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Palaeoecological study of Lochs Arkaig, Huamavat and Shiel

Final Report to Marine Harvest

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Executive summary

This is the final report to Marine Harvest on the ‘Palaeoecological study of Lochs Arkaig, Huamavat and Shiel’. The primary objective was to examine the diatom assemblages in sediment cores to assess the trophic status of the three lochs over approximately the last 100-150 years, and to determine conditions prior to the installation of fish farms at these sites.

Short sediment cores were collected from the deep basin of three lochs, Loch Arkaig, Loch Huamavat and Loch Shiel, in February 2007. The cores were extruded in the field, stratigraphic changes were noted and the percentage dry weight and organic matter content of each core were subsequently determined in the laboratory. Sediment samples from each core were analysed for ^{210}Pb, ^{226}Ra, ^{137}Cs and ^{241}Am by direct gamma assay in order to provide radiometric dates. The results indicate that the sediment cores from Lochs Arkaig, Huamavat and Shiel cover a period of approximately 200, 120 and 150 years, respectively.

Diatom preservation was good in all cores and six samples were analysed from each site. The main taxa in the diatom records of all three lochs were present in an existing diatom phosphorus training set developed for deep lakes and therefore the transfer function was applied to reconstruct diatom-inferred total phosphorus (DI-TP) concentrations.

The results show that all three lochs were oligotrophic during the nineteenth century with baseline DI-TP concentrations of ~4-6 $\mu g\ l^{-1}$. Of the three lochs, only Loch Arkaig has experienced marked changes in the diatom flora indicative of eutrophication, with an associated increase in DI-TP to values of 9-11 $\mu g\ l^{-1}$. The timing of these changes occurs between 1980 and 1998 but, owing to the low resolution of the study, the exact date of onset of enrichment cannot be determined. Notwithstanding the limitations of the data, the major shifts have occurred post-1980 and are therefore coincident with the arrival of the fish farm in 1986.

At Lochs Huamavat and Shiel, the diatom changes are minor and therefore the palaeoecological data suggest that fish farm production has not had an adverse influence on the diatom flora of these two lochs. These sites still appear to be in their original oligotrophic condition. Nevertheless, there are subtle changes towards the top of these cores and continued monitoring is recommended.

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Cover photograph: View across Loch Huamavat, South Harris

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SPECIFICATION

Statement of understanding, purpose and aims of project

The primary objective of this project is to use palaeoecological techniques, principally diatom assemblages, to assess the trophic status of three lochs, Lochs Arkaig, Huamavat and Shiel, over approximately the last 100-150 years and to determine conditions prior to the installation of fish farms at these sites. The focus will be on establishing total phosphorus (TP) concentrations for ~1850 to represent reference conditions, for ~1980 to represent pre-fish farm development, for the mid-1980s onwards following the establishment of the fish farms, and for the surface sample to represent current conditions.

In summary, for each loch, the following was required:

1. Collection of a short (~40 cm) gravity core
2. Sub-sampling and standard sediment analysis (% dry weight, % organic matter, wet density)
3. Radiometric dating (^{210}Pb, ^{137}Cs) to provide a chronology for approximately the last 150 years
4. Preparation and analysis of six diatom samples (standard count of 300 valves per sample)
5. Data entry and taxonomic harmonisation with existing diatom transfer function
6. Reconstruction of past TP concentrations based on the diatom transfer function
7. Data interpretation and reporting alongside the results of a previous core taken from Loch Shiel (SHIE2) in 1998, reported in Bennion *et al.* (2001).

METHODS

Core collection

A short sediment core, approximately 30-40 cm long, was collected from each loch in February 2007 using a Glew gravity coring device. Cores were taken from the deep-water basins and locations were recorded by GPS. Summary details of the cores are given in Table 1.

Extrusion and core description

The cores were extruded in the field at 0.5 cm intervals and any visible stratigraphic changes were noted (Table 1). The percentage dry weight (%DW) which gives a measure of the water content of the sediment, and the percentage loss on ignition (%LOI 550) which gives a measure of the organic matter content, were determined in the laboratory on every sample from each core by standard techniques (Dean, 1974). Wet density was measured on selected samples using a 2cm^3 capacity brass phial in order to facilitate the calculations of sediment accumulation rates once the cores were dated.

Radiometric dating

A reliable method of establishing a chronology for sediment cores is to use radiometric dating techniques (Appleby, 2001). ^{210}Pb occurs naturally in lake sediments as one of the radioisotopes in the ^{238}U decay series. It has a half-life of 22.26 years, making it suitable for dating sediments laid down over the past 100-150 years. The total ^{210}Pb activity in sediments comprises supported and unsupported ^{210}Pb. In most samples the supported ^{210}Pb can be assumed to be in radioactive equilibrium with ^{226}Ra and the unsupported activity at any level of a core is obtained by subtracting the ^{226}Ra activity from the total ^{210}Pb (Appleby *et al*., 1986).

^{210}Pb dates for sediment cores can be calculated using both the constant rate of ^{210}Pb supply (CRS) model and the constant initial ^{210}Pb concentration (CIC) model (Appleby & Oldfield, 1978). The CRS model is most widely accepted; it assumes that the ^{210}Pb supply is dominated by direct atmospheric fallout, resulting in a constant rate of supply of ^{210}Pb from the lake waters to the sediments irrespective of net dry mass accumulation rate changes. If there are interruptions to the ^{210}Pb supply, for example sediment focusing, dates are calculated either by the CIC model or by using a composite of both models. The factors controlling the choice of model are described in full in Appleby & Oldfield (1983).

^{137}Cs (half-life 30 years) and ^{241}Am are artificially produced radionuclides, introduced to the study area by atmospheric fallout from nuclear weapons testing and nuclear reactor accidents. ^{137}Cs activity in sediments prior to the 1986 Chernobyl nuclear accident derives mainly from nuclear weapons testing fallout. Where this isotope is strongly adsorbed on to sediments, the activity versus depth profile is presumed to reflect varying fallout rate and useful chronological markers are provided by the onset of ^{137}Cs fallout in 1954, and peak fallout in 1963.

Sediment samples from each of the cores were analysed for ^{210}Pb, ^{226}Ra, ^{137}Cs and ^{241}Am by direct gamma assay in the Bloomsbury Environment Institute at University College London using either an ORTEC HPGe GWL series well-type, or an ORTEC HPGe LOAX series planar-type, coaxial low background intrinsic germanium detector. Lead-210 was determined via its gamma emissions at 46.5keV, and ^{226}Ra by the 295keV and 352keV gamma rays emitted by its daughter isotope ^{214}Pb following three weeks storage in sealed containers to allow radioactive equilibration. Cesium-137 and ^{241}Am were measured by their emissions at 662kev and 59.5kev.

The absolute efficiencies of the detector were determined using calibrated sources and sediment samples of known activity. Corrections were made for the effect of self absorption of low energy gamma rays within the sample.

The raw data are presented in Appendix 1 and the chronologies are described below.

Diatom analysis

Diatom slides were prepared from selected sub-samples of the three cores using standard techniques (Battarbee *et al*., 2001). Initially, four slides from each core were scanned to assess degree of preservation and to determine whether there were any shifts in the diatom assemblages. Subsequently, six sub-samples from the core, selected to cover the period of interest, were fully analysed. At least 300 valves were counted from each sample using a Leitz research microscope with a 100x oil immersion objective (magnification 1000x) and phase contrast. Principal floras used in identification were Krammer & Lange-Bertalot (1986-1991) although other taxonomic floras and references were employed as necessary. Slides are archived at the ECRC. All diatom data are expressed as percentage relative abundance (% relative abundance) and plots were produced in the software package C^2 (Juggins, 2003).

Indirect ordination techniques (principal components analysis – PCA) (ter Braak & Prentice, 1988) were used to analyse the variance downcore within the diatom assemblages, using CANOCO version 4.5 (ter Braak & Smilauer, 2002). The technique summarises the main floristic changes in the diatom data and helps to identify zones of change within complex species-rich data sets. Prior to the analysis, the diatom assemblage data were square-root transformed to reduce the effect of dominant species within the data and to stabilise the data variance. The sample scores for PCA axis 1 are illustrated in the summary diatom diagrams.

Diatom transfer functions

In recent years, the technique of weighted averaging (WA) regression and calibration, developed by ter Braak (e.g. 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 quantitatively infer lake total phosphorus (TP) concentrations (Hall & Smol, 1999), whereby modern diatom TP optima and tolerances are calculated for each taxon based on their distribution in the training set, and then past TP concentrations are derived from the weighted average of the optima of all diatoms present in a given fossil sample. The methodology and the advantages of WA over other methods of regression and calibration are well documented (e.g. ter Braak & van Dam, 1989).

