity reference lake and therefore its selection as an appropriate reference site for lakes of this type impacted by eutrophication seems logical.

There are three good matches in the cladocera dataset, Little Sea Mere, Loch Grogary and Llyn Fanod. These are all medium alkalinity waters, the two former sites being shallow and the latter being deep. A macrophyte survey of Little Sea Mere carried out in September 2003 recorded almost total plant coverage with taxa characteristic of relatively nutrient poor waters, including *Chara* spp., *Nitella translucens*, *Myriophyllum alterniflorum*, *Potamogeton berchtoldii*, *Potamogeton obtusifolius*, *Potamogeton perfoliatus*, *Littorella uniflora*, *Isoetes echinospora*, *Elodea nuttallii*, and *Elatine hexandra* (unpublished Environment Agency data).

Owing to the lack of good diatom analogues, the combined dataset fails to produce any close matches. The three best analogue sites are Bayfield Loch, Llyn Fanod and Loch Grogary, all medium alkalinity waters. These lakes are currently mesotrophic with diverse plant populations covering a large proportion of the lake bed (Bennion, personal observation during sampling). Their selection as potential reference sites for medium alkalinity, shallow lakes such as Loch Davan, therefore, seems appropriate.

Felbrigg Lake

The squared chord distance dissimilarity scores between the Felbrigg Lake reference sample and the training set samples are given for the diatom dataset, the cladocera dataset and the combined dataset in Table 5.3 and Figure 5.6. There are no close analogues (i.e. score <0.475) in the diatom dataset, the best matches being Frensham Great Pond (0.606), Loch Watston (0.635), and Oxwich Pool (0.639). Like Felbrigg Lake, these are high alkalinity, shallow waters and contain similar species to the Felbrigg Lake reference sample being dominated by the non-planktonic *Fragilaria* spp. The reason for the relatively high dissimilarity scores is that these samples do not contain *Fragilaria elliptica*. There are four close matches in the cladocera dataset, Frensham Great Pond, Oxwich Pool, Loch Watston and Llyn Helyg. The former three sites are the same as those with the best diatom matches and the fourth is a medium alkalinity, shallow lake. The combined dataset produces two close matches, Frensham Great Pond and Oxwich Pool. Loch Watston is also a reasonable analogue (0.509).

Grobby Pool

The squared chord distance dissimilarity scores between the Grobby Pool reference sample and the training set samples are given for the diatom dataset, the cladocera dataset and the combined dataset in Table 5.4 and Figure 5.7. There are no close analogues (i.e. score <0.475) in the diatom dataset, the best matches being Oxwich Pool (0.607), Llyn Llygeirian (0.664) and Loch Watston (0.685). Like Grobby Pool, these are high alkalinity, shallow waters and contain similar species to the Grobby Pool reference sample being dominated by the non-planktonic *Fragilaria* spp. The reason for the high dissimilarity scores is that these samples do not contain the relatively high abundances of the planktonic taxa, *Cyclostephanos dubius* and *Aulacoseira granulata* var. *angustissima*, seen in the Grobby Pool reference sample. There are six close matches in the cladocera dataset, Frensham Great Pond, Llyn Helyg, Oxwich Pool, Loch Watston, Broomlee

Lough and Loch Ardnave. These are all shallow lakes, two being medium alkalinity, three being high alkalinity and one being a marl system. Two of these sites are the same as those with the best diatom matches. The combined dataset fails to produce any close analogues with scores <0.475 but there are three relatively good matches, Oxwich Pool (0.490), Frensham Great Pond (0.525) and Loch Watston (0.550). These three sites were also the closest matches using the combined dataset for Felbrigg Lake.

Oxwich Pool and Loch Watston currently support diverse, abundant plant populations of emergent, submerged and floating-leaved taxa (Bennion, personal observation during sampling) and work package 2 identified Loch Watston as a good example of a reference lake for the high alkalinity, shallow waterbody type. Their selection as potential reference sites for high alkalinity, shallow lakes such as Felbrigg Lake and Groby Pool, therefore, seems appropriate. Frensham Great Pond, however, appears to be exhibiting signs of enrichment. A macrophyte survey of the lake carried out in September 2003 recorded very few submerged species and a blue-green algal bloom was visible on the sampling date (unpublished Environment Agency data). The site warden has observed a decline in plant cover over the past few years. Nevertheless, a number of emergent, submerged and floating-leaved taxa were present, namely *Chara globularis*, *Potamogeton pectinatus*, *Potamogeton berchtoldii*, *Nymphaea alba*, *Glyceria maxima*, *Phragmites australis*, and *Acorus calamus*.

Multi-proxy palaeoecological studies of Groby Pool and Felbrigg Lake have been undertaken and these provide useful datasets for validating the selection of analogue sites. The lower part of the core sequences can be used to define the pre-disturbance communities of the lakes. At Groby Pool, they indicate a relatively diverse (c. 15-20 taxa), 'mesotrophic' macrophyte assemblage (e.g. Characeae, *Myriophyllum spicatum*, *Myriophyllum alterniflorum*, *Utricularia vulgaris*, and *Littorella uniflora*), dominance by benthic diatoms (*Fragilaria* spp.), and plant-associated Chydoridae and chironomids (Sayer *et al.* 1999, Bennion 2001). At Felbrigg Lake, *Chara* spp and *Myriophyllum spicatum* remains were observed in the early plant macrofossil assemblages (Sayer, unpublished). A number of these plant taxa are present in the current macrophyte floras of the selected analogue sites. For instance, Characeae, *Myriophyllum spicatum*, *Myriophyllum alterniflorum*, and *Utricularia vulgaris* were observed in Oxwich Pool in June 2003 (Bennion, personal observation during sampling), and *Chara globularis* was observed in Frensham Great Pond in September 2003 (unpublished Environment Agency data). These data suggest that the selected analogues are appropriate for Felbrigg Lake and Groby Pool. However, very few sites in our training set currently support *Littorella uniflora*, a species typically found in relatively nutrient-poor waters. Its presence in the reference samples of the Groby Pool core indicates that the lake was considerably less eutrophic than it is today. Thus whilst the analogue matching method appears to produce reasonable matches for our test lakes, there is clearly scope to improve the results by the addition of further lakes to the training set. If insufficient numbers of suitable analogue sites are present in the current lake population then the fuller palaeoecological record can be employed to identify reference conditions, as detailed in chapter 4.

5.4 Summary of findings

An analogue matching training set was developed comprising 30 lakes, 266 diatom taxa and 41 cladocera taxa. The diatom dataset has good representation of both non-planktonic and planktonic forms and includes taxa associated with oligotrophic through to eutrophic waters. The cladocera dataset has good representation of taxa from the full range of habitats including planktonic, semi-planktonic, benthic and plant associated species.

Three subsets of the training set were applied to the reference samples (~1850 AD) of three lakes to test the value of the analogue matching approach for identifying appropriate reference sites for lakes impacted by eutrophication, i) the diatom data alone, ii) the cladocera data alone, and iii) the diatom and cladocera data combined. The squared chord distance dissimilarity coefficient was employed to determine the best analogues for the 'reference' assemblages of the three test lakes. The 5th percentile (score < 0.475) is used to define good analogue sites.

For Loch Davan, a medium alkalinity, shallow lake, there were no close analogues in the diatom dataset. Black Loch was the closest match (score 0.783) but did not contain *Cyclotella comensis*. Black Loch has been identified as a good example of a medium alkalinity reference lake (see chapter 3) and therefore its selection as a reference site for Loch Davan seems appropriate. There were three good matches in the cladocera dataset, Little Sea Mere, Loch Grogary and Llyn Fanod. These are all medium alkalinity waters. The combined dataset failed to produce any close matches because of the lack of good diatom analogues. The best matches were Bayfield Loch, Llyn Fanod and Loch Grogary, all medium alkalinity waters. These lakes are currently mesotrophic with diverse plant populations covering a large proportion of the lake bed. Their selection as potential reference sites for medium alkalinity, shallow lakes such as Loch Davan seems appropriate.

For Felbrigg Lake, a high alkalinity, shallow lake, there were no close analogues in the diatom dataset, the best matches being three high alkalinity, shallow lakes, Frensham Great Pond, Loch Watston, and Oxwich Pool. The absence of *Fragilaria elliptica* in these samples resulted in the relatively high dissimilarity scores. The same three lakes were found to be the closest matches in the cladocera dataset. In the combined dataset, two of these sites were close matches, Frensham Great Pond and Oxwich Pool, and Loch Watston was also a reasonable analogue .

The selected analogue sites for Groby Pool, another high alkalinity, shallow lake, were very similar to those of Felbrigg Lake. There were no close analogues in the diatom dataset but Oxwich Pool, Llyn Llygeirian and Loch Watston were reasonable matches. The absence of planktonic taxa, *Cyclostephanos dubius* and *Aulacoseira granulata* var. *angustissima* in the training set resulted in the relatively high dissimilarity scores. There were six close matches in the cladocera dataset, Frensham Great Pond, Llyn Helyg, Oxwich Pool, Loch Watston, Broomlee Lough and Loch Ardnave. The combined dataset did not contain any close analogues but there were three relatively good matches, Oxwich Pool, Frensham Great Pond and Loch Watston. These three sites were also the closest matches using the combined dataset for Felbrigg Lake. Oxwich Pool and Loch Watston currently support diverse, abundant macrophyte populations, and Loch Watston has been identified as a good example of a reference lake for the high alkalinity, shallow waterbody type (chapter 3). Their selection as potential reference sites for Felbrigg Lake and Groby Pool, therefore, seems appropriate. Frensham Great Pond is showing signs of recent enrichment and therefore seems less suitable as a reference lake.

Validation of the choice of reference sites for Felbrigg Lake and Groby Pool using the fuller palaeoecological record contained in reference samples of sediment cores suggests that the selected analogues are appropriate for these lakes. However, there were few lakes in the current population with good matches to the Groby Pool pre-enrichment macrophyte assemblage which was comprised of relatively nutrient-poor taxa such as *Littorella uniflora* and *Utricularia vulgaris*.

In summary, the results suggest that the analogue matching technique does have the potential to be a useful tool for identifying appropriate reference sites for lakes impacted by eutrophication. The present study is limited by the small size of the training set but nevertheless close analogues were found for all sites based on the cladocera dataset and for two of the three sites based on the combined dataset. The diatom dataset produced the poorest analogues indicating that a larger training set with a greater number of reference lakes is required to maximise the possibility of finding good matches. A typical diatom assemblage contains many more taxa than a cladocera assemblage and thus it may be expected that the training set needs to be larger in order to find good analogues for diatoms. Indeed the present training set for acidified lakes is comprised of 83 lakes. We therefore recommend that the training set is expanded in future. For diatoms, the technique may be improved by reducing the dataset to common taxa only and this will be explored in future. The development of a chironomid training set, alongside the diatom and cladocera datasets, may enable further refinement of the technique. Further validation of the choice of reference sites is advised. This might involve analysis of a range of biological remains in the reference samples of the test lakes (e.g. chironomids, macrofossils) and then comparison with contemporary ecological data from the analogue sites.

Table 5.1 List of lakes in the analogue matching training set

WBID	OSNAME	Amphora site/core code	Grid ref	Map no	DOM FWS	¹ Max Depth (m) (coring location)	² Mean depth (m)	Alt (m)	Area (ha)	Sampling date	pH	Cond uS cm ⁻¹	Revised typology based on data
SCOTLAND													
27309	St Marys Loch	MARY/MARY3	NT 252229	73	2	48.5	22.2	246	288.05	24-Jun-03	7.2	68	LA, D
19381	Loch Meiklie	MEIK/MEIK1	NH 434301	26	1	6.2 (13.7)	6.7	114	79.10	20-Jun-03	7.11	95	LA, D
20197	Loch Lonachan	LONA/LONA1	NG 626189	32	4	9.7	>3	155	13.8	25-Jun-02	7.03	120	MA,D
24998	Black Loch	BLAL/ BLAL1	NT 075961	58	4	6.2	>3	288	3.9	28-Jun-02	7.52	110	MA,D
26217	Loch Lossit	LOSS/LOSS1	NR 408652	60	1	13.7	6	98	16.94	21-Jun-03	7.99	220	MA, D
26162	Loch nan Cadhan	NCAD/NCAD1	NR 404668	60	1	10.9	4	77	5.88	22-Jun-03	7.8	200	MA, D
14677	Loch Grogary	GROG/GROG1	NF 716711	18	1	2	<3	3	8.5	26-Jun-02	7.23	300	MA,Sh
20108	Loch Cill Chriosd	CCHR/ CCHR1	NG 611205	32	4	1.3	<3	24	20.8	24-Jun-02	6.96	140	MA,Sh
24742	Loch Mahaick	MAHA/ MAHA1	NN 706068	57	5	2.1	<3	204	11.8	29-Jun-02	6.5	92	MA,Sh
14593	Bayfield Loch	BAYL/BAYL1	NH 821718	21	1	1.8	1.5	127	9.18	19-Jun-03	7.8	200	MA, Sh
25899	Ardnave Loch	CZNR27/ARDN1	NR 284727	60	1	1.2	1	18	11.08	21-Jun-03	7.86	220	MA, Sh
14403	Loch Achnacloich	ACHN/ ACHN1	NH 665736	21	3	7.3	>3	117	6.6	24-Jun-02	7.7	215	HA,D
24933	Loch Watston	WATO/ WATO1	NN 711003	57	5	3.6	<3	44	6.6	29-Jun-02	8.11	210	HA,Sh
2712	Loch Watten	WATT/ WATT1	ND 229561	12	5	3.2	<3	17	372.8	21-Jun-02	8.6	255	HA,Sh
27398	Martnaham Loch	MARH/MARH1	NS 394173	70	5	6.5 (8.8)	2.9	85	40.19	23-Jun-03	8.24	330	HA, Sh
2161	Loch Borralie	BORR/ BORR1	NC 381668	9	5	17	>3	17	36.7	23-Jun-02	8.2	305	Marl,D
27494	Branxhome Easter Loch	BRAX/BRAX3	NT 434118	79	2	7	3	266	6.09	24-Jun-03	8.22	280	Marl, Sh
ENGLAND													
29000	Crummock Water	CRUM/CRUM1	NY 157188	89	2	42	>3	96	249.7	01-Jul-02	6.02	na	LA,D
29052	Buttermere	BUTM/BUTM1	NY 182157	89	3	27	>3	103	90.9	01-Jul-02	5.76	na	LA,D
46102	Little Sea Mere	LITT/LITT1	SZ 029846	195	2	1.5	<3	5	31.4	23-Sep-02	na	na	MA,Sh
44031	Frensham Great Pond	FREN/FREN1	SU 845401	186	2	2	<3	61	29.2	24-Sep-02	na	na	HA,Sh
45108	Burton Mill Pond	BURT/BURT1	SU 974175	197	5	2	<3	16	21.9	25-Sep-02	na	na	HA,Sh
32787	Melchett Mere	MELC/MELC1	SJ 750811	109	4	6.9	3	47	6.83	26-Jun-03	8.05	620	HA, Sh
29647	Hawes Water	CZSD47/HAWE1	SD 477766	97	5	12.2	>3	8	5.7	18-Sep-02	na	na	Marl,D
28172	Broomlee Lough	BROL/BROL1	NY 790697	87	4	1.9	1	257	27.94	25-Jun-03	8.25	260	Marl, Sh
WALES													
38544	Llyn Fanod	FNOD/FNOD3	SN 602643	146	2	8.3	3.8	309	5.25	28-Jun-03	7.07	100	MA, D
32961	Llyn Helyg	HELY/HELY1	SJ 112772	116	5	1.1	0.7	179	19.05	27-Jun-03	9.5	240	MA, Sh
41973	Oxwich Pool	OXWI/OXW1	SS 503872	172	5	1.1	1	4	7.77	29-Jun-03	7.27	290	HA, Sh
32435	Llyn Llygeirian	CZSH38/LLYG1	SH 346898	114	5	1	<3	45	11.1	08-Jul-02	na	na	HA,Sh
NORTHERN IRELAND													
	Lough Vearty	VEAR/VEAR1	G 994658	17		5.2	<3	110	47	30-Aug-02	na	108	MA, Sh

¹ Measured maximum depth is given in parentheses for lakes where the cores were not taken at the deepest point.

² Measured mean depths are given where known. Otherwise an estimate of whether mean depth is <3m or >3m is given.

Figure 5.1 Summary plot of the common diatom taxa in the analogue matching training set

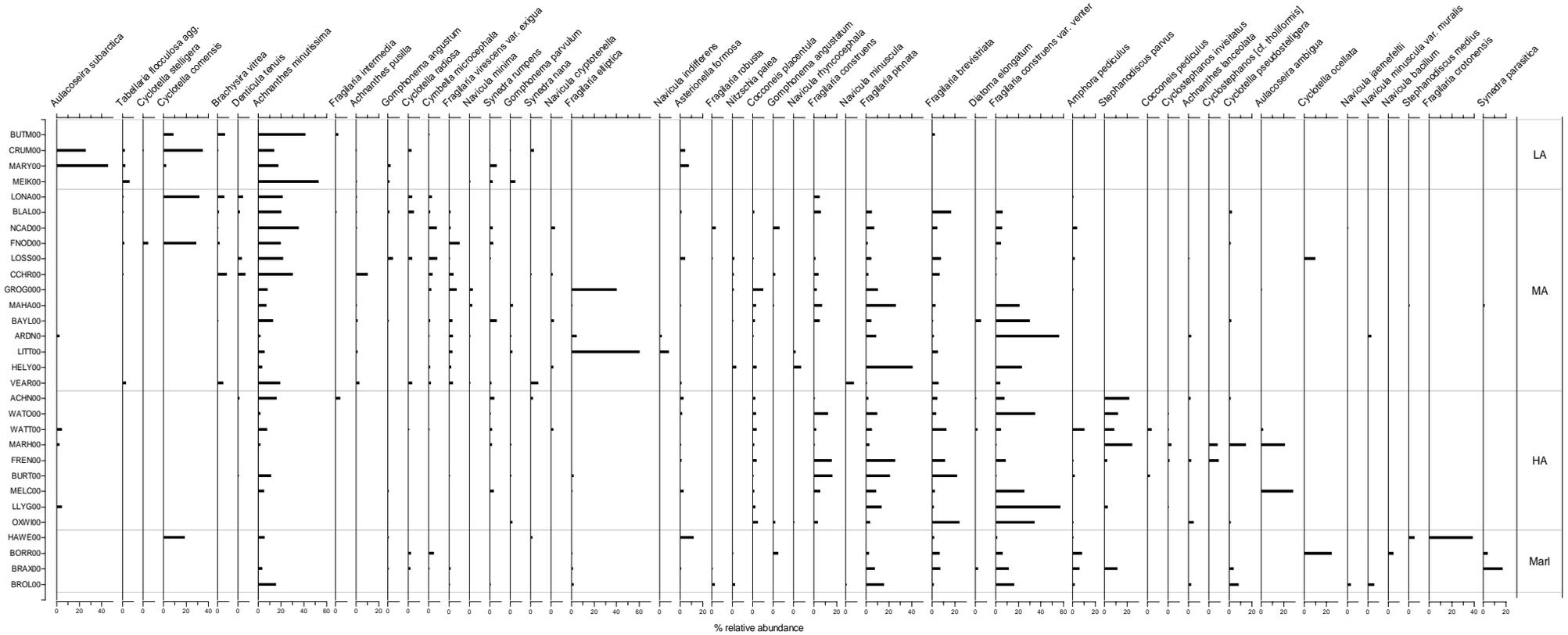


Figure 5.2 Summary plot of the common cladocera taxa in the analogue matching training set

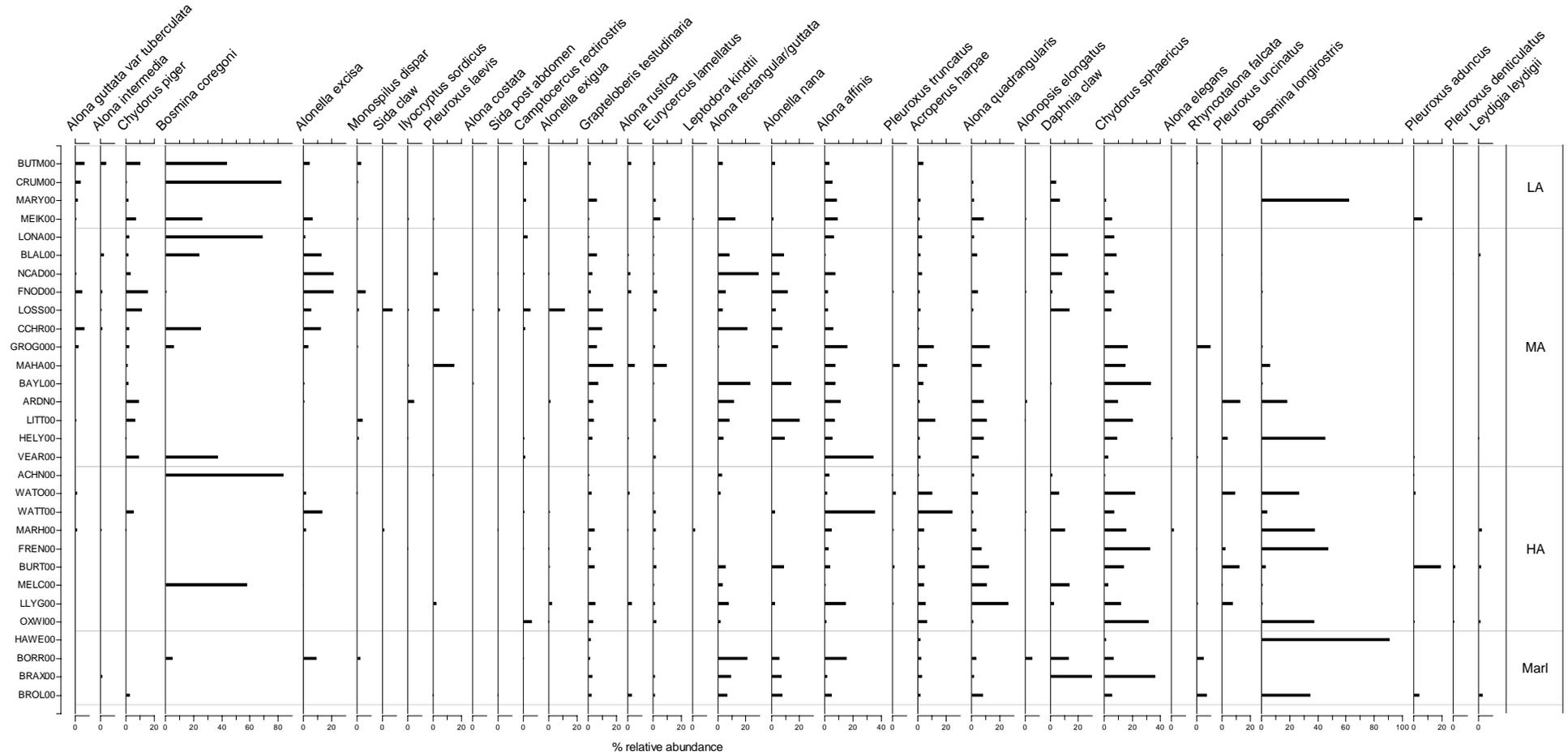


Figure 5.3 Summary plot of the common diatom taxa in the reference samples of the three test lakes

