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ENVIRONMENTAL CHANGE
RESEARCH CENTRE

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Palaeolimnological surveys of selected large lakes in the north of Ireland

Final report to the Department for the Environment (NI),
Environment and Heritage Service, with funding from the
INTERREG programme

N.J. Anderson, P.G. Appleby, S. Patrick, H. Bennion &
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Executive summary

1. To assess recent change in the larger lakes in the north of Ireland, sediment cores were taken from Lough Oughter, Upper and Lower MacNean (all part of the Lough Erne system), and Lough Allen.

2. Cores were extruded and sliced into 1 cm sections for analysis of their water content and organic content (as loss-on-ignition at 550°C). Selected levels within each core were analysed for ^{241}Am, ^{226}Ra, ^{210}Pb and ^{137}Cs content to enable chronologies to be derived for individual cores.

3. ^{210}Pb chronologies were derived for cores from Lough Oughter, Upper MacNean and Lough Allen. The radionuclide data for Lower Lough MacNean were difficult to interpret and it was concluded that the core record is incomplete, presumably due to the very shallow nature of the lake which results in resuspension. Much of the lake probably does not accumulate sediment on a permanent basis.

4. Sediment accumulation rates are very high for all cores with the exception of Lough Allen (30 cm depth = 1900 AD). The core from Lough Oughter covers only approximately 80 years (and is similar to the core taken from Upper Lough Erne at Tongree in the first phase of the study). The core from Upper Lough MacNean, which was a short core (ca. 35 cm) only covered the last 50-60 years. These cores are comparable to the results derived from the first Interreg Large Lakes project, where very high sediment accumulation rates were derived from both Upper and Lower Lough Erne,

5. As well as the general high sediment accumulation rates, all cores show considerable variability in their accumulation rates over time, with substantial increases in the post-war period (Manor House), around 1960 (Lough Oughter) and more recently (Upper Lough MacNean).

6. Diatom analyses were made of cores from Lough Allen, Upper and Lower Lough MacNean and Lough Oughter. All the diatom stratigraphies indicate varying degrees of change, over slightly varying timescales. Eutrophication inferences can be concluded from the changes at Lough Oughter (starting around 1960) due to the increase of small *Stephanodiscus* and related species, indicative of nutrient enrichment. Changes at Upper Lough MacNean tend to indicate declining nutrient concentrations with the increase of *Cyclotella comensis* agg. Lough Allen has a long period with dominance by *Aulacoseira* spp (but percentages vary), indicating considerable natural variability. Clear changes occur in the upper 5 cm (ca. 1990) at Lough Allen and their interpretation is inconclusive. However, the lake is clearly beginning to change.

7. Diatom analyses were completed on cores taken from Upper Lough Erne (Tongree) and Lower Lough Erne (Manor House) for the first phase of the project so that diatom changes could be tracked over a long period as possible.

8. As a result of the poor results derived from the application of the Northern Irish phosphorus inference model to the diatom assemblages in sediment cores analysed as part of phase 1, a Weighted Averaging (WA) regression and calibration model was developed

specifically for larger lakes. Surface sediment samples from 18 large lakes in the north of Ireland were amalgamated with 28 large lakes from Scotland and Europe. The resultant model appears to work well, measured as goodness of fit between measured, in-lake phosphorus and that estimated by diatoms. The model has good error statistics: $RMSE_{jack} = 0.2$; $r2= 0.7$)

9. The "Large Lakes" diatom-phosphorus inference model was applied to the cores from Upper Lough MacNean, Lough Oughter and Lough Allen, as well as the 1994 cores from Manor House and Tongree. The results for all cores are interesting. The good agreement between monitored TP concentrations and DI-TP results for the Broad Lough core agree very well (ca. 45 μg TP l^{-1}), suggesting that the model is working well and the results are reliable. Increases in diatom-inferred TP, albeit slight are inferred at Oughter and Tongree, whereas Lough Allen and Upper Lough MacNean have decreasing inferred-TP concentrations in the period since 1940. These changes may relate to land management changes. At Manor House there is a long-term upward trend, from background concentrations around 30 μg TP l^{-1}, starting around the late 1950s. There are however, considerable variability in the records, indicating the problems of determining change in lakes from limited monitoring data.

10. The results from the different aspects of the core studies (diatoms and sediment dry mass accumulation rates) are synthesised and discussed in relation to possible causal mechanisms. The disturbed nature of the ^{210}Pb records, increased dry mass accumulation rates and changing diatom assemblages at all sites are indicative of rapid and continuing change in the large lakes of the north of Ireland.

1. Introduction – eutrophication in Ireland

The large lakes in the north-west of Ireland form an important aspect of the region's environmental resource and its aesthetic, and hence tourist, appeal. The lakes are extensively utilised for recreational activities, including boating and fishing. As a result they represent a fundamental aspect of the regional economy. Therefore, any deleterious change in the water quality of the lakes has implications for tourism as well as water utilisation. Given, the importance of the lakes to the regional economy, a management plan has been drawn up for the Lough Erne system (e.g. *Proposals for a Water Quality Management Strategy for the River Erne Catchment*).

In a broader context, lake eutrophication has become a major concern throughout Ireland with many lakes showing signs of nutrient enrichment (e.g. Wilson, 1998; Allot *et al.*, 1998; HMSO, 1990; Gibson *et al.*, 1995). Nutrient increases in the large lakes of the western part of Ireland have been implicated for deleterious changes in salmonid fisheries (e.g. Allot *et al.*, 1998). In Northern Ireland, an extensive survey in the early 1990s indicated that very few (1%) small lakes had total phosphorus (TP) concentrations below 10 μg TP l^{-1} (Gibson *et al.* 1995). Although the modal concentration of the lakes in this survey was between 31 and 40 μg TP l^{-1}, a large percentage (38%) of lakes had TP concentrations in excess of 100 μg TP l^{-1} (Gibson *et al.* 1995). Using the standard OECD classification, there are very few oligotrophic lakes today in Northern Ireland.

Given the limited urban developments in most of the catchments, the effects of land management changes, in particular agriculture, are being implicated in these changes. Although occasional point agricultural sources (e.g. animal slurry disposal) can be identified, point sewage sources have been reduced substantially in the 1970s and 1980s (Foy & Withers 1995). Despite these reductions, P-loading has increased. For example, Foy *et al.* (1995) reported increased non-point loadings of soluble phosphorus to Lough Neagh despite reduced point sources inputs. Simple agricultural budget calculations combined with soil P tests suggest that there is a increasing phosphorus pool in agricultural soils which is slowly releasing P to surface waters and hence aquatic systems (Tunney *et al.* 1998).

2. Present-day trends in nutrients in the larger lakes of the North of Ireland

The larger lakes in the north of Ireland tend to have lower TP concentrations that the smaller lakes, with the general exception of Lough Neagh and parts of the Lough Erne system. The TP concentrations in both Loughs Neagh and Erne, however, never reach the extremes of the smaller lakes (cf. Gibson, 1986; Gibson *et al.*, 1980; Gibson *et al.*, 1995). Upper and Lower MacNean have TP concentrations in the ~20 and 30 μg TP l^{-1} respectively (Table 1), Lough Oughter around 50 μg TP l^{-1} while Garadice has a TP concentration of over 100 μg TP l^{-1}. It is only in the lakes further west, with less developed agricultural catchments (and a greater percentage of semi-natural vegetation) that low TP concentrations are found. Lough Melvin has a mean TP of around 20 μg TP l^{-1}, while Lough Allen has a TP concentration of ~17 μg TP l^{-1}.

For the majority of the large lakes there is little or no information available beyond occasional spot water sampling. Two notable exceptions are Lough Neagh and Lough Erne, lakes that have been monitored by DANI for some time (Gibson, 1986; Gibson *et al.*, 1980). There are now nearly 15 years of available data for Lower Lough Erne (Hayward *et al.*, 1993; Foy *et al.*, 1993). There is no real discernible trend in the Lough Erne TP data, with concentrations varying around 45-50 μg TP l^{-1} (Foy *et al.* 1993). Interestingly, these data contrast to the palaeolimnological evidence for both considerable change this century (Battarbee 1986b) and more recently (over the last 20-30 years; see Anderson *et al.*, 1996).

3. Previous Palaeolimnological studies of lake eutrophication in the North of Ireland

Prior to the first INTERREG report on large lakes (Anderson *et al.*, 1996), our understanding of the long term history of the larger lakes in the north-west of Ireland was confined to Battarbee's studies of the Lough Erne system (Battarbee 1986b). He (Battarbee, 1986b) concluded that there was a two-stage enrichment, with a first phase starting around 1900 and a second after 1950. This interpretation for eutrophication was based on increased accumulation rates of the total number of diatoms reaching the sediment. There were relatively small changes in the composition of diatoms present in the lake, apart from an increase proportion of planktonic diatoms and increases in small centric species in the upper parts of the cores. Anderson (1997b), concluded from the application of a diatom-phosphorus transfer function (which permits quantitative inferences to be made from diatoms preserved in lake sediments) that some of the small eutrophic lakes surveyed by Gibson *et al.* (1995) had undergone enrichment, over varying time periods but particularly since 1950. The six small lakes studied by Anderson (1997b) are probably reasonably representative in that they were all agricultural catchments without nutrient point sources.

4. Previous palaeolimnological work within INTERREG

Our previous work within INTERREG aimed to follow up Battarbee's earlier studies and contrast the sediment record with the monitoring data available for parts of the Lough Erne system. An attempt was also made to infer total phosphorus using Anderson's diatom-phosphorus calibration dataset, which was originally developed for application to small lakes (Anderson *et al.*, 1993). The results of the diatom analyses were interesting in that large changes in composition of the diatom flora were recorded, especially when compared with Battarbee's results, most notably the arrival of the small, planktonic diatom *Skeletonema subsalsum*, first observed by Gibson in phytoplankton counts in 1980 (Gibson *et al.* 1993). The diatom-inferred TP results were inconclusive in that they heavily over-estimated TP concentrations in the Lough Erne cores. The dry mass accumulation rates (derived from ^{210}Pb dating) proved to be very interesting in that large increases were recorded after 1950 at both the Manor House and Broad Lough (main basin) locations within the Lower Lough. We tentatively suggested that these changes might be due to land management changes (Anderson *et al.*, 1996), which would have substantial implications for management strategies within the catchment. It was possible however, that the increases in sediment accumulation might have been due to in-lake processes, such as water level change (perhaps leading to resuspension events – see Gibson & Guillot 1997) or temporary changes in sediment storage in the riverine, upper-part of the system. These ambiguities led us to suggest a second phase of the Large Lakes project (below).

5. Aims of the INTERREG phase II project

Diatom analyses of sediment cores from Manor House and Tongree in the Lough Erne system started in phase I were to be completed and further cores taken and analysed from Lough Oughter.

A better understanding of processes affecting water quality and sediment accumulation rates operating in the Lough Erne region was to be attempted through detailed analyses of sediment cores from two small loughs within the Erne catchment.

As well as attempting to understand change within the Lough Erne system – it was felt that sediment cores taken from other large lakes in the north-west would be useful in attempting to understand land management changes and their effect on water quality. Phase I studies at Lough Melvin – a lake considered to be near pristine in an Irish context – had proved to be inconclusive (diatoms were only preserved in the upper most 2 cm), so detailed diatom analysis of ^{210}Pb sediment cores in phase II focused on both basins of Lough MacNean and Lough Allen.

To improve the representivity of the TP-diatom models in the specific context of large lakes in the north of Ireland 10 other large lakes in the region were selected for surface sediment diatom and water chemistry analysis.

6. Study Sites

Lough Oughter is a relatively large riverine-lake complex situated south of Belturbet. It forms part of the River Erne catchment. Its catchment area is predominantly lowland grassland agriculture. Lower and Upper Lough MacNean are also part of the River Erne catchment but are situated in its western part.

The MacNean catchment straddles the border between Northern Ireland and the Republic and includes a larger percentage of upland unimproved pasture and semi-natural vegetation (including some forested areas). The two parts of the lake are quite different with the Upper Lough having a greater mean depth (7 m) – the lake bathymetry is complex with a number of basins over 10 m deep and numerous islands (the maximum depth is around 20 m). The Lower Lough is quite different with large areas less than 3 m deep and a single basin around 10 m deep situated close to the northern shore.

Lough Allen is a large lake (3500 ha), deep (30 m) lake situated south-west of Lough MacNean. The small town of Drumshanbo is situated on the southerly shore.

The two small lakes in the Erne catchment selected for multi-coring were both situated on the eastern side of Lough Erne, one close to the Broad Lough (Bresk: Irish Grid reference - H201601) and one in the catchment area of the Upper Lough (Back Lough: Irish Grid Reference H 458 307). Both are small and relatively shallow (23 ha and 4.25 ha respectively) and have relatively high nutrient concentrations (82 and 98 µg TP l^{-1} in July 1997 respectively). The catchment of Back Lough is agricultural and while that of Lough Bresk is also primarily agricultural, it is more disturbed as a result of the building of a railway embankment (now disused). Both lakes have small inflowing streams and so drain catchments reasonably representative of the inputs to the larger Lough Erne system.

Table 1 Location details and phosphorus concentrations for the study lakes

	Upper Lough Erne	**Lower Lough Erne**	**Lough Oughter**
Location	54° 14′ N 7 °32′W	54° 30′ N 7 °50′W	54° 01′ N 8 °25′W
Altitude	46 m	45.7 m	53 m
Catchment area	3514 km^2	4212 km^2	NK
Lake area*	34.5 km^2	109.5 km^2	13 km^2
Mean Depth	2.3 m	11.9 m	NK
Maximum depth	27 m	69 m	10 m
Lake volume	0.08 x 10^9 m^3	1.3 x 10^9 m^3	NK
Mean TP concentration	70-80 µg TP l^{-1}	45-50 µg TP l^{-1}	~48 µg TP l^{-1}

*Excluding islands

	Upper Lough MacNean	**Lower Lough MacNean**	**Lough Allen**
Location	54° 17′ N 7 °55′W	54° 16′ N 7 °50′W	54° 05′ N 8 °05′W
Altitude	55 m	55 m	55 m
Catchment area	NK	NK	NK
Lake area	10.1 km^2	5.16 km^2	35 km^2
Mean Depth	6 m	11 m	NK
Maximum depth	24 m	1.7 m	30
Lake volume	NK	NK	NK
Mean TP concentration	23 µg TP l^{-1}	30 µg TP l^{-1}	17 µg TP l^{-1}

NK = not known/computed

7. Methods

7.1. Fieldwork

One metre Mackereth cores were obtained from Loughs Allen (code ALLN 1) and Oughter (OUGT 1) in May 1997. Two short cores (MACU 1 & 2) were obtained from Upper Lough MacNean in November 1996 using a Glew-corer. The Lower Lough was cored in July 1997 and surface sediments from a further 10 lakes were cored using a Glew corer for the "Large Lakes" training set. For these samples, only the surface 0.5 cm was retained together with a basal sample (ca. 30 cm depth).

Water samples were also taken from these lakes and sent to the Aquatic Sciences Division at DANI for analysis.

7.2. Core extrusion and analysis

Short cores for both surface sediments (training set development) were extruded in the field, in 0.5 cm slices. The 1 m Mackereth cores were transported vertically back to the laboratory where they were extruded vertically into 1 cm slices. Percent dry weight (%DW) and loss-on-ignition (%LOI) analyses were done using standard techniques (Dean 1974). Measurements were made on consecutive samples over the surface 20 cm for most cores and at alternative cms below that depth. For the shorter cores, analyses were made on all samples.

7.3. Dating

After freeze drying and sub-sampling for loss-on-ignition analyses, the remaining sediment was sent to the Radiometric Dating Laboratory at the University of Liverpool. Samples were analysed for ^{210}Pb, ^{226}Ra, ^{241}Am, ^{137}Cs and ^{134}Cs using standard gamma assay (Appleby *et al.*, 1986).

Radiometric dates calculated using the CRS ^{210}Pb dating models (Appleby *et al.* 1978), together with dated levels determined from the ^{137}Cs and ^{241}Am stratigraphies (Appleby *et al.* 1991). Use of the CIC model was in most cases precluded by irregular variations in the ^{210}Pb profile. Where discrepancies with the ^{137}Cs/^{241}Am dates were significant, adjustments to the ^{210}Pb dates have been made using procedures described in Appleby (1998). Core chronologies based on these considerations are given in Appendix 1.