The reconstructions of diatom-inferred total phosphorus (DI-TP) for Lochs Arkaig, Huamavat and Shiel were produced using a training set of 56 relatively large, deep lakes (> 10 m maximum depth) from Scotland, Northern Ireland, Cumbria, southern Norway and central Europe, with annual mean TP concentrations ranging from 1-73 μg TP l^{-1}, and a median value for the dataset of 22 μg TP l^{-1} (Bennion *et al.,* 2004). The training set contains 139 diatom taxa. The best model was generated with simple WA and inverse deshrinking. The model performs well and has relatively low errors of prediction with an apparent root mean square error (RMSE) and a RMSE of prediction (RMSEP) of 0.20 and 0.25 $\log_{10}$ μg TP l^{-1}, respectively.

The model was applied following taxonomic harmonisation between the training set and core species data. The reconstructions were implemented using C^2 (Juggins, 2003). The TP data used in the models were $\log_{10}$-transformed annual mean concentrations (μg TP l^{-1}) as model performance is improved when the data are logged. However, inferred values have been transformed back to μg TP l^{-1} for the presentation of the results and for the purposes of discussion.

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

NAME	WBID	NGR	CORING DATE	SITE CODE	CORE CODE	CORING WATER DEPTH (M)	CORING LOCATION	CORE LENGTH (CM)	CORE TYPE	CORE NOTES
Loch Arkaig	21490	NN083909	26/02/07	ARKA	ARKA1	90	NN13408, 90012	38	Glew	Good core, flocculant surface, undisturbed top. Taken in east basin approx half a mile east of fish farms at Muich. 0-23 cm dark brown, organic; 23-32 cm light greyish brown, more minerogenic; 32 cm to base mid brown, organic.
Loch Huamavat (Huamnabhat)	13354	NG083883	24/02/07	HUAM	HUAM1	7	NG08328, 88523	32	Glew	Taken north of fish cages. Homogenous, black, peaty, organic; flocculant surface. Abundant plant detritus (*Calluna*?) and live chironomids
Loch Shiel	21925	NM797717	27/02/07	SHIE	SHIE5	105	NM86984, 77549	35	Glew	Taken approx 2 km southwest of nearest fish cages in northeast basin. Good core; undisturbed top. Dark brown, homogenous with orange band at 3-4 cm. Abundant plant remains visible from 31 cm to base

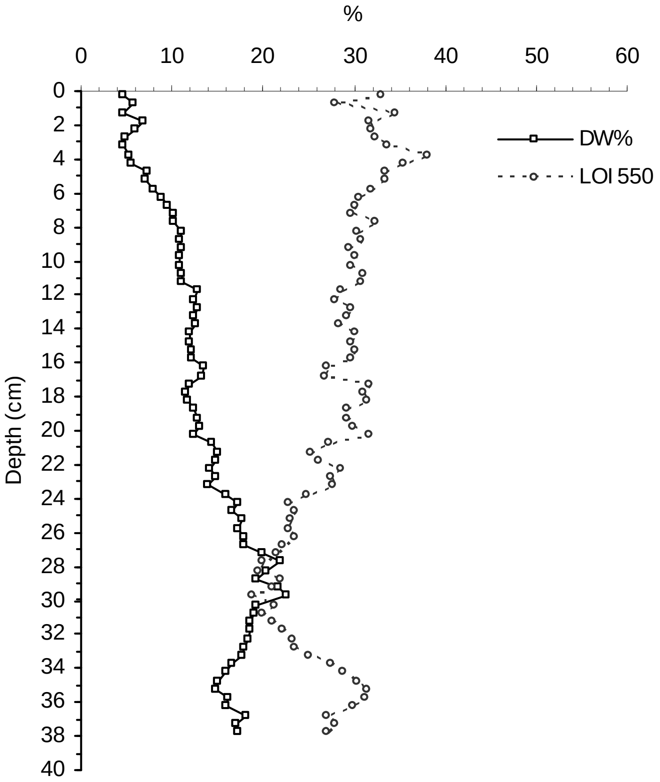
RESULTS AND DISCUSSION

Loch Arkaig, Highland Region

Core description

The 38 cm core, ARKA1, was taken in the eastern basin of the loch in a water depth of ~90 m. There were three clear zones in the core. The upper 23 cm section was dark brown in colour with a relatively high organic matter content of ~30%. The section from 23-32 cm was a light greyish brown with higher clay content and hence lower %LOI values of ~20%. The lowermost section from 32 cm to the core base was mid-brown in colour and relatively organic with %LOI values of ~30% (Figure 1).

Figure 1 Percentage dry weight and organic matter profiles of ARKA1



Radiometric dating

Lead-210 Activity

Total ^{210}Pb activity does not reach equilibrium with the supporting ^{226}Ra in this core (Appendix 1). Unsupported ^{210}Pb activities, calculated by subtracting ^{226}Ra activity from total ^{210}Pb activity, decline more or less exponentially with depth from 4 cm downwards, suggesting that the sedimentation rates in this section are relatively stable (Figure 2). The decline of unsupported ^{210}Pb activities from 4 cm upwards implies that sedimentation rate has been increasing in recent years. High unsupported ^{210}Pb (20888 Bq m^{-2}) indicates a mean ^{210}Pb supply rate of 650 ± 15.8 Bq m^{-2} yr^{-1} which is significantly higher than the estimated atmospheric flux for the European continent.

Artificial Fallout Radionuclides

The ^{241}Am activities versus depths have a well-resolved peak at 12.75 (sample 12.5 – 13 cm) in the core, indicating the 1963 fallout maximum of nuclear weapons testing. The ^{137}Cs activities versus depths have two relatively well-resolved peaks (Figure 2c). High ^{137}Cs concentration at about 12.75 cm confirms the 1963 fallout maximum of the nuclear weapon testing, and the peak at 8.75 cm (sample 8.5 – 9 cm) almost certainly records fallout from the 1986 Chernobyl accident.

Core Chronology

The use of the CIC model was precluded by the non-monotonic nature of the ^{210}Pb data and, therefore, chronological data were calculated using the CRS model (Appleby *et al.*, 1978). The CRS model places 1963 at 13 cm and 1986 in between 8 and 9 cm (Table 2, Figure 3). These two dates are in very good agreement with the ^{137}Cs and ^{241}Am records. The CRS model shows that sedimentation rates were relatively stable from the 1890s to the 1990s, followed by a gradual increase since the 1990s from ~0.027 g cm^{-2} y^{-1} to ~ 0.039 g cm^{-2} y^{-1} at the present day (Table 2). If the sediment accumulation rates are extrapolated beyond the dated section of the core then the core base (38 cm) represents approximately 1800 AD.

Table 2 ARKA1 Chronology

Depth	Drymass	Cum unsupp	Chronology			Sedimentation Rate		
			Date	Age	Std			% Std
cm	g/cm^2	Bq/m^2	AD	yr	±	g/cm^2/yr	cm/yr	±
0	0	20887.7	2007	0				
1	0.0582	19993.3	2006	1	2	0.0392	0.62	4.4
2	0.123	18945.7	2004	3	2	0.0362	0.602	4.1
3	0.1788	18021.5	2002	5	2	0.0343	0.553	3.8
4	0.2384	17056.4	2000	7	2	0.0325	0.496	3.7
5	0.3096	15901.3	1998	9	2	0.0313	0.417	4.3
6	0.3879	14673.1	1996	11	2	0.0298	0.343	4.8
7	0.4873	13129.4	1992	15	2	0.0273	0.285	5.4
8	0.5906	11665.2	1988	19	2	0.0255	0.237	5.6
9	0.7072	10129.4	1984	23	2	0.0259	0.216	4.8
10	0.8305	8722	1979	28	2	0.0253	0.196	5.5
11	0.9623	7434	1974	33	2	0.0259	0.197	6.3
12	1.0954	6320.3	1969	38	2	0.0258	0.192	6.9
13	1.2329	5337.1	1963	44	2	0.0245	0.178	7.8
14	1.3702	4517.5	1958	49	3	0.0263	0.19	9.9
15	1.5082	3839.1	1953	54	3	0.028	0.201	11.8
16	1.6479	3302.1	1948	59	3	0.0293	0.206	13.3
17	1.7892	2829.4	1943	64	4	0.0298	0.206	15
18	1.9358	2396.7	1937	70	5	0.0279	0.187	17
19	2.0824	2030.2	1932	75	5	0.026	0.168	19.1
20	2.2343	1696.5	1926	81	6	0.0245	0.153	21.2
21	2.4025	1361.1	1919	88	8	0.0241	0.149	23.4

22	2.5706	1092	1912	95	10	0.0237	0.145	25.6
23	2.7388	876.1	1905	102	13	0.0233	0.141	27.8
24	2.9069	702.9	1898	109	15	0.0229	0.138	30

Figure 2 Fallout radionuclides in Loch Arkaig core ARKA1 showing (a) total ^{210}Pb, (b) unsupported ^{210}Pb and (c) ^{137}Cs concentrations versus depth