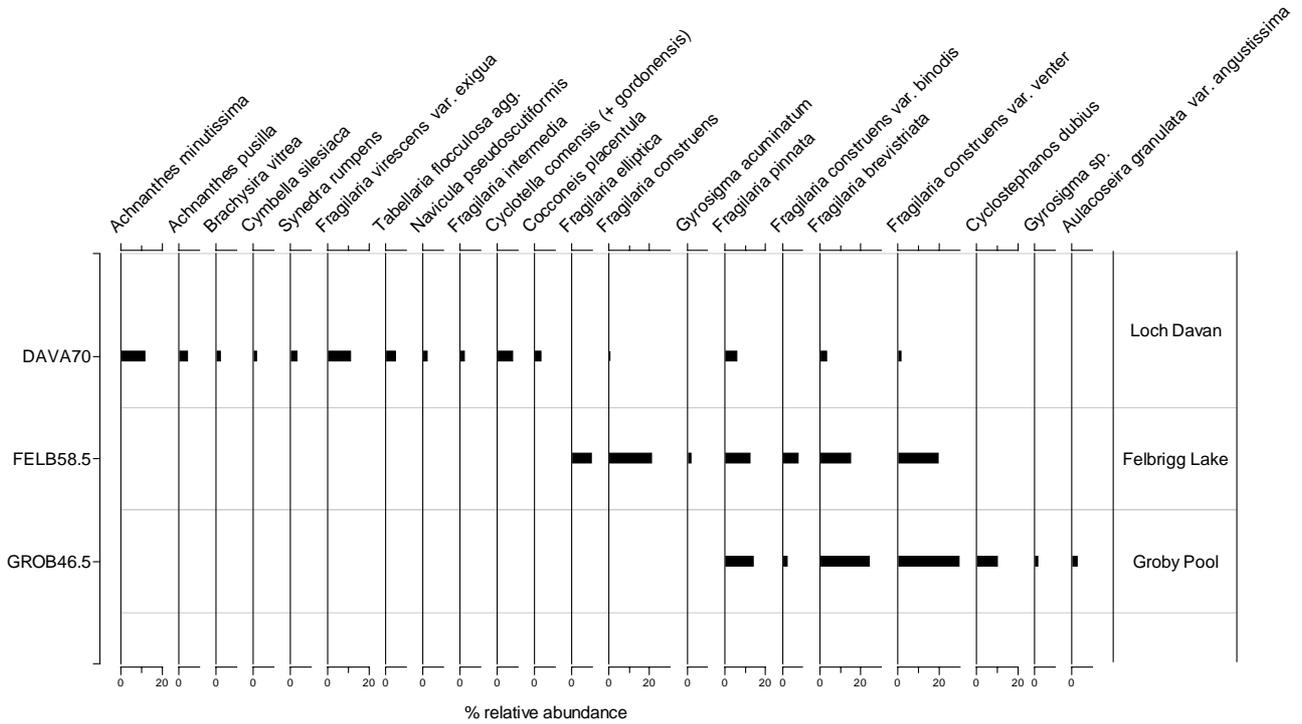


Figure 5.4 Summary plot of the cladocera taxa in the reference samples of the three test lakes (crosses indicate rare taxa, occurring at <2%)

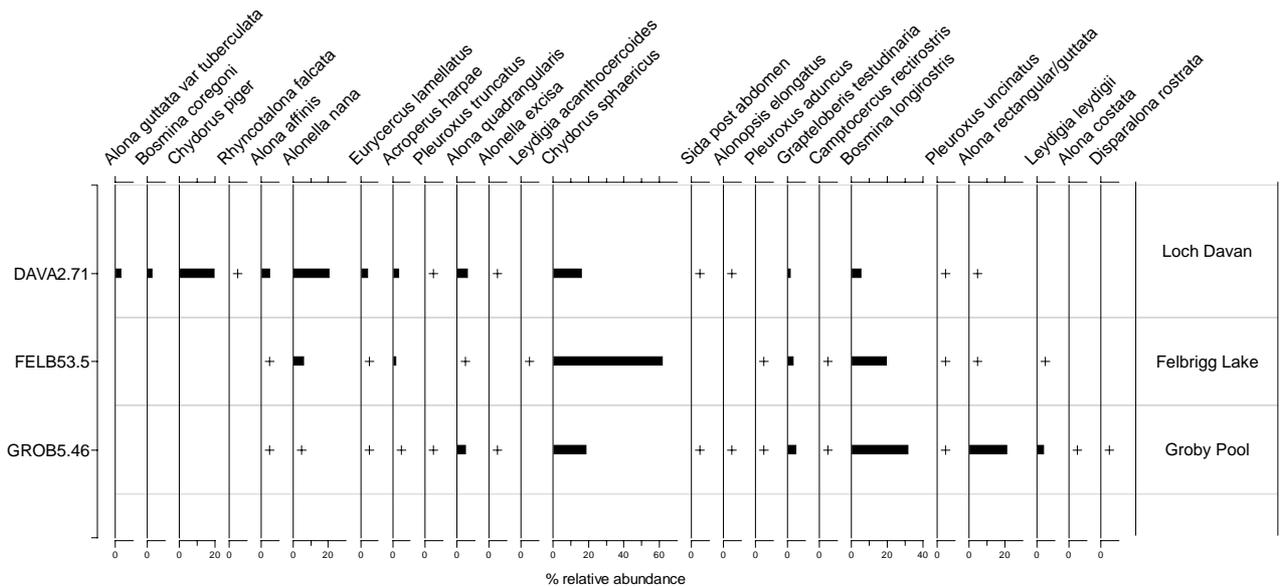


Table 5.2 Squared chord distance dissimilarity scores between the samples in the analogue matching training set and the reference sample from Loch Davan

	Diatoms only		Cladocera only		Combined
BLAL	0.783	LITT	0.296	BAYL	0.676
VEAR	0.786	GROG	0.367	FNOD	0.696
BAYL	0.847	FNOD	0.374	GROG	0.732
CCHR	0.868	BAYL	0.504	BLAL	0.748
NCAD	0.941	ARDN	0.549	VEAR	0.764
BURT	0.978	BROL	0.556	MEIK	0.798
MAHA	0.984	MEIK	0.589	BROL	0.827
MEIK	1.006	HELY	0.625	LITT	0.834
FNOD	1.019	WATT	0.627	CCHR	0.842
LOSS	1.022	WATO	0.689	BURT	0.844
ACHN	1.037	BURT	0.710	MAHA	0.859
BUTM	1.075	BLAL	0.713	HELY	0.862
GROG	1.097	LLYG	0.720	ARDN	0.873
HELY	1.098	MAHA	0.734	NCAD	0.880
BROL	1.098	VEAR	0.741	WATT	0.900
WATT	1.172	FREN	0.767	LOSS	0.922
MELC	1.180	MARH	0.798	BUTM	0.971
LONA	1.185	CCHR	0.816	WATO	0.985
ARDN	1.198	BORR	0.818	FREN	1.015
OXWI	1.215	NCAD	0.820	OXWI	1.035
FREN	1.262	LOSS	0.821	BRAX	1.060
WATO	1.280	BRAX	0.833	LONA	1.082
BRAX	1.287	OXWI	0.854	LLYG	1.085
CRUM	1.333	BUTM	0.868	BORR	1.115
MARY	1.360	MARY	0.914	MELC	1.120
LITT	1.371	LONA	0.979	MARY	1.137
BORR	1.413	MELC	1.059	MARH	1.143
LLYG	1.450	HAWA	1.242	ACHN	1.161

Table 5.3 Squared chord distance dissimilarity scores between the samples in the analogue matching training set and the reference sample from Felbrigg Lake

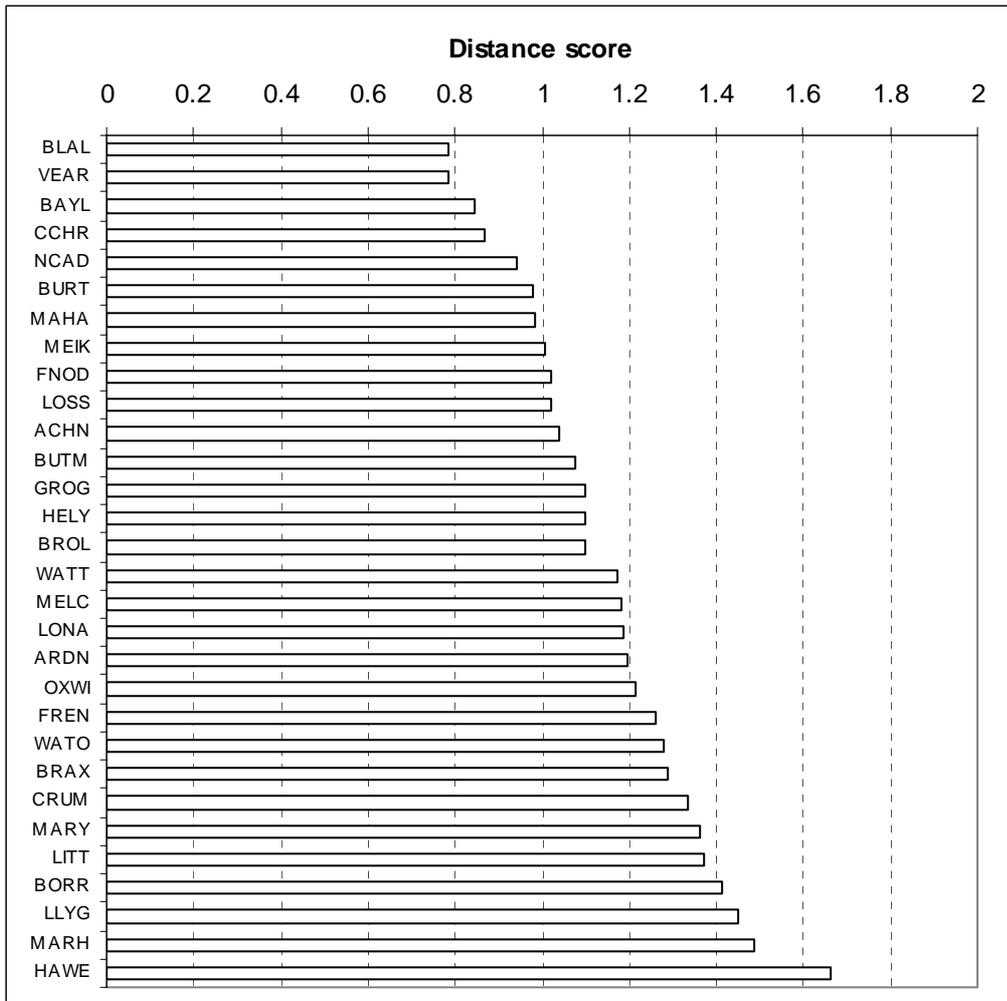
	Diatoms only			Cladocera only			Combined
FREN	0.606		FREN	0.196		FREN	0.401
WATO	0.635		OXWI	0.239		OXWI	0.439
OXWI	0.639		WATO	0.381		WATO	0.509
BURT	0.745		HELY	0.434		BURT	0.677
MAHA	0.745		BAYL	0.511		MAHA	0.753
ARDN	0.855		MARH	0.548		BAYL	0.755
MELC	0.891		BROL	0.608		HELY	0.768
LLYG	0.911		BURT	0.609		ARDN	0.777
BLAL	0.960		BRAX	0.629		BRAX	0.844
BAYL	0.998		LITT	0.681		LLYG	0.858
BRAX	1.058		ARDN	0.699		BROL	0.867
WATT	1.090		GROG	0.759		GROG	0.946
HELY	1.101		MAHA	0.761		LITT	0.994
BROL	1.124		HAWE	0.803		BLAL	1.021
GROG	1.133		LLYG	0.805		WATT	1.043
ACHN	1.262		MARY	0.834		MARH	1.086
BORR	1.266		WATT	0.996		MELC	1.128
LITT	1.306		FNOD	1.069		BORR	1.198
NCAD	1.388		BLAL	1.082		HAWE	1.244
LOSS	1.389		BORR	1.129		LOSS	1.280
CCHR	1.403		LOSS	1.171		NCAD	1.322
VEAR	1.517		MEIK	1.234		FNOD	1.374
MARH	1.624		NCAD	1.255		MARY	1.401
LONA	1.653		LONA	1.360		ACHN	1.458
FNOD	1.678		MELC	1.365		VEAR	1.463
HAWE	1.683		VEAR	1.409		CCHR	1.477
BUTM	1.770		CCHR	1.550		LONA	1.507
MEIK	1.930		ACHN	1.654		MEIK	1.582
MARY	1.968		BUTM	1.702		BUTM	1.736
CRUM	1.994		CRUM	1.932		CRUM	1.964

Table 5.4 Squared chord distance dissimilarity scores between the samples in the analogue matching training set and the reference sample from Groby Pool

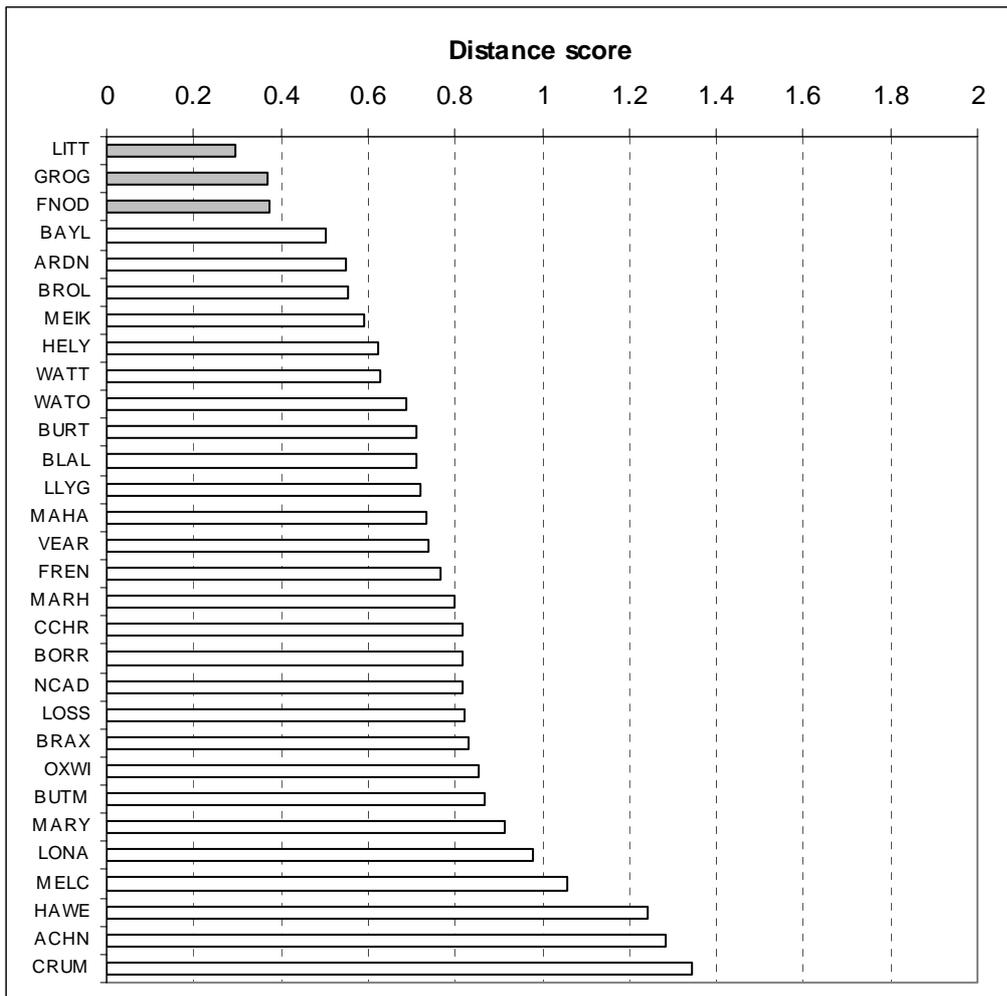
	Diatoms only			Cladocera only			Combined
OXWI	0.607		FREN	0.319		OXWI	0.490
LLYG	0.664		HELY	0.337		FREN	0.525
WATO	0.685		OXWI	0.370		WATO	0.550
FREN	0.728		WATO	0.414		ARDN	0.612
ARDN	0.774		BROL	0.427		HELY	0.624
MAHA	0.876		ARDN	0.449		LLYG	0.696
HELY	0.908		MARH	0.559		BROL	0.759
MELC	1.023		BAYL	0.625		BAYL	0.834
BRAX	1.029		BURT	0.638		BURT	0.837
BURT	1.032		HAWE	0.684		MAHA	0.875
BAYL	1.040		MARY	0.694		BRAX	0.953
BLAL	1.043		LLYG	0.726		BLAL	1.037
BROL	1.087		MAHA	0.870		MARH	1.059
WATT	1.096		BRAX	0.872		BORR	1.101
ACHN	1.162		LITT	0.882		NCAD	1.121
NCAD	1.298		BORR	0.889		WATT	1.138
BORR	1.310		NCAD	0.938		MELC	1.144
LOSS	1.395		GROG	0.955		HAWE	1.170
VEAR	1.411		FNOD	0.973		LOSS	1.254
CCHR	1.487		BLAL	1.026		GROG	1.276
MARH	1.555		MEIK	1.059		FNOD	1.307
GROG	1.592		LOSS	1.107		LITT	1.319
FNOD	1.635		WATT	1.175		MARY	1.331
HAWE	1.652		CCHR	1.183		CCHR	1.338
LITT	1.752		MELC	1.261		ACHN	1.368
BUTM	1.773		LONA	1.530		MEIK	1.464
LONA	1.828		VEAR	1.533		VEAR	1.475
MEIK	1.864		ACHN	1.569		LONA	1.682
CRUM	1.963		BUTM	1.603		BUTM	1.691
MARY	1.963		CRUM	1.909		CRUM	1.939

Figure 5.5 Histograms of the squared chord distance dissimilarity scores between samples in the analogue matching training set and the Loch Davan reference sample. Samples where the scores are below the critical value at the 5th percentile (<0.475) are shown as shaded bars.

a) Diatoms only



b) Cladocera only



c) Diatoms and Cladocera combined

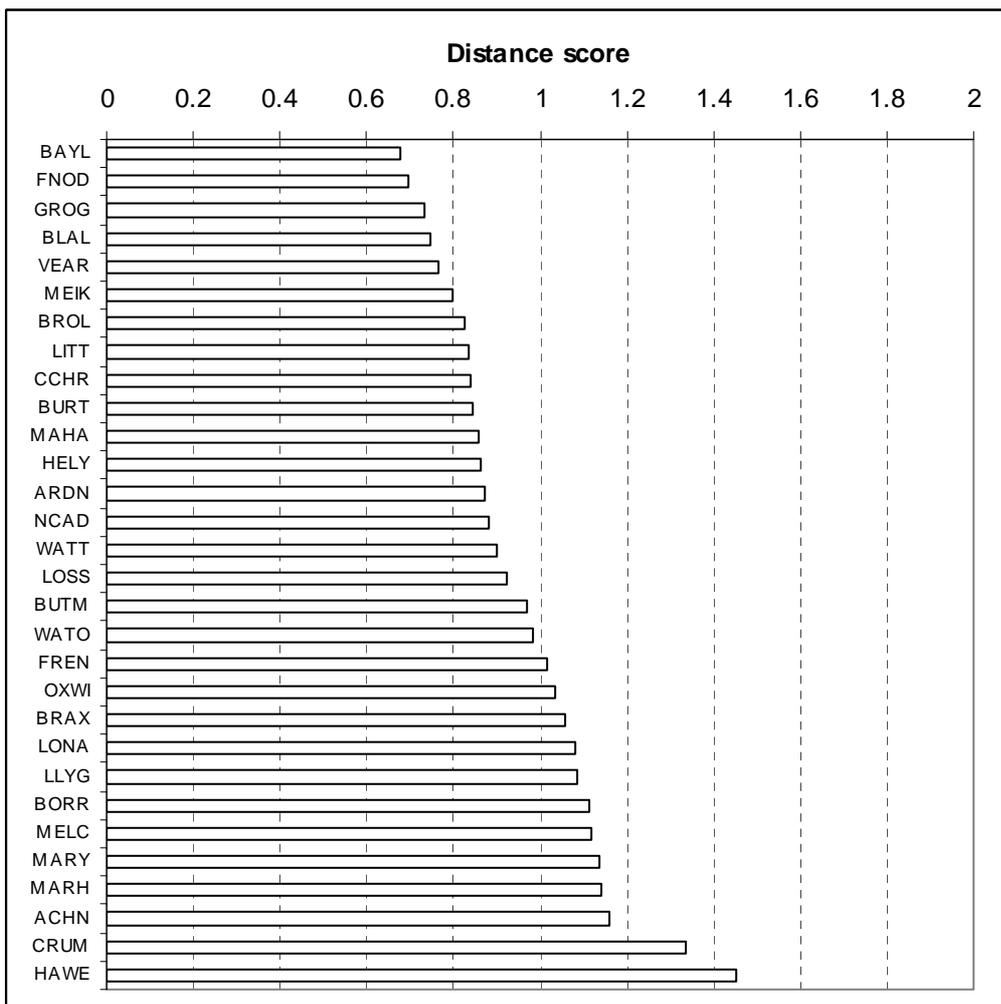
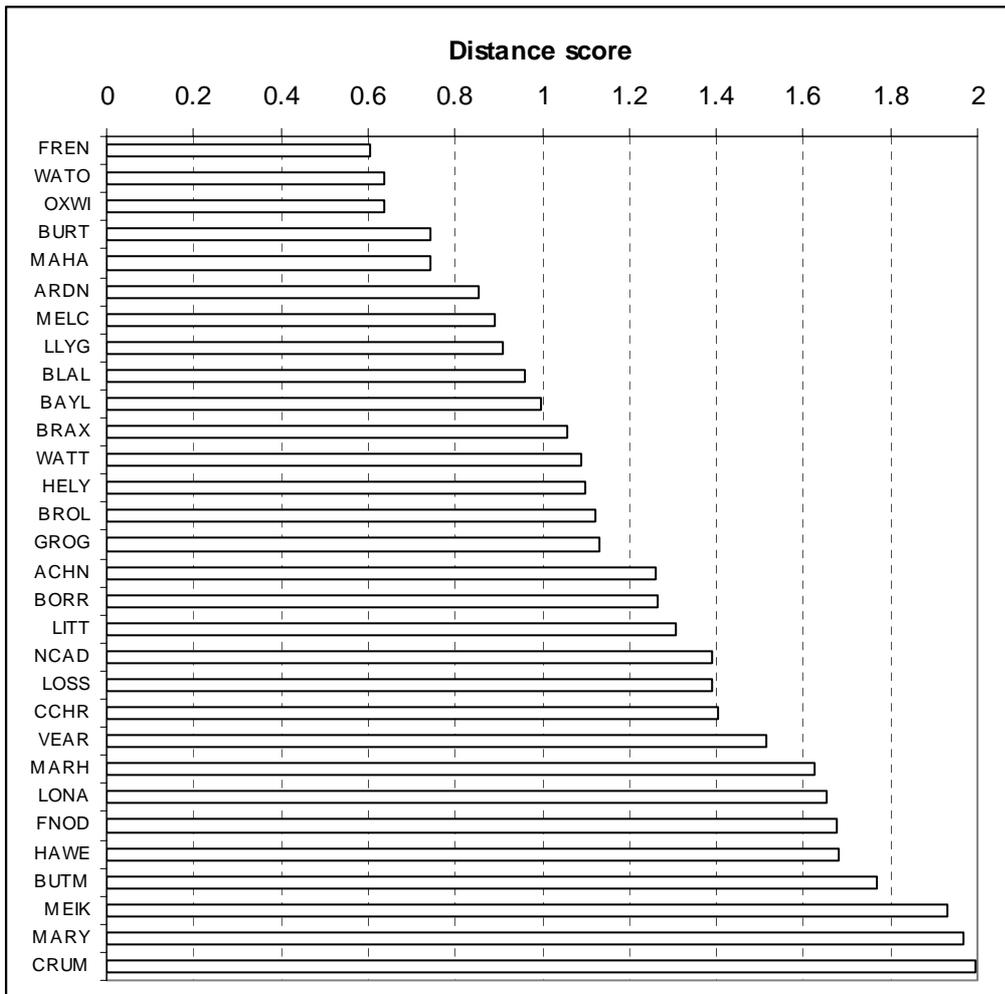
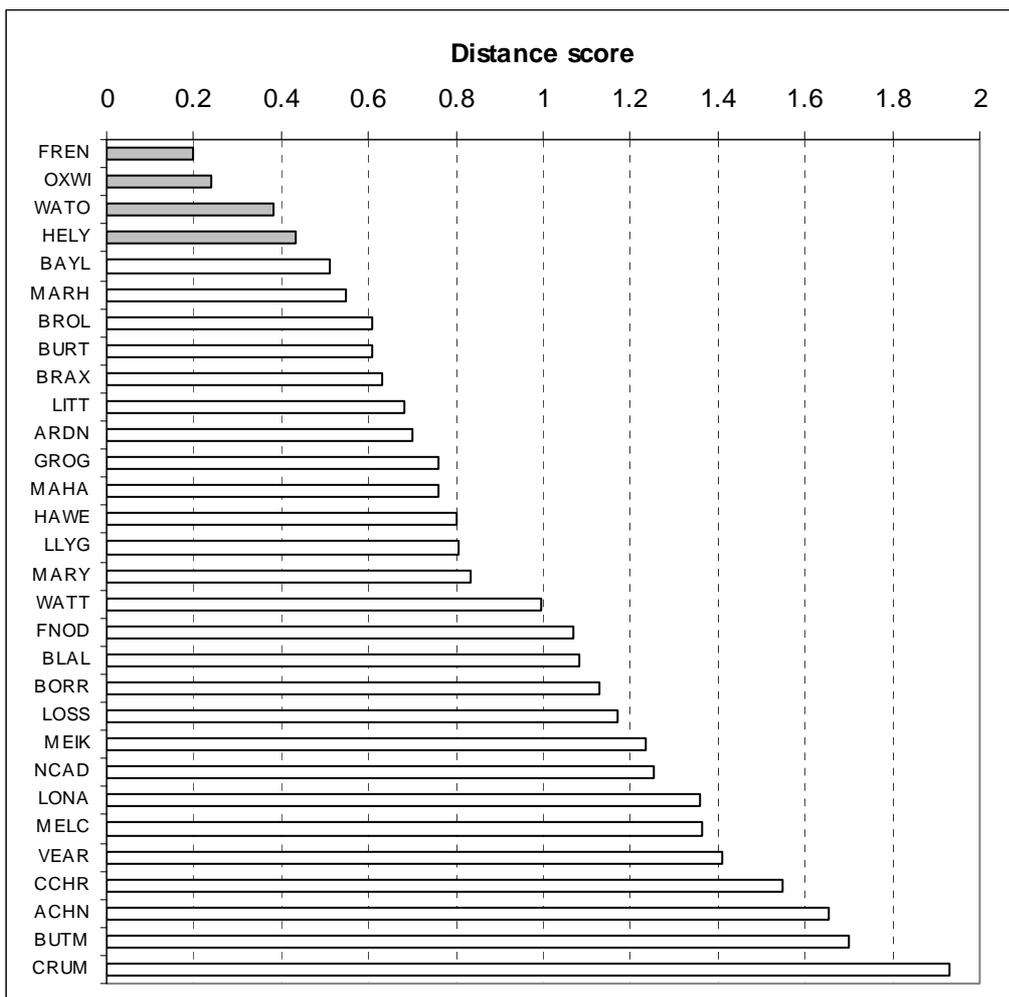