7.4. Diatom analysis

The preparation of samples for diatom analysis followed standard methodology (Renberg, 1990). Around 300 valves were counted for each sample and the results expressed as a percentage of total count (Battarbee, 1986a).

7.5. Development of a diatom-phosphorus transfer function for large lakes

Previous experience with model development had indicated it would be necessary to include different datasets from outside the north of Ireland because a minimum of 30-35 lakes are required to achieve minimal performance. To create a reasonably robust diatom-phosphorus inference model for large lakes, 18 surface sediment samples from the north of Ireland were amalgamated with 25 large Scottish lakes and three from Europe (Table 2). Lakes cored specifically for the purpose of creating the training set were also supplemented by surface samples form the cores studies within this project (Table 2).

The phosphorus range of the sampled lakes ranged from ~1 to 130 µg TP l^{-1} (Table 2). Preliminary analysis of the dataset using detrended correspondence analysis (DCA) indicated that there were a number of outliers and these lakes were removed prior to final model formulation.

Table 2 Location and phosphorus concentrations for lakes used in the Large lakes training set

Lakes cored directly for training set development

Lough	**Location**	**TP concentration µg TP l^{-1}**
Sheelin	53° 48′ N 7 °18′W	23
Owel	53° 33′ N 7 °22′W	17
Ennel	53° 28′ N 7 °23′W	33
Gara	53° 57′ N 8 °26′W	30
Ree	53° 28′ N 7 °58′W	39
Skean	54° 03′ N 8 °13′W	30
Meelagh	53° 03′ N 8 °10′W	116
Garadice*	54° 03′ N 7 °42′W	129
Belhavel*	54° 12′ N 8 °10′W	NK
Gill	54° 15′ N 8 °20′W	22
Arrow	53° **3′ N 7 °***′W	15
Key	53° **′ N 7 ° **′W	17
Lough Neagh*	54° 35′ N 7 ° 30′W	110
Surface sediment samples from long-core studies (see Table 1)		
MacNean Upper		23
Lough Erne: (Upper, Manor House and Broad Lough) (3)	*See Table 1*	73, 62, 54
Allen		17
Lakes from Scotland (25) and Europe (3)		1-100

* Not used in Final model

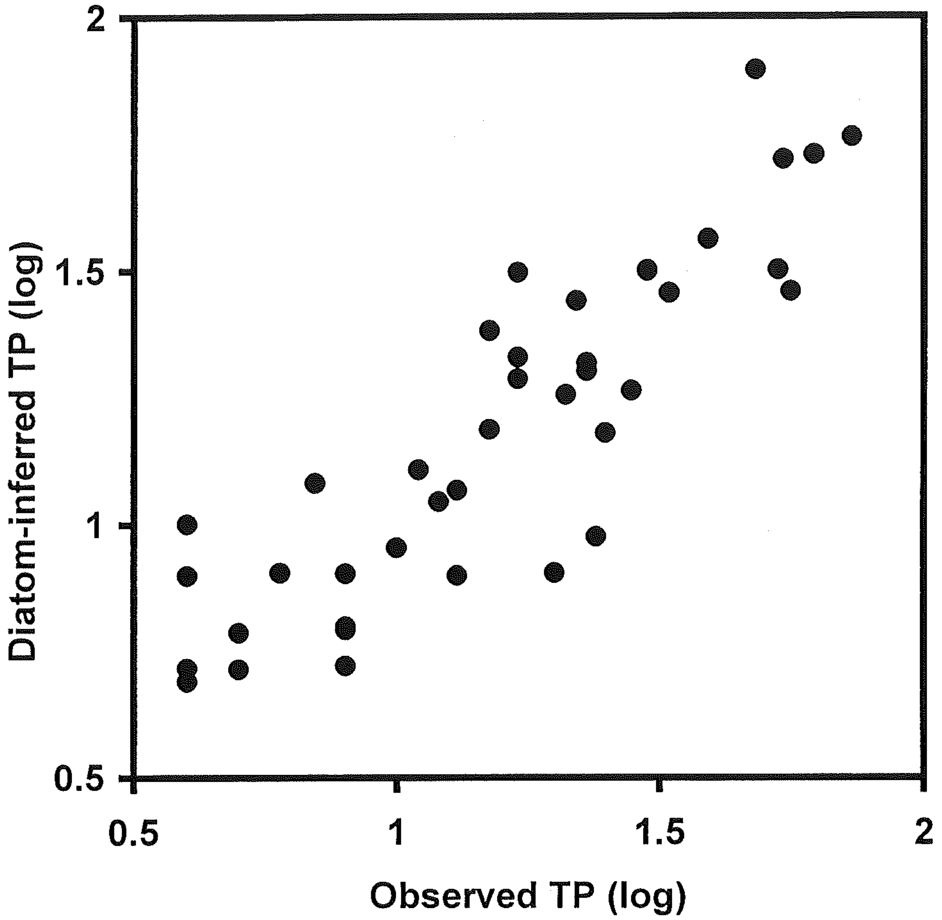
Total phosphorus was modelled using the "Large lakes" diatom-training set, using the program CALIBRATE (S. Juggins, unpublished program). TP concentrations were log-transformed prior to analysis and both the classical and inverse de-shrinking (see Bennion *et al.*, 1996 for further details) options were used. The final calibration dataset consisted of 41 lakes covering a P range of 3 to 73 µg TP l^{-1}. The modelled results using Classical deshrinking fit better over the full gradient although the errors tend to be slightly higher than with inverse deshrinking (which has the lowest errors) (see Table 3, Fig. 1) The different models perform quite well, with $RMSE_{jack}$ values around 0.20 to 0.26 and r^2 values of 0.58 to 0.70 (See Table 3). Compared with other training sets these results are very acceptable (see Anderson 1997a for a discussion).

Table 3 Comparison of error statistics for the Inference Models for Total Phosphorus for Large lakes

Model	*RMSE*	R^2
WA with Inverse Deshrinking		
WA	0.188	0.75
WAtol*	0.157	0.82
WA_{Jack}	0.243	0.58
WA_{Jack}Tol	0.204	0.70
WA with Classical Deshrinking		
WA	0.218	0.75
WAtol	0.173	0.82
WA_{jack}	0.26	0.59
WA_{Jack}Tol	0.21	0.71

*Tol = WA with Tolerance down waiting
*Jack = Jacknifed error estimates

Figure 1 Modelled versus observed TP concentrations for large lakes using Weighted Averaging Regression and Calibration (with inverse deshrinking)



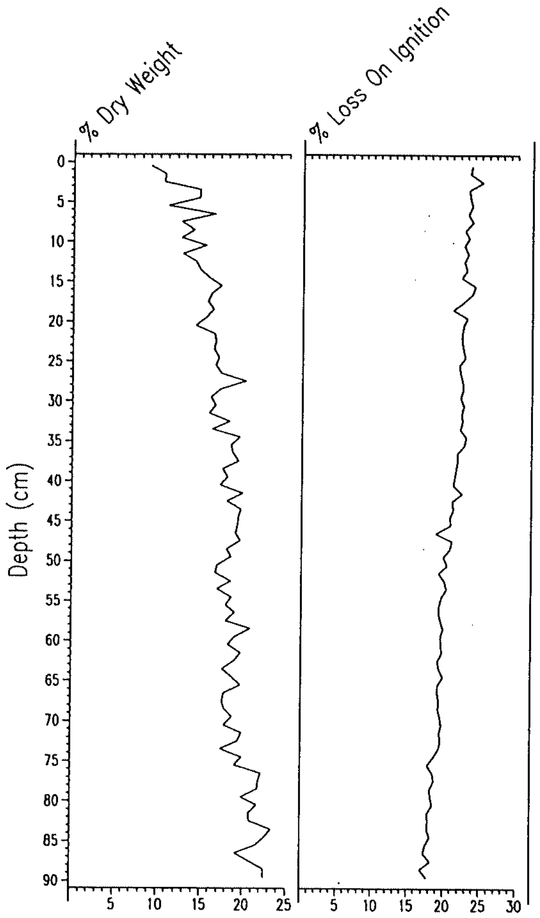
8. Results

8.1. Lough Oughter

8.1.1. Dry weight and Loss-on-ignition

The loss-on-ignition (LOI) profile is nearly featureless, increasing linearly from 17 % at 90-cm depth to 22 % at the core surface (Fig. 2). Dry Weight is relatively uniform at 20% between 65 and 30 cm depth, from where it declines to <10% at the core surface. There is a suggestion of slightly higher values over the lowermost 15 cm of the core.

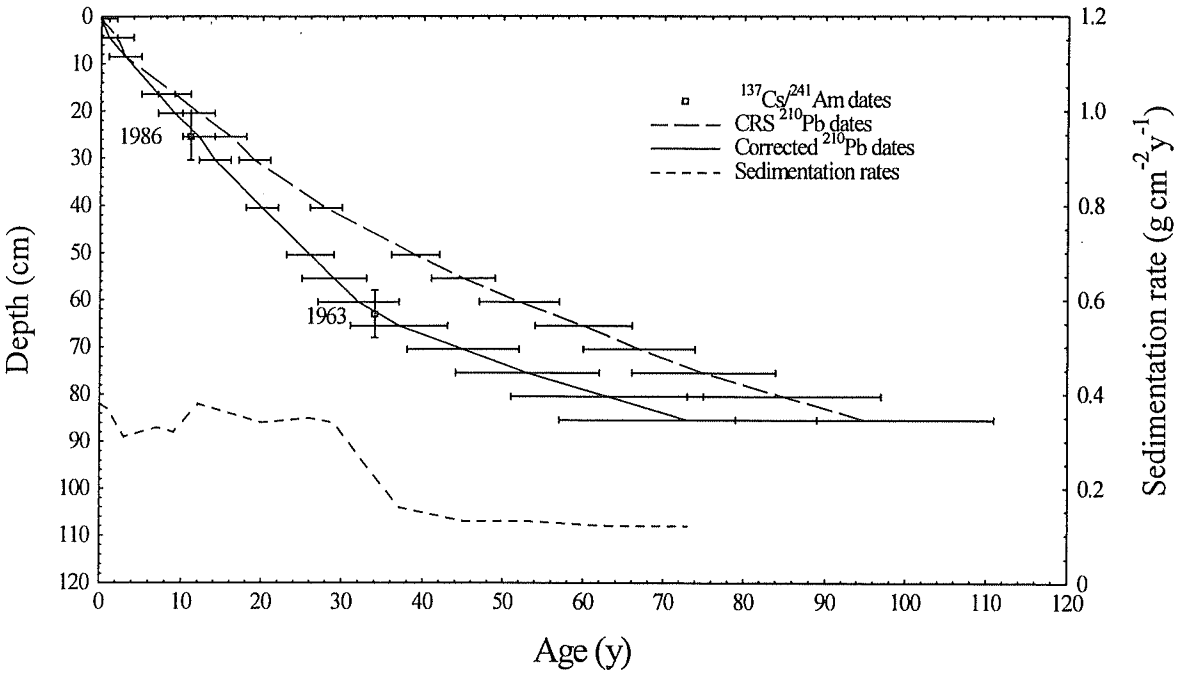
Figure 2. Dry weight (%) and Loss-on-ignition (%) profiles for Lough Oughter (core OUGT1, 1997)



8.1.2. Dating

There is a poor agreement between the CRS model chronology and the ^{137}Cs-dates (Fig. 3), suggesting that the ^{210}Pb chronology is uncertain. This discrepancy may be due to the enhanced ^{210}Pb flux associated with increased sedimentation rates over the uppermost 60 cm. The final ^{210}Pb chronology has been corrected using the Cs peaks as reference points. The sediment accumulation rate is very fast, the core covers only the last 70-80 years. The data indicate that the sediment accumulation has doubled in the last 30-35 years.

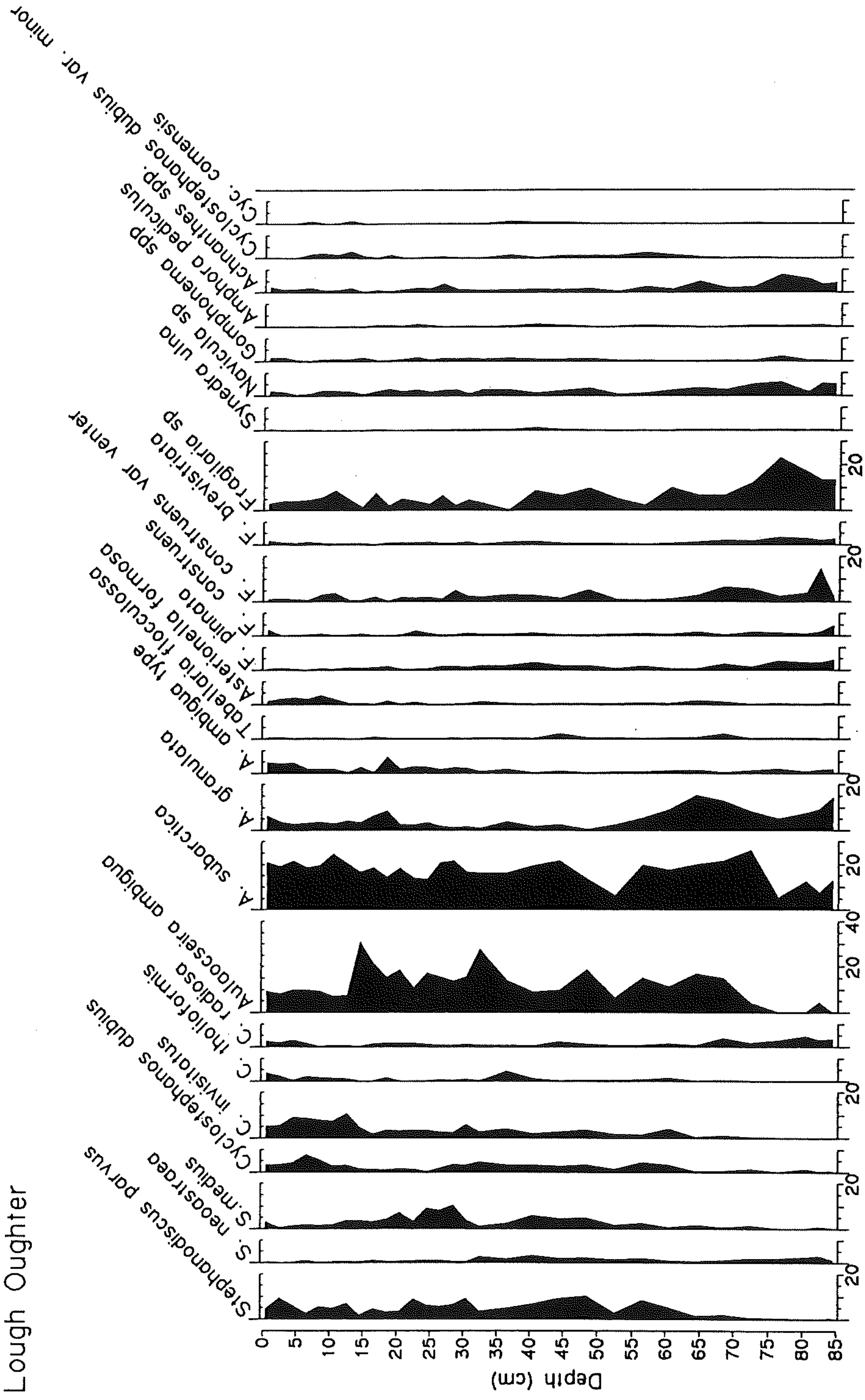
Figure 3 Radiometric chronology of Oughter Lough core OUGT1 showing CRS model ^{210}Pb dates together with dates determined from the ^{137}Cs and ^{241}Am stratigraphy. Also shown are corrected ^{210}Pb dates and sedimentation rates calculated using the ^{137}Cs/241Am dates.