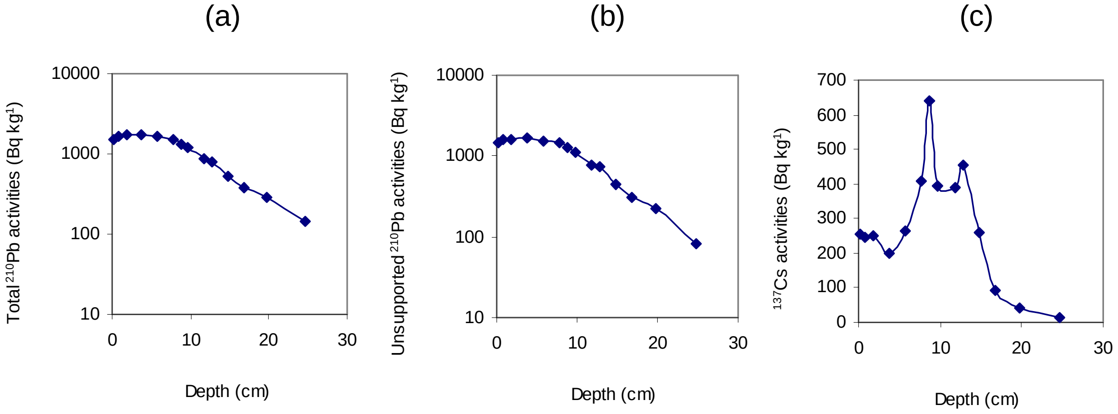
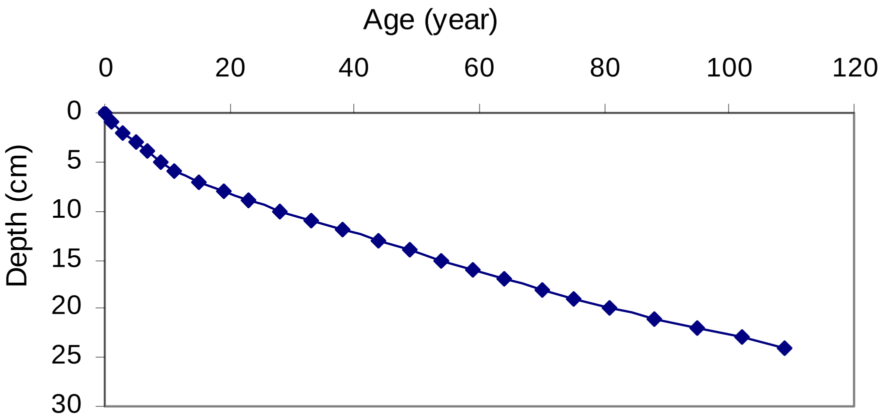


Figure 3 Radiometric chronology of Loch Arkaig core ARKA1



Diatom analyses

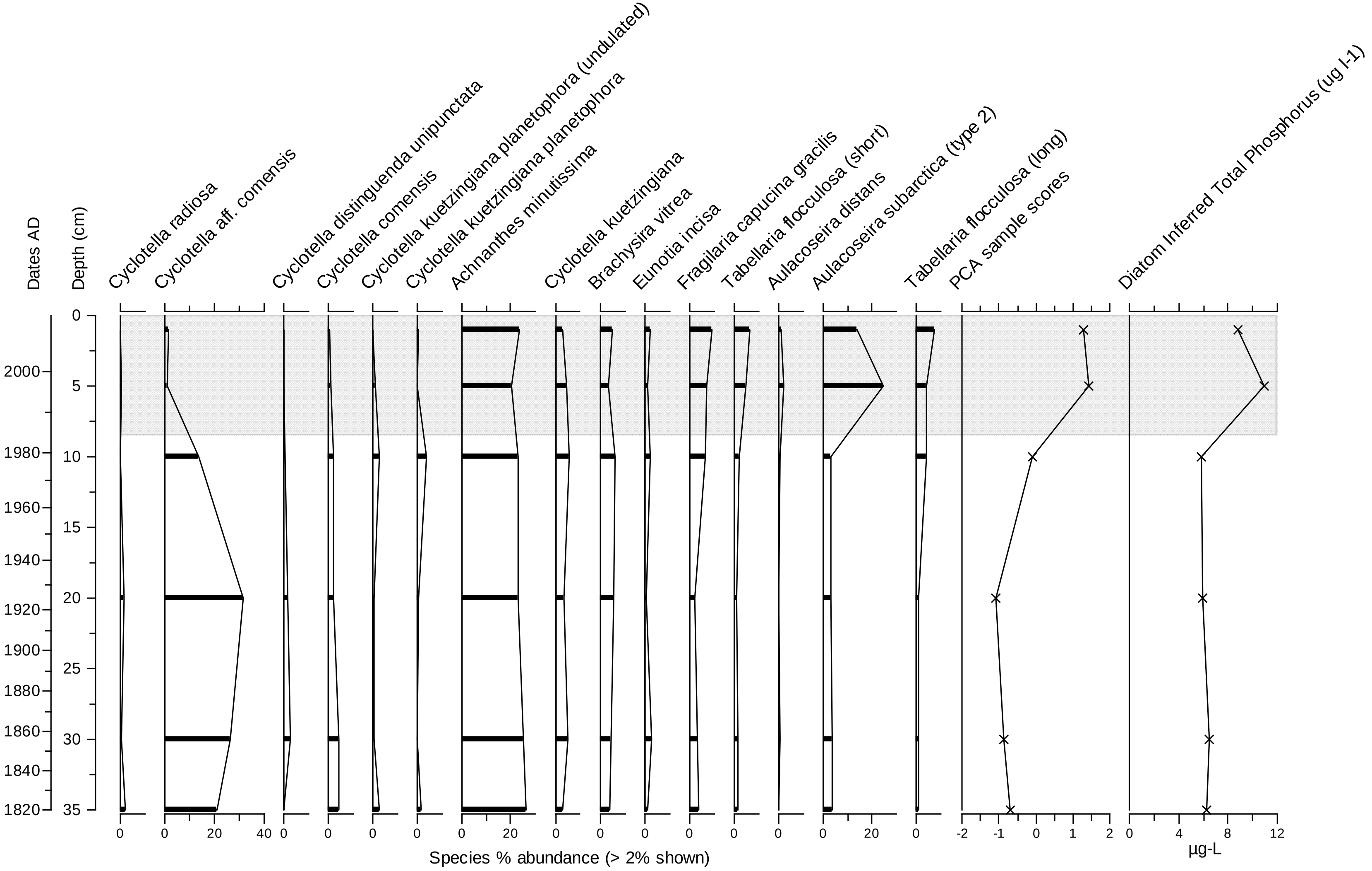
A total of 125 diatom species were identified within core ARKA1 and those taxa occurring at ≥2% abundance are shown in Figure 4. The major taxa in the sediment core were well represented in the training set with greater than 85% of the fossil assemblage being present in the training set for all samples. Between 35 cm – 20cm (representing sediments older than ~1930 AD) the core is dominated by *Cyclotella* aff. *comensis* and *A. minutissima,* both occurring at over 20% abundance*.* Other *Cyclotella* species (*C. comensis*, *C. kuetzingiana* and *C. distinguenda* var. *unipunctata*) are also present at low abundances as is *Brachysira* *vitrea, Fragilaria capucina* var. *gracilis* and *Aulacoseira subarctica* (type 2). The DI-TP is relatively stable within this period with values of ~6 µg l^{-1}. Between 20 and 10 cm (representing 1926-1979 AD) *C.* aff. *comensis* begins to decline from maximum values of 31% to 13% at 10 cm, and *C. kuetzingiana* var. *planetophora*, *C. kuetzingiana* var. *planetophora* (undulated), *C. kuetzingiana* and *F. capucina* var. *gracilis* all increase slightly. However, DI-TP remains at ~6 µg l^{-1}.

Between 10 and 5 cm (representing 1979-1998 AD) *C.* aff. *comensis* continues to decline with a corresponding marked increase in *A. subarctica* (type 2) from 3% to 24%. *A. minutissima* is still dominant within this section and in fact the abundance of this taxon remains relatively constant throughout the whole core. The floristic changes are reflected in a shift in PCA sample scores and an increase in DI-TP from ~6 to ~11 µg l^{-1}. According to Marine Harvest records, the fish farm was established on the loch in 1986 (represented by the grey shading in Figure 4) and the most marked changes in the diatom assemblages have therefore occurred since this time. Hence, it seems likely that the recent changes in the diatom flora and associated increase in DI-TP concentrations are related to the fish farm operations.

In the uppermost section of the core between 5 and 0 cm (1998-2006) the DI-TP decreases slightly from ~11 to ~9 µg l^{-1}, corresponding to a decrease in *A. subarctica* (type 2). The DI-TP at the core surface of 8.8 µg l^{-1} compares favourably with the measured mean TP concentration reported for January 2007 of 8.4 µg l^{-1}, which is just before the core was taken in February 2007 (Environmental Services, Institute of Aquaculture 2007), suggesting that the diatom model is producing reliable values for this loch. However, measured TP values for November 2006 and March 2007 were substantially lower (3.9 and 3.2 µg l^{-1}, respectively) indicating a January 2007 peak in TP concentrations (Environmental Services, Institute of Aquaculture 2007).