Figure 5.6 Histograms of the squared chord distance dissimilarity scores between samples in the analogue matching training set and the Felbrigg Lake reference sample. Samples where the scores are below the critical value at the 5th percentile (<0.475) are shown as shaded bars.

a) Diatoms only



b) Cladocera only



c) Diatoms and Cladocera combined

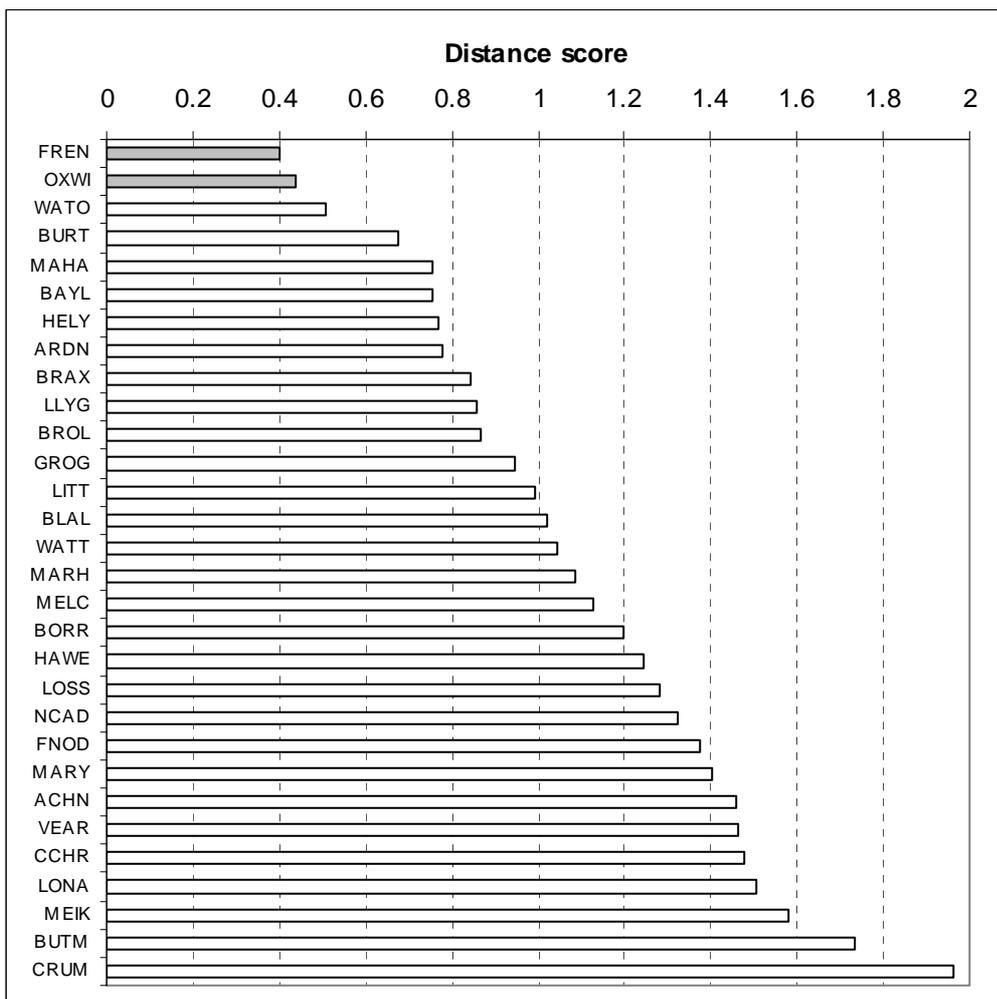
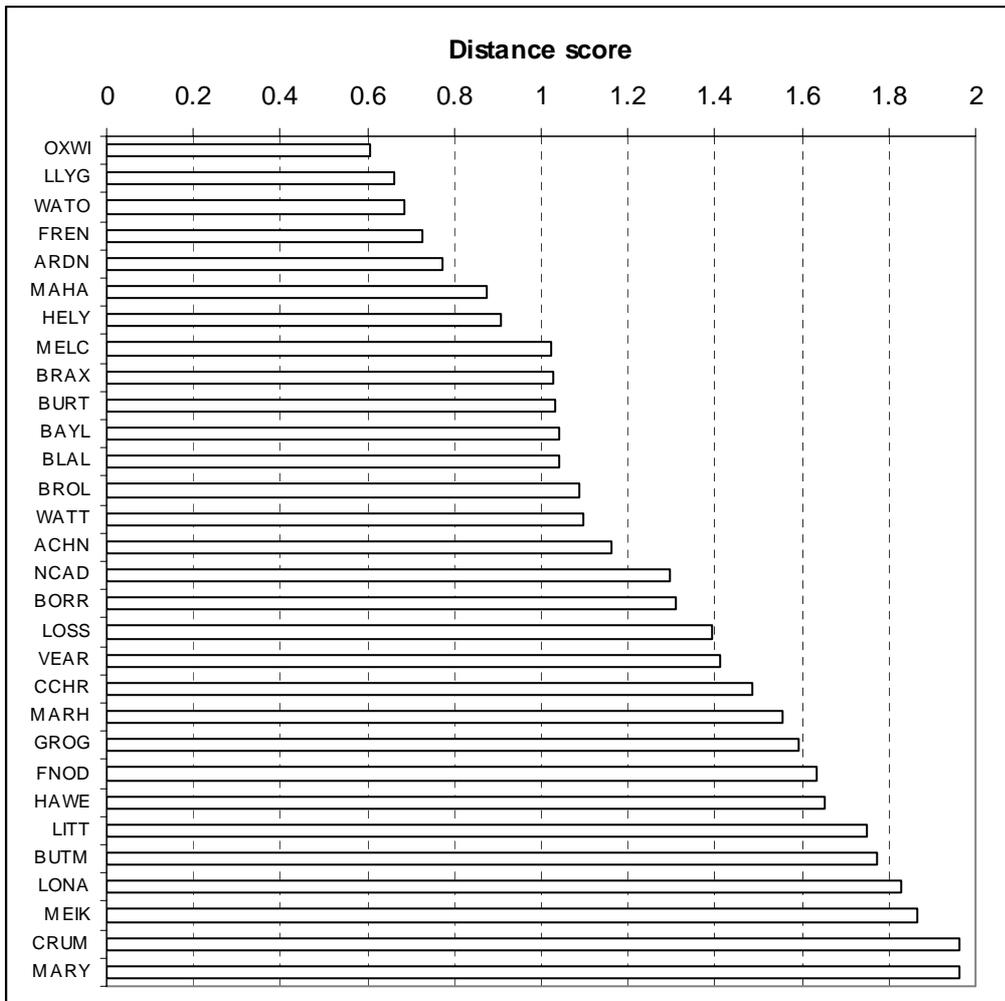
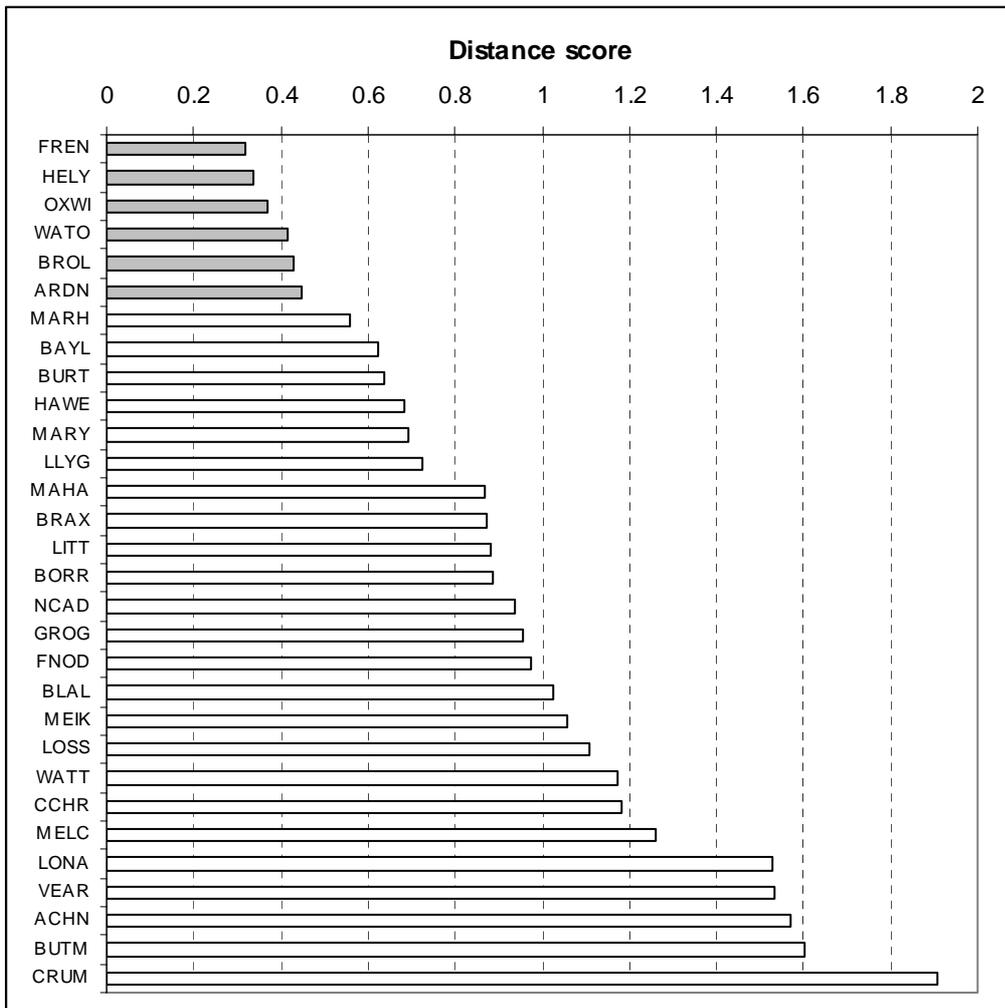


Figure 5.7 Histograms of the squared chord distance dissimilarity scores between samples in the analogue matching training set and the Groby Pool reference sample. Samples where the scores are below the critical value at the 5th percentile (<0.475) are shown as shaded bars.

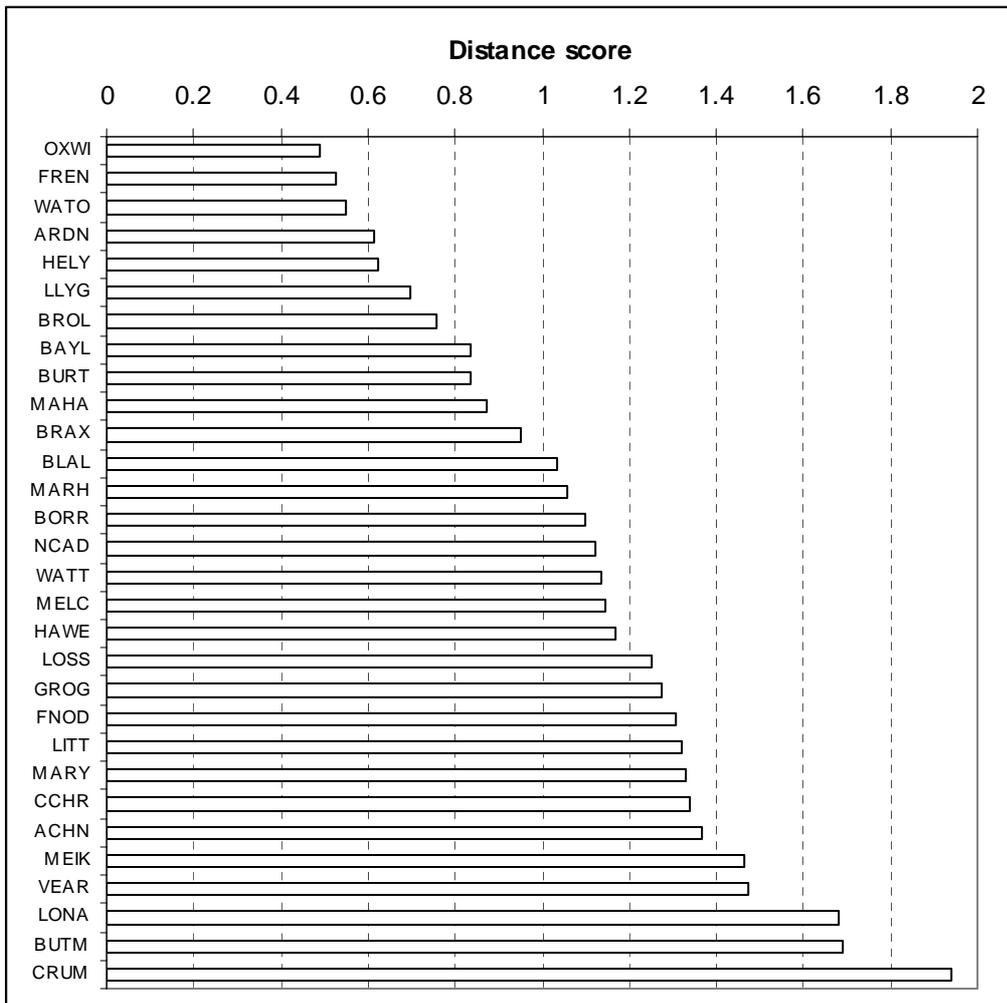
a) Diatoms only



b) Cladocera only



c) Diatoms and Cladocera combined



6. SUMMARY AND RECOMMENDATIONS

6.1 Overview of project findings

One of the primary objectives of the project was to examine the diatom record preserved in lake sediments to undertake an ecological classification of lakes from the UK, using data from a pre-impacted (reference) condition. We aimed to use this classification to check the validity of the GB Lake Typology, being produced from physical/geochemical parameters, in the absence of a full set of “present day” un-impacted reference sites. Secondly, the project aimed to utilise more detailed diatom data from sediment cores of ~30 lakes to check the validity of “present day” reference sites for the main lake types. Thirdly, the project aimed to explore the use of a wider range of biological quality elements (i.e. other than diatoms) for defining site specific reference conditions, and finally to test the application of analogue matching techniques for identifying appropriate reference sites for nutrient-stressed waterbodies.

All four of the project objectives have been achieved and a summary of the key findings follows.

Work package 1

1. The diatom classification of the reference samples from 219 UK lakes into eight groups (based on TWINSPAN) shows good agreement with the GB Lake Typology scheme, indicating that the latter has ecological relevance. Diatom reference conditions were, therefore, determined for the main lake types. However, it is advised that the GB Lake Typology scheme is further validated using other biological groups such as chironomids and cladocera.

2. Approximately 36% of lakes in the existing 219 lake dataset exhibit low floristic change (squared chord distance dissimilarity score of <0.475) and examples of reference lakes are given for the main lake types. Approximately 50% of lakes in the existing dataset exhibit considerable floristic change with squared chord distance dissimilarity scores of >0.58. In the low alkalinity lakes, these changes appear to largely reflect acidification, whereas in the medium alkalinity, high alkalinity and marl groups, the diatom changes are indicative of eutrophication.

Work package 2

1. A set of reference lakes were identified for a number of the main lake types based on analysis of diatom assemblages preserved in 31 lake sediment cores. The following sites provide good examples of reference lakes based on the low degree of floristic change observed in ~four to five samples throughout the sediment record:

Low alkalinity, deep: Buttermere and Crummock Water.

Medium alkalinity, deep: Loch Lonachan, Black Loch and Ullswater.

Medium alkalinity, shallow: Loch Cill Chrìosd and Little Sea Mere.

High alkalinity, deep: Loch Achnacloich.

High alkalinity, shallow: Burton Mill Pond, Frensham Great Pond, Llyn Llygeirian, Loch Watston and Loch Watten.

2. A further set of lakes exhibit only slight deviation from the assemblages in the bottom of the cores and could, therefore, be described as good status:

Medium alkalinity, deep: Muckle Water, Loch Skealtar, Lough Lattone and Lough Scolban.

Medium alkalinity, shallow: Loch Mahaick.

3. Both examples of low alkalinity, shallow lakes have experienced significant floristic change and, therefore, reference lakes are not identified for this type. Reference to the bigger dataset of 219 lakes is advised for selection of potential reference sites for this lake type. Analysis of the three marl lakes identified problems with using diatoms to assess floristic change in these systems owing to silica dissolution. Consequently, reference lakes are not identified for the marl lakes. Given the high abundance of non-planktonic *Fragilaria* spp. in the high alkalinity, shallow lake diatom records and the low sensitivity of these taxa to water quality shifts, we recommend that further biological groups (e.g. chironomids, cladocera, plant macrofossils) are analysed to confirm reference status for this lake type.

4. In summary, of the 31 cores analysed, thirteen could be classified as reference lakes with low floristic change, five lakes could be classified as good status with only slight shifts from the lower core assemblages, and thirteen exhibit considerable changes in the diatom assemblages and are thus considered to be at less than good status.

5. Application of diatom transfer functions to the fossil diatom assemblages in the 31 cores enabled typical ranges of 'reference' total phosphorus (TP) concentrations to be determined for the main lake types: Low alkalinity lakes $< 10 \mu\text{g l}^{-1}$, Medium alkalinity lakes $10\text{-}20 \mu\text{g l}^{-1}$, High alkalinity and Marl lakes $20\text{-}40 \mu\text{g l}^{-1}$. These values should be used as guidelines only, because TP concentrations are clearly site specific and will depend on a range of factors.

Work package 3

1. Multi-proxy analysis of fossil remains in reference samples (~1850 AD) and surface samples of two lakes, Lake of Menteith and Llangorse Lake, demonstrated the potential of the fuller palaeoecological record for defining site-specific reference conditions for a range of biological elements and for assessing ecological change. The data reflect a shift in the functioning of both lake from benthic-littoral to planktonic dominated production.

2. The data for the reference samples of the Lake of Menteith cores indicate a healthy ecosystem at ~1850 AD with diverse communities of diatoms, chironomids, cladocera and aquatic macrophytes, and assemblages typical of a relatively nutrient poor, circumneutral system. The surface samples indicate that a relatively healthy ecosystem exists today but with lower diversity in communities of diatoms, chironomids, cladocera and aquatic macrophytes, and assemblages more typical of a mesotrophic, circumneutral system. The data are in agreement with previously published fossil diatom records and recent observations in demonstrating that the lake has undergone enrichment. This appears to have had a cascading effect through the whole system. The plant macrofossil and aquatic pollen records suggest a reduction in plant abundance in the open water and a shift towards more nutrient tolerant plants. This is reflected in the cladocera community where a decline in plant associated taxa in the open water was observed. The system is now more plankton dominated with greater abundance of planktonic cladocera and diatoms, and a less diverse chironomid community.

3. The data for the reference samples of the Llangorse Lake cores indicate a healthy ecosystem in the past with diverse communities of diatoms, chironomids, cladocera and aquatic macrophytes. Numerous plant-associated cladocera taxa and attached forms of diatom suggest that macrophytes were present in the lake. The assemblages are typical of an alkaline system of intermediate trophic status. The surface samples indicate a more productive system than in the past with plankton dominated diatom and cladocera communities, chironomids associated with eutrophic waters, and the presence of nutrient-tolerant aquatic macrophytes. The assemblages are typical of a nutrient-rich, alkaline system. The data are in agreement with previous diatom based palaeoecological work and monitoring data which provide evidence of eutrophication. The multi-proxy data indicate a decline in the areal coverage of plants in the open water and a change in plant composition away from charophytes toward more nutrient-tolerant species. A general shift from a littoral, plant dominated system to a more pelagic system has occurred with the planktonic diatoms and pelagic cladocera expanding at the expense of the plant-associated and bottom-dwelling taxa. A general shift towards a more nutrient tolerant chironomid fauna was also observed. The data indicate that the lake was already relatively productive around 150 years ago but has become enriched over the last 100-150 years.

Work package 4

1. An analogue matching training set was developed comprising 30 lakes, 266 diatom taxa and 41 cladocera taxa. Three subsets of the training set were applied to the reference samples (~1850 AD) of three lakes to test the value of the analogue matching approach for identifying appropriate reference sites for lakes impacted by eutrophication, i) the diatom data alone, ii) the cladocera data alone, and iii) the diatom and cladocera data combined. The squared chord distance dissimilarity

coefficient was employed to determine the best analogues for the 'reference' assemblages of the three test lakes.

2. For Loch Davan, a medium alkalinity, shallow lake, there were no close analogues in the diatom dataset (Black Loch was the closest match), three good matches in the cladocera dataset (Little Sea Mere, Loch Grogary and Llyn Fanod), and no close matches in the combined dataset (Bayfield Loch, Llyn Fanod and Loch Grogary were the best matches). The lakes with the closest matches are all medium alkalinity waters and are currently mesotrophic with diverse plant populations covering a large proportion of the lake bed. Their selection as potential reference sites for medium alkalinity, shallow lakes such as Loch Davan therefore seems appropriate.

3. For Felbrigg Lake, a high alkalinity, shallow lake, there were no close analogues in the diatom dataset (Frensham Great Pond, Loch Watston, and Oxwich Pool were the best matches), four close matches in the cladocera dataset (Frensham Great Pond, Loch Watston, Oxwich Pool and Llyn Helyg), and two close matches in the combined dataset (Frensham Great Pond and Oxwich Pool). Loch Watston was also a reasonable analogue using the combined dataset.

4. For Groby Pool, another high alkalinity, shallow lake, there were no close analogues in the diatom dataset (Oxwich Pool, Llyn Llygeirian and Loch Watston were the best matches), six close matches in the cladocera dataset (Frensham Great Pond, Llyn Helyg, Oxwich Pool, Loch Watston, Broomlee Lough and Loch Ardnave) and no close analogues in the combined dataset, although Oxwich Pool, Frensham Great Pond and Loch Watston were relatively good matches. These three sites were also the closest matches using the combined dataset for Felbrigg Lake. Oxwich Pool and Loch Watston currently support diverse, abundant macrophyte populations, and the latter has been identified as a good example of a reference lake for the high alkalinity, shallow waterbody type. Validation of the choice of reference sites for Felbrigg Lake and Groby Pool using the fuller palaeoecological record suggests that the selected analogues are appropriate for these lakes, although there were few lakes with a present day macrophyte flora similar to that of the Groby Pool pre-enrichment macrophyte assemblage, which was comprised of relatively nutrient-poor taxa.

5. In summary, the results suggest that the analogue matching technique does have the potential to be a useful tool for identifying appropriate reference sites for lakes impacted by eutrophication, although a larger training set with a greater number of reference lakes is required to improve the diatom analogues.

6.2 Recommended protocol

On the basis of this study, the following protocol is recommended for using palaeoecological techniques to identify lake reference conditions according to the Water Framework Directive.