8.1.3. Diatom stratigraphy

The diatom stratigraphy is dominated by meso- to eutrophic planktonic taxa, in particular, *Aulacoseira ambigua* and *A. subarctica* (Fig. 4). The values of *A. granulata* and *Fragilaria* spp. are higher in the lowermost 30 cm. The decrease in values of these two taxa is the result of increased percentages of the *Stephanosdiscus-Cyclostephanos* complex small, centric planktonic taxa indicative of increased nutrient availability. In particular, *Cyclostephanos invisitatus* increased to ~10 % in the surface 12 cm.

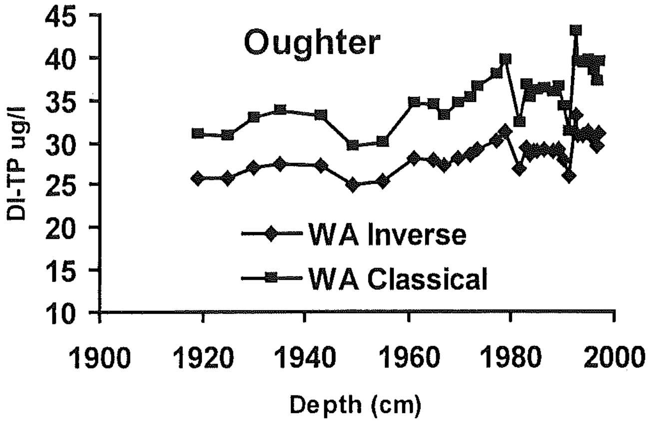
Figure 4. Relative frequency (%) stratigraphy for Lough Oughter (core OUGT 1, 1997).



8.1.4. Diatom-inferred total Phosphorus

DI-TP concentrations show a slight upward trend of the length of the core, covering the last 70 years. Results from two models are presented here (Fig. 5) as the WA with inverse deshrinking gives a concentration of ca. 30 µg TP l^{-1} at the surface, which compares to a measured value of 48 µg TP l^{-1}. With classical deshrinking the surface value reconstructs to 40 µg TP l^{-1}. It is difficult to determine which model is more accurate as there is only the single water sample measurement available for comparison. The trends of the two models are, however, identical. Plotted against time (Fig. 5), there is a suggestion of an increase in the immediate post-war period but with a decline in the 1980s.

Figure 5. Diatom-inferred TP profiles plotted against time for Lough Oughter

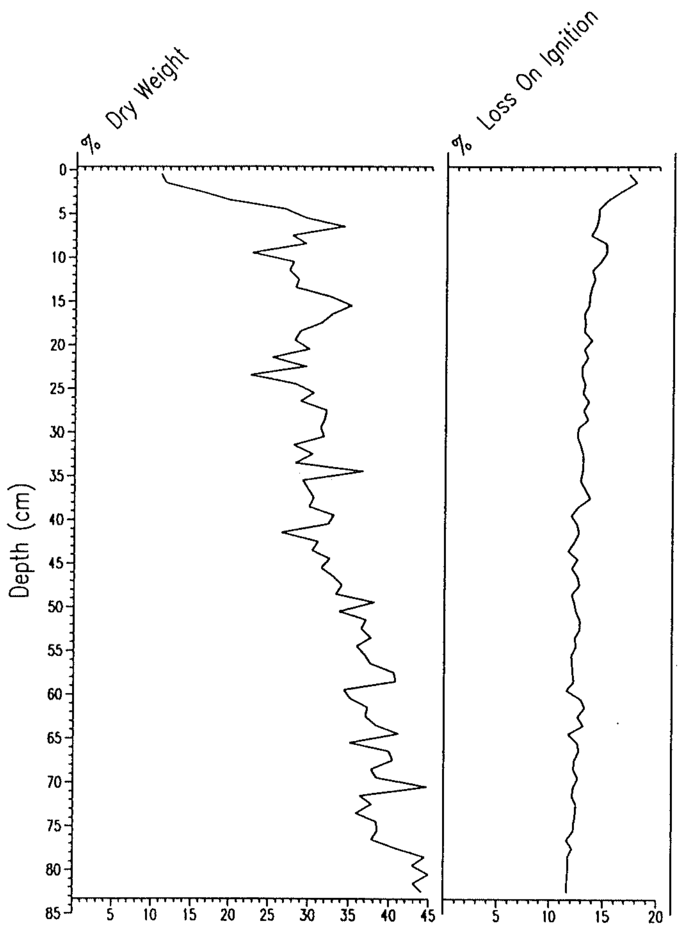


8.2. Lough Allen

8.2.1. Dry weight and Loss-on-ignition

Dry weight values are high (>25%) throughout the core apart for the uppermost 5 cm where they decline to ~10%. The LOI profile is nearly constant at 12% until the core surface where it increases to 18% (Fig. 6).

Figure 6 Dry weight (%) and Loss-on-ignition (%) profiles for Lough Allen (core ALLN1, 1997)



8.2.2. Dating

As with Lough Oughter, the ^{210}Pb CRS chronology does not match the Cs dates so the final ^{210}PB chronology used is a composite model (Fig. 7). This suggests that accumulation rates increased up to ~1960 but that there have been rapid and substantial but temporary increases in dry mass accumulation over the last 30 years, with the most recent occurring ca. 1986. The whole-core record (ca. 90 cm) probably covers in excess of 200 years.

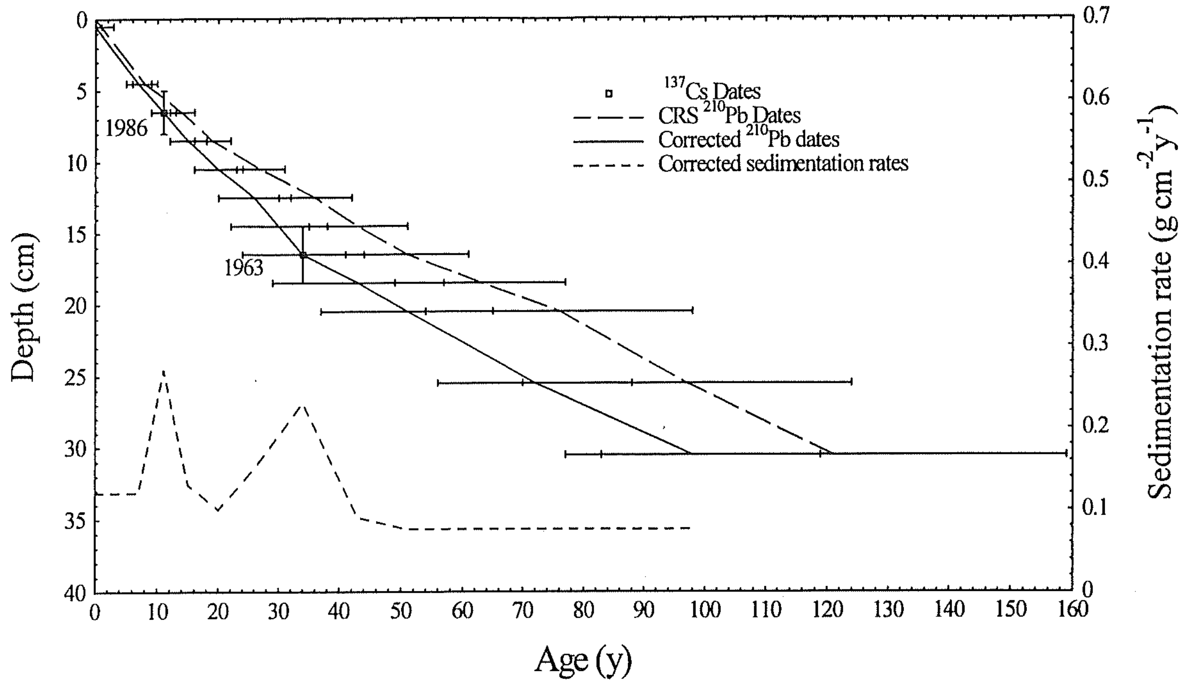
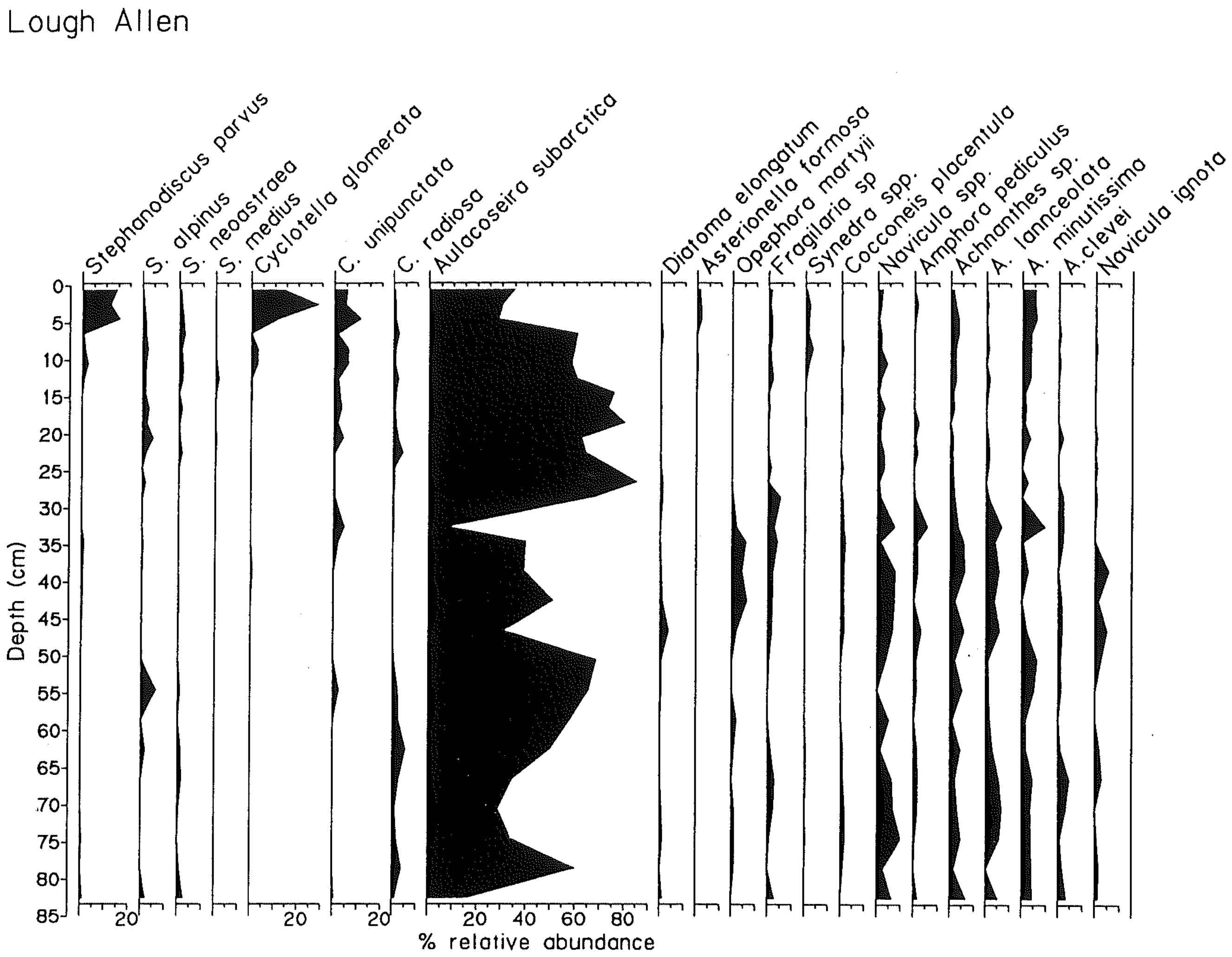


Figure 7 Radiometric chronology of Lough Allen (core ALLN 1) showing CRS model ^{210}Pb dates together with dates determined from the ^{137}Cs and ^{241}Am dates.

8.2.3. Diatom stratigraphy

The diatom profiles are dominated by *Aulacoseira subarctica* although values vary between 20 and 80% (Fig. 8). There are two important changes in the stratigraphies, the first occurs at ca. 25 cm depth and is the diversification of the plankton flora: *Stephanodiscus alpinus*, *S. neoastraea*, *Cyclotella unipunctata* and *C. radiosa* all become present consistently. The second change occurs at 6 cm and is the rapid increase in abundance of *S. parvus* and *C. glomerata*. It is in this period also that *Asterionella* is recorded, albeit it at very low values.

Figure 8 Relative frequency (%) diatom stratigraphy for Lough Allen, (core ALLN1, 1997).



8.2.4. Diatom-inferred total Phosphorus

Plotted against depth (Fig. 9), DI-TP values are relatively constant at 22-25 µg TP l^{-1} below 20 cm depth. Above this depth, there is an irregular decline to a surface value of ca. 20 µg TP l^{-1}. Plotted against time phosphorus concentrations are constant from 1880 to 1940. The last 50 years have seen a systematic, if irregular decline in phosphorus concentrations (Fig. 10).

Figure 9 Diatom-inferred TP for Lough Allen plotted against sediment depth.

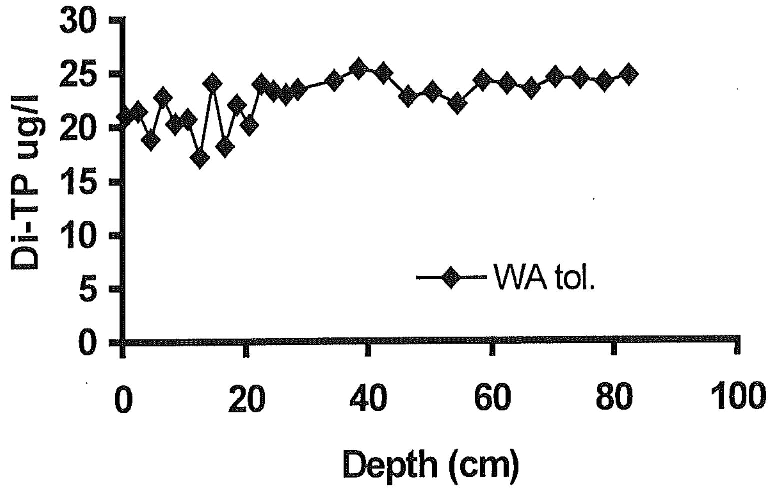
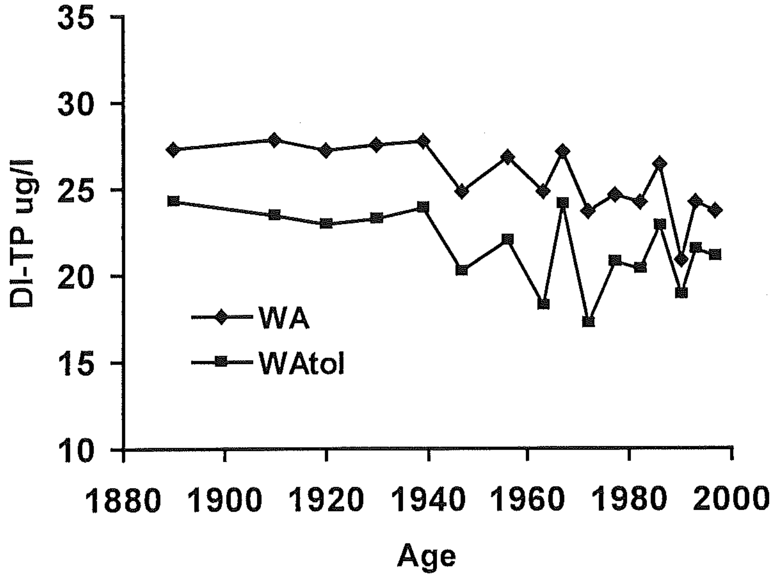


Figure 10 Diatom-inferred TP for Lough Allen plotted against ^{210}Pb age

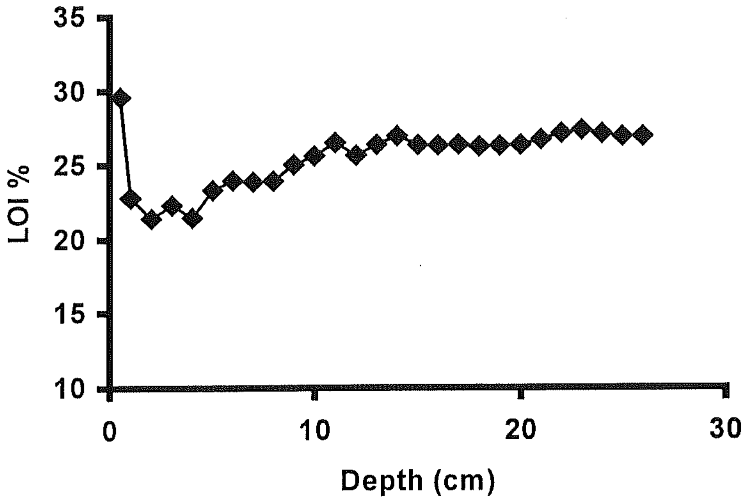


8.3. Lower Lough MacNean

8.3.1. Loss-on-ignition

LOI values are constant below ~12 cm depth at 25%. Above this depth they decline slowly to minimum values (21%) at 2-3 cm. There is a clear surface peak with maximum observed value of nearly 30 % (Fig. 11).