In summary, the diatom record of Loch Arkaig exhibits a major change throughout the period represented by the sediment core, which dates from ~1800 AD. The assemblages shift from dominance by taxa typically found in oligotrophic waters to taxa associated with more productive (mesotrophic) conditions at some time between 1980 and 1998. This is further illustrated by application of the diatom-phosphorus transfer function which indicates that TP concentrations in the loch were ~6 µg l^{-1} until around 1980 and had almost doubled to ~11 µg l^{-1} by 1998. The diatom data provide evidence that whilst the loch remains in oligotrophic status according to the water quality survey data, it has changed ecologically in response to recent enrichment and is no longer in a reference state. The palaeoecological data indicate that an ecologically important threshold has been crossed. Given the low resolution of the present study, the exact date of onset of enrichment cannot be determined but the major shifts have occurred post-1980 and are therefore coincident with the arrival of the fish farm.

Figure 4 Summary diatom diagram of Loch Arkaig core ARKA1 **(only taxa occurring at >2% maximum abundance are shown); shaded area represents the period during which the fish farm has been in operation**

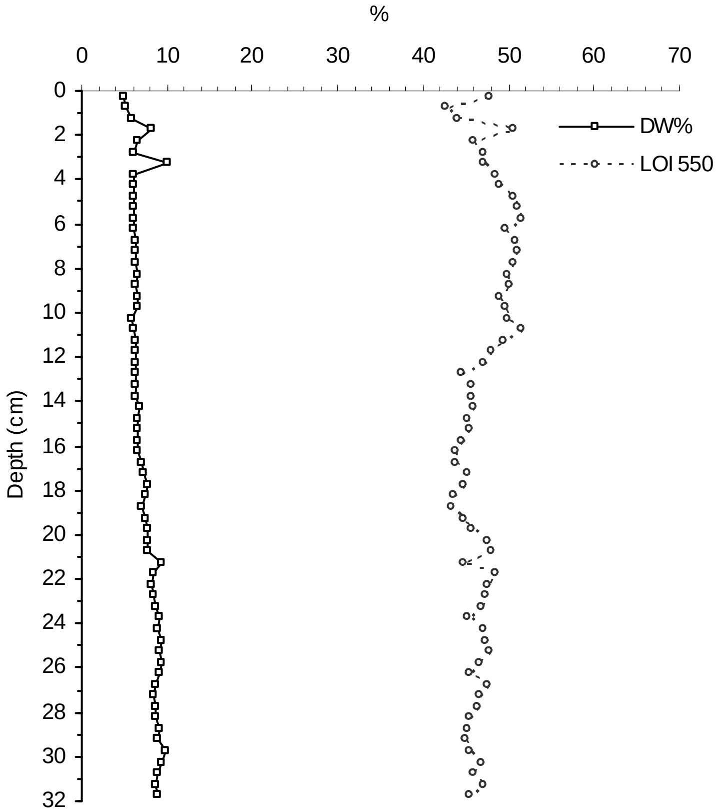


Loch Huamavat (Huamnabhat), South Harris

Core description

The 32 cm core, HUAM1, was taken just to the north of the fish cages in a water depth of ~7 m, which was the deepest point recorded with the echo sounding device. The core was a black, organic peat throughout (LOI ~ 45-50%) with abundant plant remains (Figure 5).

Figure 5 Percentage dry weight and organic matter profiles of HUAM1



Radiometric dating

Lead-210 Activity

Total ^{210}Pb activity does not reach equilibrium with the supporting ^{226}Ra in this core (Appendix 1). Unsupported ^{210}Pb activities, calculated by subtracting ^{226}Ra activity from total ^{210}Pb activity, decline more or less exponentially with depth from 8 cm downwards, suggesting that the sedimentation rates in this section are relatively stable (Figure 6). The decline of unsupported ^{210}Pb activities from 8 cm upwards implies recent increase in the sedimentation rate. High unsupported ^{210}Pb (14437 Bq m^{-2}) indicates a mean ^{210}Pb supply rate of 449.6 ± 14 Bq m^{-2} yr^{-1}, which is significantly higher than the estimated atmospheric flux for the European continent.

Artificial Fallout Radionuclides

The ^{137}Cs activities versus depths have a relatively well-resolved peak in this core (Figure 6). High ^{137}Cs concentration at about 9.75 cm (sample 9.5-10 cm) almost certainly records fallout from the 1986 Chernobyl accident. There is trace ^{241}Am around 16.75 cm, indicating the 1963 fallout maximum from the atmospheric testing of nuclear weapons. It appears that the high fallout of ^{137}Cs from the 1986 Chernobyl accident has obscured the signal of ^{137}Cs from the 1963 fallout.

Core Chronology

Use of the CIC model was precluded by the non-monotonic nature of the ^{210}Pb data. Chronological data were therefore calculated using the CRS model (Appleby *et al*., 1978). The CRS model indicates that the core represents the period from ~1880, and places 1963 at just above 16 cm and 1986 at just above 10 cm, both being in good agreement with the ^{137}Cs and ^{241}Am records (Table 3, Figure 7). Calculated sedimentation rates using the CRS model show that accumulation rates were relatively stable from the 1880s to the 1990s, followed by a gradual increase since the 1990s from ~0.022 g cm^{-2} y^{-1} to ~0.058 g cm^{-2} y^{-1} at the present day.

Table 3 HUAM1 Chronology

Depth	Drymass	Cum unsupp	Chronology			Sedimentation Rate		
			Date	Age	Std			% Std
cm	g/cm^2	Bq/m^2	AD	yr	±	g/cm^2/yr	cm/yr	±
0	0	14437.2	2007	0				
1	0.0611	13972	2006	1	2	0.0583	0.9	8.1
2	0.1267	13454.7	2005	2	2	0.0567	0.845	6.9
3	0.1958	12828.7	2003	4	2	0.0441	0.661	6.8
4	0.2636	12188.4	2002	5	2	0.0341	0.514	6.5
5	0.3273	11457.5	2000	7	2	0.0315	0.482	5.7
6	0.3914	10723.6	1997	10	2	0.0287	0.442	5.4
7	0.4571	9906.5	1995	12	2	0.0251	0.383	6.7
8	0.5232	9097.4	1992	15	2	0.022	0.33	7.7
9	0.5906	8206.7	1989	18	2	0.0199	0.298	7.8
10	0.6579	7361.2	1985	22	2	0.018	0.268	8.2
11	0.7245	6490.9	1981	26	2	0.0161	0.24	9.3
12	0.7913	5716.1	1977	30	2	0.0149	0.222	10.3
13	0.8587	5014.4	1973	34	2	0.0159	0.235	11.1
14	0.926	4398.9	1969	38	2	0.017	0.247	11.8
15	0.9944	3865.6	1965	42	2	0.0178	0.255	12.6
16	1.0662	3414.9	1961	46	3	0.0181	0.25	13.6
17	1.1394	3028.4	1957	50	3	0.0193	0.254	14.6
18	1.2166	2717	1953	54	3	0.023	0.285	15.3
19	1.2938	2437.7	1950	57	3	0.0266	0.316	16
20	1.3798	2144.7	1946	61	3	0.0258	0.301	16.4

21	1.4687	1874.7	1941	66	4	0.0235	0.272	16.7
22	1.5575	1638.6	1937	70	4	0.0211	0.242	17.1
23	1.6464	1432.3	1933	74	4	0.0188	0.212	17.4
24	1.7353	1252	1928	79	5	0.0164	0.183	17.8
25	1.8256	1076	1924	83	5	0.0147	0.16	19.1
26	1.92	878.9	1917	90	6	0.0146	0.158	23.6
27	2.0143	717.9	1911	96	8	0.0145	0.156	28.1
28	2.1087	586.4	1904	103	9	0.0144	0.154	32.5
29	2.203	479	1898	109	10	0.0144	0.152	37
30	2.2979	389.6	1891	116	11	0.0141	0.149	40.8
31	2.3943	312.8	1884	123	14	0.0135	0.141	42.8

Figure 6 Fallout radionuclides in Loch Huamavat core HUAM1 showing (a) total ^{210}Pb, (b) unsupported ^{210}Pb and (c) ^{137}Cs concentrations versus depth