As a first step, existing palaeoecological datasets should be explored to classify reference samples and estimate deviation from that sample. We recommend the simple top and bottom approach whereby the bottom represents the reference condition and the top sample represents current condition. Where sediment cores have been dated, the sample representative of ~1850 AD should be selected as the reference sample, otherwise the bottom-most sample should be used. As a broad guide, a sediment accumulation rate of ~0.2 cm yr⁻¹ is typical for deeper, less productive sites, and core lengths in the range 25-35 cm are suitable. For shallow, more productive waters, average sediment accumulation rates are typically in the range 0.4-0.5 cm yr⁻¹ and therefore core lengths of ~50-70 cm are usually adequate.

Classification techniques such as TWINSpan are employed to classify the reference samples, following harmonisation of the taxonomy. The groups produced from the classification are then compared with the GB Lake Typology to assess degree of overlap and thereby determine the ecological relevance of the scheme. In the present study a national diatom dataset was used as this is the most comprehensive set of fossil data for UK lakes at present. However, the same methods could be applied to remains of other fossil groups such as chironomids and cladocera to further test the validity of the GB Lake Typology. This is recommended given the importance of

factors other than alkalinity and lake depth, such as temperature and substrate, in explaining the distribution of faunal groups.

To assess deviation from the reference sample, we recommend that the squared chord distance dissimilarity coefficient is calculated between the reference sample and the surface sample of each lake sediment core. The 5th percentile (score < 0.475) is used to define sites with low floristic change and hence to identify potential reference lakes. The squared chord distance dissimilarity score is a useful tool for assessing degree of floristic change. However, it does not provide any information on the nature or timing of the species shifts, and should therefore be used in combination with other methods for assessing reference sites.

As a second step, more detailed analysis should be carried out on candidate reference lakes. Analysis of four to five samples at roughly equidistant intervals throughout the sediment record of each lake is recommended. Ideally, a chronology should be approximated for each core using low resolution radiometric dating or the spheroidal carbonaceous particle (SCP) dating method. Analysis of five samples, taken at roughly equidistant levels from the sediment surface to the core base, is recommended.

The squared chord distance dissimilarity coefficient between the assemblages in the bottom (reference) sample and the upper samples is then calculated to assess degree of change. The 5th percentile (score < 0.475) is used to define sites with low floristic change between the bottom sample and the upper samples (as above). The ordination technique, detrended correspondence analysis (DCA), is then performed on the data from each core to assess nature and direction of floristic change.

Finally, appropriate diatom transfer functions should be applied to reconstruct pH for low alkalinity systems and total phosphorus (TP) for all lakes. This aids identification of the key pressures and allows chemical reference conditions to be assessed. Harmonisation of the fossil data and training set data is essential prior to data analysis.

A combination of the squared chord distance dissimilarity scores, the ordination results and the diatom based environmental reconstructions is then used to confirm whether lakes are at reference condition (i.e. squared chord distance dissimilarity score < 0.475 , no major species shifts, insignificant change in pH and/or TP). Where only slight deviations from the reference sample occur, the lake may be described as good status. For lakes that experience significant floristic change, the magnitude and direction of change can be determined and any change in pH or TP quantified.

In the present study, analysis was undertaken on diatom assemblages only, as diatoms are particularly sensitive to water quality change and shifts in the diatom community often correspond closely to changes in other biological groups. However, the same methods could be applied to remains of other fossil groups such as chironomids, cladocera, ostracods, plant macrofossils and pollen to assess degree of change in these biological elements and to provide further information to support selection of reference lakes. Indeed for marl systems, owing to problems of dissolution, and for high alkalinity, shallow systems owing to dominance of insensitive *Fragilaria* spp., indicators other than diatoms should be analysed (e.g. ostracods, cladocera, chironomids) to identify appropriate reference sites for these lake types.

Thirdly, multi-proxy palaeoecological techniques can be employed to provide an integrated basin-wide assessment of reference condition for lakes. This is particularly recommended for high profile sites or for sites where few reference lakes are available in the current population. The analysis of a single open water core is recommended for diatoms and chironomids. Sediment samples from deep, open water zones generally represent the entire chironomid fauna and diatom flora of the lake. They incorporate both littoral and profundal taxa and should, therefore, reflect general lake conditions.

The analysis of littoral cores is essential for plant macrofossils as the remains tend not to be transported far from the source plant. Spatial variability dictates that multiple cores are required to reconstruct a reliable site vegetation history. We advise that at least two littoral cores are taken (preferably more) and that reference samples are pooled prior to analysis to provide a spatially integrated sample, and likewise for the surface samples. In large lakes it may be necessary to collect cores from a number of bays representative of the various lake habitats. It is recommended that both plant macrofossils and pollen remains are analysed in order to provide as complete a vegetation history as possible.

The analysis of zooplankton ephippia and chitinous cladocera remains in a single open water core is sufficient although the additional analysis of ephippia in littoral cores is desirable to establish a broad picture of ecological change.

The use of low resolution radiometric dating or the spheroidal carbonaceous particle technique for providing an estimate of ~1850 AD for each core is essential when analysing data from a number of different cores. We recommend that the ~1850 AD sample is taken to represent the 'reference sample'. The present study involved the analysis of a single sample from each core in order to define the reference condition. However, we advise that two or three additional samples in the same section of the core are analysed to improve the reliability of the data and, for plant macrofossils, that a number of contemporaneous samples are aggregated to provide spatially integrated data.

Fourthly, the analogue matching technique can be employed to identify appropriate reference sites for impacted lakes. This is recommended when designing restoration strategies for lakes as the data are valuable for target setting. Datasets already exist for defining reference sites for acidified systems based on diatom and cladocera assemblages (Simpson, 2003). A similar 30 lake diatom and cladocera training set was developed in the current project for demonstrating the application of the technique to nutrient stressed systems. However, this requires expansion and inclusion of more reference lakes in order to improve the diatom analogues. The method involves analysis of diatoms and cladocera assemblages in the surface samples from a set of lakes thought to be relatively unimpacted and covering a broad environmental gradient (e.g. a range of alkalinity, pH, TP and depth values). The diatom and cladocera assemblages in the samples representative of ~1850 AD are then analysed and the squared chord distance dissimilarity measure is employed (as above) to determine the best analogues for the 'reference' assemblages. Indeed any number of samples at intervals through the sediment sequence can be analysed in this way to define the best analogues for various points in time (e.g. 1850, 1900, 1950, 1970). During method development, the choice of reference sites can be validated by comparing biological remains in the reference samples of the impacted lakes with contemporary ecological data from the analogue sites. For example, does the macrophyte flora at reference condition in the impacted lake (as inferred by plant macrofossils and pollen remains) concord with the present day macrophyte community in the selected analogue lakes? The development of a chironomid training set, alongside the diatom and cladocera datasets, may enable further refinement of the technique.

In conclusion, simple techniques such as ordination, clustering and dissimilarity measures applied to palaeoecological data, combined with transfer functions, offer powerful techniques for characterising and validating lake types, identifying reference lakes, defining ecological and chemical reference conditions, and assessing deviation from the reference state. The resolution of any study will depend on the questions being asked of the data and ultimately the resources available. However, the current project illustrates that palaeolimnological studies need not always be highly detailed and thus expensive, and that valuable information can be produced from relatively low resolution studies at large numbers of lakes to aid implementation of the WFD at the national level.

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Appendix 1

List of all sites included in the project with the waterbody ID (WBID) and GB Lake Typology (N=224)

WBID	Site name	Grid reference	GB_Typology ¹	Depth of reference sample (cm)	Dating method ²
35738	Martham South Broad	TG 458201	B, Sh	100	R
14403	Loch Achnacloich	NH 665736	HA, D	40	None
24843	Loch Leven	NO 150025	HA, D	89	R
24851	Loch Rusky	NN 615034	HA, D	56	None
26178	Loch Ballygrant	NR 405662	HA, D	na	na
27867	Mill Loch	NY 077833	HA, D	80	R
32761	Llyn yr Wyth Eidion	SH 474819	HA, D	5	None
32804	Tatton Mere	SJ 755801	HA, D	25	None
35211	Cröse Mere	SJ 430305	HA, D	60	R
36566	Betton Pool	SJ 511079	HA, D	88	R
	Lough Augher	H 560535	HA, D	34	Correlation
	Lough Ballywillin	J 481532	HA, D	44	R
	Lough Creeve	H 738512	HA, D	48	R
	Macnean Upper Lough	H 040400	HA, D	22	R
1678	Loch of Swannay	HY 304293	HA, Sh	15	None
1753	Loch of Harray	HY 295155	HA, Sh	74	None
2712	Loch Watten	ND 229561	HA, Sh	15	None
4444	Loch Hempriggs	ND 343471	HA, Sh	80	None
14019	Loch Eye	NH 830795	HA, Sh	99	R
16456	Loch Ussie	NH 505574	HA, Sh	90	R
24933	Loch Watston	NN 711003	HA, Sh	50	None
26392	Castle Semple Loch	NS 365590	HA, Sh	80	R
27398	Martnaham Loch	NS 394173	HA, Sh	25	None
27899	Castle Loch	NY 090815	HA, Sh	80	R
28336	Carlingwark Loch	NX 765615	HA, Sh	89	R
30244	Hornsea Mere	TA 190470	HA, Sh	40	Correlation
32435	Llyn Llygeirian	SH 346898	HA, Sh	20	None
32787	Melchett Mere	SJ 750811	HA, Sh	15	None
34780	Hanmer Mere	SJ 454395	HA, Sh	26	None
34827	Felbrigg Lake	TG 191388	HA, Sh	82	R
35655	Barton Broad	TG 363215	HA, Sh	60	R
35724	Aqualate Mere	SJ 772204	HA, Sh	na	na
35953	Wroxham Broad	TG 308165	HA, Sh	100	R
35981	Rollesby Broad	TG 464142	HA, Sh	77	R
36202	Upton Broad	TG 388134	HA, Sh	50	R
36710	Llyn Hir	SN 789675	HA, Sh (LA, Sh)	16	R
39683	Eleven Acre Lake	SP 675369	HA, Sh	50	R
40067	Llangorse Lake	SO 132265	HA, Sh	123	R
40608	Marsworth Reservoir	SP 922137	HA, Sh	140	R
41973	Oxwich Pool	SS 503872	HA, Sh	20	None
44031	Frensham Great Pond	SU 845401	HA, Sh	30	None
45108	Burton Mill Pond	SU 974175	HA, Sh	70	None
45652	Hatchet Pond	SU 367016	HA, Sh	86	R
46472	Slapton Ley	SX 824435	HA, Sh	55	R

	Tongree (Upper Lough Erne)	H 310310	HA, Sh	86	R
2077	Long Loch	ND 204759	LA, D	40	R
2648	Loch na Larach	NC 217583	LA, D	24	R
5073	Loch a Cham Alltain	NC 283446	LA, D	16	None
6759	Loch Coire na Saidhe Duibhe	NC 450360	LA, D	19	None
8266	Loch Bealach Cornaidh	NC 208282	LA, D	24	None
9299	Loch nan Cuaran	NC 292238	LA, D	22	None
10905	Lochan Nigheadh	NC 182148	LA, D	15	None
11315	Loch na Creige Duibhe	NC 005118	LA, D	31	None
11424	Lochan Fhionnlaidh	NC 191103	LA, D	16	None
11862	Lochanan Dubha	NC 147055	LA, D	28	None
11999	Loch na Cric	NC 166037	LA, D	20	None
12733	Loch na Béiste	NG 885943	LA, D	22	None
12848	Loch nam Badan Boga	NH 099930	LA, D	24	None
12918	Loch na h'Airbhe	NH 103924	LA, D	16	None
13791	Loch Toll an Lochain	NH 832074	LA, D	20	None
13800	Loch Muighbhlaraidh	NH 635830	LA, D	10	None
14057	Loch Maree	NG 985675	LA, D	35	R
14413	Loch a' Mhadaidh	NH 199732	LA, D	22	None
16906	Loch Sgamhain	NH 100530	LA, D	12	None
17147	Loch nan Eion	NG 925508	LA, D	35	None
17334	Loch Coire Fionnaraich	NG 945498	LA, D	15.9	R, SCP
18209	Loch Coire nan Arr	NG 808422	LA, D	11	R
18690	Loch Teanga	NF 818383	LA, D	30	R
19381	Loch Meiklie	NH 434301	LA, D	30	None
20328	Loch Kemp	NH 612323	LA, D	32	R
20633	Loch Tarff	NH 425100	LA, D	19	None
21160	Loch Coire an Lochan	NH 943004	LA, D	4.5	R
21191	Loch Einich	NN 913990	LA, D	30	R
21265	Lochan Uaine	NO 001981	LA, D	16	R
21723	Lochnagar	NO 252859	LA, D	16	R
21755	Loch nan Eun	NO 230854	LA, D	10	R
21790	Loch Muick	NO 290830	LA, D	37	R
21843	Dubh Loch	NO 238828	LA, D	34	R
22308	Loch Doilet	NM 808678	LA, D	36	R
22782	Loch Rannoch	NN 610580	LA, D	3	R
22839	Loch Laidon	NN 380542	LA, D	26	R
22963	Loch Uisge	NM 808550	LA, D	20	R
24020	Lochan Lairig Cheile	NN 558278	LA, D	14	None
24447	Loch Lomond North Basin	NS 365945	LA, D	27	R
24447	Loch Lomond South Basin	NS 365945	LA, D	20	R
24459	Loch Lubnaig	NN 585130	LA, D	32	R
24745	Loch Tinker	NN 445068	LA, D	18	R
24754	Loch Chon	NN 421051	LA, D	14	R
27309	St Marys Loch	NT 252229	LA, D	30	None
27604	Loch Doon	NX 495985	LA, D	50	R
27824	Round Loch of the Dungeon	NX 466846	LA, D	15	R
27872	Loch Neldricken	NX 445829	LA, D	13	R
27900	Loch Valley	NX 445817	LA, D	9	R
27912	Loch Narroch	NX 453816	LA, D	16	R
27927	Round Loch of Glenhead	NX 450804	LA, D	21	R
27948	Loch Dee	NX 470790	LA, D	30	R

28130	Loch Grannoch	NX 541691	LA, D	34	R
28206	Loch Skerrow	NX 605682	LA, D	44	R
28986	Loweswater	NY 126217	LA, D	35	R
29000	Crummock Water	NY 157188	LA, D	36	None
29052	Buttermere	NY 182157	LA, D	24	None
29062	Ennerdale Water	NY 110150	LA, D	16	R
29183	Wast Water	NY 165060	LA, D	15	R
31426	Tunnel End Reservoir	SE 037121	LA, D	32	R
33474	Oak Mere	SJ 575678	LA, D	30	None
33836	Llyn Idwal	SH 645596	LA, D	24	SCP
33843	Llyn Clyd	SH 635587	LA, D	24	R
33962	Llyn Alwen	SH 898567	LA, D	25	None
33998	Llyn Glas	SH 601547	LA, D	12	R
34002	Llyn Cwellyn	SH 560549	LA, D	24	SCP
34039	Llyn Mymbyr	SH 708574	LA, D	25	None
34319	Llyn Llaji	SH 649483	LA, D	22	R
34400	Llyn Conwy	SH 780463	LA, D	40	R
34987	Lake Bala or Llyn Tegid	SH 905347	LA, D	36	R, SCP
35035	Llyn Eiddew Bach	SH 646345	LA, D	8	R
35650	Llyn Irdlyn	SH 630220	LA, D	40	R
36182	Llyn y Gadair	SH 707135	LA, D	29	None
36267	Llyn Cau	SH 715124	LA, D	25	None
37834	Llynoedd Ieuan	SN 794812	LA, D	26	SCP
38544	Llyn Fanod	SH 603643	LA, D	40	SCP
40297	Llyn y Fan Fawr	SN 831217	LA, D	25	None
	Blue Lough	J 328252	LA, D	15	R
	Lough Muck	B 958083	LA, D	23	R
	Loughaunayella	M 101310	LA, D	40	R
	Lough Maam	B 927159	LA, D	20	R
	Lough Maumwee	L 977485	LA, D	34	R
	Lough Veagh	C 018212	LA, D	72	R
4435	Un-Named	NC 168478	LA, Sh	40	None
7166	Loch Cùl Fraioch	NC 025330	LA, Sh	16	None
7669	Loch na Gaineimh	NC 765304	LA, Sh	18	None
7824	Loch nan Eun	NC 232298	LA, Sh	22	None
7921	Loch Coire a' Bhaic	NC 247295	LA, Sh	12	None
8975	Loch Bealach na h-Uidhe	NC 264256	LA, Sh	24	None
9070	Lochan Feòir	NC 229252	LA, Sh	15	None
9145	Lochan Fleodach Coire	NC 275248	LA, Sh	24	None
10714	Loch na Gruagaich	NC 243158	LA, Sh	20	None
11238	Loch na Beiste	NC 004125	LA, Sh	29	None
12469	Loch Dubh Camas an Lochain	NG 871972	LA, Sh	25	None
16452	Loch Bharranch	NG 977575	LA, Sh	8	None
17629	Loch Dallas	NJ 092475	LA, Sh	24	None
19091	Loch Mhic Leoid	NJ 008347	LA, Sh	24	None
20928	Loch Coire nan Chàmh	NG 974038	LA, Sh	5	None
21557	Unnamed H	NO 653909	LA, Sh	14	None
22223	Lochan Dubh	NM 895710	LA, Sh	20	R
33861	Llyn y Foel-frech	SH 919593	LA, Sh	32	None
33862	Llyn Bochlwyd	SH 654593	LA, Sh	30	None
35233	Gloyw Llyn	SH 647298	LA, Sh	25	None
35439	Llyn y Bi	SH 670265	LA, Sh	10	R

35550	Llyn Dulyn	SH 662244	LA, Sh	16	R
35578	Llyn Cwm Mynach	SH 678238	LA, Sh	14	R
37080	Llyn Glanmerin	SN 755991	LA, Sh	25	None
38422	Llyn Eiddwen	SN 606670	LA, Sh	40	SCP
38525	Llyn Gynon	SN 800647	LA, Sh	32	R
40571	Llyn Llech Owain	SN 569151	LA, Sh	25	None
44464	Cranmer Pond	SU 794324	LA, Sh	35	R
44482	Woolmer Pond	SU 788321	LA, Sh	12	R
1674	Muckle Water	HY 395300	MA, D	23	None
8293	Loch Bealach a' Bhùirich	NC 264256	MA, D	23	None
14935	Loch Skealtar (Sgealtair)	NF 897686	MA, D	37	None
18767	Loch Ness	NH 535295	MA, D	48	R
19494	Loch Iain Oig	NG 792292	MA, D	16	None
20197	Loch Lonachan	NG 626189	MA, D	30	None
20922	Loch Bad an Losguinn	NH 158038	MA, D (LA, D)	24	None
21925	Loch Shiel	NM 866771	MA, D	32	R
23531	Loch of Butterstone	NO 058449	MA, D	30	R
23553	Marlee Loch	NO 145443	MA, D	84	None
23557	Loch of Craiglush	NO 042444	MA, D	84	None
23559	Loch of Lowes	NO 049439	MA, D	35	R
23561	Loch of Clunie	NO 115442	MA, D	84	None
24025	Loch Awe North Basin	NM 930065	MA, D	43	R
24025	Loch Awe South Basin	NM 930065	MA, D	35	R
24132	Loch Earn	NN 640235	MA, D	30	R
24919	Lake of Menteith	NN 580005	MA, D	40	R
24996	Loch Eck	NS 141939	MA, D	70	R
24998	Black Loch	NT 075961	MA, D	68	None
25000	Loch Glow	NT 087957	MA, D	36	None
26162	Loch nan Cadhan	NR 404668	MA, D	25	None
26217	Loch Lossit	NR 408652	MA, D	25	None
27808	Loch Enoch	NX 446853	MA, D (LA, D)	32	R
28847	Bassenthwaite Lake	NY 214296	MA, D	40	R
28955	Ullswater	NY 425204	MA, D	20	None
29328	Esthwaite Water	SD 358969	MA, D	50	R
36544	Bomere Pool	SJ 498080	MA, D	60	None
	Lough Allen	54o 05' N, 8o 05'W	MA, D	38	R
	Lough Brantry	H 749539	MA, D	34	R
	Lough Corbet	J 181449	MA, D	74	R
	Friary Lough	H 748558	MA, D	40	R
	Lough Heron	J 410502	MA, D	49	R
	Lough Oughter	54o 01' N, 8o 25'W	MA, D	84	R
	Lough Patrick	H 884193	MA, D	22	R
	Lattone Lough	H 001455	MA, D	40	None
	Lough Scolban	G 995605	MA, D	50	None
14593	Bayfield Loch	NH 821718	MA, Sh	30	None
14677	Loch Grogary (Croghearraidh)	NF 716711	MA, Sh	116	None
20108	Loch Cill Chrìosd	NG 611205	MA, Sh	80	None
20757	Loch of Skene	NJ 785075	MA, Sh	30	R
21123	Loch Davan	NJ 442007	MA, Sh	60	R
21189	Loch Kinord	NO 442995	MA, Sh	40	R
24742	Loch Mahaick	NN 706068	MA, Sh	30	None
25899	Ardnave Loch	NR 284727	MA, Sh	na	na

26566	Kilbirnie Loch	NS 330545	MA, Sh	80	R
32961	Llyn Helyg	SJ 112772	MA, Sh	25	None
34622	Llyn Glasfryn	SH 402422	MA, Sh	23	None
39796	Talley Upper	SN 633332	MA, Sh	25	None
39813	Talley Lower	SN 632337	MA, Sh	25	None
46102	Little Sea Mere	SZ 029846	MA, Sh	10	None
	Lough Vearly	G 994658	MA, Sh	60	None
2161	Loch Borralie	NC 381668	Marl, D	60	None
29479	Semer Water	SD 918874	Marl, D	10	None
29647	Hawes Water	SD 477766	Marl, D	10	None
32792	Llyn Cadarn	SH 492811	Marl, D	na	na
2176	Loch Caladail	NC 396666	Marl, Sh	10	None
27494	Branxhome Easter Loch	NT 434118	Marl, Sh	30	None
28165	Greenlee Lough	NY 774698	Marl, Sh	70	None
28172	Broomlee Lough	NY 790697	Marl, Sh	20	None
29844	Malham Tarn	SD 895667	Marl, Sh	60	R
41602	Bosherston Lake, Central	SR 976946	Marl, Sh	25	R
41602	Bosherston Lake, Lower	SR 978952	Marl, Sh	50	None
41602	Bosherston Lake, Upper	SR 978960	Marl, Sh	30	None
38907	Llyn Berwyn	SN 743568	P, D	120	R
10307	Loch Dubh Cadhafuaraich	NC 682183	P, Sh	16	None
29250	Birkdale Tarn	NY 851018	P, Sh	na	na
35046	Clarepool Moss	SJ 435343	P, Sh	30	None
41210	Llyn Fach	SN 905370	P, Sh	25	None

KEY

	Surface sediment data only (poor preservation)
	No data (poor preservation)
1	Misclassified by GB Lake Typology. Reallocated type given in parentheses
2 R	Radiometric dating methods
2 SCP	Spheroidal carbonaceous particle method
2 None	No dating
2 Correlation	Correlated with previously dated core

Appendix 2

List of the common diatom taxa in the samples analysed in the project with diatcode, full name and authority