Figure 11 Loss-on-ignition (%) profile for Lower Lough MacNean (core MACL1, 1997)



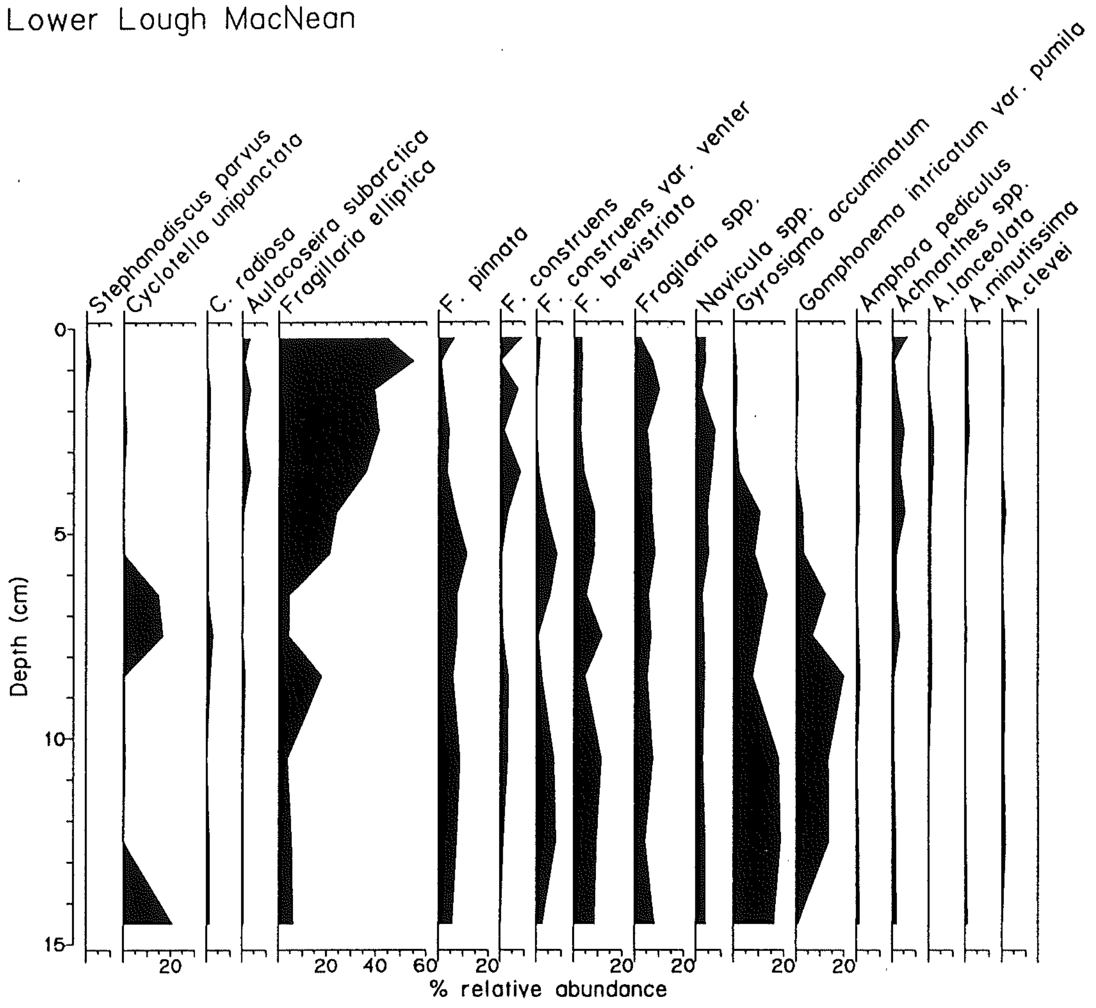
8.3.2. Dating

The radionuclide data are inconclusive. Although there is an apparently normal exponential decline in ^{210}Pb activity with depth, the total unsupported inventory is very low (less than half the atmospheric flux). ^{137}Cs showed no peaks and cannot be used for chronological control while ^{241}Am was not detected. The implication is that the sediment record is incomplete (see Appendix 1).

8.3.3. Diatom stratigraphy

The diatom stratigraphy is quite different to the other lakes in that it is dominated by benthic and periphytic taxa (Fig. 12). Apart from two peaks (ca. 20%) of *Cyclotella unipunctata*, plankton values are very low. The upper half of the analysed section (ca.7 cm) is dominated by increasing values of *Fragilaria pinnata*. There are substantial contributions from a number of other *Fagilaria* species. Below 5 cm, *Gyrosigma accuminatum* and *Gomphonema intricatum* var. *pumila* are the dominant taxa, both reaching over 15%.

Figure 12 Relative frequency (%) diatom stratigraphy for Lower Lough MacNean (core MACL1, 1997)



8.3.4. *Diatom-inferred Total Phosphorus*

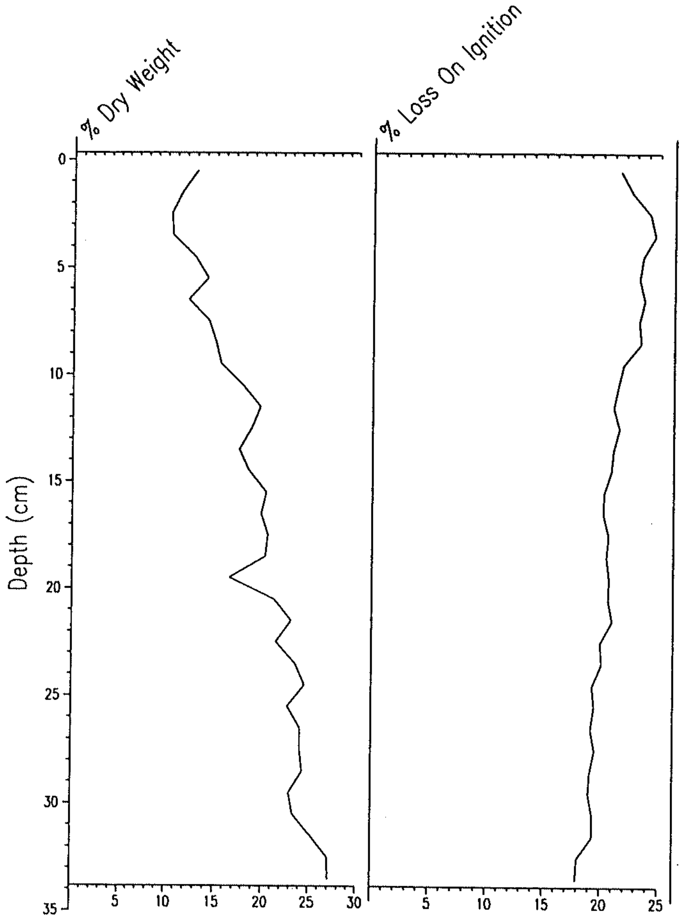
Given the high values of benthic and periphytic taxa in this core, and the problematic dating, reconstructions of phosphorus values were not attempted.

8.4. Upper Lough MacNean

8.4.1. Dry weight and Loss-on-ignition

Percent dry weight values decrease steadily from maximum values at the base of the core (25%) to only ca. 5% at the core surface. LOI values increase steadily above 30 cm depth, reaching 22% at the core top (Fig. 13).

Figure 13 Dry weight (%) and Loss-on-ignition (%) profiles for Upper Lough MacNean (core MACU, 1996).



8.4.2. Dating

The interpretation of the radionuclide results is complex, in part due to the inferred high sediment accumulation rates and the length of the core recovered (Fig. 14). At the base of the analysed section, ^{210}Pb activity is still significantly higher than the supporting ^{226}Ra values. Only one peak of ^{137}Cs was found and is assumed to be from Chernobyl. These data suggest that the core covers only the last 50-60 years.

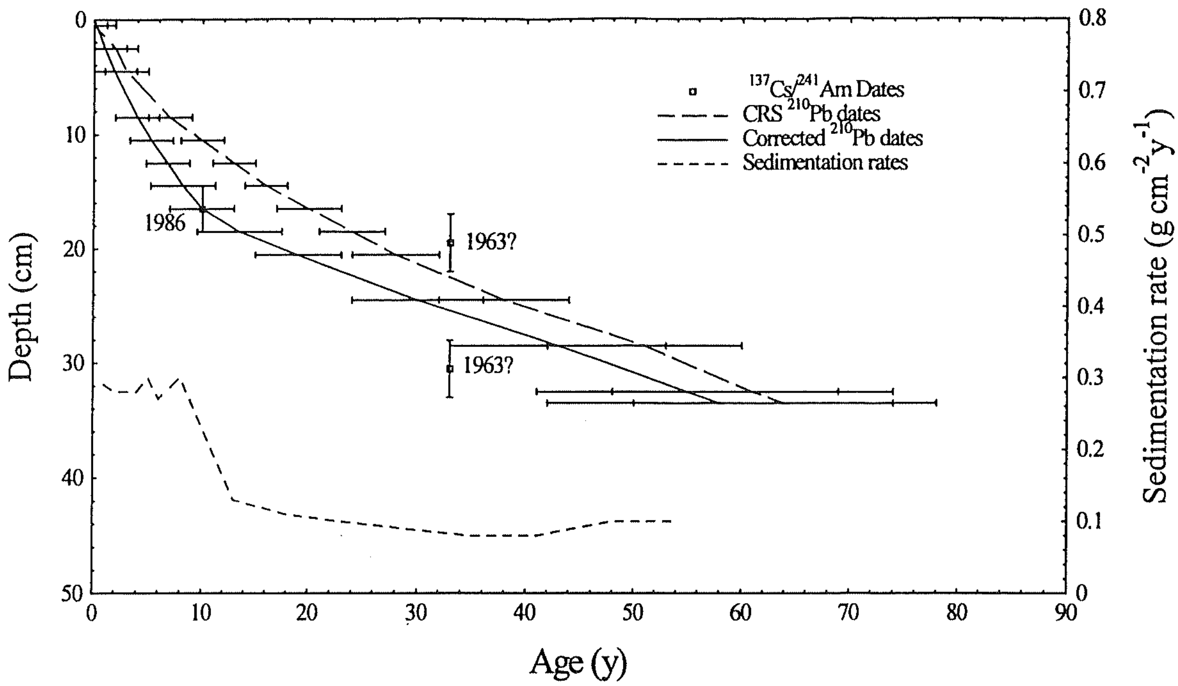
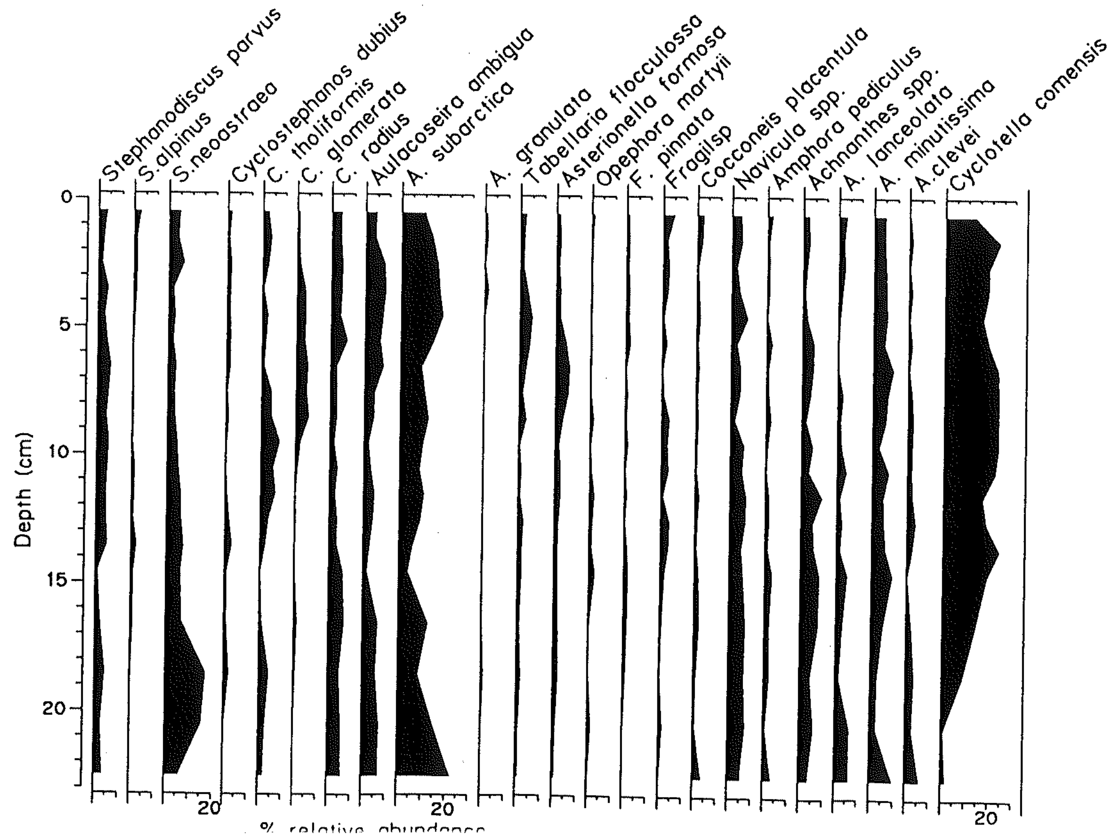


Figure 14 Radiometric chronology of Upper Lough MacNean (core MACU 1) showing CRS model ^{210}Pb dates together with dates determined from the ^{137}Cs dates.

8.4.3. Diatom stratigraphy

The core is dominated by planktonic taxa although there are also substantial percentages of *Navicula* and *Achnanthes* species. The two dominant planktonic taxa are *Cyclotella comensis* and *A. subarctica* together with *C. radius* and *A. ambigua*. The abundance of *S. neoastraea* is highest below 17-cm depth (Fig. 15). The main change in the diatom assemblages is the increase in *C. comensis*.

Figure 15 Relative frequency (%) diatom stratigraphy for Upper Lough MacNean (core MACU1, 1996)



8.4.4. Diatom-inferred total Phosphorus

The results of the application of both WA models (Fig. 16) show similar trends and reconstructed values are not significantly different between them. From around 1970 DI-TP concentrations decline from ~25 µg TP l^{-1} to 1985 when they increase again to similar values. In the early 1990s, concentrations dropped to a low of 15 µg TP l^{-1} since they increased to values around 20 µg TP l^{-1}.