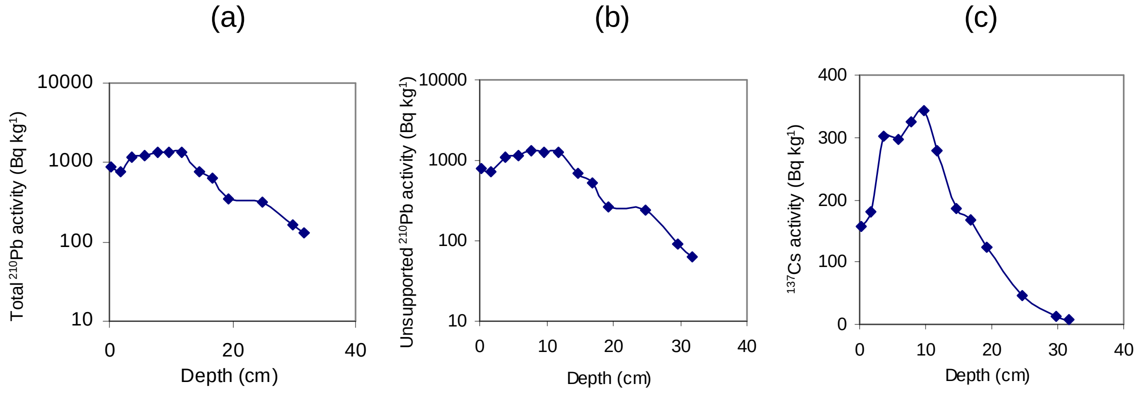
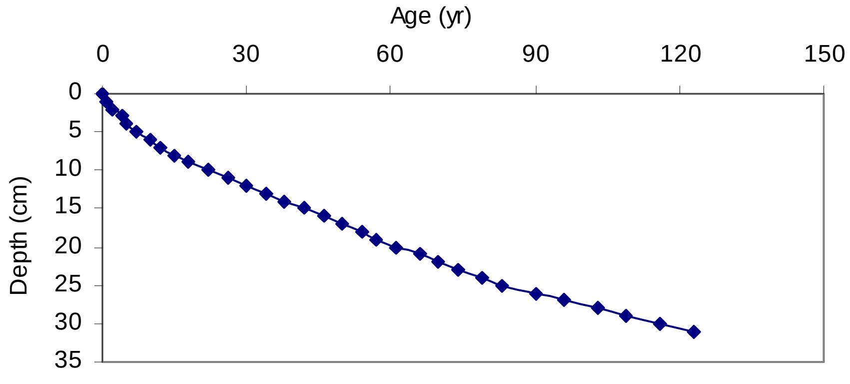


Figure 7 Radiometric chronology of Loch Huamavat core HUAM1



Diatom analyses

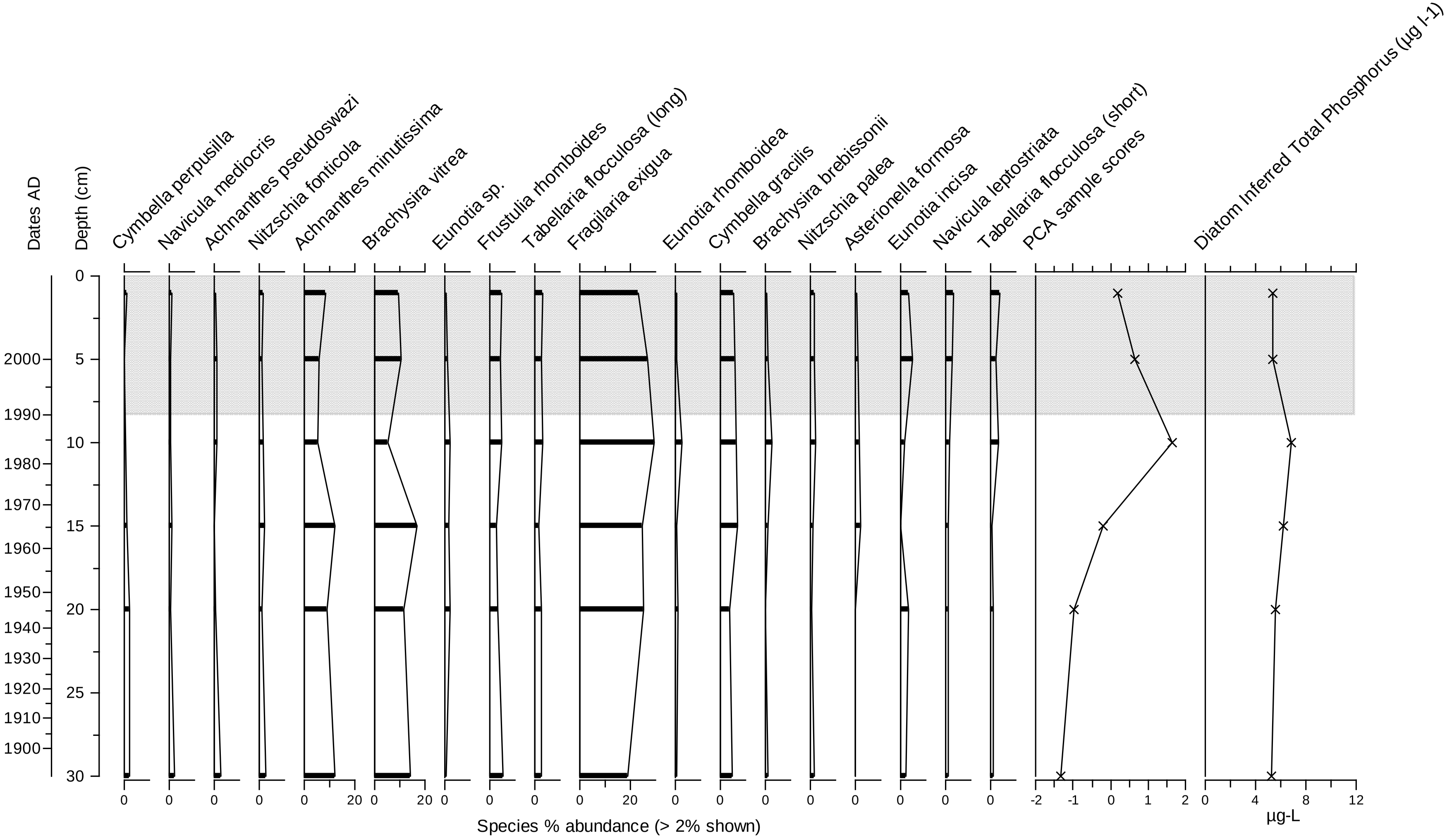
A total of 143 diatom species were identified from core HUAM1 and those species occurring at ≥ 2 % abundance are shown in Figure 8. The major taxa in the sediment core were well represented in the training set with greater than 75% of the fossil assemblage being present in the training set for all samples. The lowermost section of the core (30-15 cm, representing ~1890-1965 AD) is dominated by *Achnanthes minutissima*, *Brachysira vitrea*, *Fragilaria exigua* and, to a lesser extent, *Frustulia rhomboides* and *Cymbella gracilis*. The PCA sample scores throughout this period remain relatively stable indicating little diatom compositional change. Similarly, the DI-TP concentrations during this period are relatively stable at ~5-6 µg

l^{-1}. Between 15 and 10 cm (representing ~1965-1985 AD) *A. minutissima* and *B. vitrea* decline in abundance with a corresponding increase in *F. exigua* and *Tabellaria flocculosa* (short). These changes are reflected in a change in the PCA sample scores and a very slight increase in the DI-TP to a maximum of ~7 µg l^{-1} in 1985 AD.

The uppermost section of the core (10-0 cm), representing ~1985-2006 AD, is characterised by slight increases in *B. vitrea, Eunotia incisa* and *Navicula leptostriata.* These floristic changes are also reflected by the shift in the PCA sample scores. According to Marine Harvest records, the fish farm was established on the loch in 1991 (represented by the grey shading in Figure 8) and therefore this section of the core encompasses the period during which the fish farm was introduced. However, the DI-TP results indicate stable concentrations of ~5 µg l^{-1}, suggesting that there has not been any enrichment associated with the introduction of the fish cages or during the subsequent years of production.

In summary, changes in the diatom composition and DI-TP throughout the Loch Huamavat core are relatively minor, with present day DI-TP values similar to those estimated for the bottom of core which dates back to ~1880. The palaeoecological data suggest that fish farm production has not had an adverse influence on the diatom flora of the loch and the site still appears to be in its original oligotrophic condition.