Code	Name
AC001A	<i>Achnanthes lanceolata</i> (Breb. ex Kutz.) Grun. in Cleve & Grun. 1880
AC002A	<i>Achnanthes linearis</i> (W. Sm.) Grun. in Cleve & Grun. 1880
AC004A	<i>Achnanthes pseudoswazi</i> J.R. Carter 1963
AC005A	<i>Achnanthes calcar</i> Cleve 1891
AC006A	<i>Achnanthes clevei clevei</i> Grun. in Cleve & Grun. 1880
AC007A	<i>Achnanthes oestrupii</i> (A. Cleve-Euler) Hust. 1930
AC008A	<i>Achnanthes exigua</i> Grun. in Cleve & Grun. 1880
AC013A	<i>Achnanthes minutissima minutissima</i> Kutz. 1833
AC014A	<i>Achnanthes austriaca austriaca</i> Hust. 1922
AC014C	<i>Achnanthes austriaca helvetica</i> Husted 1933
AC016A	<i>Achnanthes delicatula</i> Kutz.
AC018A	<i>Achnanthes laterostrata</i> Hust. 1933
AC019A	<i>Achnanthes nodosa</i> A. Cleve-Euler 1900
AC022A	<i>Achnanthes marginulata</i> Grun. in Cleve & Grun. 1880
AC023A	<i>Achnanthes conspicua conspicua</i> A. Mayer 1919
AC025A	<i>Achnanthes flexella</i> (Kutz.) Brun 1880
AC028A	<i>Achnanthes saxonica</i> Krasske in Hust. 1933
AC034A	<i>Achnanthes suchlandtii</i> Hust. 1933
AC035A	<i>Achnanthes pusilla pusilla</i> Grun. in Cleve & Grun. 1880
AC039A	<i>Achnanthes didyma didyma</i> Hust. 1933
AC044A	<i>Achnanthes levanderi</i> Hust. 1933
AC046A	<i>Achnanthes altaica</i> (Poretzky) A. Cleve-Euler 1953
AC048A	<i>Achnanthes scotica</i> Jones & Flower
AC049A	<i>Achnanthes ploenensis</i> Hust. 1930
AC060A	<i>Achnanthes curtissima</i> J.R. Carter 1963
AC082A	<i>Achnanthes kriegeri</i> Krasske 1943
AC083A	<i>Achnanthes laevis</i> Ostr. 1910
AC116A	<i>Achnanthes rossii</i> Hust. 1954
AC119A	<i>Achnanthes saccula</i> J.R. Carter in J.R. Carter & Watts 1981
AC126A	<i>Achnanthes subsalsa</i> J.B. Petersen 1928
AC134A	<i>Achnanthes helvetica</i> (Husted) Lange-Bertalot in LB & K 1989
AC134C	<i>Achnanthes helvetica minor</i> Flower & Jones 1989
AC136A	<i>Achnanthes subatomoides</i> (Hust.) Lange-Bertalot & Archibald in Krammer & Lange-Bertalot 1985
AC141A	<i>Achnanthes bioretii</i> Germain 1957
AC142A	<i>Achnanthes kuelbsii</i> Lange-Bertalot 1989
AC143A	<i>Achnanthes oblongella</i> Ostr. 1902
AC146A	<i>Achnanthes lacus-vulcani</i> Lange-Bertalot & Krammer 1989
AC151A	<i>Achnanthes abundans</i> Manguin in Gourelly & Manguin 1954
AC152A	<i>Achnanthes carissima</i> Lange-Bertalot 1990
AC153A	<i>Achnanthes impexa</i> Lange-Bertalot 1989
AC158A	<i>Achnanthes grana</i> Hohn & Helleman 1963
AC161A	<i>Achnanthes ventralis</i> (Krasske) Lange-Bertalot 1989
AC166A	<i>Achnanthes chlidanos</i> Hohn & Helleman 1963
AC182A	<i>Achnanthes rosenstockii</i> Lange-Bertalot 1989
AC184A	<i>Achnanthes zieglerei</i> Lange-Bertalot 1991
AC9999	<i>Achnanthes</i> sp.
ACT01A	<i>Actinella punctata</i> Lewis
AM001A	<i>Amphora ovalis ovalis</i> (Kutz.) Kutz. 1844
AM004A	<i>Amphora veneta veneta</i> Kutz. 1844
AM006A	<i>Amphora coffeaeformis coffeaeformis</i> (Ag.) Kutz. 1844
AM008A	<i>Amphora thumensis</i> (Mayer) A. Cleve
AM010A	<i>Amphora fagediana</i> Krammer 1985
AM012A	<i>Amphora pediculus</i> (Kutz.) Grun.
AM013A	<i>Amphora inariensis</i> Krammer
AM9999	<i>Amphora</i> sp.
AN9999	<i>Anomoeoneis</i> sp.
AP001A	<i>Amphipleura pellucida</i> (Kutz.) Kutz. 1844
AS001A	<i>Asterionella formosa formosa</i> Hassall 1850
AS003A	<i>Asterionella ralfsii</i> W. Sm. 1856
AU001C	<i>Aulacoseira italica valida</i> (Grun. in Van Heurck) Simonsen 1979
AU002A	<i>Aulacoseira ambigua</i> (Grun. in Van Heurck) Simonsen 1979
AU003A	<i>Aulacoseira granulata</i> (Ehrenberg)Simonsen 1979
AU003B	<i>Aulacoseira granulata angustissima</i> (O. Mull.) Simonsen 1979
AU004A	<i>Aulacoseira lirata lirata</i> (Ehrenb.) R. Ross in Hartley 1986
AU004B	<i>Aulacoseira lirata lacustris</i> (Grun. in Van Heurck) R. Ross in Hartley 1986
AU004D	<i>Aulacoseira lirata alpigena</i> (Grun.) Haworth
AU005A	<i>Aulacoseira distans</i> (Ehrenb.) Simonsen 1979
AU005D	<i>Aulacoseira distans tenella</i> (Nygaard) R. Ross in Hartley 1986
AU005E	<i>Aulacoseira distans nivalis</i>
AU005J	<i>Aulacoseira distans laevis</i> (Grun.) Haworth
AU009A	<i>Aulacoseira islandica islandica</i> (O. Mull.) Simonsen 1979
AU010A	<i>Aulacoseira perglabra</i>
AU010B	<i>Aulacoseira perglabra florinae</i>
AU020A	<i>Aulacoseira subarctica</i> (O.Mull.) Haworth

AU022A	<i>Aulacoseira subborealis</i> SWAP 1989
AU031A	<i>Aulacoseira alpigena</i> (Grunow) Krammer 1990
AU9999	<i>Aulacoseira</i> sp.
BR001A	<i>Brachysira vitrea</i> (Grun.) R. Ross in Hartley 1986
BR002A	<i>Brachysira foliis</i> (Ehrenb.) R. Ross in Hartley 1986
BR003A	<i>Brachysira serians</i> (Breb. ex Kutz.) Round & Mann 1981
BR003B	<i>Brachysira serians modesta</i> Cleve-Euler
BR004A	<i>Brachysira styriaca</i> (Grun. in Van Heurck) R. Ross in Hartley 1986
BR005A	<i>Brachysira zellensis</i> (Grun.) Round & Mann 1981
BR006A	<i>Brachysira brebissonii</i> brebissonii R. Ross in Hartley 1986
BR9999	<i>Brachysira</i> sp.
CA001A	<i>Caloneis latiuscula</i> (Kutz.) Cleve 1894
CA002A	<i>Caloneis bacillum bacillum</i> (Grun.) Cleve 1894
CA003A	<i>Caloneis silicula</i> (Ehrenb.) Cleve 1894
CA009A	<i>Caloneis obtusa</i> Cleve 1894
CA013A	<i>Caloneis permagna</i> (J.W. Bail.) Cleve 1894
CA014A	<i>Caloneis alpestris</i> (Grun.) Cleve 1894
CA018A	<i>Caloneis tenuis</i> Gregory (Krammer) 1985
CA041A	<i>Caloneis pulchra</i> Messikommer 1927
CA9999	<i>Caloneis</i> sp.
CC001A	<i>Cyclostephanos dubius</i> (Fricke in A. Schmidt) Round 1982
CC002A	<i>Cyclostephanos invisitatus</i> Theriot, Stoermer & Hakansson, comb. nov. 1987
CC9997	<i>Cyclostephanos</i> [cf. <i>tholiformis</i>] H. Bennion 1992
CL001A	<i>Cymatopleura solea</i> (Breb. & Godey) W. Sm. 1851
CL9999	<i>Cymatopleura</i> sp.
CM002A	<i>Cymbella turgida</i> Greg. 1856
CM003A	<i>Cymbella sinuata sinuata</i> Greg. 1856
CM004A	<i>Cymbella microcephala microcephala</i> Grun. in Van Heurck 1880
CM005A	<i>Cymbella aspera aspera</i> (Ehrenb.) H. Perag. in Pell. 1889
CM006A	<i>Cymbella cistula cistula</i> (Ehrenb. in Hempr. & Ehrenb.) Kirchner 1878
CM007A	<i>Cymbella cymbiformis cymbiformis</i> Ag. 1830
CM008A	<i>Cymbella hybrida</i> Grun. ex Cleve 1894
CM009A	<i>Cymbella naviculiformis</i> Auersw. ex Heib. 1863
CM010A	<i>Cymbella perpusilla</i> A. Cleve 1895
CM012A	<i>Cymbella laevis</i> Naegeli ex Kutz. 1849
CM013A	<i>Cymbella helvetica helvetica</i> Kutz. 1844
CM014A	<i>Cymbella aequalis</i> W. Sm. ex Grev 1855
CM015A	<i>Cymbella cesatii cesatii</i> (Rabenh.) Grun. in A. Schmidt 1881
CM016A	<i>Cymbella amphicephala amphicephala</i> Naegeli ex Kutz. 1849
CM017A	<i>Cymbella hebridica</i> (Grun. ex Cleve) Cleve 1894
CM018A	<i>Cymbella gracilis</i> (Rabenh.) Cleve 1894
CM020A	<i>Cymbella gaeumannii</i> Meister 1934
CM022A	<i>Cymbella affinis</i> Kutz. 1844
CM026A	<i>Cymbella cuspidata</i> Kutz. 1844
CM029A	<i>Cymbella ehrenbergii</i> Kutz. 1844
CM031A	<i>Cymbella minuta minuta</i> Hilse ex Rabenh. 1862
CM033A	<i>Cymbella hustedtii</i> Krasske 1923
CM034A	<i>Cymbella diluviana</i> (Krasske) M.-B. Florin 1971
CM038A	<i>Cymbella delicatula</i> Kutz. 1849
CM045A	<i>Cymbella prostrata prostrata</i> (Berkeley) Brun 1880
CM047A	<i>Cymbella incerta</i> Grun. in Cleve & Moller 1878
CM050A	<i>Cymbella subaequalis</i> Grun. in Van Heurck 1880
CM051A	<i>Cymbella elginensis</i> Krammer 1981
CM052A	<i>Cymbella descripta</i> (Hust.) Krammer & Lange-Bertalot 1985
CM057A	<i>Cymbella mesiana</i> Cholnoky
CM070A	<i>Cymbella caespitosa</i> (Kutz.) Brun 1880
CM085A	<i>Cymbella lapponica</i> Grun. ex Cleve 1894
CM086A	<i>Cymbella leptoceros leptoceros</i> (Ehrenb.) Kutz. 1844
CM099A	<i>Cymbella reinhardtii</i> Grun. ex A. Schmidt 1875
CM103A	<i>Cymbella silesiaca</i> Bleisch ex Rabenh. 1864
CM107A	<i>Cymbella subcuspidata</i> Krammer 1982
CM109A	<i>Cymbella tumidula</i> Grun. ex A. Schmidt 1875
CM9999	<i>Cymbella</i> sp.
CO001A	<i>Cocconeis placentula placentula</i> Ehrenb. 1838
CO005A	<i>Cocconeis pediculus</i> Ehrenb. 1838
CO006A	<i>Cocconeis diminuta</i> Pant. 1902
CO066A	<i>Cocconeis neodiminuta</i> Krammer 1991
CO067A	<i>Cocconeis neothumensis</i> Krammer 1991
CO9999	<i>Cocconeis</i> sp.
CP017A	<i>Campylodiscus hibernicus</i> Ehrenb. 1845
CP9999	<i>Campylodiscus</i> sp.
CY002A	<i>Cyclotella pseudostelligera</i> Hust. 1939
CY003A	<i>Cyclotella meneghiniana meneghiniana</i> Kutz. 1844
CY004A	<i>Cyclotella stelligera</i> (Cleve & Grun. in Cleve) Van Heurck 1882
CY005A	<i>Cyclotella michiganiana</i> Skvortzow
CY007A	<i>Cyclotella glomerata</i> Bachm. 1911
CY009A	<i>Cyclotella ocellata</i> Pant. 1902
CY010A	<i>Cyclotella comensis</i> Grun. in Van Heurck 1882
CY011A	<i>Cyclotella atomus</i> Hust. 1937
CY016A	<i>Cyclotella arentii</i> Kolbe 1948
CY019A	<i>Cyclotella radiosa</i> (Grunow) Lemmerman 1900
CY9991	<i>Cyclotella kuetzingiana</i> agg.
CY9999	<i>Cyclotella</i> sp.

DE001A	<i>Denticula tenuis tenuis</i> Kutz. 1844
DE002A	<i>Denticula elegans</i> Kutz. 1844
DE003A	<i>Denticula kuetzingii</i> Grun.
DE9999	<i>Denticula</i> sp.
DP001A	<i>Diploneis ovalis</i> (Hilse) Cleve 1894
DP002A	<i>Diploneis petersenii</i> Hust. 1937
DP007A	<i>Diploneis oblongella oblongella</i> (Naegeli ex Kutz.) R. Ross 1947
DP009A	<i>Diploneis elliptica elliptica</i> (Kutz.) Cleve 1894
DP010A	<i>Diploneis finnica</i> (Ehrenb.) Cleve 1894
DP018A	<i>Diploneis boldtiana</i> Cleve 1894
DP041A	<i>Diploneis interrupta interrupta</i> (Kutz.) Cleve 1894
DP046A	<i>Diploneis minuta</i> J.B. Petersen 1928
DP065A	<i>Diploneis parma</i> Cleve 1891
DP067A	<i>Diploneis modica</i> Hustedt 1945
DP9999	<i>Diploneis</i> sp.
DT001A	<i>Diatoma elongatum</i> (Lyngb.) Ag. 1824
DT002A	<i>Diatoma hyemale hyemale</i> (Roth) Heib. 1863
DT002B	<i>Diatoma hyemale mesodon</i> (Ehrenb.) Kirchner 1878
DT003A	<i>Diatoma vulgare vulgare</i> Bory 1824
DT9999	<i>Diatoma</i> sp.
EP001A	<i>Epithemia sorex sorex</i> Kutz. 1844
EP007A	<i>Epithemia adnata adnata</i> (Kutz.) Rabenh. 1853
EP021A	<i>Epithemia smithii</i> Carruthers 1864
EP023A	<i>Epithemia frickei</i> Krammer 1987
EP9999	<i>Epithemia</i> sp.
EU002A	<i>Eunotia pectinalis pectinalis</i> (O.F. Mull.) Rabenh. 1864
EU002B	<i>Eunotia pectinalis minor</i> (Kutz.) Rabenh. 1864
EU002C	<i>Eunotia pectinalis ventralis</i> (Ehrenb.) Hust. 1911
EU002D	<i>Eunotia pectinalis undulata</i> (Ralfs) Rabenh. 1864
EU002E	<i>Eunotia pectinalis minor impressa</i> (Ehr.) Hust.
EU003A	<i>Eunotia praeurupta praeurupta</i> Ehrenb. 1843
EU004A	<i>Eunotia tenella</i> (Grun. in Van Heurck) A. Cleve 1895
EU005A	<i>Eunotia alpina</i> (Naeg. ex Kutz.) Hust. in A. Schmidt 1913
EU007A	<i>Eunotia bidentula</i> W. Sm. 1856
EU009A	<i>Eunotia exigua exigua</i> (Breb. ex Kutz.) Rabenh. 1864
EU010A	<i>Eunotia faba</i> (Ehrenb.) Grun. in Van Heurck 1881
EU010B	<i>Eunotia faba intermedia</i>
EU011A	<i>Eunotia rhomboidea</i> Hust. 1950
EU013A	<i>Eunotia arcus arcus</i> Ehrenb. 1837
EU014A	<i>Eunotia bactriana</i> Ehrenb. 1854
EU015A	<i>Eunotia denticulata denticulata</i> (Breb. ex Kutz.) Rabenh. 1864
EU016A	<i>Eunotia diodon</i> Ehrenb. 1837
EU017A	<i>Eunotia flexuosa flexuosa</i> Kutz. 1849
EU018A	<i>Eunotia formica</i> Ehrenb. 1843
EU019A	<i>Eunotia iatrisiensis</i> Foged 1970
EU020A	<i>Eunotia meisteri meisteri</i> Hust. 1930
EU021A	<i>Eunotia sudetica</i> O. Mull. 1898
EU024A	<i>Eunotia glacialis</i> Meister 1912
EU025A	<i>Eunotia fallax</i> A. Cleve 1895
EU026A	<i>Eunotia praeurupta-nana</i> Berg
EU027A	<i>Eunotia trinacria</i> Krasske 1929
EU028A	<i>Eunotia microcephala</i> Krasske ex Hust. 1932
EU028B	<i>Eunotia microcephala tridentata</i> (A. Mayer) Hust.
EU032A	<i>Eunotia serra serra</i> Ehrenb. 1837
EU034A	<i>Eunotia parallela parallela</i> Ehrenb. 1843
EU035A	<i>Eunotia major major</i> (W. Sm.) Rabenh. 1864
EU040A	<i>Eunotia paludosa</i> Grun. 1862
EU045A	<i>Eunotia nymanniana</i> Grun. in Van Heurck 1881
EU047A	<i>Eunotia incisa</i> W. Sm. ex Greg. 1854
EU048A	<i>Eunotia naegeli</i> Migula 1907
EU051A	<i>Eunotia vanheurckii</i> Patr. 1958
EU051B	<i>Eunotia vanheurckii intermedia</i> (Krasske) Cleve
EU056A	<i>Eunotia minutissima</i> A. Cleve-Euler 1934
EU057A	<i>Eunotia exgracilis</i> A. Berg ex A. Cleve-Euler 1953
EU070A	<i>Eunotia bilunaris</i> (Ehrenb.) F.W. Mills 1934
EU070B	<i>Eunotia bilunaris mucophila</i> LB & Norpel 1991
EU104A	<i>Eunotia steinecke</i> Petersen 1950
EU105A	<i>Eunotia subarcuatoides</i> Alles, Norpel, Lange-Bertalot 1991
EU106A	<i>Eunotia rhynchocephala</i> Hustedt 1936
EU108A	<i>Eunotia intermedia</i> (Hust) Norpel, Lange-Bertalot & Alles 1991
EU109A	<i>Eunotia circumborealis</i> Norpel & LB 1991
EU112A	<i>Eunotia arculus</i> (Grunow) LB & Norpel
EU114A	<i>Eunotia muscicola</i> Krasske 1939
EU9999	<i>Eunotia</i> sp.
FR001A	<i>Fragilaria pinnata pinnata</i> Ehrenb. 1843
FR002A	<i>Fragilaria construens construens</i> (Ehrenb.) Grun. 1862
FR002B	<i>Fragilaria construens binodis</i> (Ehrenb.) Grun. 1862
FR002C	<i>Fragilaria construens venter</i> (Ehrenb.) Grun. in Van Heurck 1881
FR002D	<i>Fragilaria construens exigua</i> (W. Sm.) Schulz 1922
FR003A	<i>Fragilaria bicapitata</i> A. Mayer 1917
FR005A	<i>Fragilaria virescens virescens</i> Ralfs 1843
FR005D	<i>Fragilaria virescens exigua</i> Grun. in Van Heurck 1881
FR006A	<i>Fragilaria brevistriata brevistriata</i> Grun. in Van Heurck 1885

FR008A	<i>Fragilaria crotonensis</i> Kitton 1869
FR009A	<i>Fragilaria capucina capucina</i> Desm. 1825
FR009B	<i>Fragilaria capucina mesolepta</i> (Rabenh.) Rabenh. 1864
FR009G	<i>Fragilaria capucina rumpens</i> (Kutz.) Lange-Bertalot 1991
FR009H	<i>Fragilaria capucina gracilis</i> (Oestrup) Hustedt 1950
FR009J	<i>Fragilaria capucina perminuta</i> (Grun.) L-B. 1991
FR009L	<i>Fragilaria capucina amphicephala</i> (Grun) L-B 1991
FR010A	<i>Fragilaria constricta constricta</i> Ehrenb. 1843
FR011A	<i>Fragilaria lapponica</i> Grun. in Van Heurck 1881
FR013A	<i>Fragilaria oldenburgiana</i> Hust.
FR014A	<i>Fragilaria leptostauron leptostauron</i> (Ehrenb.) Hust. 1931
FR015A	<i>Fragilaria lata</i> (Cleve-Euler) Renberg 1977
FR016A	<i>Fragilaria heidenii</i> Ostr. 1910
FR018A	<i>Fragilaria elliptica</i> Schum. 1867
FR019A	<i>Fragilaria intermedia</i> Grun. in Van Heurck 1881
FR045A	<i>Fragilaria parasitica</i> (W. Sm.) Grun. in Van Heurck 1881
FR045B	<i>Fragilaria parasitica constricta</i> A. Mayer 1912
FR045E	<i>Fragilaria parasitica subconstricta</i> Grun. in Van Heurck 1881
FR056A	<i>Fragilaria pseudoconstruens</i> Marciniak 1982
FR057A	<i>Fragilaria fasciculata</i> (Agardh) Lange-Bertalot sensu lato 1980
FR063A	<i>Fragilaria robusta</i> (Fusey) Manguin
FR065A	<i>Fragilaria leptostauron martyi</i> (Heribaud) LB 1991
FR070A	<i>Fragilaria spinarum</i> L-B & Metzeltin 1996
FR082A	<i>Fragilaria incognita</i> Reichardt 1988
FR9999	<i>Fragilaria</i> sp.
FU001A	<i>Frustulia vulgaris vulgaris</i> (Thwaites) De Toni 1891
FU002A	<i>Frustulia rhomboides rhomboides</i> (Ehrenb.) De Toni 1891
FU002B	<i>Frustulia rhomboides saxonica</i> (Rabenh.) De Toni 1891
FU002F	<i>Frustulia rhomboides viridula</i> (Breb. ex Kutz.) Cleve 1894
FU9999	<i>Frustulia</i> sp.
GO001A	<i>Gomphonema olivaceum</i> (Hornemann) Breb. 1838
GO001C	<i>Gomphonema olivaceum minutissimum</i> Hust.
GO003A	<i>Gomphonema angustatum angustatum</i> (Kutz.) Rabenh. 1864
GO003B	<i>Gomphonema angustatum productum</i> Grun. in Van Heurck 1880
GO004A	<i>Gomphonema gracile</i> Ehrenb. 1838
GO005A	<i>Gomphonema lagerheimi</i> A. Cleve 1895
GO006A	<i>Gomphonema acuminatum acuminatum</i> Ehrenb. 1832
GO006C	<i>Gomphonema acuminatum coronatum</i> (Ehrenb.) W. Sm. 1853
GO007A	<i>Gomphonema bohemicum</i> Reichelt & Fricke in A. Schmidt 1902
GO008A	<i>Gomphonema subtile subtile</i> Ehrenb. 1843
GO010A	<i>Gomphonema constrictum</i> Ehrenb. ex Kutz. 1844
GO013A	<i>Gomphonema parvulum parvulum</i> (Kutz.) Kutz. 1849
GO014A	<i>Gomphonema intricatum</i> Kutz. 1844
GO014B	<i>Gomphonema intricatum pumilum</i> Grun. in Van Heurck 1880
GO019A	<i>Gomphonema augur</i> Ehr.
GO020A	<i>Gomphonema affine</i> Kutz. 1844
GO024A	<i>Gomphonema clevei</i> Fricke in A. Schmidt 1902
GO029A	<i>Gomphonema clavatum</i> Ehr.
GO036A	<i>Gomphonema dichotomum</i> Kutz. 1833
GO050A	<i>Gomphonema minutum</i> (Ag.) Ag. 1831
GO073A	<i>Gomphonema angustum</i> Agardh 1831
GO076A	<i>Gomphonema bavaricum</i> Reichardt & Lange-Bertalot 1991
GO080A	<i>Gomphonema pumilum</i> (Grun.) Reichardt & L-B
GO082B	<i>Gomphonema grovei lingulatum</i> (Hustedt) LB 1985
GO9999	<i>Gomphonema</i> sp.
GY001A	<i>Gyrosigma attenuatum</i> (Kutz.) Rabenh. 1853
GY005A	<i>Gyrosigma acuminatum</i> (Kutz.) Rabenh. 1853
GY9999	<i>Gyrosigma</i> sp.
HN001A	<i>Hannaea arcus arcus</i> (Ehrenb.) Patr. in Patr. & Reimer 1966
MA001A	<i>Mastogloia smithii smithii</i> Thwaites ex W. Sm. 1856
MA009A	<i>Mastogloia baltica</i> Grun. in Van Heurck 1880
MA9999	<i>Mastogloia</i> sp.
ME015A	<i>Melosira varians</i> Ag. 1827
ME019A	<i>Melosira arentii</i> (Kolbe) Nagumo & Kobayasi 1977
MR001A	<i>Meridion circulare circulare</i> (Grev.) Ag. 1831
NA001A	<i>Navicula tuscula tuscula</i> Ehrenb. 1840
NA002A	<i>Navicula jaernefeltii</i> Hust. 1942
NA003A	<i>Navicula radiosa radiosa</i> Kutz. 1844
NA005A	<i>Navicula seminulum</i> Grun. 1860
NA006A	<i>Navicula mediocris</i> Krasske 1932
NA007A	<i>Navicula cryptocephala cryptocephala</i> Kutz. 1844
NA007B	<i>Navicula cryptocephala veneta</i> (Kutz.) Rabenh. 1863
NA008A	<i>Navicula rhyncocephala rhyncocephala</i> Kutz. 1844
NA009A	<i>Navicula lanceolata</i> (Agardh) Kutz.
NA013A	<i>Navicula pseudoscutiformis</i> Hust. 1930
NA014A	<i>Navicula pupula pupula</i> Kutz. 1844
NA014B	<i>Navicula pupula rectangularis</i> (Greg.) Grun. in Cleve & Grun. 1880
NA014D	<i>Navicula pupula mutata</i> (Krasske) Hust. 1930
NA015A	<i>Navicula hassiaca</i> Krasske 1925
NA016A	<i>Navicula indifferens</i> Hust. 1942
NA017A	<i>Navicula ventralis</i> Krasske 1923
NA021A	<i>Navicula cincta</i> (Ehrenb.) Ralfs in Pritch. 1861
NA022A	<i>Navicula halophila</i> (Grun. ex Van Heurck) Cleve 1894