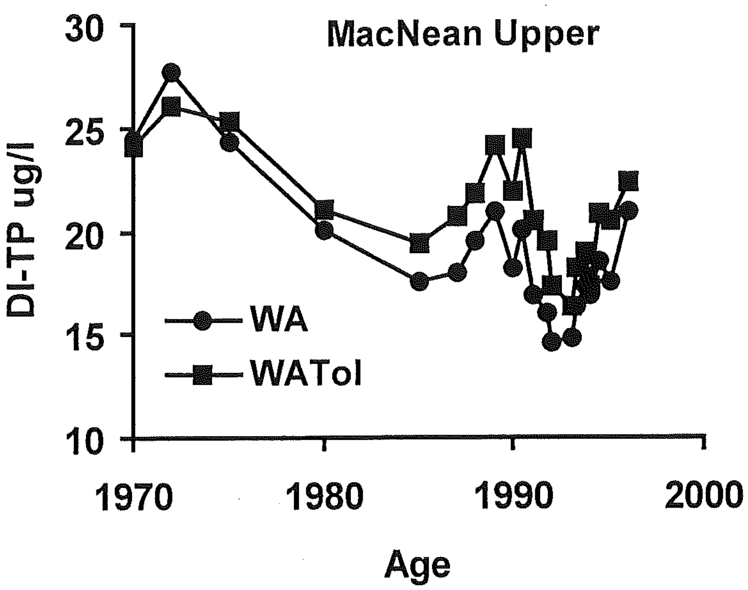


Figure 16 Diatom-inferred TP profiles plotted against time for Upper Lough MacNean

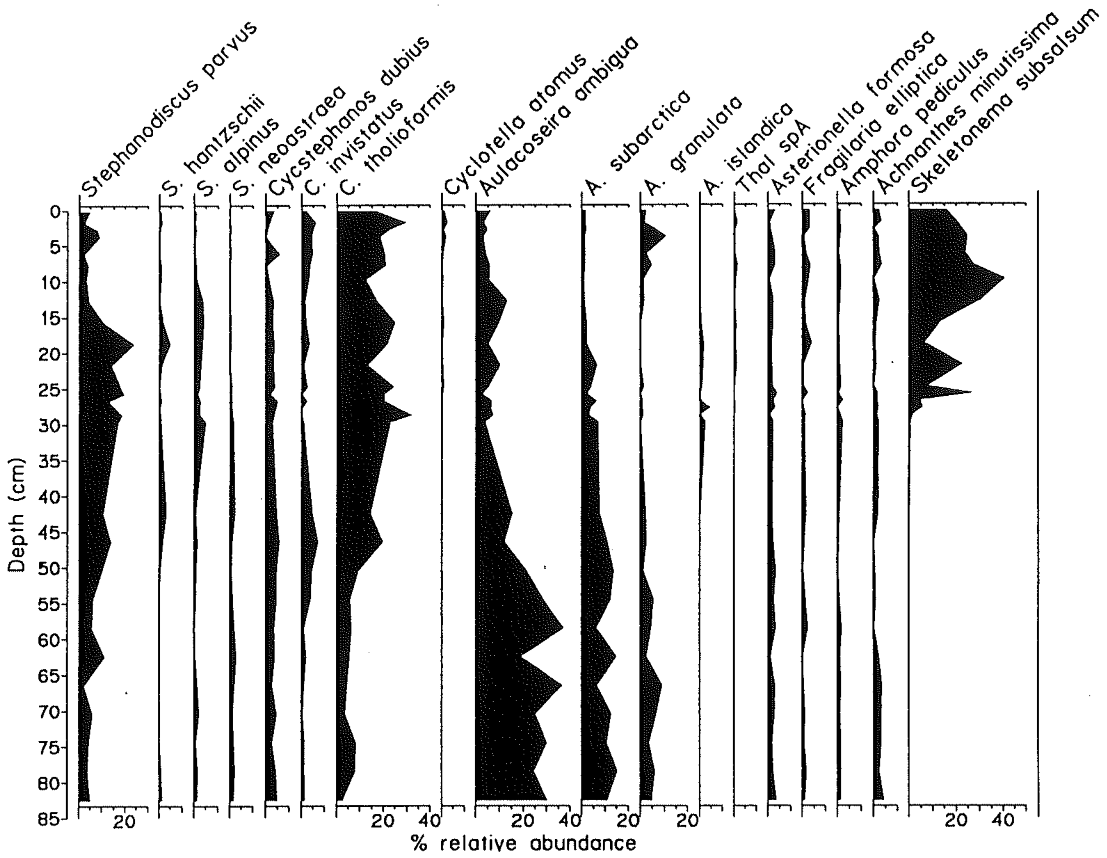
8.5. Diatom analyses from the 1994 Lough Erne cores: Manor House and Tongree

In the original study, the sediment accumulation rates were much higher than expected and so diatom analyses did not cover the full ^{210}Pb period. Here we present further analyses that extend the time period covered by diatom analysis.

8.5.1. Diatom stratigraphy – Lower Lough Erne - Manor House (MH2)

The full core analysis shows striking changes in diatom stratigraphy (Fig. 17). The core is dominated by centric planktonic taxa – a complex of small *Stephanodiscus* and *Cyclostephanos* spp together with *Aulacoseira amibuga* and *A. subarctica.* The major change occurs at ~ 65 cm with the decline of the two main *Aulacoseira* spp. and their replacement by *Cyclostephanos* cf. *tholiformis* primarily and *S. parvus* to a lesser extent. At 30 cm, *A. subarctica* declines to trace values and *S. parvus* declines from its maximum occurrence (20%). *Skeletonema subsalsum* (see Anderson *et al.* 1996; Gibson *et al.*, 1993) first occurred at 27 cm but increases rapidly from ca. 20 cm to reach maximum values of ~40% at 10 cm. In the upper half of the core *Skeletonema* is co-dominant with *C. cf. tholiformis*.

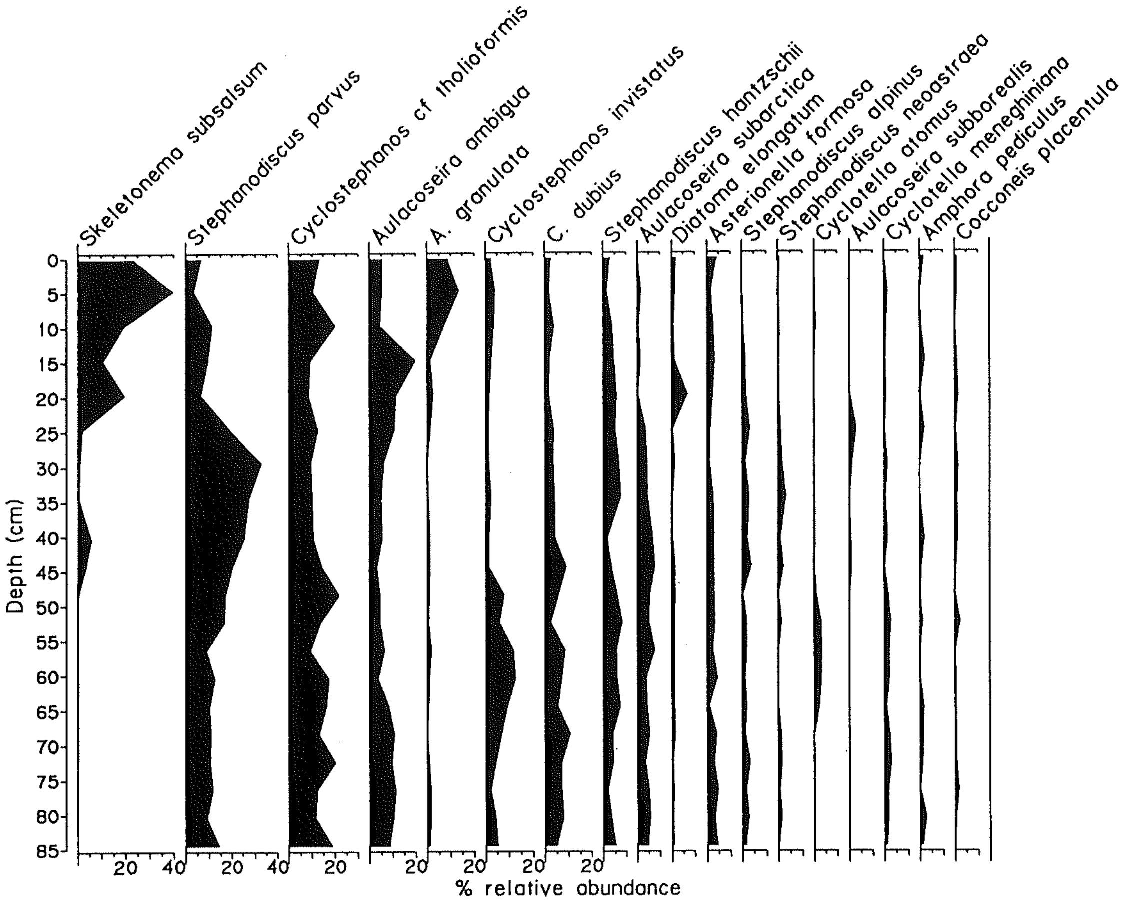
Figure 17 Relative frequency (%) diatom stratigraphy for Lower Lough Erne, Manor House (core MH2, 1994)



8.5.2. Diatom stratigraphy – Upper Lough Erne - Tongree

The sediment accumulation rate at Tongree was extremely fast (Anderson *et al.* 1995). The core covers only ca. 35 years and so the diatom analyses were completed at 4 cm intervals (Fig. 18). The whole core is dominated by small centric diatom species. The major change in the diatom assemblages is the expansion of *Skeletonema subsalsum* above 20 cm (ca. 1989). Prior to this there is a slight increase in *Stephanodiscus parvus* which reaches nearly 40% at 30 cm. Below 45 cm *Cyclostephanos invisitatus* is more abundant (ca. 10%) as are *Aulacoseira ambigua* and *C. dubius*.

Figure 18 Relative frequency (%) diatom stratigraphy for Upper Lough Erne, Tongree (core TG2, 1994)

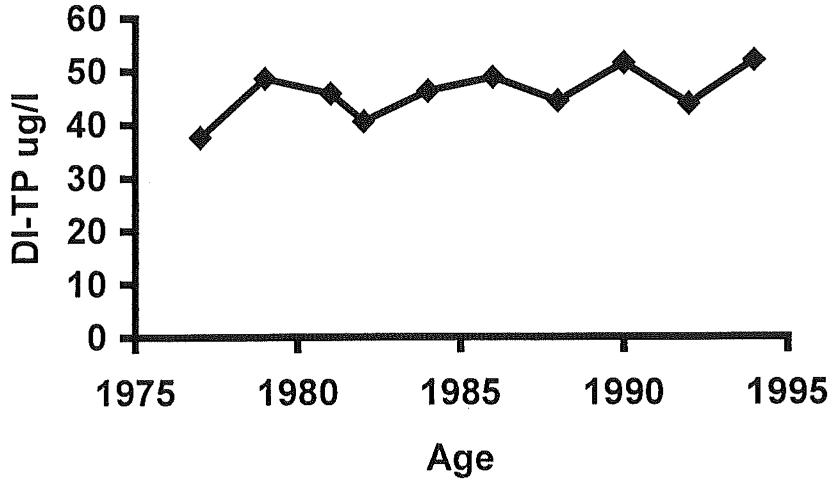


8.5.3. Diatom-inferred total Phosphorus: Lower Lough Erne (Manor House and the Broad Lough) and the Upper Lough Erne (Tongree)

The new “Large Lakes” diatom-phosphorus inference model was also applied to the diatom analyses undertaken as part of the first phase of the project.

The diatom-inferred TP concentrations for the Broad Lough show no systematic trend and vary between 40 and 50 μg TP l^{-1} for the period 1975 to 1995 (Fig. 19). These concentrations are in remarkably good agreement with the monitoring results for the same period (Foy *et al.* 1993) where there is also no trend recorded since monitoring began in 1975.

Figure 19 Diatom-inferred TP profiles plotted against time for Lower Lough Erne (Broad Lough, core BRDL 1)



In the Manor House core, DI-TP concentrations are uniform at ca. 30 µg TP l^{-1} for the period 1920 until around 1960 (Fig. 20). From the late 1950s, early 1960s, inferred-TP concentrations start to increase steadily until ca. 1980 when there is a very rapid increase from ~50 µg TP l^{-1} to between 65 and 85 µg TP l^{-1}. In the most recent period there is a substantial difference between the WA and WA_{tol} inferred TP concentrations (see discussion). The simple WA-model indicates a continuing upward trend, whereas the tolerance down weighted model, although variable, indicates no discernible trend. While monitoring data are scarce for the Manor House area of the lake, the data available (C. Gibson pers. comm.) suggest that values are higher than the Broad Lough and vary around 65 µg TP l^{-1}. These values agree well with those derived from the simple WA model (Fig. 20).

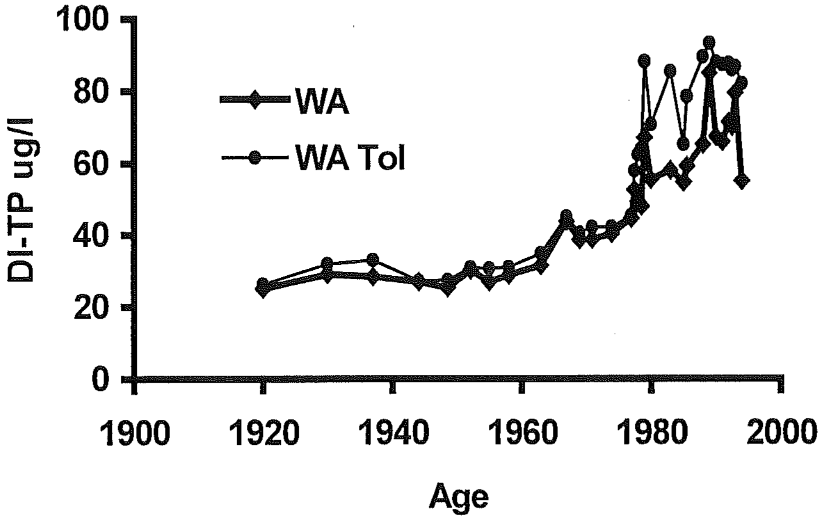


Figure 20 Diatom-inferred TP profiles plotted against time for Lower Lough Erne (Manor House, core MH 2)

At Tongree, results from both models are constant around 40 μg TP l^{-1} below 45 cm (ca. 1980). The WA_{tol} model indicates a short increase in the early 1980s followed by a more sustained increase throughout the 1990s (Fig. 21). The simple WA-model concentration inferences are constant until the late 1980s when there is an abrupt increase to ~80 μg TP l^{-1}.

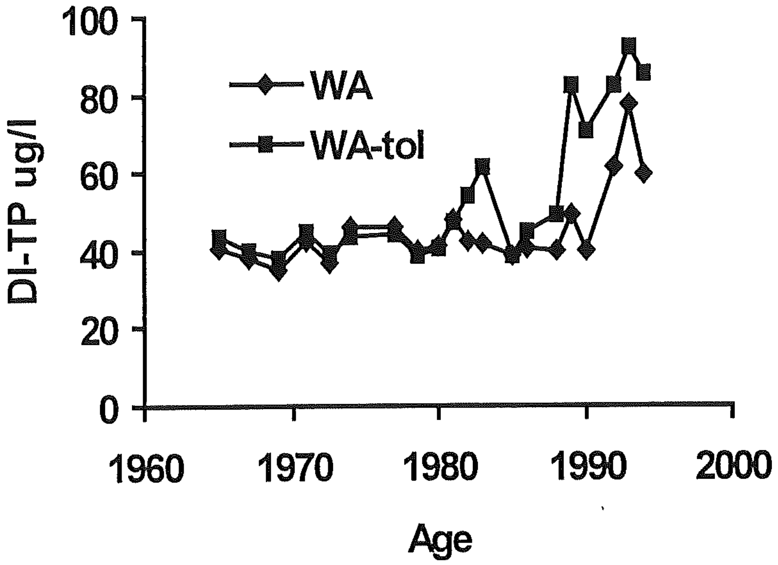


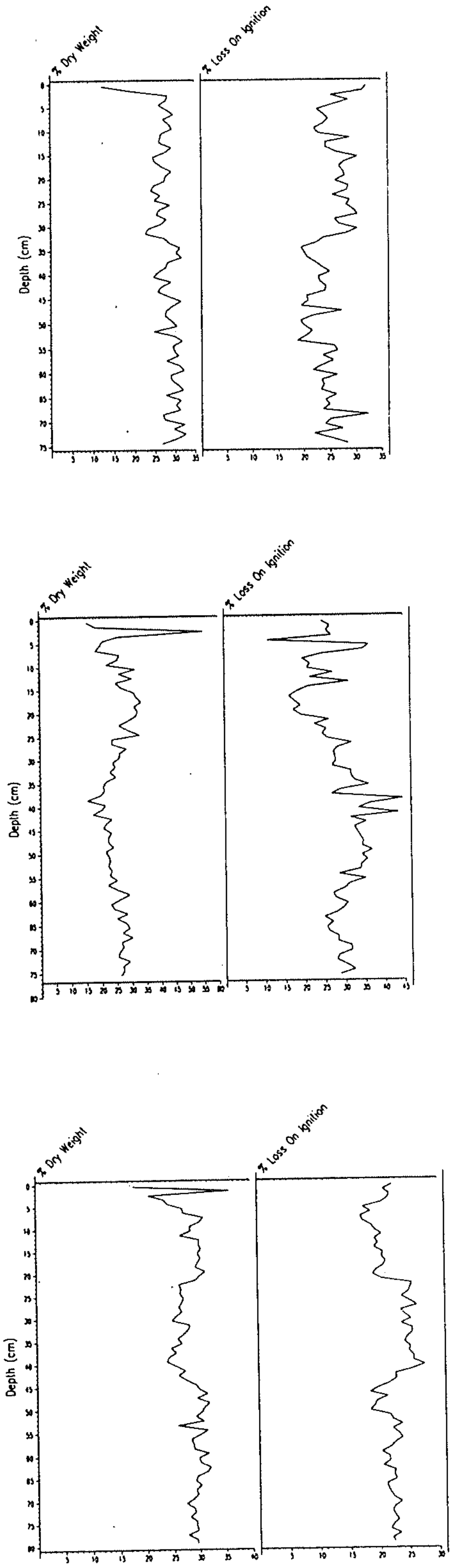
Figure 21 Diatom-inferred TP profiles plotted against time for Upper Lough Erne (Tongree, core TG2)

8.6. Lough Bresk and Back Lough

8.6.1. Dry weight and loss-on-ignition: Lough Bresk

Seven cores were taken from Lough Bresk covering a range of water depths (3-8.5 m). There is reasonable consistency in the %DW profiles but loss-on-ignition profiles tend to be more variable. There is some variability of both %DW and LOI profiles in the shallower water cores (e.g. cf. Bresk cores BRK 4 and 5 with BRK 7 – see Fig. 22) compared to those from deeper water.