Figure 8 Summary diatom diagram of Loch Huamavat core HUAM1 **(only taxa occurring at >2% maximum abundance are shown); shaded area represents the period during which the fish farm has been in operation**

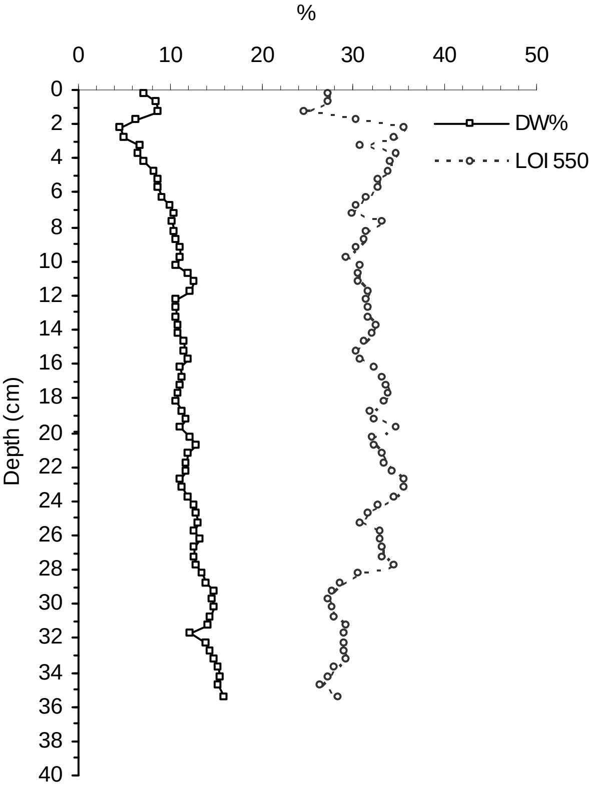


Loch Shiel, Highland Region

Core description

The 35 cm core, SHIE5, was taken in the northeast basin of the loch in a water depth of ~105 m. The core was dark brown with few visible changes except for an orange-brown band at ~3-4 cm. The core was relatively organic throughout with %LOI values of ~30-35% in all but the upper few centimetres and the lowermost 7 cm where values were just below 30% (Figure 9). There were abundant plant remains from 31 cm to the core base.

Figure 9 Percentage dry weight and organic matter profiles of SHIE5



Radiometric dating

Lead-210 Activity

Total ^{210}Pb activity does not reach equilibrium with the supporting ^{226}Ra in this core (Appendix 1). Unsupported ^{210}Pb activities, calculated by subtracting ^{226}Ra activity from total ^{210}Pb activity, decline more or less exponentially with depth from 4 cm downwards, suggesting that the sedimentation rates in this section are relatively stable (Figure 10). Decline in unsupported ^{210}Pb activities in the top part of the core (4 cm upwards) implies increase in sedimentation rate in recent years. High unsupported ^{210}Pb (19088 Bq m^{-2}) indicates a mean ^{210}Pb supply rate of 594.4 ± 14.2 Bq m^{-2} yr^{-1}, which is significantly higher than the estimated atmospheric flux for the European continent.

Artificial Fallout Radionuclides

The ^{137}Cs activities versus depth have two relatively well-resolved peaks in this core (Figure 10). The peak at 14.75 cm (sample 14.5-15 cm) in the ^{137}Cs record is almost certainly from the 1963 fallout maximum of nuclear weapon testing. This is confirmed by the ^{241}Am peak at the same depth. The peak at 8.75 cm (sample 8.5-9 cm) records fallout from the 1986 Chernobyl accident.

Core Chronology

Due to the increase in sedimentation rate in the upper sediments, unsupported ^{210}Pb activities have been diluted and use of the CIC model was precluded by the non-monotonic nature of the ^{210}Pb data. Chronological data were therefore calculated using the CRS model (Appleby *et al*., 1978). The CRS model places 1963 at 15 cm and 1986 at 8-9 cm, both dates being in good agreement with the ^{137}Cs and ^{241}Am records. Calculated sedimentation rates using the CRS model show that the sedimentation rates are relatively stable from the 1840s to around 2000, with a mean sedimentation rate of ~0.027 g cm^{-2} y^{-1}, followed by an increase from 0.031 g cm^{-2} y^{-1} to 0.077 g cm^{-2} y^{-1} in the last few years (Table 4, Figure 11).

Table 4 SHIE5 Chronology

Depth	Drymass	Cum unsupp	Chronology			Sedimentation Rate		
			Date	Age	Std			% Std
cm	g/cm^2	Bq/m^2	AD	yr	±	g/cm^2/yr	cm/yr	±
0	0	19088.4	2007	0				
1	0.0842	18487	2006	1	2	0.0769	0.961	7.5
2	0.1608	17796	2005	2	2	0.0579	0.838	4.7
3	0.2238	17005	2003	4	2	0.0425	0.614	5.7
4	0.2917	16095.7	2002	5	2	0.031	0.423	5.8
5	0.3768	14762.7	1999	8	2	0.0303	0.333	3.7
6	0.4732	13360.3	1996	11	2	0.0291	0.27	3.9
7	0.5848	11937.2	1992	15	2	0.0307	0.274	4.2
8	0.6963	10665.6	1988	19	2	0.0323	0.278	4.5
9	0.8118	9531.9	1985	22	2	0.0339	0.282	4.8
10	0.9393	8524.9	1981	26	2	0.0354	0.286	5.2
11	1.0666	7624.3	1978	29	2	0.0369	0.291	5.6
12	1.1948	6812.6	1974	33	2	0.0375	0.292	6.1
13	1.3252	6070.8	1970	37	2	0.0357	0.278	6.7
14	1.4555	5409.8	1967	40	2	0.0338	0.265	7.3
15	1.5846	4786.5	1963	44	2	0.0319	0.251	7.9
16	1.7098	4145.6	1958	49	2	0.0298	0.234	8.2
17	1.835	3590.5	1953	54	2	0.0277	0.217	8.5
18	1.9602	3109.7	1949	58	2	0.0256	0.201	8.7
19	2.0854	2693.3	1944	63	2	0.0235	0.184	9
20	2.2121	2314.2	1939	68	3	0.0221	0.172	9.7
21	2.3431	1941.7	1934	73	3	0.0227	0.176	11.6
22	2.4741	1629.1	1928	79	3	0.0234	0.179	13.5

23	2.6051	1366.8	1922	85	3	0.024	0.182	15.4
24	2.7361	1146.8	1917	90	4	0.0246	0.186	17.3
25	2.8693	958.1	1911	96	4	0.0245	0.181	18.3
26	3.0094	790.2	1905	102	4	0.0221	0.155	16.7
27	3.1523	646.7	1898	109	5	0.0203	0.136	15.7
28	3.3036	516.9	1891	116	7	0.0206	0.138	16.7
29	3.4548	413.2	1884	123	8	0.0209	0.14	17.7
30	3.6061	330.2	1877	130	10	0.0212	0.141	18.7
31	3.7573	264	1870	137	11	0.0215	0.143	19.7
32	3.9086	211	1862	145	12	0.0218	0.145	20.6
33	4.0598	168.6	1855	152	14	0.0221	0.147	21.6
34	4.2111	134.8	1848	159	15	0.0224	0.148	22.6

Figure 10 Fallout radionuclides in Loch Shiel core SHIE5 showing (a) total ^{210}Pb, (b) unsupported ^{210}Pb and (c) ^{137}Cs concentrations versus depth

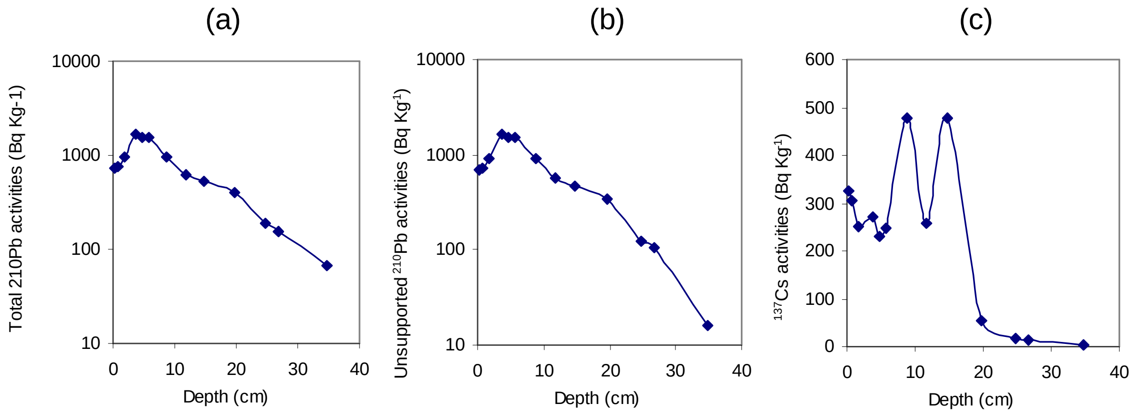
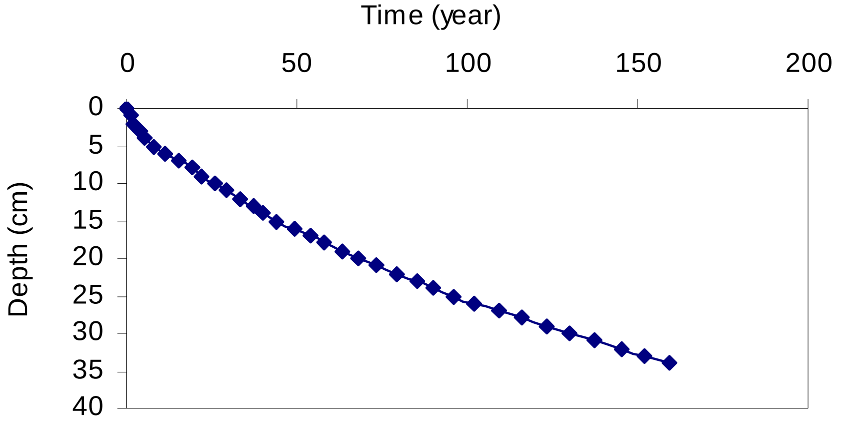