NA023A	<i>Navicula gregaria</i> Donk. 1861
NA025A	<i>Navicula mutica mutica</i> Kutz. 1844
NA028A	<i>Navicula scutelloides</i> W. Sm. ex Greg. 1856
NA030A	<i>Navicula menisculus menisculus</i> Schum. 1867
NA032A	<i>Navicula cocconeiformis cocconeiformis</i> Greg. ex Greville 1855
NA033A	<i>Navicula subtilissima</i> Cleve 1891
NA034A	<i>Navicula rostellata</i> Kutz. 1844
NA036A	<i>Navicula perpusilla</i> (Kutz.) Grun. 1860
NA037A	<i>Navicula angusta</i> Grun. 1860
NA038A	<i>Navicula arvensis</i> Hust.
NA039A	<i>Navicula festiva</i> Krasske 1925
NA040A	<i>Navicula hoefleri</i> Chohn. in Chohn. & Schindler 1953
NA041A	<i>Navicula heimansii</i> Van Dam & Kooy.
NA042A	<i>Navicula minima minima</i> Grun. in Van Heurck 1880
NA043A	<i>Navicula subatomoides</i> Hust. ex Patr. 1945
NA044A	<i>Navicula krasskei</i> Hust. 1930
NA045A	<i>Navicula bryophila bryophila</i> J.B. Petersen 1928
NA046A	<i>Navicula contenta contenta</i> Grun. in Van Heurck 1885
NA047A	<i>Navicula protracta protracta</i> Grun. in Cleve & Grun. 1880
NA048A	<i>Navicula soehrensii soehrensii</i> Krasske 1923
NA049A	<i>Navicula jentzschii</i> Grun. 1882
NA050A	<i>Navicula clementis clementis</i> Grun. 1882
NA053A	<i>Navicula subcostulata</i> Hust. 1934
NA055A	<i>Navicula graciloides</i> A. Mayer 1919
NA056A	<i>Navicula cuspidata cuspidata</i> (Kutz.) Kutz. 1844
NA057A	<i>Navicula elginensis elginensis</i> (Greg.) Ralfs in Pritch. 1861
NA063A	<i>Navicula trivialis</i> Lange-Bertalot 1980
NA064A	<i>Navicula exilis</i> Kutz. 1844
NA065A	<i>Navicula gastrum</i> (Ehrenb.) Kutz. 1844
NA066A	<i>Navicula capitata capitata</i> Ehrenb. 1838
NA066B	<i>Navicula capitata hungarica</i> (Grun.) R. Ross 1947
NA066C	<i>Navicula capitata lueneburgensis</i> (Grun.) Patr. in Patr. & Reimer 1966
NA068A	<i>Navicula impexa</i> hust. 1961
NA071A	<i>Navicula bacillum bacillum</i> Ehrenb. 1840
NA076A	<i>Navicula variostrata</i> Krasske 1923
NA079A	<i>Navicula pseudolanceolata</i> Lange-Bertalot 1980
NA079B	<i>Navicula pseudolanceolata densilineolata</i> Lange-Bertalot 1985
NA082A	<i>Navicula muralis</i> Grun. in Van Heurck 1880
NA084A	<i>Navicula atomus</i> (Kutz.) Grun. 1860
NA088A	<i>Navicula meniscus</i> Schum. 1867
NA095A	<i>Navicula tripunctata tripunctata</i> (O.F. Mull.) Bory 1822
NA096A	<i>Navicula accomoda</i> Hust. 1950
NA099A	<i>Navicula bremensis</i> Hust. 1957
NA102A	<i>Navicula laevis</i> Kutz. 1844
NA112A	<i>Navicula minuscula minuscula</i> Grun. in Van Heurck 1880
NA112D	<i>Navicula minuscula muralis</i> (Grun. in Van Heurck) Lange-Bertalot in Lange-Bertalot & Rumrich 1981
NA114A	<i>Navicula subrotundata</i> Hust. 1945
NA115A	<i>Navicula difficillima</i> Hust. 1950
NA116A	<i>Navicula brockmannii</i> Hust. 1934
NA121A	<i>Navicula begeri</i> Krasske 1932
NA123A	<i>Navicula modica</i> Hust. 1945
NA124A	<i>Navicula molestiformis</i> Hust.
NA128A	<i>Navicula schoenfeldii</i> Hust. 1930
NA129A	<i>Navicula seminuloides</i> Hust. 1937
NA133A	<i>Navicula schassmannii</i> Hust. 1937
NA134A	<i>Navicula subminuscula</i> Manguin
NA135A	<i>Navicula tenuicephala</i> Hust. 1942
NA140A	<i>Navicula madumensis</i> E.G. Jorg. 1948
NA144A	<i>Navicula utermohlii</i> Hust. 1943
NA149A	<i>Navicula digitulus</i> Hust. 1943
NA156A	<i>Navicula leptostriata</i> Jorgensen 1948
NA158A	<i>Navicula cumbriensis</i> Haworth 1987
NA158B	<i>Navicula cumbriensis minor</i> Atkinson nov. var.
NA160A	<i>Navicula submolesta</i> Hust. 1949
NA161A	<i>Navicula absoluta</i> Hust. 1950
NA164A	<i>Navicula concentrica</i> J.R. Carter in J.R. Carter & Watts 1981
NA166A	<i>Navicula submuralis</i> Hust.
NA167A	<i>Navicula hoefleri</i> Sensu Ross et Sims
NA168A	<i>Navicula vitabunda</i> Hust. 1930
NA175A	<i>Navicula gerloffii</i> Schimanski 1978
NA190A	<i>Navicula agrestis</i> Hust. 1937
NA322A	<i>Navicula detenta</i> Hust. 1943
NA389B	<i>Navicula gallica perpusilla</i> (Grun) Lange-Bertalot 1985
NA400A	<i>Navicula glomus</i> J.R. Carter in J.R. Carter & Watts 1981
NA402A	<i>Navicula gottlandica</i> Grun. in Van Heurck 1880
NA415A	<i>Navicula harderi</i> Hust. in Brendemuhl 1948
NA427A	<i>Navicula humerosa humerosa</i> Breb. ex W. Sm. 1856
NA433C	<i>Navicula ignota palustris</i> (Hust.) J.W.G. Lund 1946
NA433D	<i>Navicula ignota acceptata</i> (Hustedt) Lange-Bertalot 1985
NA565A	<i>Navicula perminuta</i> Grun. in Van Heurck 1880
NA577A	<i>Navicula porifera</i> Hust. 1944
NA577B	<i>Navicula porifera opportuna</i> (Hust.) LB 1985
NA590A	<i>Navicula pseudoventralis</i> Hust. 1953

NA650A	<i>Navicula stroemii</i> Hust. 1931
NA669A	<i>Navicula suchlandtii</i> Hust. 1943
NA738A	<i>Navicula vitiosa</i> Schimanski 1978
NA743A	<i>Navicula subrhyncocephala</i> Hustedt 1935
NA745A	<i>Navicula capitoradiata</i> Germain 1981
NA748A	<i>Navicula lucinensis</i> Hustedt 1950
NA751A	<i>Navicula cryptotenella</i> Lange-Bertalot 1985
NA753A	<i>Navicula sublucidula</i> Hust. 1950
NA755A	<i>Navicula kuelbsii</i> Lange-Bertalot 1985
NA766A	<i>Navicula heimansioides</i> Lange-Bertalot 1993
NA787A	<i>Navicula muraliformis</i> Hust. ex Brendemuhl 1949
NA799A	<i>Navicula argens</i> Skv. 1937
NA9886	<i>Navicula</i> [cf. <i>seminulum</i>] NJA+HB, Eutrophic sites 1992
NA9999	<i>Navicula</i> sp.
NE002A	<i>Neidium productum</i> (W. Sm.) Cleve 1894
NE003A	<i>Neidium affine</i> (Ehrenb.) Pfitz. 1871
NE003B	<i>Neidium affine longiceps</i> (Greg.) Cleve 1896
NE003C	<i>Neidium affine amphirhynchus</i> (Ehrenb.) Cleve 1894
NE004A	<i>Neidium bisulcatum bisulcatum</i> (Lagerst.) Cleve 1894
NE006A	<i>Neidium alpinum</i> Hust. 1943
NE012A	<i>Neidim glaberrimum</i> (Ostr.) R. Ross in Hartley 1986
NE016A	<i>Neidium apiculatum</i> Reimer 1959
NE036A	<i>Neidium ampliatum</i> (Ehren) Krammer 1985
NE9999	<i>Neidium</i> sp.
NI002A	<i>Nitzschia fonticola</i> Grun. in Van Heurck 1881
NI005A	<i>Nitzschia perminuta</i> (Grun. in Van Heurck) M. Perag. 1903
NI006A	<i>Nitzschia sigma sigma</i> (Kutz.) W. Sm. 1853
NI007A	<i>Nitzschia hungarica</i> Grun. 1862
NI008A	<i>Nitzschia frustulum</i> (Kutz.) Grun. in Cleve & Grun. 1880
NI009A	<i>Nitzschia palea palea</i> (Kutz.) W. Sm. 1856
NI009C	<i>Nitzschia palea debilis</i> (Kutz.) Grun. in Cleve & Grun. 1880
NI011A	<i>Nitzschia commutata</i> Grun. in Cleve & Grun. 1880
NI014A	<i>Nitzschia amphibia amphibia</i> Grun. 1862
NI015A	<i>Nitzschia dissipata</i> (Kutz.) Grun. 1862
NI017A	<i>Nitzschia gracilis</i> Hantzsch 1860
NI020A	<i>Nitzschia angustata angustata</i> (W. Sm.) Grun. in Cleve & Grun. 1880
NI024A	<i>Nitzschia sublinearis</i> Hust. 1930
NI025A	<i>Nitzschia recta</i> Hantzsch ex Rabenh. 1861
NI027A	<i>Nitzschia microcephala</i> Grun. in Cleve & Grun. 1880
NI028A	<i>Nitzschia capitellata</i> Hust. 1930
NI030A	<i>Nitzschia acidoclinata</i> Lange Bertalot
NI031A	<i>Nitzschia linearis linearis</i> W. Sm. 1853
NI033A	<i>Nitzschia paleacea</i> (Grun. in Cleve & Grun.) Grun. in Van Heurck 1881
NI042A	<i>Nitzschia acicularis</i> (Kutz.) W. Sm. 1853
NI043A	<i>Nitzschia inconspicua</i> Grun. 1862
NI044A	<i>Nitzschia intermedia</i> Hantzsch ex Cleve & Grun. 1880
NI063A	<i>Nitzschia agnita</i> Hust. 1957
NI072A	<i>Nitzschia bremensis bremensis</i> Hust. 1930
NI099A	<i>Nitzschia flexa</i> Schum. 1862
NI127A	<i>Nitzschia levidensis</i> (W. Sm.) Grun. in Van Heurck 1881
NI186A	<i>Nitzschia valdestriata</i> Aleem & Hust. 1951
NI193A	<i>Nitzschia perminuta</i> (Grun.) M. Perag. 1903
NI198A	<i>Nitzschia lacuum</i> Lange-Bertalot 1980
NI199A	<i>Nitzschia angustatula</i> Lange-Bertalot 1987
NI201A	<i>Nitzschia graciliformis</i> Lange-Bertalot & Simonsen 1978
NI202A	<i>Nitzschia alpina</i> Hustedt 1943
NI210A	<i>Nitzschia bacilliformis</i> Hustedt 1922
NI211A	<i>Nitzschia bacillum</i> Hustedt in A.Schmidt et al 1922
NI212A	<i>Nitzschia fossilis</i> (Grun.)Grun in Van Heurck 1881
NI213A	<i>Nitzschia rosenstockii</i> Lange-Bertalot 1980
NI9999	<i>Nitzschia</i> sp.
OP001A	<i>Opephora martyi</i> Herib.1902
OP008A	<i>Opephora olseni</i> Moller 1950
PE001A	<i>Peronia heribaudii</i> Brun & M. Perag. in Herib. 1893
PE002A	<i>Peronia fibula</i> (Breb. ex Kutz.) R. Ross 1956
PI001B	<i>Pinnularia gibba linearis</i> Hust. 1930
PI004A	<i>Pinnularia interrupta</i> W. Smith
PI005A	<i>Pinnularia major major</i> (Kutz.) W. Sm. 1853
PI007A	<i>Pinnularia viridis viridis</i> (Nitzsch) Ehrenb. 1843
PI011A	<i>Pinnularia microstauron microstauron</i> (Ehrenb.) Cleve 1891
PI014A	<i>Pinnularia appendiculata</i> (Ag.) Cleve 1896
PI015A	<i>Pinnularia abaujensis</i> (Pant.) R. Ross in Hartley 1986
PI016A	<i>Pinnularia divergentissima</i> (Grun.in Van Heurck) Cleve 1896
PI018A	<i>Pinnularia biceps biceps</i> Greg. 1856
PI022A	<i>Pinnularia subcapitata subcapitata</i> Greg. 1856
PI023A	<i>Pinnularia irrorata</i> (Grun. in Van Heurck) Hust. 1939
PI024A	<i>Pinnularia stomatophora stomatophora</i> (Grun. ex A. Schmidt) Cleve 1891
PI038A	<i>Pinnularia nobilis</i> (Ehrenb.) Ehrenb. 1843
PI056A	<i>Pinnularia rupestris</i> Hantzsch in Rabenh. 1861
PI132A	<i>Pinnularia lundii</i> Hust. 1954
PI170A	<i>Pinnularia braunii</i> (Grun.) Cleve
PI9999	<i>Pinnularia</i> sp.
RC002A	<i>Rhoicosphenia abbreviata</i> (Ag.) Lange-Bertalot 1980

RH001A	<i>Rhopalodia gibba gibba</i> (Ehrenb.) O. Mull. 1895
RH009A	<i>Rhopalodia brebissonii</i> Krammer 1987
RH010A	<i>Rhopalodia acuminata</i> Krammer 1987
RH9999	<i>Rhopalodia</i> sp.
SA001A	<i>Stauroneis anceps anceps</i> Ehrenb. 1843
SA001B	<i>Stauroneis anceps gracilis</i> Rabenh. 1864
SA003A	<i>Stauroneis smithii smithii</i> Grun. 1860
SA005A	<i>Stauroneis legumen</i> (Ehrenb.) Kutz. 1844
SA006A	<i>Stauroneis phoenicenteron phoenicenteron</i> (Nitzsch) Ehrenb. 1943
SA008A	<i>Stauroneis producta</i> Grun. in Van Heurck 1880
SA9999	<i>Stauroneis</i> sp.
SE001A	<i>Semiorbis hemicyclus</i> (Ehrenb.) Patr. in Patr. & Reimer 1966
SP001A	<i>Stenopterobia intermedia</i> (F.W. Lewis) A. Mayer 1913
SP002A	<i>Stenopterobia sigmatella</i> (Greg.) R. Ross in Hartley 1986
SP005A	<i>Stenopterobia delicatissima</i> (Lewis) M. Perag. 1897
SP9999	<i>Stenopterobia</i> sp.
ST001A	<i>Stephanodiscus hantzschii</i> Grun. in Cleve & Grun. 1880
ST002A	<i>Stephanodiscus tenuis</i> Hust. 1939
ST003A	<i>Stephanodiscus astraea</i> (Ehrenb.) Grun. in Cleve & Grun. 1880
ST006A	<i>Stephanodiscus niagarae</i> Ehr.
ST009A	<i>Stephanodiscus alpinus</i> Hust.
ST010A	<i>Stephanodiscus parvus</i> Stoermer & Hakansson 1984
ST014A	<i>Stephanodiscus medius</i> Hakansson 1986
ST021A	<i>Stephanodiscus minutulus</i> (Kutz.) Cleve & Moller
ST022A	<i>Stephanodiscus neoastraea</i> Hakansson & Hickel 1986
ST9999	<i>Stephanodiscus</i> sp.
SU001A	<i>Surirella angusta</i> Kutz. 1844
SU004A	<i>Surirella biseriata</i> Breb. & Godey 1835
SU005A	<i>Surirella linearis linearis</i> W. Sm. 1853
SU006A	<i>Surirella delicatissima</i> Lewis 1864
SU016A	<i>Surirella minuta</i> Breb. ex Kutz. 1849
SU064A	<i>Surirella splendida</i> (Ehrenb.) Kutz. 1844
SU073A	<i>Surirella brebissonii brebissonii</i> Krammer & Lange-Bertalot 1987
SU9999	<i>Surirella</i> sp.
SY001A	<i>Synedra ulna ulna</i> (Nitzsch) Ehrenb. 1836
SY001C	<i>Synedra ulna danica</i> (Kutz.) Van Heurck 1885
SY002A	<i>Synedra rumpens rumpens</i> Kutz. 1844
SY002B	<i>Synedra rumpens familiaris</i> (Kutz.) Hust. 190
SY003A	<i>Synedra acus acus</i> Kutz. 1844
SY003C	<i>Synedra acus angustissima</i> (Grun. in Van Heurck) Van Heurck 1885
SY004A	<i>Synedra parasitica</i> (W. Sm.) Hust. 1930
SY008A	<i>Synedra pulchella pulchella</i> Ralfs ex Kutz. 1844
SY009A	<i>Synedra nana</i> Meister 1912
SY010A	<i>Synedra minuscula</i> Grun. in Van Heurck 1881
SY015A	<i>Synedra tabulata</i> (Ag.) Kutz. 1844
SY017A	<i>Synedra radians</i> Kutz. 1844
SY9999	<i>Synedra</i> sp.
TA002A	<i>Tabellaria fenestrata</i> (Lyngb.) Kutz. 1844
TA003A	<i>Tabellaria binalis</i> (Ehrenb.) Grun. in Van Heurck 1881
TA003B	<i>Tabellaria binalis elliptica</i> Flower (unpub) 1986
TA004A	<i>Tabellaria quadrisepata</i> Knudson 1952
TA9996	<i>Tabellaria flocculosa</i> agg.
TH016A	<i>Thalassiosira guillardii</i> Hasle 1978
UN9995	Centric undifferentiated
UN9999	Unknown
UR9999	<i>Urosolenia</i> sp.

Appendix 3 The TWINSPAN site end-groups of the 219 sites analysed in work package 1 (sites are ordered by TWINSPAN end-group; reallocated type for those sites misclassified by the GB Lake Typology is given in parentheses)

WBID	Site name	Twinspan site end-group	GB_Typology
2648	Loch na Larach	1	LA, D
33474	Oak Mere	1	LA, D
	Blue Lough	1	LA, D
17629	Loch Dallas	1	LA, Sh
19091	Loch Mhic Leoid	1	LA, Sh
40571	Llyn Llech Owain	1	LA, Sh
44464	Cranmer Pond	1	LA, Sh
44482	Woolmer Pond	1	LA, Sh
38907	Llyn Berwyn	1	P, D
2077	Long Loch	2	LA, D
5073	Loch a Cham Alltain	2	LA, D
11424	Lochan Fhionnlaidh	2	LA, D
11999	Loch na Cric	2	LA, D
12848	Loch nam Badan Boga	2	LA, D
12918	Loch na h'Airbhe	2	LA, D
17334	Loch Coire Fionnaraich	2	LA, D
21160	Loch Coire an Lochan	2	LA, D
21265	Lochan Uaine	2	LA, D
21843	Dubh Loch	2	LA, D
22839	Loch Laidon	2	LA, D
27872	Loch Neldricken	2	LA, D
27900	Loch Valley	2	LA, D
27912	Loch Narroch	2	LA, D
27927	Round Loch of Glenhead	2	LA, D
28130	Loch Grannoch	2	LA, D
	Lough Muck	2	LA, D
	Lough Maam	2	LA, D
	Lough Maumwee	2	LA, D
7824	Loch nan Eun	2	LA, Sh
7921	Loch Coire a' Bhaic	2	LA, Sh
10714	Loch na Gruagaich	2	LA, Sh
12469	Loch Dubh Camas an Lochain	2	LA, Sh
16452	Loch Bharranch	2	LA, Sh
20928	Loch Coire nan Chàmh	2	LA, Sh
22223	Lochan Dubh	2	LA, Sh
35578	Llyn Cwm Mynach	2	LA, Sh
20922	Loch Bad an Losguinn	2	MA, D (LA, D)
27808	Loch Enoch	2	MA, D (LA, D)
36710	Llyn Hir	3	HA, Sh (LA, Sh)
6759	Loch Coire na Saidhe Duibhe	3	LA, D
8266	Loch Bealach Cornaidh	3	LA, D
9299	Loch nan Cuaran	3	LA, D
10905	Lochan Nigheadh	3	LA, D
11315	Loch na Creige Duibhe	3	LA, D
11862	Lochanan Dubha	3	LA, D
12733	Loch na Béiste	3	LA, D
13791	Loch Toll an Lochain	3	LA, D
13800	Loch Muighbhlairaidh	3	LA, D
14413	Loch a' Mhadaidh	3	LA, D
16906	Loch Sgamhain	3	LA, D
17147	Loch nan Eion	3	LA, D
18209	Loch Coire nan Arr	3	LA, D
18690	Loch Teanga	3	LA, D
20328	Loch Kemp	3	LA, D
21723	Lochnagar	3	LA, D
21755	Loch nan Eun	3	LA, D
22308	Loch Doilet	3	LA, D
22963	Loch Uisge	3	LA, D
24020	Lochan Lairig Cheile	3	LA, D
24745	Loch Tinker	3	LA, D
24754	Loch Chon	3	LA, D
27824	Round Loch of the Dungeon	3	LA, D

28206	Loch Skerrow	3	LA, D
29062	Ennerdale Water	3	LA, D
31426	Tunnel End Reservoir	3	LA, D
33836	Llyn Idwal	3	LA, D
33843	Llyn Clyd	3	LA, D
33962	Llyn Alwen	3	LA, D
33998	Llyn Glas	3	LA, D
34039	Llyn Mymbyr	3	LA, D
34319	Llyn Llagi	3	LA, D
34400	Llyn Conwy	3	LA, D
35650	Llyn Irddyn	3	LA, D
37834	Llynoedd Ieuan	3	LA, D
38544	Llyn Fanod	3	LA, D
	Loughaunayella	3	LA, D
	Lough Veagh	3	LA, D
7166	Loch Cùl Fraioch	3	LA, Sh
7669	Loch na Gaineimh	3	LA, Sh
9070	Lochan Feòir	3	LA, Sh
11238	Loch na Beiste	3	LA, Sh
21557	Unnamed H	3	LA, Sh
33861	Llyn y Foel-frech	3	LA, Sh
33862	Llyn Bochlwyd	3	LA, Sh
35233	Gloyw Llyn	3	LA, Sh
35439	Llyn y Bi	3	LA, Sh
35550	Llyn Dulyr	3	LA, Sh
37080	Llyn Glanmerin	3	LA, Sh
38422	Llyn Eiddwen	3	LA, Sh
38525	Llyn Gynon	3	LA, Sh
8293	Loch Bealach a' Bhùirich	3	MA, D
14935	Loch Skealtair (Sgealtair)	3	MA, D
18767	Loch Ness	3	MA, D
19494	Loch Iain Oig	3	MA, D
10307	Loch Dubh Cadhafuaraich	3	P, Sh
41210	Llyn Fach	3	P, Sh
14057	Loch Maree	4	LA, D
21191	Loch Einich	4	LA, D
21790	Loch Muick	4	LA, D
27604	Loch Doon	4	LA, D
27948	Loch Dee	4	LA, D
34002	Llyn Cwellyn	4	LA, D
36182	Llyn y Gadair	4	LA, D
36267	Llyn Cau	4	LA, D
21925	Loch Shiel	4	MA, D
1753	Loch of Harray	5	HA, Sh
14019	Loch Eye	5	HA, Sh
45652	Hatchet Pond	5	HA, Sh
19381	Loch Meiklie	5	LA, D
4435	Un-Named	5	LA, Sh
26162	Loch nan Cadhan	5	MA, D
14593	Bayfield Loch	5	MA, Sh
14677	Loch Grogary (Croghearraidh)	5	MA, Sh
20108	Loch Cill Chriosd	5	MA, Sh
21123	Loch Davan	5	MA, Sh
21189	Loch Kinord	5	MA, Sh
34622	Llyn Glasfryn	5	MA, Sh
46102	Little Sea Mere	5	MA, Sh
35046	Clarepool Moss	5	P, Sh
24851	Loch Rusky	6	HA, D
27867	Mill Loch	6	HA, D
1678	Loch of Swannay	6	HA, Sh
4444	Loch Hempriggs	6	HA, Sh
16456	Loch Ussie	6	HA, Sh
20633	Loch Tarff	6	LA, D
22782	Loch Rannoch	6	LA, D
24447	Loch Lomond North Basin	6	LA, D
24447	Loch Lomond South Basin	6	LA, D
24459	Loch Lubnaig	6	LA, D
27309	St Marys Loch	6	LA, D
28986	Loveswater	6	LA, D