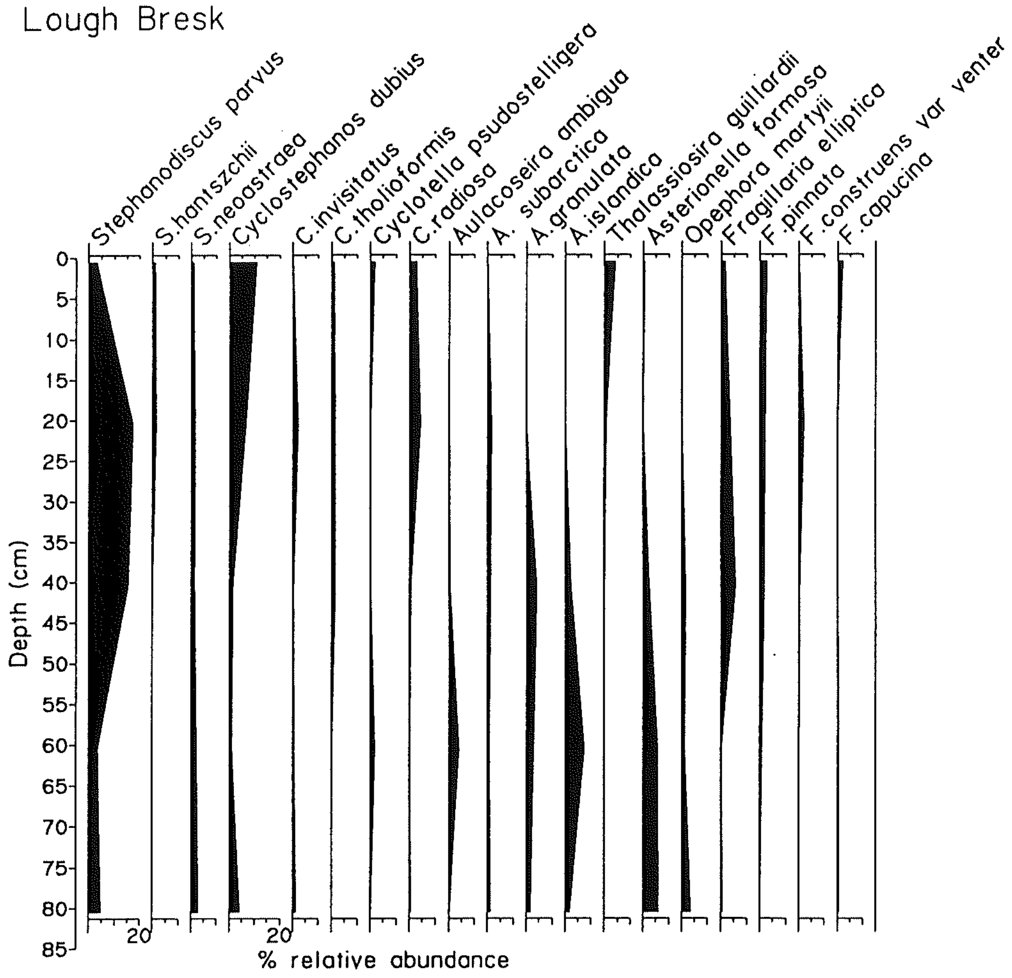
Figure 22 Dry weight (%) and Loss-on-ignition (%) profiles for selected cores from Lough Bresk (cores BRK4,5,7, 1997)



8.6.2. Diatom stratigraphy: Lough Bresk

The bottom section of the core analysed for diatoms is dominated by *Asterionella formosa* and *Aulacoseira islandica*. The central part of the core is dominated by increasing abundance of *Stephanodiscus parvus*. The upper samples show increases in *Thalassiosira guillardii* and *Cyclstephanos dubius*. These preliminary analyses indicate unambiguously an eutrophication sequence typical of many small lakes in Northern Ireland (Anderson 1997b).

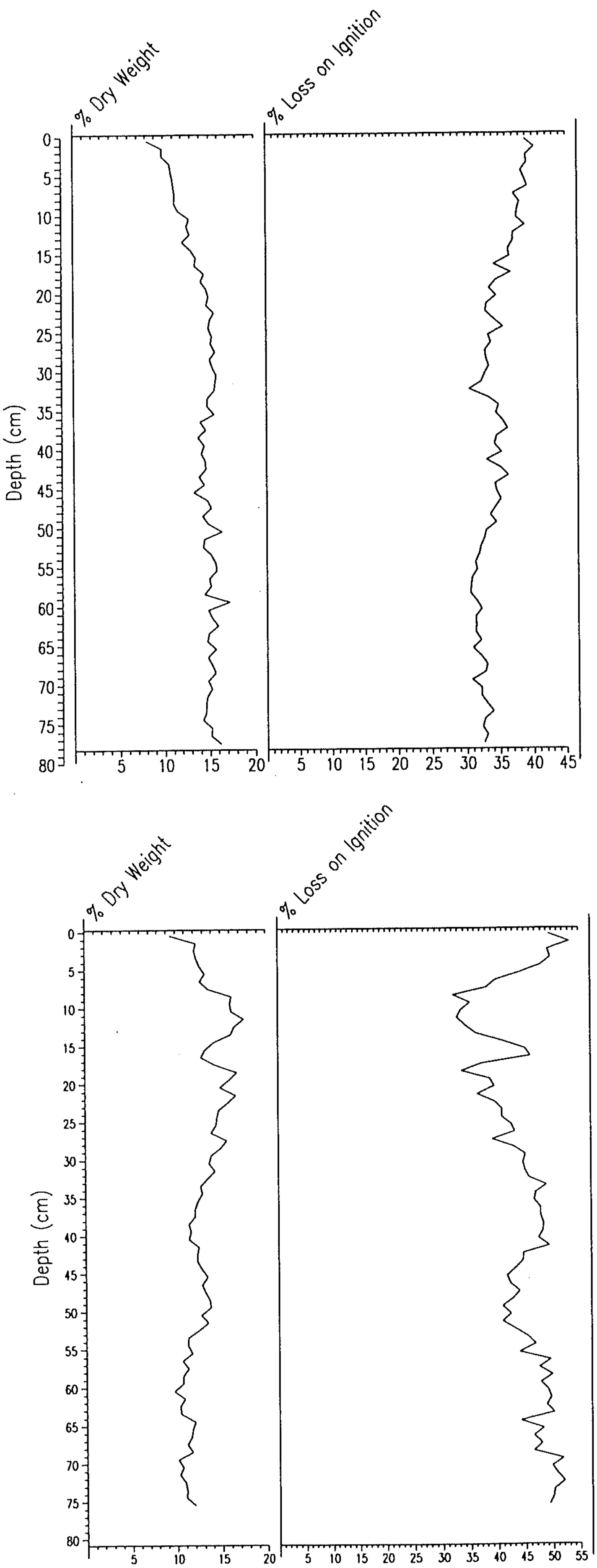
Figure 23 Relative frequency (%) diatom stratigraphy for Lough Bresk



8.6.3. Dry weight and Loss-on-ignition: Back Lough

At Back Lough, 6 cores were taken from a range of water depths (2.6 m to 6.6 m, the maximum depth of the lake). The sediments have quite a high organic content; loss-on-ignition values are over 30 % for all cores. Two groups were discernible and representative profiles are shown here (Fig. 24).

Figure 24 Dry weight (%) and Loss-on-ignition (%) profiles for selected cores from Back Lough (cores BACK1,4, 1997)



9. Discussion

The palaeolimnological investigation of the larger lakes has provided clear evidence of change in all lakes, although not all the changes are necessarily deleterious. For example, it appears that at Lower Lough MacNean nutrient concentrations are decreasing according to the diatom mode. Below, the results from this study are discussed in three main sections: sediment accumulation rates, diatom assemblages and diatom-inferred nutrient changes and finally, management implications.

9.1. Sediment accumulation rates

Overall, the most striking aspect of the dry mass accumulation rates derived from ^{210}Pb dating was the high rates recorded. At Lough Oughter and Tongree (Upper Lough Erne) the accumulation rates are so high that the 1 m sediment cores do not cover the last 100 years. This situation contrasts markedly to those changes recorded in small lakes (Anderson, 1997) where 1 m cores cover 150-200 years in most cases. However, even in the lakes further west, there are still high dry mass accumulation rates; for example, at Upper Lough MacNean and Lough Allen (Figs 7 and 14)

Overall trends

There was a clear post-1950 increase in dry mass accumulation rates (DMAR) in Lower Lough Erne (both at Manor House and the Broad Lough, see Anderson *et al.* 1996). The analyses from this project also indicate that DMAR increased in the early 1960s at Lough Oughter and to a lesser extent at Lough Allen.

While the major increase occurred in the early 1960s at Lough Oughter and has been sustained since, which matches with the record at Tongree (ULE), there have been more recent increases in DMAR. At Lough Allan there was an increase around 1964 but also a brief but substantial increase around 1987. This latter date agree well with the sustained increase at Upper Lough MacNean since 1986. At the Manor House site on Lower Lough Erne there was also a peak in DMAR around 1986 together with increases in the early 1970s.

The ^{210}Pb record at Lower Lough MacNean was not interpretable and is almost certainly a result of its very shallow mean depth in relation to its surface area. The lake is probably not accumulating sediment permanently. Wind stress and storm tracks will have resulted in severe resuspension and mixing of the sediment leading to hiatuses and sediment movement within the basin, as well as mineralisation of organic material. As a result the sediment record has to be considered incomplete, as indicated by the lack of ^{241}Am in sediments (see Appendix 1, Dating report).

^{210}Pb Synthesis

Apart from Lower Lough MacNean, all cores show a significantly increase in sedimentation rates after 1960. Sedimentation rates in Upper Lough MacNean are comparable to those in Lough Allen, but only about half those in Lough Allen. Perhaps coincidentally, of the other lakes studied in this region, Lough Melvin, geographically the closest to Lower Lough MacNean, is the only other site not to show a sustained increase after 1960. Sedimentation rates in Upper Lough MacNean, Allen and Oughter are similar to those in Lower Lough Erne, though 3-6 times lower than the values recorded in Upper Lough Erne (Table 4).

Table 4 Mean sedimentation rates for the INTERREG cores

	Pre-1960 g cm^{-2} y^{-1}	Post-1960 g cm^{-2} y^{-1}
Lower L Erne		
BRDL1	0.090	0.19
MH2	0.23	0.44
Upper L Erne TG2		0.90
Melvin	0.041	0.034
MacNean Upper	0.10	0.15
MacNean Lower	0.027	0.027
Allen	0.080	0.14
Oughter	0.13	0.33

Table 5 Radionuclide Parameters for INTERREG Sediment Cores

	Unsupported ^{210}Pb						^{137}Cs	
	Maximum activity		Inventory		Flux		Inventory	
	Bq kg^{-1}	±	Bq m^{-2}	±	Bq $m^{-2}y^{-1}$	±	Bq m^{-2}	±
Lower L Erne								
BRDL1	371	37	13150	640	410	20	26200	550
MH2	93	11	8950	540	280	20	29380	410
Upper L Erne TG2	61	9	10280	560	320	17	36820	590
Melvin	207	14	2542	164	79	6	5690	110
MacNean Upper	170	18	9140	710	285	22	24250	380
MacNean Lower	134	16	1480	180	46	5	5420	150
Allen	155	18	4910	450	150	14	22800	450
Oughter	118	15	10310	550	320	17	19500	320
Mean			7600		237		21260	

All cores other than Lower Lough MacNean and Lough Melvin have radionuclide inventories well in excess of the values determined by direct fallout (Table 5). The ^{210}Pb fluxes recorded in Lough Erne, Upper Lough MacNean and Lough Oughter are about 3 times atmospheric, and that in Lough Allen, twice atmospheric. A distinguishing characteristic of these sites is the high weapons ^{137}Cs to ^{210}Pb ratio. The mean value is 3 times that typical of Cumbrian lakes. This could indicate that the high radionuclide inventories reflect significant catchment inputs as well as the effects of sediment focussing. These could occur via erosive inputs, though another possible cause in catchments with acid peaty soils is migration in soluble form. Comparisons with Chernobyl ^{137}Cs inventories could help resolve this issue. High

Chernobyl inventories are likely to occur at sites where sediment focussing is relatively strong. This appears to be the case in Upper Lough Erne and Lough Allen.

9.2. Diatom community change and inferred nutrient histories

9.2.1. A WA-diatom model for inferring phosphorus concentrations in Large Lakes

Diatoms are ecologically very sensitive and have proved to be very useful environmental indicators in a variety of applied problems, most notably acidification and eutrophication (Anderson 1993). The ecological requirements of many species are relatively well understood and it has, as a result, been possible to model diatom responses to pH and nutrients (especially TP) relatively well. These predictive models have been used with some success, for example in Northern Ireland in relation to both diffuse and point-source eutrophication (Anderson *et al.*, 1993; Anderson & Rippey, 1994; Anderson 1997b; Rippey *et al.*, 1997). In larger lakes, however, light perhaps exerts greater influence on diatoms than in smaller lakes (the diatoms may spend relatively more time out of the photic zone). The diatom-inference models developed for Northern Ireland and north-west Europe (Anderson 1997a; Bennion *et al.* 1996) do not work well when applied to diatom assemblages from cores taken in larger systems. They tend to over estimate TP concentrations quite considerably (Anderson *et al.* 1996). This in part, a result of the difference in nutrient concentrations between small and large lakes (as, for example, in Ireland; see Table 2 and Gibson *et al.*, 1995).

The development of the Large Lakes training set for this study has to be seen as an interesting and positive development in applied diatom ecology and palaeolimnology. The Large Lakes training set is still preliminary compared to the north-west European training set for small lakes consists of nearly 150 lakes (Bennion *et al.*, 1996). The predictive errors for the latter are, as a result, very good (see Anderson 1995, Bennion *et al.* 1996). However, the errors for the models developed here (Table 3) are very comparable and the application to core assemblages seem to support this conclusion. In comparing the diatom-inferred TP concentrations with measured values it should be remembered that for many of the larger lakes there is relatively little data available. This in part, of course, contributes to the errors in the original model – it is important to have good water chemistry. Moreover, phosphorus concentrations in lakes are quite variable on a seasonal and inter-annual basis (see data in Foy *et al.* [1993] for example for Lough Erne). However, for the Broad Lough (Lower Lough Erne) where there is water chemistry data available for over ten years, there is a very good agreement between the diatom model and the observed values (both are around 40-50 $\mu g\ l^{-1}$ on an annual basis).