Figure 11 Radiometric chronology of Loch Shiel core SHIE5



Diatom analyses

A total of 127 diatom species were identified from core SHIE5 and those species ≥ 2% abundance are illustrated in Figure 12. The major taxa in the sediment core were well represented in the training set with greater than 80% of the fossil assemblage being present in the training set for all samples. The lowermost core section of SHIE5 (30-20 cm), representing ~1880-1940 AD, is dominated by *A. minutissima*, *B. vitrea, Cyclotella kuetzingiana* var. *planetophora* (undulated form) and, to a lesser extent, *T. flocculosa* (short) and *Eunotia incisa*. During this period *A. minutissima* declines slightly from a maximum abundance of 32% at 30 cm to 20% at 20 cm with slight increases in the planktonic species *C. kuetzingiana* var. *planetophora*. The DI-TP during this period is relatively low and stable at 4 µg l^{-1} indicating that the lake was oligotrophic at this time. Between 20 and 15 cm (~1940-1960 AD) *A. minutissima* continues to decline slightly with small increases in *C. kuetzingiana* var. *planetophora, Peronia fibula* and *F. rhomboides*, with *B. vitrea* remaining at ~10% abundance. The DI-TP during this period remains unchanged at ~4 µg l^{-l}.

Between 15 and 10 cm (~1963-1980 AD) there are only minor changes in the percentages of the dominant taxa and the DI-TP remains stable at 4 µg l^{-1}. The PCA sample scores, however, indicate that the largest shift in diatom composition occurs within this period. The scores are driven by small changes in the abundance of *Achnanthes pseudoswazi, Achnanthes subatomoides*, *Eunotia rhomboidea* and *Fragilaria capucina* (which have high negative loadings on PCA axis 1) which all occur at ≤ 2% abundance within the core.

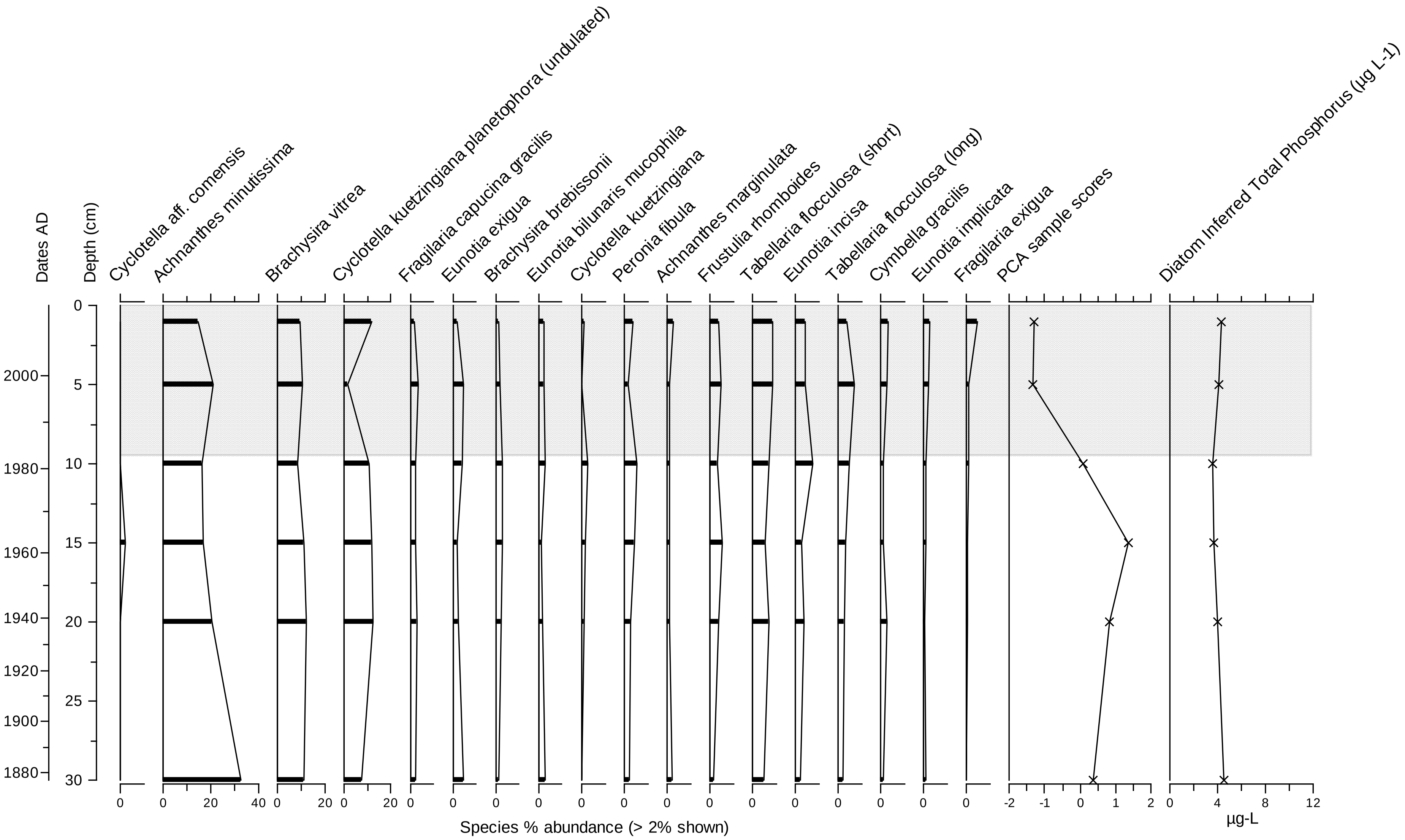
Between 10 and 5 cm (representing ~1981-1999 AD) abundances of *C. kuetzingiana* var. *planetophora, Peronia fibula* and *E. incisa* decrease, whilst *A. minutissima* and *Tabellaria flocculosa* (short and long varieties) increase slightly. According to Marine Harvest records, the fish farm was established on the loch in 1983 (represented by the grey shading in Figure 12) and therefore this section of the core encompasses the period during which the fish farm was introduced. However, the DI-TP results indicate stable concentrations of ~4 µg l^{-1}, suggesting that there has not been any enrichment associated with the introduction of the fish cages or during the subsequent years of production.

In the uppermost section of the core between 5-0 cm (representing ~1999 to 2006) the DI-TP remains relatively stable and present day DI-TP concentrations (4.3 µg l^{-1}) are similar to those inferred for the bottom of the core (4.5 µg l^{-1}) which dates back to ~1880. The DI-TP for the surface sample compares favourably with the measured mean TP concentrations for Loch Shiel recorded as 3.9 µg l^{-1} in January 2006 (Environmental Services, Institute of Aquaculture report, 2007) suggesting that the reconstruction is reliable for this site.

The findings are very similar to those from SHIE2, a core taken in 1998 (Bennion *et al.*, 2001). Notwithstanding the superior diatom preservation in the upper part of SHIE5, the assemblages of both cores are comprised of the same diatom taxa typically associated with nutrient-poor waters, and DI-TP concentrations are stable at ~4 µg l^{-1} in SHIE2 and SHIE5.

In summary, the diatom changes in SHIE5 are minimal throughout the record and the DI-TP values have remained relatively stable for the last 120 years indicating that the fish farm has had little impact on the diatom flora within the loch. The loch has been oligotrophic throughout the whole of the period represented by the sediment core.

Figure 12 Summary diatom diagram of Loch Shiel core SHIE5 (only taxa occurring at >2% maximum abundance are shown); shaded area represents the period during which the fish farm has been in operation



CONCLUSION

The study has shown that all three lochs were oligotrophic during the nineteenth century with baseline DI-TP concentrations of ~4-6 µg l^{-1}. Of the three lochs, only Loch Arkaig has experienced marked changes in the diatom flora indicative of eutrophication with an associated increase in DI-TP to values of 9-11 µg l^{-1}. The timing of these changes occurs between 1980 and 1998 but, owing to the low resolution of the study, the exact date of onset of enrichment cannot be determined. Notwithstanding the limitations of the data, the major shifts have occurred post-1980 and are therefore coincident with the arrival of the fish farm in 1986. At Lochs Huamavat and Shiel, the palaeoecological data suggest that fish farm production has not had an adverse influence on the diatom flora of these two lochs and the sites still appear to be in their original oligotrophic condition. Nevertheless, there are subtle changes towards the top of these cores and continued monitoring is recommended.