29000	Crummock Water	6	LA, D
29052	Buttermere	6	LA, D
29183	Wast Water	6	LA, D
34987	Lake Bala or Llyn Tegid	6	LA, D
35035	Llyn Eiddew Bach	6	LA, D
40297	Llyn y Fan Fawr	6	LA, D
1674	Muckle Water	6	MA, D
20197	Loch Lonachan	6	MA, D
23531	Loch of Butterstone	6	MA, D
23553	Marlee Loch	6	MA, D
23557	Loch of Craiglush	6	MA, D
23559	Loch of Lowes	6	MA, D
23561	Loch of Clunie	6	MA, D
24025	Loch Awe North Basin	6	MA, D
24025	Loch Awe South Basin	6	MA, D
24132	Loch Earn	6	MA, D
24919	Lake of Menteith	6	MA, D
24996	Loch Eck	6	MA, D
28847	Bassenthwaite Lake	6	MA, D
28955	Ullswater	6	MA, D
29328	Esthwaite Water	6	MA, D
	Lough Patrick	6	MA, D
	Lattone Lough	6	MA, D
	Lough Scolban	6	MA, D
26566	Kilbirnie Loch	6	MA, Sh
35738	Martham South Broad	7	B, Sh
14403	Loch Achnacloich	7	HA, D
24843	Loch Leven	7	HA, D
32761	Llyn yr Wyth Eidion	7	HA, D
36566	Betton Pool	7	HA, D
	Lough Augher	7	HA, D
24933	Loch Watston	7	HA, Sh
26392	Castle Semple Loch	7	HA, Sh
27398	Martnaham Loch	7	HA, Sh
28336	Carlingwark Loch	7	HA, Sh
30244	Hornsea Mere	7	HA, Sh
32435	Llyn Llygeirian	7	HA, Sh
32787	Melchett Mere	7	HA, Sh
34827	Felbrigg Lake	7	HA, Sh
35655	Barton Broad	7	HA, Sh
35953	Wroxham Broad	7	HA, Sh
35981	Rollesby Broad	7	HA, Sh
36202	Upton Broad	7	HA, Sh
39683	Eleven Acre Lake	7	HA, Sh
40067	Llangorse Lake	7	HA, Sh
40608	Marsworth Reservoir	7	HA, Sh
41973	Oxwich Pool	7	HA, Sh
44031	Frensham Great Pond	7	HA, Sh
45108	Burton Mill Pond	7	HA, Sh
46472	Slapton Ley	7	HA, Sh
8975	Loch Bealach na h-Uidhe	7	LA, Sh
9145	Lochan Fleodach Coire	7	LA, Sh
24998	Black Loch	7	MA, D
25000	Loch Glow	7	MA, D
26217	Loch Lossit	7	MA, D
36544	Bomere Pool	7	MA, D
20757	Loch of Skene	7	MA, Sh
24742	Loch Mahaick	7	MA, Sh
32961	Llyn Helyg	7	MA, Sh
39796	Talley Upper	7	MA, Sh
39813	Talley Lower	7	MA, Sh
	Lough Vearty	7	MA, Sh
2161	Loch Borrallie	7	Marl, D
29479	Semer Water	7	Marl, D
29647	Hawes Water	7	Marl, D
2176	Loch Caladail	7	Marl, Sh
27494	Branxhome Easter Loch	7	Marl, Sh
28165	Greenlee Lough	7	Marl, Sh
28172	Broomlee Lough	7	Marl, Sh

29844	Malham Tarn	7	Marl, Sh
41602	Bosherston Lake, Central	7	Marl, Sh
41602	Bosherston Lake, Lower	7	Marl, Sh
41602	Bosherston Lake, Upper	7	Marl, Sh
32804	Tatton Mere	8	HA, D
35211	Crose Mere	8	HA, D
	Lough Ballywillin	8	HA, D
	Lough Creeve	8	HA, D
	Macnean Upper Lough	8	HA, D
2712	Loch Watten	8	HA, Sh
27899	Castle Loch	8	HA, Sh
34780	Hanmer Mere	8	HA, Sh
	Tongree (Upper Lough Erne)	8	HA, Sh
	Lough Allen	8	MA, D
	Lough Brantry	8	MA, D
	Lough Corbet	8	MA, D
	Friary Lough	8	MA, D
	Lough Heron	8	MA, D
	Lough Oughter	8	MA, D

Appendix 4

Squared chord distance dissimilarity scores between the 219 core tops and reference samples analysed in work package 1 (lakes are placed in order of increasing dissimilarity score within each GB lake type; reallocated type for those sites misclassified by the GB Lake Typology is given in parentheses)

Sample code	Site name	Grid ref	Squared Chord Distance dissimilarity score	GB_Typology
MART	Martham South Broad	TG 458201	0.711	B, Sh
SCM41	Tatton Mere	SJ755801	0.269	HA, D
WYTH	Llyn yr Wyth Eidion	SH 474819	0.319	HA, D
ACHN	Loch Achnacloch	NH 665736	0.336	HA, D
MACU	Macnean Upper Lough	H 040400	0.429	HA, D
AUGH	Lough Augher	H 560535	0.532	HA, D
MILL	Mill Loch	NY 077833	0.626	HA, D
RUSK	Loch Rusky	NN 615034	0.692	HA, D
BWILL	Lough Ballywillin	J 481532	0.697	HA, D
LEVE	Loch Leven	NO 150025	0.744	HA, D
CREEV	Lough Creeve	H 738512	1.189	HA, D
CROSE	Cröse Mere	SJ 430305	1.278	HA, D
SCM27	Betton Pool	SJ 511079	1.766	HA, D
FREN	Frensham Great Pond	SU 845401	0.156	HA, Sh
BURT	Burton Mill Pond	SU 974175	0.257	HA, Sh
OXWI	Oxwich Pool	SS503872	0.260	HA, Sh
WATT	Loch Watten	ND 229561	0.314	HA, Sh
WATO	Loch Watston	NN 711003	0.323	HA, Sh
LLYG	Llyn Llygeirian	SH 346898	0.340	HA, Sh
TONG	Tongree (Upper Lough Erne)	H 310310	0.417	HA, Sh
UPTO	Upton Broad	TG 388134	0.421	HA, Sh
USSI	Loch Ussie	NH 505574	0.438	HA, Sh
FELB	Felbrigg Lake	TG 191388	0.449	HA, Sh
ELE	Eleven Acre Lake	SP 675369	0.501	HA, Sh
SCM16	Hanmer Mere	SJ 454395	0.540	HA, Sh
HATC	Hatchet Pond	SU 367016	0.579	HA, Sh
MARH	Martnaham Loch	NS394173	0.589	HA, Sh
BART	Barton Broad	TG 363215	0.654	HA, Sh
HARY	Loch of Harray	HY 295155	0.706	HA, Sh
SWAN	Loch of Swannay	HY 304293	0.734	HA, Sh
MELC	Melchett Mere	SJ750811	0.754	HA, Sh
SLT	Slapton Ley	SX 824435	0.758	HA, Sh
ROLL	Rollesby Broad	TG 464142	0.791	HA, Sh
EYE	Loch Eye	NH 830795	0.829	HA, Sh
HORN	Hornsea Mere	TA 190470	0.893	HA, Sh
HIR	Llyn Hir	SN 789675	0.904	HA, Sh (LA, Sh)
CASL	Castle Loch	NY 090815	1.003	HA, Sh
WROX	Wroxham Broad	TG 308165	1.052	HA, Sh
MAR	Marsworth Reservoir	SP 922137	1.090	HA, Sh
CARL	Carlingwark Loch	NX 765615	1.104	HA, Sh
LLAN	Llangorse Lake	SO 132265	1.193	HA, Sh
SEMP	Castle Semple Loch	NS 365590	1.205	HA, Sh
HEMP	Loch Hempriggs	ND 343471	1.340	HA, Sh
MARE	Loch Maree	NG 985675	0.129	LA, D
CRUM	Crummock Water	NY 157188	0.160	LA, D
MWE	Lough Maumwee	L 977485	0.177	LA, D
SAID	Loch Coire na Saidhe Duibhe	NC 450360	0.190	LA, D
LUBN	Loch Lubnaig	NN 585130	0.204	LA, D
FHIO	Lochan Fhionnlaidh	NC 191103	0.214	LA, D

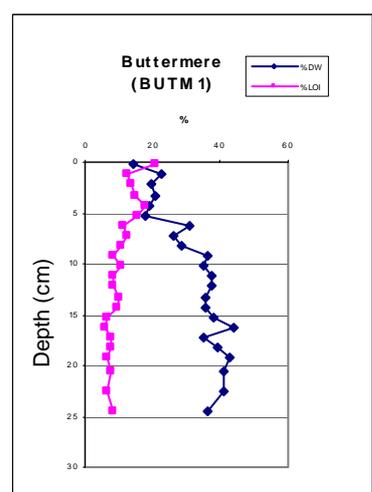
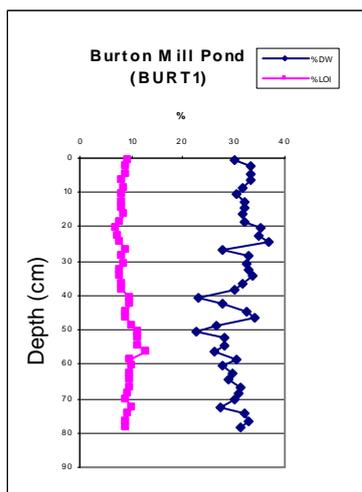
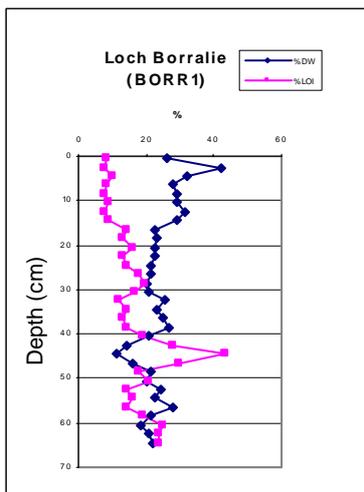
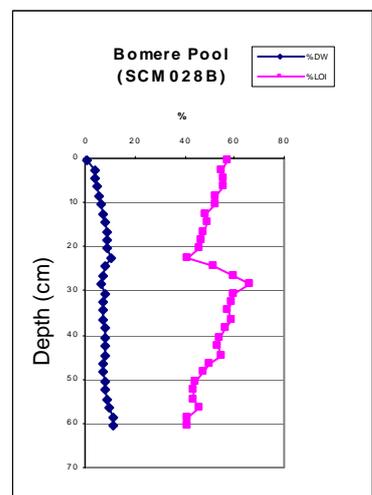
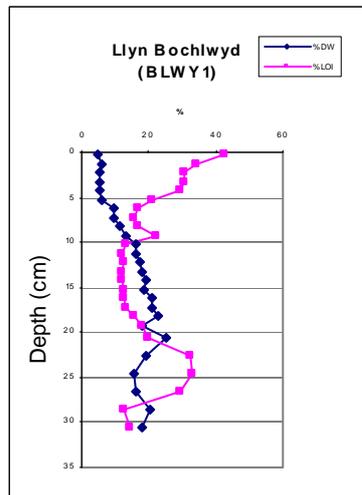
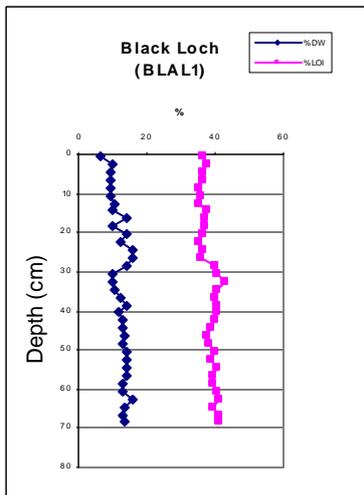
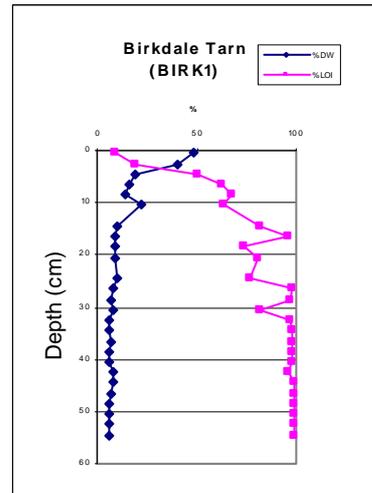
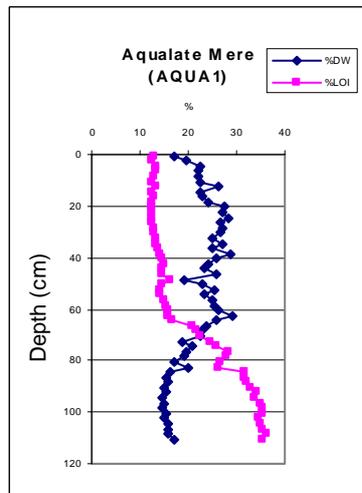
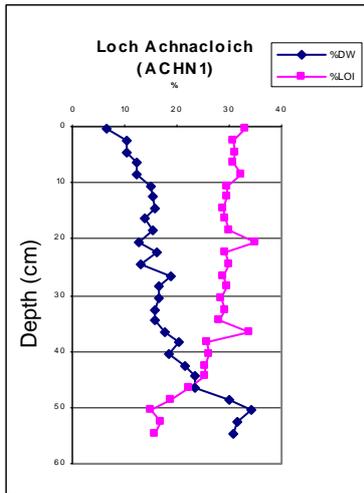
UIS	Loch Uisge	NM 808550	0.218	LA, D
LOMO	Loch Lomond North Basin	NS 365945	0.226	LA, D
NIGH	Lochan Nigheadh	NC182148	0.229	LA, D
MARY	St Marys Loch	NT252229	0.231	LA, D
LOCH	Loch Toll an Lochain	NH 832074	0.232	LA, D
CW030	Llyn Cau	SH 715124	0.234	LA, D
ARR	Loch Coire nan Arr	NG 808422	0.246	LA, D
CW021	Llyn y Fan Fawr	SN 831217	0.246	LA, D
LAMH	Loch a' Mhadaidh	NH 199732	0.249	LA, D
RANN	Loch Rannoch	NN 610580	0.253	LA, D
TARF	Loch Tarff	NH 425100	0.265	LA, D
TEAN	Loch Teanga	NF 818383	0.286	LA, D
IDWA	Llyn Idwal	SH 645596	0.314	LA, D
VEAG	Lough Veagh	C 018212	0.339	LA, D
CUAR	Loch nan Cuaran	NC 292238	0.343	LA, D
DOI	Loch Doilet	NM 808678	0.349	LA, D
UAI	Lochan Uaine	NO 001981	0.363	LA, D
MAAM	Lough Maam	B 927159	0.367	LA, D
SKE	Loch Skerrow	NX 605682	0.371	LA, D
CREI	Loch na Creige Duibhe	NC 005118	0.385	LA, D
DUH	Dubh Loch	NO 238828	0.400	LA, D
BEIS	Loch na Béiste	NG 885943	0.403	LA, D
MEIK	Loch Meiklie	NH434301	0.427	LA, D
LAI	Loch Laidon	NN 380542	0.427	LA, D
DUBH	Lochanan Dubha	NC 147055	0.431	LA, D
GLAS	Llyn Glas	SH 601547	0.435	LA, D
WAST	Wast Water	NY 165060	0.436	LA, D
COR	Loch Coire an Lochan	NH 943004	0.438	LA, D
KEMP	Loch Kemp	NH 612323	0.469	LA, D
BUTM	Buttermere	NY 182157	0.476	LA, D
EINI	Loch Einich	NN 913990	0.483	LA, D
LNEI	Loch nan Eion	NG 925508	0.491	LA, D
LACH	Lochan Lairig Cheile	NN 558278	0.493	LA, D
EIB	Llyn Eiddew Bach	SH 646345	0.509	LA, D
IRD	Llyn Irddyn	SH 630220	0.511	LA, D
NELD	Loch Neldricken	NX445829	0.520	LA, D
FNOD	Llyn Fanod	SH 603643	0.521	LA, D
NARR	Loch Narroch	NX 453816	0.531	LA, D
LOWS	Lweswater	NY 126217	0.537	LA, D
MUIC	Loch Muick	NO 290830	0.542	LA, D
HAIR	Loch na h'Airbhe	NH 103924	0.542	LA, D
CORN	Loch Bealach Cornaidh	NC 208282	0.549	LA, D
MUIG	Loch Muighbhlairaidh	NH 635830	0.555	LA, D
CW027	Llyn Mymbyr	SH 708574	0.566	LA, D
LAR	Loch na Larach	NC 217583	0.577	LA, D
RLGH	Round Loch of Glenhead	NX 450804	0.579	LA, D
CON	Llyn Conwy	SH780463	0.596	LA, D
LCFR	Loch Coire Fionnaraich	NG 945498	0.602	LA, D
TUN	Tunnel End Reservoir	SE 037121	0.603	LA, D
LYEL	Loughaunayella	M 101310	0.621	LA, D
VAL	Loch Valley	NX 445817	0.648	LA, D
LOMO	Loch Lomond South Basin	NS 365945	0.662	LA, D
CLYD	Llyn Clyd	SH 635587	0.675	LA, D
NAGA	Lochnagar	NO 252859	0.677	LA, D
ENN	Ennerdale Water	NY 110150	0.679	LA, D
EUN	Loch nan Eun	NO 230854	0.732	LA, D
LDE	Loch Dee	NX 470790	0.745	LA, D
BOGA	Loch nam Badan Boga	NH 099930	0.766	LA, D
SGAM	Loch Sgamhain	NH 100530	0.766	LA, D
BALA	Lake Bala or Llyn Tegid	SH 905347	0.771	LA, D
BLU	Blue Lough	J 328252	0.775	LA, D

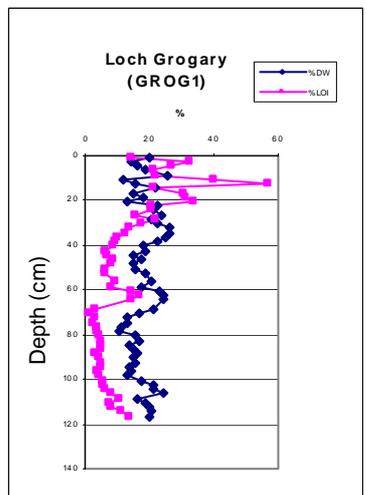
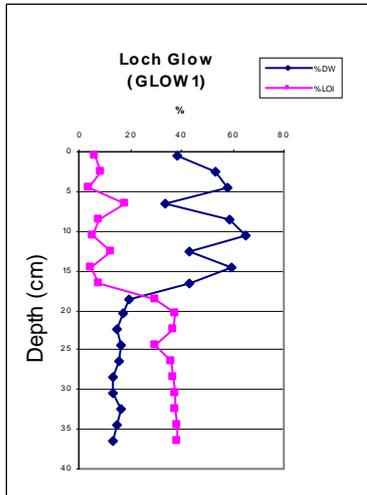
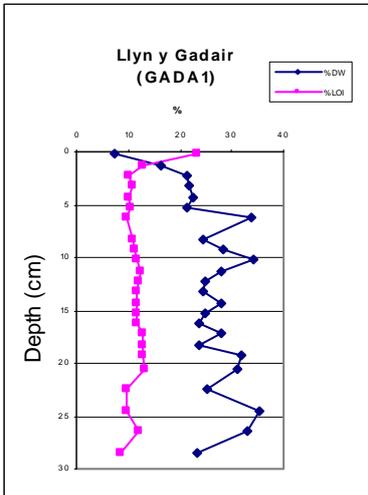
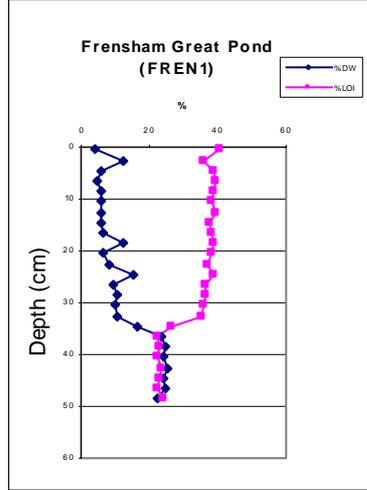
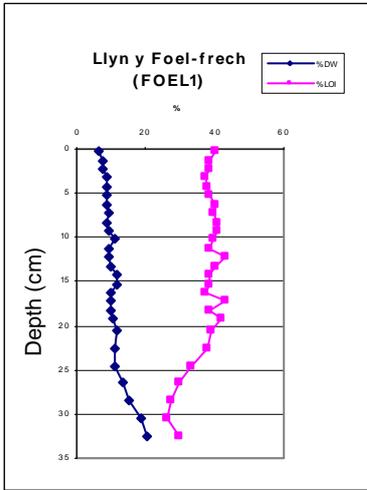
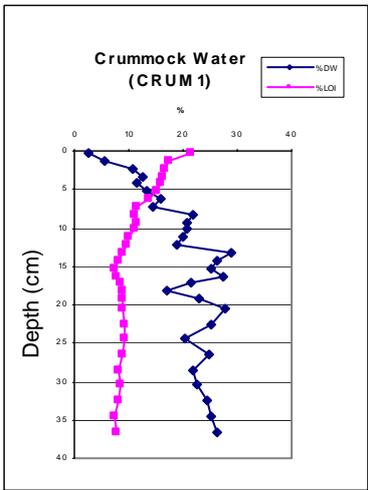
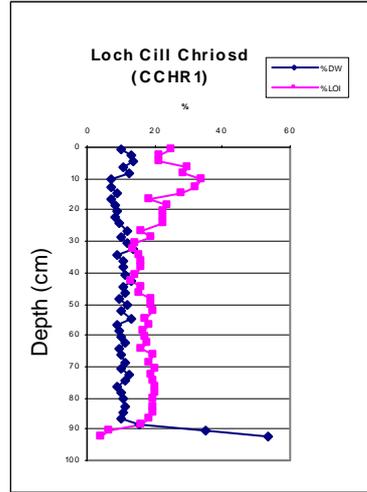
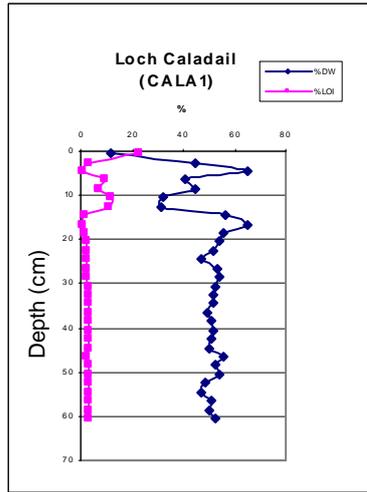
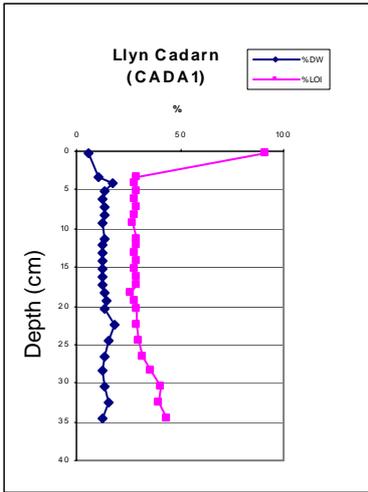
CWEL	Llyn Cwellyn	SH 560549	0.803	LA, D
CW024	Llyn Alwen	SH 898567	0.830	LA, D
CHAM	Loch a Cham Alltain	NC 283446	0.833	LA, D
CHN	Loch Chon	NN 421051	0.856	LA, D
RLDN	Round Loch of the Dungeon	NX 466846	0.873	LA, D
LGR	Loch Grannoch	NX 541691	0.907	LA, D
LMCK	Lough Muck	B 958083	0.909	LA, D
TINK	Loch Tinker	NN 445068	0.921	LA, D
LAG	Llyn Llagi	SH 649483	0.968	LA, D
CRIC	Loch na Cric	NC 166037	1.020	LA, D
OAKM	Oak Mere	SJ 575678	1.132	LA, D
LON	Long Loch	ND 204759	1.145	LA, D
DOON	Loch Doon	NX 495985	1.208	LA, D
IEU	Llynoedd Ieuan	SN 794812	1.388	LA, D
GADA	Llyn y Gadair	SH 707135	1.396	LA, D
NABE	Loch na Beiste	NC 004125	0.266	LA, Sh
FEOI	Lochan Feòir	NC 229252	0.271	LA, Sh
BHAI	Loch Coire a' Bhaic	NC 247295	0.303	LA, Sh
LOD	Lochan Dubh	NM 895710	0.304	LA, Sh
UN02	Un-Named	NC 168478	0.329	LA, Sh
BHAR	Loch Bharranch	NG 977575	0.334	LA, Sh
GAIN	Loch na Gaineimh	NC 765304	0.335	LA, Sh
MYN	Llyn Cwm Mynach	SH 678238	0.336	LA, Sh
NAHU	Loch Bealach na h-Uidhe	NC 264256	0.359	LA, Sh
CNAM	Loch Coire nan Chàmh	NG 974038	0.370	LA, Sh
NEUN	Loch nan Eun	NC 232298	0.379	LA, Sh
GRUA	Loch na Gruagaich	NC 243158	0.404	LA, Sh
HHHH	Unnamed H	NO 653909	0.482	LA, Sh
DALL	Loch Dallas	NJ 092475	0.501	LA, Sh
FLEO	Lochan Fleodach Coire	NC 275248	0.534	LA, Sh
CW017	Llyn Llech Owain	SN 569151	0.538	LA, Sh
CW009	Llyn Glanmerin	SN 755991	0.601	LA, Sh
CULF	Loch Cùl Fraioch	NC 025330	0.614	LA, Sh
CRAN	Cranmer Pond	SU 794324	0.645	LA, Sh
GYN	Llyn Gynon	SN 800647	0.651	LA, Sh
DUL	Llyn Dulyn	SH 662244	0.721	LA, Sh
DCAL	Loch Dubh Camas an Lochain	NG 871972	0.748	LA, Sh
EIDW	Llyn Eiddwen	SN 606670	0.774	LA, Sh
MHIC	Loch Mhic Leoid	NJ 008347	0.866	LA, Sh
WOOL	Woolmer Pond	SU 788321	0.871	LA, Sh
CW028	Gloyw Llyn	SH 647298	1.002	LA, Sh
FOEL	Llyn y Foel-frech	SH 919593	1.149	LA, Sh
BLWY	Llyn Bochlwyd	SH 654593	1.253	LA, Sh
YBI	Llyn y Bi	SH 670265	1.346	LA, Sh
LONA	Loch Lonachan	NG 626189	0.228	MA, D
SHIE	Loch Shiel	NM 866771	0.244	MA, D
IOIG	Loch Iain Oig	NG 792292	0.258	MA, D
LOSG	Loch Bad an Losguinn	NH 158038	0.262	MA, D (LA, D)
ULLS	Ullswater	NY425204	0.277	MA, D
HUID	Loch Bealach a' Bhùirich	NC 264256	0.283	MA, D
CRAI	Loch of Craiglush	NO 042444	0.324	MA, D
NCAD	Loch nan Cadhan	NR404668	0.377	MA, D
ECK	Loch Eck	NS 141939	0.423	MA, D
BLAL	Black Loch	NT 075961	0.430	MA, D
LOSS	Loch Lossit	NR408652	0.443	MA, D
ENO	Loch Enoch	NX 446853	0.472	MA, D (LA, D)
NESS	Loch Ness	NH 535295	0.472	MA, D
OUGH	Lough Oughter	54o 01' N, 8o 25'W	0.515	MA, D
BRAN	Lough Brantry	H749539	0.553	MA, D
ALLN	Lough Allen	54o 05' N, 8o 05'W	0.564	MA, D
LATT	Lattone Lough	H 001455	0.565	MA, D