It is clear that the results from the application of the new diatom-inferred TP model to the cores used in this study are considerably better than in the previous report (Anderson *et al.* 1996). All the inferred values for core surface samples are quite close to the measured values for all lakes. At Tongree and Manor House sites (Upper and Lower Lough Erne respectively) the inferred-TP results are complicated by the sudden arrival and shift to dominance of *Skeletonema subsalsum* (Figs 20 and 21). This diatom was only observed in the Lough Erne system and so has only three occurrences in the training set. As a result, it has a poorly defined TP optimum. The estimated TP optima for individual species forms the basis of weighted averaging regression and calibration models. While poorly defined TP-optima are true for most of the species because the training set is still quite small (ca. 40 lakes), this is particularly true for *Skeletonema subsalsum*. Its expansion at Tongree and Manor House (Figs 17 and 18) leads to a large variation in the inferred TP value for the uppermost sections of these cores (See Figs 20 and 21). The variation observed at these sites is greater than the differences observed between WA and WA_{tol}-inferred values at the other lakes (compare DI-TP profiles in Fig. 10 with Figs 20 & 21).

Comparing diatom changes and inferred-TP profiles
At Lough Allen there are important changes in the diatom assemblages, most notably the increase of *Stephanodiscus parvus*, a diatom normally associated with increasing nutrient concentrations and eutrophication (see Anderson 1990, 1997b). Interestingly, at Lough Allen its increase occurs with the increase of *Cyclotella glomerata*, a planktonic diatom associated with nutrient poor conditions. The DI-TP profile suggests a decrease in nutrient conditions since ca. 1940. A similar form of *Stephanodiscus parvus* was observed in Lough Melvin. It may be that this form, particular to larger lakes is not responding directly to phosphorus. Whatever, the core analyses indicate that the lake is changing. There is some variability in the lower section of the core but some of this change has to be considered natural.

At Upper Lough MacNean, the DI-TP results indicate a reduction in nutrient concentrations. In this case, the model results are driven by an increase in *Cyclotella comensis* agg. (see Figs 15 and 16) a diatom associated with nutrient poorer conditions in both large and small lakes across Europe. While the changes are quite small and probably within the error limits of the diatom model, the trends are unambiguous. The core also has quite a high accumulation rate and the results in both diatom and DI-TP indicate the high degree of variability temporal variability in this lake. The decrease in inferred TP concentrations may reflect, in part, the longer term growth of conifers in the catchment. Marginal agricultural land is increasingly being given over to afforestation. While forestry practice during the planting of seedlings (fertilisation etc.) may lead to nutrient enrichment (see Gibson 1976), eventually tree growth may result in reduced loss of nutrients to surface runoff as a greater proportion of the nutrient pool is retained in tree biomass.

At Tongree, the DI-TP results indicate that the increase above post-war background concentrations of 40 μg TP l^{-1} occurred very recently (late-1980s) (Fig. 21). Likewise at Lough Oughter, although there is a long term increase (with considerable variability over the last 50 years) there is a suggestion of an increase around 1990. However, importantly at Lough Oughter and Manor House (Lower Lough Erne) there is a subtle but very distinct change in the plankton diatom flora in the early 1960s. This change is the expansion of small centric taxa (most notably *Stephanodiscus parvus*, and importantly *Cyclostephanos dubius*, *C. invisitatus* and *C. cf. tholioformis*), all diatoms indicative of increasing eutrophication (see Anderson 1990, 1997b). Although the Tongree core covers a very short time period and, as a result, does not record the increase in *S. parvus* and *S. tholiformis* – they are already dominant - it is a reasonable conclusion that similar changes occurred in this part of Lough Erne. This expansion of small *Stephanodiscus* and *Cyclostephanos* species is at the expense of *Aulacoseira* spp. which have probably been the dominant planktonic diatoms for the last few hundred years in these lakes (See Lough Allen [Fig. 8]); cf. the earlier periods of Lough Erne: Battarbee 1986b).

The good agreement of the Broad Lough DI-TP results and monitored data has already been referred to (above). The results from the Manor House core, while somewhat problematical (because of the increase in *S. subsalsum*) are also very interesting. The results indicate low concentrations up until 1960 when there is a sustained increase. The simple WA model suggests that this increase continues to the core surface (with the exception of the surface sample). Much of the change in the DI-TP (both model variations) is, of course, attributable to the arrival of *S. subsalsum*. This invasion by a normally brackish water diatom around 1980 is still not really understood (Gibson *et al.* 1993) but may be considered indicative of recent changes in the lake and/or its catchment.

9.3. Implications for the management and conservation of large lakes

Palaeolimnological data are important because they extend the timescale of monitoring to periods that pre-date the establishment of routine monitoring by government environment and conservation agencies. The approach is particularly valid for lakes that have little of no systematic data available for them (Anderson, 1993).

Palaeolimnological studies of large lakes are not uncommon, but the majority of projects focus on smaller, relatively deep lakes because of the more reliable sediment depositional environment. However, while smaller lakes are perhaps more optimal for palaeolimnological study, this study shows that the reasonably coherent results can be obtained from larger lakes. With the exception of Lower Lough MacNean, we have managed to obtain reliable chronologies and associated analyses. The larger lakes studied elsewhere are often extremely deep systems with the result that sediment disturbance is much less of a problem. The lakes studied here (with the exception of the Broad Lough) are not overly deep in relation to their surface area. This relative shallowness, combined with their exposed sitting on the western seaboard of Europe and the windy nature of the Irish climate means that the lakes do not thermally stratify permanently (for example, Lough Melvin and Lough Allen).

Some of the changes appear to be relatively recent (e.g. post-1980 at Upper Lough MacNean [increased sediment accumulation rate] and Lough Allen [diatom changes]), which contrasts with the smaller lakes where nutrient enrichment although speeded up since 1950, has been occurring for some time (Anderson 1997b). These results, when combined with species invasion such as that of *Skeletonema subsalsum* observed in Lough Erne, suggest that the lakes are changing and that we cannot afford to be too complacent in defining and implementing both monitoring and remedial action.

Both the diatom and sediment accumulation rate results from this study indicate that the large lakes of the north of Ireland are in a state of flux. If the lakes were in a relatively stable state, it is very unlikely that the complex ^{210}Pb distribution profiles observed in the cores would have been found. The results of these core studies are clearly complimentary to contemporary lake management and monitoring programmes. They indicate clearly the dynamic nature of lakes whether in a state of apparent enrichment (Manor House area of Lower Lough Erne) or nutrient reduction (Upper Lough MacNean), and hence the difficulty of determining change without a systematic monitoring programme.

Substantial changes have already occurred in some parts of the system (immediately post-war and in the early 1960s), for example in the riverine parts of Upper Lough Erne as well as in the Manor House area of the Lower Lough, immediately downstream of Enniskillen. While some changes may be due to in-lake processes associated with sediment stortage (and hence nutrient availability) and movement within the system, the overall disturbed nature of the cores studied indicates that changed land management (Wilcock, 1979) must also be of considerable importance.

10. Acknowledgements

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11. References

Allot, N. (and 8 others). (1998). Land use and aquatic systems in the Republic of Ireland. In Giller, P.S. (ed.) *Studies in Irish Limnology.* Marine Institute. pp.1-18.

Anderson, N.J., (1990). Biostratigraphy and taxonomy of some small *Stephanodiscus* and *Cyclostephanos* species in a eutrophic lake, and their ecological implications. *British Phycological Journal* **25**: 217-235.

Anderson, N.J., (1993). Natural versus anthropogenic change in lakes: the role of the sediment record. *Trends in Ecology & Evolution*, **8**: 356-361.

Anderson N.J. (1997a) Reconstructing historical phsophorus concentrations in rural lakes using diatom models. in Tunney, H., Carton, O.T., Brookes, P.C. & Johnston, A.E. (eds) *Phosphorus loss from soil to water.* CAB International. pp. 95-118.

Anderson, N.J. (1997b) Historical changes in epilimnetic phosphorus concentrations in six rural lakes in Northern Ireland *Freshwater Biology* **38:** 427-440.

Anderson, N.J. & Rippey, B. (1994) Monitoring lake recovery from eutrophication using the sediment record: a comparison of diatom-inferred phosphorus and the geochemical record. *Freshwater Biology* 32: 625-639.

Anderson, N.J., Rippey, B. & Gibson, C.E. (1993) A comparison of sedimentary and diatom-inferred phosphorus profiles: implications for defining pre-disturbance nutrient conditions. *Hydrobiologia* **253**, 357-366.

Anderson, N.J., Patrick, S.T. and Appleby, P.G. (1996) Palaeolimnological survey sof Lough Erne and Louygh Melvin (Northern Ireland). *Environmental Change Research Centre University College London, Research Report* **no. 28**. pp. 30 + appendix

Appleby,P.G. (1998). Dating recent sediments by ^{210}Pb: Problems and solutions. *Proc. 2nd NKS/EKO-1 Seminar, Helsinki*, 2-4 April 1997, STUK, Helsinki, pp 7-24.

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

Appleby, P.G., Nolan, P.J., Gifford, D.W., Godfrey, M.J., Oldfield, F., Anderson, N.J. & Battarbee, R.W. (1986) ^{210}Pb dating by low background gamma counting *Hydrobiologia* **143**, 21-27.

Appleby, P.G., Richardson, N. & Nolan, P.J. (1991) ^{241}Am dating of lake sediments. *Hydrobiologia* **214**, 35-42.

Battarbee, R.W. (1986a). Diatom analysis. *Handbook of Holocene Palaeoecology & Palaeohydrology.* (Ed. by B.E. Berglund), pp. 527-570. J. Wiley, Chichester.

Battarbee, R.W. (1986b). The eutrophication of Lough Erne inferred from changes in the diatom assemblages of ^{210}Pb- and ^{137}Cs-dated sediment cores. *Proceedings of the Royal Irish Academy,* **86** Section B, 141-168.

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

Foy, R.H and Withers, P.J.A. (1995). The contribution of agricultural phosphorus to eutrophication. *The Fertilizer Society, Proceedings no. **365**.*

Foy, R.H., McGlynn, K & Gibson, C.E. (1993). Chlorophyll a and nutrients in Lough Erne. *Biology & Environment: Proc. Irish Academy* **93**B, 163-174.

Foy, R.H., Smith, R.V., Jordan, C. & Lennox, S.D. (1995). Upward trend in soluble phosphorus loadings to Lough Neagh despite phosphorus reduction at sewage treatment works. *Water Research* **29**: 1051-1063.

Gibson, C.E. (1976) An investigation into the effects of forestry plantations on the water quality of upland reservoirs in Northern Ireland. *Water Research* **19**: 995-998

Gibson, C.E. (1986) Preliminary results on phosphorus reduction in Lough Neagh - assessing the effect against a background of change. *Hydrobiological Bulletin.* **20**: 173-182.

Gibson, C.E. & Guillot, J. (1997). Sedimentation in a large lake: the importance of fluctuation in water level. *Freshwater Biology*, **37**: 597-604.

Gibson, C.E., Foy, R.H. & Fitzsimons, A.G. (1980). A limnological reconnaissance of the Lough Erne system, Ireland. *Internalionale Revue der gesamten hydrobiologie*, **65**: 49-84.

Gibson, C.E., McCall, R.D. & Dymond, A. (1993). *Skeletonema subsalsum* in a freshwater Irish lake. *Diatom Research* **8**: 65-71.

Gibson, C.E., Wu, Y., Smith, S.J. & Murphy-Wolfe, S.A. (1995) Synoptic limnology of a diverse geological region. catchment and water chemistry. *Hydrobiologia* **306**, 213-277.

Hayward, J., Foy, R.H. & Gibson, C.E. (1993). Nitrogen and phosphorus budgets in the Erne system, 1974-1989. *Biology & Environment: Proc. Irish Academy* **93**B, 33-44.

HMSO (1990) *Environmental Issues in Northern Ireland.* House of Commons Environment Committee, First Report

Renberg, I. (1990) A procedure for preparing large sets of diatom slides from sediment cores. *Journal of Paleolimnology*, **4**, 87-90.

Rippey B, Anderson, N.J. & Foy, R.H. (1997). Accuracy of diatom-inferred total phosphorus concentrations and the accelerated eutrophication of a lake due to reduced flushing. *Canadian Journal of Fisheries & Aquatic Science* **54**: *2637-2646*

Rippey, B. & Anderson, N.J. 1996 The reconstruction of lake phosphorus loading and dynamics using the sedimentary record. *Environmental Science & Technology* **30**: 1786-1788.

Tunney, H. Foy, R.H. and Carton, O.T. (1998). Phosphorus inputs to water from diffuse agricultural sources. In Wilson, J.G. (ed.,) *Eutrophication in Irish Waters*, pp. 25-39. Dublin, Royal Irish Academy.

Wilcock, D.N. (1979) Post-war land drainage, fertilizer use and environmental impact in Northern Ireland. *Journal of Environmental Management*, **8**, 137-149.

Wilson, J.G. *ed.* (1998). *Eutrophication in Irish Waters*. Royal Irish Academy

12. Appendix 1

Report on the Radiometric Dating of Four Sediment Cores from North-West Ireland

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Methods

Sediment samples from Oughter Lough core OUGT1, Allen Lough core ALLN1, Upper Lough MacNean core MACU1 and Lower Lough MacNean core MACL1 were analysed for ^{210}Pb, ^{226}Ra, ^{137}Cs and ^{241}Am by direct gamma assay in the Liverpool University Environmental Radioactivity Laboratory, using Ortec HPGe GWL series well-type coaxial low background intrinsic germanium detectors (Appleby *et al.* 1986). ^{210}Pb was determined via its gamma emissions at 46.5keV, and ^{226}Ra by the 295 keV and 352 keV γ-rays emitted by its daughter isotope ^{214}Pb following 3 weeks storage in sealed containers to allow radioactive equilibration. ^{137}Cs and ^{241}Am were measured by their emissions at 662 keV and 59.5 keV. The absolute efficiencies of the detectors were determined using calibrated sources and sediment samples of known activity. Corrections were made for the effect of self absorption of low energy γ-rays within the sample (Appleby *et al.* 1992).

Results

The results of the radiometric analyses are given in Tables 1-4 and shown graphically in Figures 1-4. Table 5 summarises a number of radiometric parameters from each core. Radiometric dates calculated using the CRS ^{210}Pb dating models (Appleby *et al.* 1978) are shown in Figures 5-8, together with dated levels determined from the ^{137}Cs and ^{241}Am stratigraphies (Appleby *et al.* 1991). Use of the CIC model was in most cases precluded by irregular variations in the ^{210}Pb profile. Where discrepancies with the ^{137}Cs/^{241}Am dates were significant, adjustments to the ^{210}Pb dates have been made using procedures described in Appleby (1998). Core chronologies based on these considerations are given in Tables 6-9.

Lough Oughter

Lead-210 Activity

Equilibrium of total ^{210}Pb activity (Figure 1a) with the supporting ^{226}Ra (corresponding to c.100 years of accumulation) appears to occur slightly below the base of the core at c.90 cm. Unsupported ^{210}Pb activity declines irregularly with depth (Figure 1b), with maximum activity occurring 16.5 cm below the surficial sediments. Since concentrations were fairly low, standard errors are a little high and too much should not be read into detailed fluctuations in the profile. Two main features can however be observed, a distinct flattening of the gradient of the profile above 60 cm, and a significant decline in ^{210}Pb activity above c.16 cm. The relatively small change in unsupported ^{210}Pb activity between 25-60 cm suggests that this part of the core is from a period of rapid sedimentation. The significant decline in ^{210}Pb activity above 10 cm points to a further change in recent years.

Artificial Fallout Radionuclides

The ^{137}Cs activity versus depth profile (Figure 1c) has two well-resolved peaks. The more recent of these, at 25.5 cm depth, almost certainly records fallout from the 1986 Chernobyl accident. Identification of the earlier feature at c.63 cm as a record of the 1963 fallout maximum from the atmospheric testing of nuclear weapons is supported by the presence of traces of ^{241}Am at about the same depth.