References

Appleby, P G. (2001). Chronostratigraphic techniques in recent sediments. In W M Last and J P Smol (eds.) *Tracking Environmental Change Using Lake Sediments. Vol. 1: Basin Analysis, Coring, and Chronological Techniques.* Kluwer Academic Publishers, Dordrecht. pp171-203.

Appleby, P G, Nolan, P J, Gifford, D W, Godfrey, M J, Oldfield, F, Anderson, N J & Battarbee, R W, (1986). 210Pb dating by low background gamma counting. *Hydrobiologia*, 141, 21-27.

Appleby, P.G. & Oldfield, F., (1978). The calculation of ^{210}Pb dates assuming a constant rate of supply of unsupported ^{210}Pb to the sediment. *Catena*, 5,1-8.

Appleby, P.G. & Oldfield, F. (1983). The assessment of ^{210}Pb data from sites with varying sediment accumulation rates. *Hydrobiologia,* 103, 29-35.

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

Bennion, H., Fluin, J., Appleby, P. & Ferrier B. (2001) Palaeolimnological investigation of Scottish freshwater lochs. *SNIFFER report SR(00)02 F.*

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

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

Environmental Services, Institute of Aquaculture, University of Stirling (2007), *Report on the Trophic Status of Loch Shiel. Total Phosphorus and Chlorophyll-a levels for 2006-07*, (9th July 2007) A report for Marine Harvest (Scotland) Ltd.

Environmental Services, Institute of Aquaculture, University of Stirling (2007), *Report on the Trophic Status of Loch Arkaig. Total Phosphorus and Chlorophyll-a levels 2006-07*, (6th July 2007) A report for Marine Harvest (Scotland) Ltd.

Hall, R.I. & Smol, J.P. (1999) Diatoms as indicators of lake eutrophication. *The Diatoms: Applications for the Environmental and Earth Sciences* (eds E.F. Stoermer & J.P. Smol), pp. 128-168. Cambridge University Press, Cambridge.

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

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

ter Braak, C.J.F. & Prentice, I.C. (1988) A theory of Gradient Analysis. *Advances in Ecological Research*, 18, 271-317.

ter Braak C. J. F. & van Dam H. (1989) Inferring pH from diatoms: a comparison of old and new calibration methods. *Hydrobiologia,* **178**, 209-223.

ter Braak, C. J. F. & Smilauer, P. (2002) CANOCO Reference manual and CanoDraw for Windows User’s guide: Software for Canonical Community Ordination (version 4.5), pp. 500. Microcomputer Power, Ithaca, New York.

Appendix 1 Radiometric dating results

1. Loch Arkaig

Pb-210 concentrations in Loch Arkaig core ARKA1

Depth	Dry Mass	Pb-210					
		Total		Supported		Unsupported	
cm	g/cm^2	Bq/Kg	±	Bq/Kg	±	Bq/Kg	±
0.25	0.0124	1533.46	36.62	74.06	5.61	1459.4	37.05
0.75	0.0412	1673.72	58.48	98.75	9.53	1574.97	59.25
1.75	0.1091	1708.7	52.25	83.12	7.76	1625.58	52.82
3.75	0.2206	1720.56	36.04	70.71	5.42	1649.85	36.45
5.75	0.363	1634.29	53.33	92.61	8.88	1541.68	54.06
7.75	0.5618	1546.57	68.34	62.35	9.95	1484.22	69.06
8.75	0.6771	1335.14	29.87	84.56	5.09	1250.58	30.3
9.75	0.7975	1199.23	31.69	73.84	4.81	1125.39	32.05
11.75	1.0611	860.19	26.79	80.58	4.58	779.61	27.18
12.75	1.1985	798.28	17.91	77.56	2.98	720.72	18.16
14.75	1.4733	525.43	30.28	76.52	5.96	448.91	30.86
16.75	1.7526	381.19	24.74	77.86	4.94	303.33	25.23
19.75	2.1923	291.9	23.32	65.35	5.28	226.55	23.91
24.75	3.033	144.47	8.31	62.33	1.87	82.14	8.52

Cs-137 and Am-241 concentrations in Loch Arkaig core ARKA1

Depth	Cs-137		Am-241	
cm	Bq/Kg	±	Bq/kg	±
0.25	255.57	7.1	0	0
0.75	245.76	10.42	0	0
1.75	251.79	9.48	0	0
3.75	201.27	5.79	0	0
5.75	263.81	9.84	0	0
7.75	407.14	15.92	0	0
8.75	638.31	8.48	0	0
9.75	391.88	7.81	3.6	1.91
11.75	388.16	7.24	7.14	1.76
12.75	453.15	5.05	20.42	1.31
14.75	258.69	7.89	15.89	2.52
16.75	91.02	4.49	2.89	1.89
19.75	43.47	3.91	0	0
24.75	13	1.02	0	0

2. Loch Huamavat

Pb-210 concentrations in Loch Huamavat core HUAM1

Depth	Dry Mass	Pb-210					
		Total		Supported		Unsupported	
cm	g/cm^2	Bq/Kg	±	Bq/Kg	±	Bq/Kg	±
0.25	0.0128	884.56	66.52	98.27	19.43	786.29	69.3
1.75	0.1094	782.27	42.5	73.45	8.28	708.82	43.3
3.75	0.2477	1194.39	63.06	83.48	11.13	1110.91	64.03
5.75	0.375	1229.01	36.99	77.17	5.91	1151.84	37.46
7.75	0.5063	1373.31	81.76	79.86	13.74	1293.45	82.91
9.75	0.6412	1347.98	78.91	64.26	12.46	1283.72	79.89
11.75	0.7745	1352.83	105.56	100.66	19.8	1252.17	107.4
14.75	0.9765	770.93	71.45	70.07	14.2	700.86	72.85
16.75	1.1201	648.59	62.28	121.54	13.18	527.05	63.66
19.25	1.3131	354.87	34.99	86.87	7.79	268	35.85
24.75	1.802	321	25.35	81	5.53	240	25.95
29.75	2.2738	164.19	20.8	74.54	5.06	89.65	21.41
31.75	2.4666	130.11	13.72	66.64	3.81	63.47	14.24

Cs-137 and Am-241 concentrations in Loch Huamavat core HUAM1

Depth	Cs-137		Am-241	
cm	Bq/Kg	±	Bq/kg	±
0.25	156.2	12.06	0	0
1.75	180.98	8.33	0	0
3.75	302.21	13.04	0	0
5.75	295.8	7.86	0	0
7.75	324.87	17.36	0	0
9.75	343.63	17.25	0	0
11.75	279.84	21	0	0
14.75	184.78	15.13	0	0
16.75	168.51	10.99	7.91	5.1
19.25	122.77	7.05	6.05	3
24.75	45.71	3.94	0	0
29.75	12.61	2.57	0	0
31.75	6.69	1.81	0	0

3. Loch Shiel

Pb-210 concentrations in Loch Shiel core SHIE5

Depth	Dry Mass	Pb-210					
		Total		Supported		Unsupported	
cm	g/cm^2	Bq/Kg	±	Bq/Kg	±	Bq/Kg	±
0.25	0.0201	723.63	39.16	43.33	6.49	680.3	39.69
0.75	0.0639	753.35	56.77	44.79	9.89	708.56	57.63
1.75	0.1451	950.87	32.37	42.96	5.57	907.91	32.85
3.75	0.271	1698.48	96.61	47.49	15.82	1650.99	97.9
4.75	0.3539	1568.79	34.51	44.6	4.78	1524.19	34.84
5.75	0.4453	1539.6	36.47	49.07	5.02	1490.53	36.81
8.75	0.78	969.64	27.23	58.39	4.92	911.25	27.67
11.75	1.1622	627.2	22.84	52.78	4.23	574.42	23.23
14.75	1.5533	533.52	28.05	56.46	5.57	477.06	28.6
19.75	2.1793	393.56	20.82	50.61	4.12	342.95	21.22
24.75	2.8343	187.95	18.99	63.33	5.1	124.62	19.66
26.75	3.1145	154.45	8.15	49.09	2.13	105.36	8.42
34.75	4.3245	67.48	6.41	51.77	1.72	15.71	6.64

Cs-137 and Am-241 concentrations in Loch Shiel core SHIE5

Depth	Cs-137		Am-241	
cm	Bq/Kg	±	Bq/kg	±
0.25	324	11.49	0	0
0.75	303.92	15.27	0	0
1.75	250.83	7.58	0	0
3.75	269.62	19.42	0	0
4.75	231.55	6.53	3.63	1.94
5.75	248.49	7.17	0	0
8.75	478.04	8.46	3.59	1.87
11.75	256.43	5.92	6.21	1.57
14.75	476.28	10	14.06	2.46
19.75	55.7	3.35	0	0
24.75	17.49	2.88	0	0
26.75	13.43	1.16	0	0
34.75	2.73	0.72	0	0