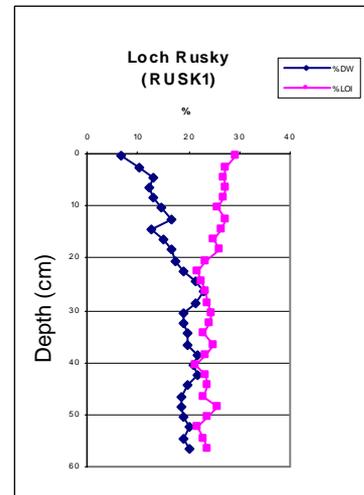
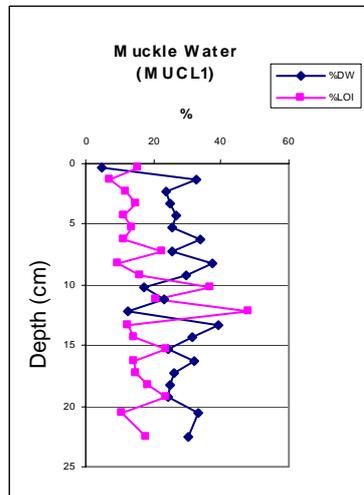
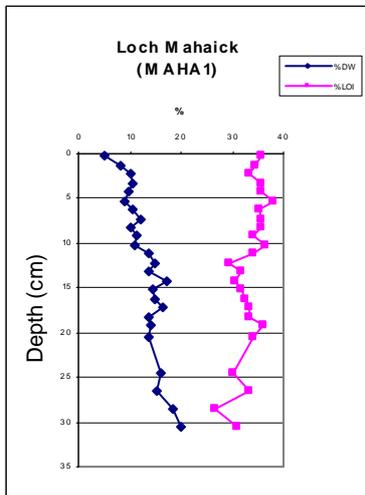
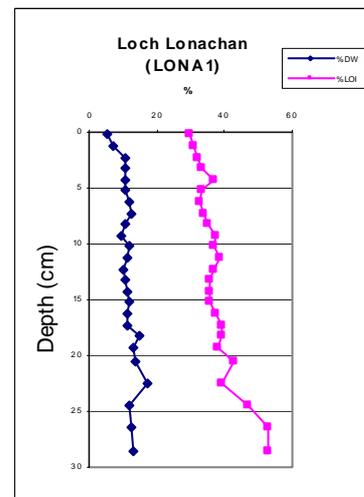
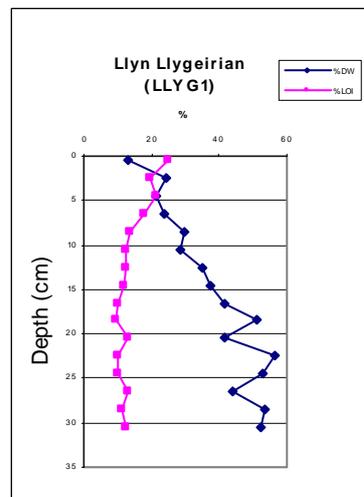
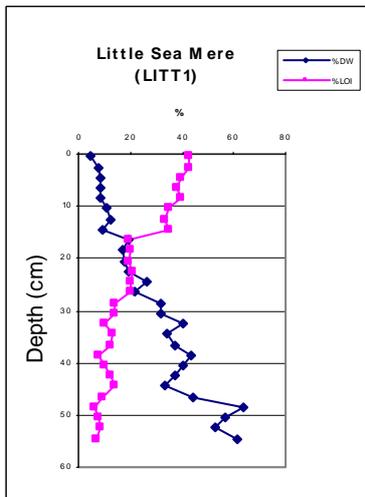
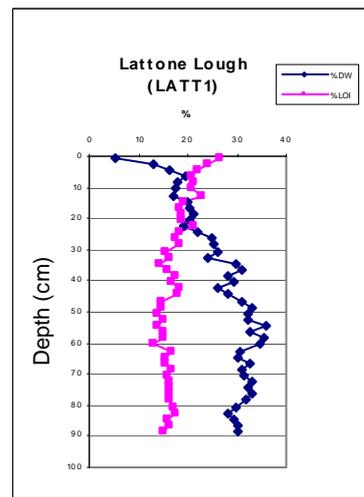
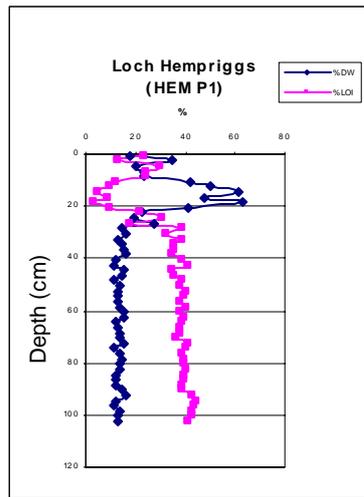
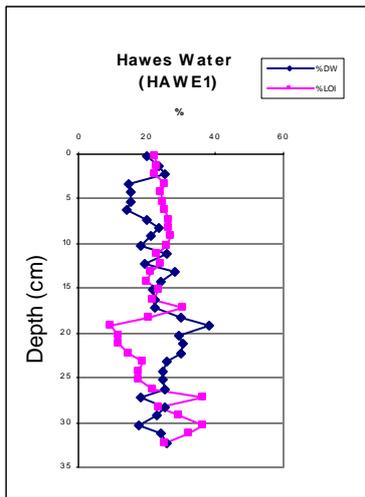
SCOL	Lough Scolban	G 995605	0.585	MA, D
MUCL	Muckle Water	HY 395300	0.621	MA, D
SKEA	Loch Skealtar (Sgealtair)	NF 897686	0.634	MA, D
CORB	Lough Corbet	J181449	0.638	MA, D
AWE	Loch Awe North Basin	NM 930 065	0.640	MA, D
BUTT	Loch of Butterstone	NO 058449	0.672	MA, D
CLUN	Loch of Clunie	NO 115442	0.729	MA, D
AWE	Loch Awe South Basin	NM 930 065	0.746	MA, D
FRIAR	Friary Lough	H748558	0.810	MA, D
MARL	Marlee Loch	NO 145443	0.883	MA, D
SCM28	Bomere Pool	SJ 498080	0.903	MA, D
MENT	Lake of Menteith	NN 580005	0.950	MA, D
GLOW	Loch Glow	NT 087957	0.956	MA, D
BASS	Bassenthwaite Lake	NY 214296	0.978	MA, D
HERON	Lough Heron	J410502	0.990	MA, D
LOWE	Loch of Lowes	NO 049439	1.177	MA, D
ESTH	Esthwaite Water	SD 358969	1.342	MA, D
PATR	Lough Patrick	H884193	1.398	MA, D
EARN	Loch Earn	NN 640235	1.616	MA, D
CCHR	Loch Cill Chriosd	NG 611205	0.299	MA, Sh
KINO	Loch Kinord	NO 442995	0.301	MA, Sh
LITT	Little Sea Mere	SZ 029846	0.317	MA, Sh
CW015	Talley Lower	SN 632337	0.526	MA, Sh
DAVA	Loch Davan	NJ 442007	0.535	MA, Sh
MAHA	Loch Mahaick	NN 706068	0.603	MA, Sh
HELY	Llyn Helyg	SJ112772	0.706	MA, Sh
BAYL	Bayfield Loch	NH821718	0.752	MA, Sh
GROG	Loch Grogary (Croghearraidh)	NF 716711	0.832	MA, Sh
SKEN	Loch of Skene	NJ 785075	0.867	MA, Sh
CW014	Talley Upper	SN 633332	0.909	MA, Sh
GLFR	Llyn Glasfryn	SH 402422	0.938	MA, Sh
VEAR	Lough Vearty	G 994658	0.991	MA, Sh
KILB	Kilbirnie Loch	NS 330545	1.368	MA, Sh
SEME	Semer Water	SD 918874	0.320	Marl, D
HAWE	Hawes Water	SD 477766	0.502	Marl, D
BORR	Loch Borralie	NC 381 668	0.843	Marl, D
BOSHEU	Bosherston Lake, Upper	SR 978960	0.404	Marl, Sh
BROL	Broomlee Lough	NY790697	0.497	Marl, Sh
MALH	Malham Tarn	SD 895667	0.516	Marl, Sh
GREE	Greenlee Lough	NY 774698	0.538	Marl, Sh
BRAX	Branxhome Easter Loch	NT434118	0.709	Marl, Sh
BOSHEL	Bosherston Lake, Lower	SR 978952	0.717	Marl, Sh
BOSHC	Bosherston Lake, Central	SR 976946	0.747	Marl, Sh
CALA	Loch Caladail	NC 396666	0.996	Marl, Sh
BER	Llyn Berwyn	SN 743568	0.828	P, D
CW018	Llyn Fach	SN 905370	0.578	P, Sh
CLAP	Clarepool Moss	SJ 435343	1.091	P, Sh
CADH	Loch Dubh Cadhafuaraich	NC 682183	1.251	P, Sh

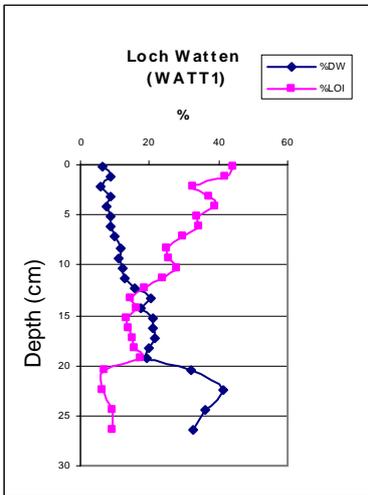
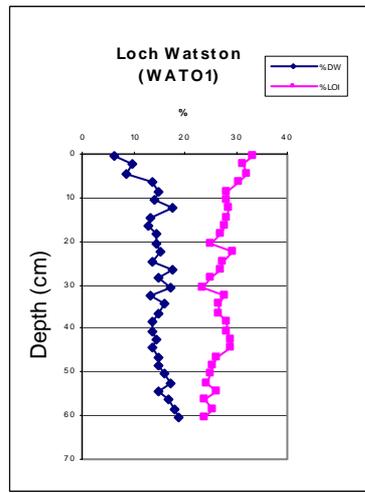
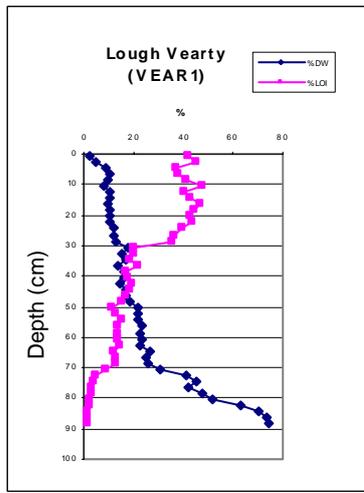
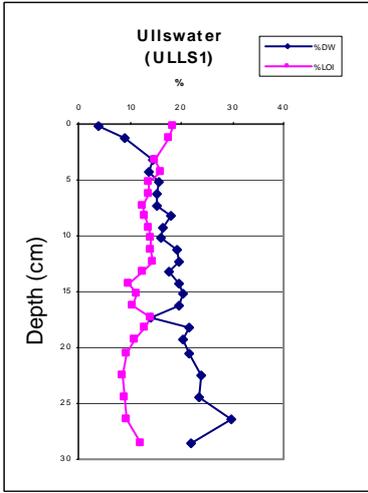
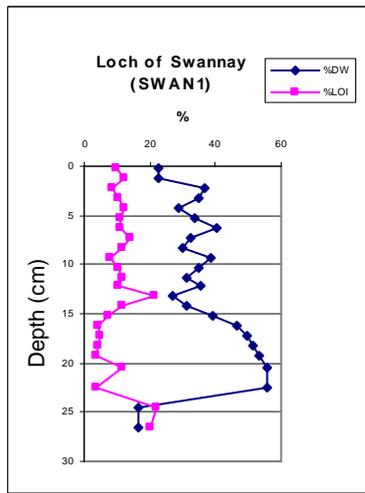
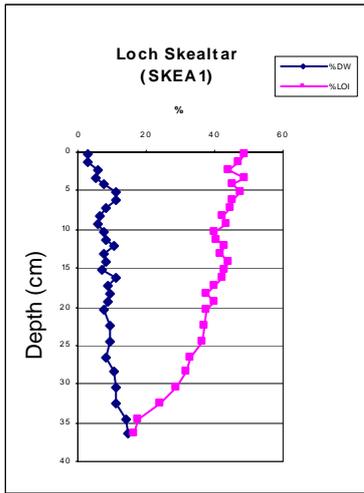
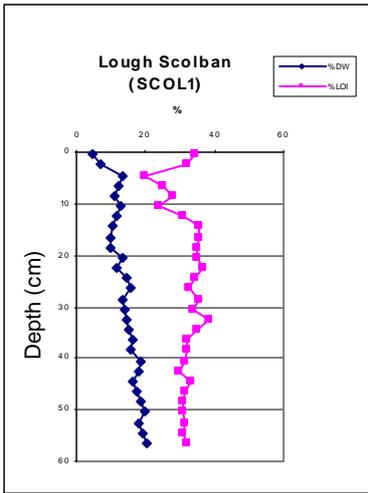
Appendix 5

Profiles of % dry weight (%DW) and % loss on ignition (%LOI) for the 34 cores taken in work package 2 (cores are ordered alphabetically by lake name)









Appendix 6

Diatom transfer function results for lakes in work package 2

a) Diatom-inferred pH (DI-pH) values based on the SWAP training set

Sample Code	Depth (cm)	DI-pH	No. taxa in sample	% of taxa in sample present in the training set
BLWY00	0	5.2	24	87
BLWY05	5	5.4	26	90
BLWY10	10	5.7	35	90
BLWY25	25	5.8	49	71
BLWY30	30	5.9	36	83
BUTM00	0	6.8	46	81
BUTM05	5	6.7	33	84
BUTM10	10	7.1	41	90
BUTM15	15	7.2	37	92
BUTM24	24	7.1	41	90
CRUM00	0	7.3	26	70
CRUM05	5	7.3	36	82
CRUM10	10	7.3	39	81
CRUM20	20	7.3	31	74
CRUM36	36	7.3	28	78
FOEL00	0	6.5	35	88
FOEL05	5	6.6	28	81
FOEL10	10	6.6	20	87
FOEL25	25	6.3	28	85
FOEL32	32	5.9	45	76
GADA00	0	5.0	21	92
GADA05	5	5.2	13	92
GADA10	10	5.7	21	99
GADA28	28	7.2	15	98
GADA29	29	7.2	16	98

b) Diatom-inferred total phosphorus (TP $\mu\text{g l}^{-1}$) values based on the Northwest European training set

Sample Code	Depth (cm)	DI-TP	No. taxa in sample	% of taxa in sample present in the training set
BLWY00	0	2	23	67
BLWY05	5	2	25	88
BLWY10	10	4	34	91
BLWY25	25	5	48	71
BLWY30	30	5	36	83
BORR00	0	71	38	89
BORR10	10	33	31	83
BORR20	20	91	24	87
BORR30	30	97	29	86
BORR50	50	154	13	92
BORR60	60	143	14	91
CALA00	0	27	23	86
CALA05	5	120	18	88
CALA10	10	82	30	83
CCHR00	0	18	31	91
CCHR20	20	20	34	92
CCHR40	40	36	35	85
CCHR60	60	23	34	93
CCHR80	80	20	41	92
FOEL00	0	19	34	87
FOEL05	5	20	28	84
FOEL10	10	19	20	90
FOEL25	25	27	27	85
FOEL32	32	5	44	74
GROG000	0	56	26	96
GROG020	20	39	37	93
GROG040	40	29	34	94
GROG100	100	14	44	96
GROG116	116	15	42	89
HAVE00	0	33	32	95
HAVE05	5	18	25	95
HAVE10	10	47	30	97
HEMP00	0	35	30	94
HEMP10	10	49	49	90
HEMP20	20	74	46	81
HEMP40	40	66	43	78
HEMP80	80	21	43	70
LITT00	0	47	20	95
LITT05	5	44	26	93
LITT10	10	40	26	94
RUSK00	0	28	36	94
RUSK10	10	19	50	89
RUSK20	20	21	54	90
RUSK30	30	16	57	89
RUSK56	56	16	53	88
SCOL00	0	24	46	93
SCOL10	10	26	51	92
SCOL20	20	22	45	90

SCOL30	30	21	50	87
SCOL50	50	24	48	87
SKEA00	0	11	30	90
SKEA05	5	12	40	90
SKEA15	15	12	37	90
SKEA30	30	11	38	91
SKEA37	37	10	39	77
SWAN00	0	41	46	92
SWAN05	5	25	45	91
SWAN10	10	23	47	90
SWAN15	15	28	50	86
VEAR00	0	23	45	85
VEAR10	10	20	56	79
VEAR20	20	18	50	82
VEAR30	30	85	36	84
VEAR60	60	86	41	95

c) Diatom-inferred total phosphorus (TP $\mu\text{g l}^{-1}$) values based on the large lakes training set

Sample Code	Depth (cm)	DI-TP	No. taxa in sample	% of taxa in sample present in the training set
ACHN00	0	25	48	94
ACHN10	10	25	46	94
ACHN20	20	20	53	91
ACHN30	30	26	49	95
ACHN40	40	27	48	86
BLAL00	0	21	53	81
BLAL10	10	20	58	84
BLAL20	20	17	55	86
BLAL40	40	17	54	82
BLAL68	68	18	44	85
BURT00	0	34	32	90
BURT05	5	31	27	93
BURT10	10	39	23	90
BURT60	60	35	29	77
BURT70	70	30	26	78
BUTM00	0	8	46	91
BUTM05	5	7	33	91
BUTM10	10	7	41	94
BUTM15	15	8	37	96
BUTM24	24	7	41	93
CRUM00	0	11	26	97
CRUM05	5	8	36	93
CRUM10	10	9	39	93
CRUM20	20	11	31	96
CRUM36	36	12	28	98
FREN00	0	45	35	95
FREN05	5	44	28	97
FREN10	10	42	32	95
FREN20	20	42	28	95
FREN30	30	43	27	96
GADA00	0	2	21	75

GADA05	5	1	13	72
GADA10	10	2	21	88
GADA28	28	5	15	93
GADA29	29	5	16	93
GLOW00	0	12	41	90
GLOW10	10	24	35	67
GLOW20	20	19	53	85
GLOW30	30	17	58	88
GLOW36	36	20	44	88
LATT00	0	19	34	96
LATT10	10	22	48	89
LATT20	20	19	46	85
LATT30	30	19	45	90
LATT40	40	16	51	81
LLYG00	0	44	26	91
LLYG05	5	42	37	93
LLYG10	10	39	36	95
LLYG20	20	38	28	96
LONA00	0	8	34	86
LONA05	5	8	40	82
LONA10	10	8	34	86
LONA20	20	8	34	88
LONA30	30	9	52	89
MAHA00	0	31	41	88
MAHA05	5	30	39	79
MAHA10	10	29	47	80
MAHA25	25	21	47	85
MAHA30	30	23	44	85
MUCL00	0	15	47	78
MUCL05	5	12	47	84
MUCL10	10	15	51	86
MUCL15	15	17	57	81
MUCL23	23	14	47	86
SCM2800	0	17	29	96
SCM2810	10	22	28	97
SCM2820	20	27	37	97
SCM2840	40	20	27	98
SCM2860	60	22	30	91
ULLS00	0	15	25	97
ULLS05	5	14	32	98
ULLS10	10	13	26	98
ULLS15	15	10	32	96
ULLS20	20	11	18	100
WATO00	0	39	33	96
WATO10	10	40	31	97
WATO20	20	38	35	98
WATO30	30	38	30	95
WATO50	50	32	37	96
WATT00	0	33	41	88
WATT05	5	32	37	89
WATT10	10	30	39	85
WATT15	15	31	48	80