Core Chronologies

Figure 5 compares CRS model ^{210}Pb dates with those inferred from the ^{137}Cs/^{241}Am stratigraphy. The significant discrepancy between them can be attributed to an increase in the ^{210}Pb flux associated with increased sedimentation rates above c.60 cm. Using the ^{137}Cs dates as reference levels, the mean post-1963 flux is calculated to be 404 Bq m^{-2} y^{-1}, compared to 142 Bq m^{-2} y^{-1} before 1963. Corrected dates calculated using the methods outlined in Appleby (1998) are shown in Figure 5, and given in detail in Table 5. These indicate a relatively uniform sedimentation rate of about 0.13 g cm^{-2} y^{-1} (0.56 cm y^{-1}) up to c.1960. During the 1960s accumulation rates nearly trebled, to about 0.35 g cm^{-2} y^{-1}. There was a small decline in the late 1980s, but values appear to have increased again during the past few years.

Lough Allen

Lead-210 Activity

Sedimentation rates appear to be much slower in this core. Equilibrium between total ^{210}Pb activity (Figure 2a) and the supporting ^{226}Ra occurs at a depth of c.25 cm. The unsupported ^{210}Pb activity declines irregularly with depth (Figure 2b), with significant non-monotonic features at 6.5 cm and 14-17 cm. Both coincide with layers of dense sediment and are presumably linked to the events giving rise to these features.

Artificial Fallout Radionuclides

The ^{137}Cs activity versus depth profile (Figure 2c) again has two well-resolved peaks. The 1986 Chernobyl accident is recorded at a depth of 6.5 cm. The 1963 weapons fallout maximum occurs at 16.5 cm. At this depth there is a peak in both ^{137}Cs and ^{241}Am concentrations.

Core Chronology

Figure 6 shows that there is again a significant discrepancy between CRS model ^{210}Pb dates with those inferred from the ^{137}Cs/^{241}Am stratigraphy. Using the ^{137}Cs dates as reference levels this can be attributed to increases in the ^{210}Pb flux associated with episodes of rapid sedimentation at 6.5 cm (dated 1986) and 14-17 cm (dated 1965). The mean post-1963 flux is calculated to be 186 Bq m^{-2} y^{-1}, compared to 88 Bq m^{-2} y^{-1} before 1963. Corrected dates calculated are shown in Figure 6, and given in detail in Table 6. These indicate a relatively uniform sedimentation rate of about 0.08 g cm^{-2} y^{-1} (0.22 cm y^{-1}) up to c.1960. It is not possible to estimate the intensity and duration of the events in the mid-1960s and mid-1980s, though in each case sedimentation rates subsequently appear to settle down to normal values relatively quickly.

Upper Lough MacNean

Lead-210 Activity

^{210}Pb activity at the base of this core (35 cm) is still significantly in excess of the supporting ^{226}Ra (Figure 3a). Since the maximum unsupported activity occurs at a depth of 16.5 cm (Figure 3b), and there is little net change above this depth, recent accumulation rates must have been quite high. A more rapid decline below 16.5 cm indicates slower sedimentation rates in the older sections, though it is unlikely that the entire record spans more than about three ^{210}Pb half-lives (c.60 years).

Artificial Fallout Radionuclides

The ^{137}Cs profile has a single well-resolved peak at a depth of 16.5 cm (Figure 3c). The relatively high concentration in the peak suggest that it dates from the 1986 Chernobyl accident. Below 16.5 cm the ^{137}Cs record is much less distinct, with moderately high concentrations through 20-30 cm. Traces of ^{241}Am were however detected both at c.20 cm and c.30 cm, and it is not possible to identify the 1963 depth with any certainty.

Core Chronology

^{210}Pb dates calculated using the CRS model are shown in Figure 7, together with the possible dates inferred from the ^{137}Cs/^{241}Am stratigraphy. The ^{210}Pb results again overestimate the date of the 1986 Chernobyl feature, almost certainly due to a recent increase in both the sediment and ^{210}Pb supply rates. The mean post-1986 sedimentation rate is estimated to be 0.27 g cm^{-2} y^{-1}, nearly three times higher than the pre-1986 value of 0.096 g cm^{-2} y^{-1} (0.35 cm y^{-1}). ^{210}Pb supply rates increased from 210 Bq m^{-2} y^{-1} before 1986 to 447 Bq m^{-2} y^{-1} since 1986. From the ^{210}Pb profile, pre-1986 accumulation rates appear to have been relatively uniform. The corrected ^{210}Pb chronology using these results, shown in Figure 7 and Table 7, places 1963 at a depth of 25 cm, mid way between the two ^{241}Am peaks. The base of the core is dated 1938. Since it can be argued that the deepest traces of ^{241}Am are the best indicator of the weapons fallout maximum, the possibility should however be kept in mind that 1963 is at c.30 cm.

Lower Lough MacNean

Lead-210 Activity

Superficially this core has the simplest record. ^{210}Pb/^{226}Ra equilibrium occurs at a depth of just 8 cm (Figures 4a), and unsupported ^{210}Pb declines more or less exponentially with depth (Figures 4b), indicating relatively uniform sedimentation. However, the unsupported ^{210}Pb inventory corresponds to a flux of just 46 Bq m^{-2} y^{-1}, half the estimated atmospheric flux, and it is questionable whether this core has a complete record of modern sediments. Sediments near the top of the core are highly compacted, with a dry bulk density more than twice that in the Upper Lough MacNean core

Artificial Fallout Radionuclides

The ^{137}Cs record was of little chronological value. There were no subsurface peaks to identify either the 1986 or 1963 depths. ^{241}Am was not detected.

Core Chronology

Figure 8 shows ^{210}Pb dates calculated using the CRS and CIC models. Since there is no reliable means for choosing between them, a chronology has been calculated using the mean sedimentation rate from both models of 0.027 g cm^{-2} y^{-1} (0.08 cm y^{-1}). The results are shown in Figure 8 and Table 8. Little confidence can be attached to these results without corroborating evidence.

References

Appleby,P.G., 1998. Dating recent sediments by ^{210}Pb: Problems and solutions. Proc. 2nd NKS/EKO-1 Seminar, Helsinki, 2-4 April 1997, STUK, Helsinki, pp7-24.

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

Appleby,P.G. & F.Oldfield, 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., N.Richardson.& P.J.Nolan, 1991. ^{241}Am dating of lake sediments. Hydrobiologia, 214:35-42.

Appleby,P.G., N.Richardson, & P.J.Nolan, 1992. Self-absorption corrections for well-type germanium detectors. *Nucl. Inst.& Methods B*, **71**:228-233.

Table 1 Fallout Radionuclide Concentrations in Lough Oughter core OUGT1

Depth		^{210}Pb						^{137}Cs		^{241}Am	
		Total		Unsupported		Supported					
cm	g cm^{-2}	Bq kg^{-1}	±	Bq kg^{-1}	±	Bq kg^{-1}	±	Bq kg^{-1}	±	Bq kg^{-1}	±
0.5	0.0	157.7	16.0	98.0	16.4	59.7	3.6	142.2	5.0	0.0	0.0
4.5	0.6	136.4	13.8	79.1	14.1	57.3	2.9	131.7	3.9	0.0	0.0
8.5	1.2	157.3	14.1	103.6	14.5	53.7	3.3	134.7	4.7	0.0	0.0
16.5	2.4	178.3	15.1	118.4	15.3	59.8	2.8	153.5	4.2	0.0	0.0
20.5	3.1	163.4	11.9	103.5	12.2	60.0	2.5	191.5	4.1	0.0	0.0
25.5	4.0	120.9	11.2	64.0	11.5	57.0	2.2	207.9	3.9	1.8	1.1
30.5	5.0	125.3	9.9	72.3	10.2	53.0	2.5	146.2	4.1	0.0	0.0
40.5	7.0	119.3	7.1	63.5	7.3	55.8	1.4	99.4	1.8	1.5	0.6
50.5	9.1	113.9	9.6	56.7	9.8	57.3	2.2	111.9	3.1	0.0	0.0
55.5	10.1	95.9	8.3	38.6	8.6	57.3	2.1	141.6	3.3	1.8	0.9
60.5	11.2	99.5	8.8	54.5	9.1	45.1	2.3	167.6	4.1	2.1	1.1
65.5	12.3	91.0	8.0	37.7	8.3	53.3	1.9	165.6	3.0	2.9	0.7
70.5	13.3	82.2	8.4	23.3	8.6	58.8	1.8	82.1	2.2	0.0	0.0
75.5	14.4	86.0	8.3	27.8	8.5	58.2	1.8	17.5	1.4	0.0	0.0
80.5	15.6	72.5	8.0	19.3	8.2	53.2	1.8	4.7	1.2	0.0	0.0
85.5	16.8	72.1	8.9	12.6	9.1	59.5	1.8	0.9	1.2	0.0	0.0

Table 2 Fallout Radionuclide Concentrations in Lough Allen core ALLN1

Depth		^{210}Pb						^{137}Cs		^{241}Am	
		Total		Unsupported		Supported					
cm	g cm^{-2}	Bq kg^{-1}	±	Bq kg^{-1}	±	Bq kg^{-1}	±	Bq kg^{-1}	±	Bq kg^{-1}	±
0.5	0.1	255.8	18.1	154.6	18.6	101.2	4.4	137.0	5.4	0.0	0.0
4.5	0.8	237.4	14.7	124.6	15.0	112.8	3.0	322.2	5.0	0.0	0.0
6.5	1.5	157.5	16.1	49.0	16.5	108.5	3.7	866.9	9.5	0.0	0.0
8.5	2.3	198.4	12.9	93.0	13.4	105.4	3.7	607.3	8.4	0.0	0.0
10.5	2.9	210.6	14.7	97.7	15.3	112.9	4.4	128.4	5.5	0.0	0.0
12.5	3.5	164.3	14.6	55.3	15.2	108.9	3.9	129.0	4.6	0.0	0.0
14.5	4.3	147.7	9.8	38.5	10.3	109.1	3.1	178.7	4.3	0.0	0.0
16.5	5.1	141.8	7.4	27.8	7.7	114.0	2.3	342.5	4.0	2.9	0.8
18.5	5.9	164.3	14.4	55.3	14.8	109.0	3.4	243.2	5.0	1.7	1.0
20.5	6.6	141.1	10.5	19.3	11.1	121.9	3.5	139.5	4.2	1.9	1.0
25.5	8.2	122.8	13.1	5.5	13.6	117.4	3.6	9.1	2.3	0.0	0.0
30.5	10.1	121.7	9.1	13.4	9.6	108.2	3.0	1.8	1.7	0.0	0.0
35.5	12.0	95.5	4.4	-1.9	4.7	97.4	1.5	0.5	0.8	0.0	0.0

Table 3 Fallout Radionuclide Concentrations in Upper Lough MacNean core MACU1

Depth		^{210}Pb						^{137}Cs		^{241}Am	
		Total		Unsupported		Supported					
cm	g cm^{-2}	Bq kg^{-1}	±	Bq kg^{-1}	±	Bq kg^{-1}	±	Bq kg^{-1}	±	Bq kg^{-1}	±
0.5	0.1	259.6	13.3	143.1	13.8	116.4	3.4	458.3	7.0	0.0	0.0
2.5	0.3	298.2	17.2	169.8	17.8	128.4	4.5	343.7	7.8	0.0	0.0
4.5	0.6	296.6	21.0	164.3	21.7	132.3	5.2	342.6	7.9	0.0	0.0
8.5	1.2	269.3	12.8	155.1	13.2	114.2	3.3	355.6	5.9	0.0	0.0
10.5	1.5	252.1	10.4	135.6	10.8	116.5	2.9	411.6	5.5	0.0	0.0
12.5	1.9	262.2	16.4	150.3	16.9	111.9	4.0	451.6	8.3	0.0	0.0
14.5	2.3	234.0	11.0	117.4	11.3	116.6	2.8	467.5	5.6	0.0	0.0
16.5	2.8	289.9	20.9	176.6	21.5	113.3	4.9	541.9	10.2	0.0	0.0
18.5	3.3	246.1	12.4	126.1	12.8	120.0	3.1	462.0	5.8	2.5	1.1
20.5	3.7	222.8	10.8	104.2	11.1	118.6	2.8	256.4	4.5	2.9	0.9
24.5	4.7	204.0	17.0	91.4	17.4	112.6	4.0	257.1	5.9	0.0	0.0
28.5	5.9	182.5	10.3	67.9	10.6	114.6	2.7	253.0	4.2	2.2	1.0
32.5	7.0	146.6	10.9	27.8	11.3	118.8	3.0	207.9	4.1	1.9	0.9
33.5	7.3	163.4	9.6	45.6	10.1	117.9	3.0	177.1	4.0	0.0	0.0

Table 4 Fallout Radionuclide Concentrations in Lower Lough MacNean core MACL1

Depth		^{210}Pb						^{137}Cs	
		Total		Unsupported		Supported			
cm	g cm^{-2}	Bq kg^{-1}	±	Bq kg^{-1}	±	Bq kg^{-1}	±	Bq kg^{-1}	±
0.25	0.0	202.3	15.7	134.1	16.1	68.2	3.4	263.9	5.8
2.5	0.8	154.5	13.7	89.5	14.0	65.0	3.1	262.3	5.4
4.5	1.6	100.9	9.1	27.4	9.5	73.5	2.7	168.5	4.2
6.5	2.2	89.4	6.4	15.0	6.7	74.3	1.9	70.7	1.9
8.5	2.8	66.3	7.4	-9.1	7.6	75.4	2.0	46.7	1.7
10.5	3.2	74.0	6.1	-0.8	6.5	74.8	2.1	32.2	1.9
12.5	3.8	92.7	10.5	17.5	10.9	75.2	2.8	26.5	2.2
14.5	4.3	74.2	10.3	-8.6	10.6	82.8	2.3	13.7	1.5
16.5	4.8	86.7	10.1	7.0	10.3	79.7	2.1	11.6	1.5
20.5	6.0	79.4	6.2	-1.0	6.5	80.5	2.1	0.5	1.4

Table 5 Radionuclide Parameters for INTERREG Sediment Cores

	Unsupported ^{210}Pb						^{137}Cs	
	Maximum activity		Inventory		Flux		Inventory	
	Bq kg^{-1}	±	Bq m^{-2}	±	Bq m^{-2}y^{-1}	±	Bq m^{-2}	±
Oughter	118	15	10310	550	320	17	19500	320
Allen	155	18	4910	450	150	14	22800	450
MacNean Upper	170	18	9140	710	285	22	24250	380
MacNean Lower	134	16	1480	180	46	5	5420	150
Mean			6460		200		17800	

Table 6 ^{210}Pb chronology of Lough Oughter core OUGT1

Depth		Chronology			Sedimentation Rate		
		Date	Age				
cm	g cm^{-2}	AD	y	±	g cm^{-2} y^{-1}	cm y^{-1}	±
0.0	0.0	1997	0	0			
5.0	0.6	1996	1	1	0.36	2.6	18
10.0	1.4	1993	4	2	0.32	2.0	15
15.0	2.2	1991	6	2	0.33	2.0	15
20.0	3.0	1988	9	2	0.32	1.8	14
25.0	3.9	1985	12	2	0.37	2.0	19
30.0	4.9	1983	14	2	0.37	1.9	16
35.0	5.9	1980	17	2	0.36	1.8	15
40.0	6.9	1977	20	2	0.35	1.7	15
45.0	8.0	1974	23	2	0.35	1.7	17
50.0	9.0	1971	26	3	0.35	1.7	20
55.0	10.0	1968	29	4	0.34	1.7	25
60.0	11.1	1965	32	5	0.27	1.3	22
65.0	12.2	1961	37	6	0.17	0.8	26
70.0	13.2	1953	44	7	0.13	0.6	39
75.0	14.2	1945	52	9	0.13	0.6	35
80.0	15.5	1935	62	12	0.12	0.5	45
85.0	16.7	1925	72	16	0.12	0.5	52

Table 7 ^{210}Pb chronology of Lough Allen core ALLN1

Depth		Chronology			Sedimentation Rate		
cm	g cm^{-2}	Date AD	Age y	±	g cm^{-2} y^{-1}	cm y^{-1}	±
0.0	0.00	1997	0	0			
2.0	0.34	1994	3	1	0.12	0.61	15
4.0	0.71	1991	6	2	0.12	0.56	16
6.0	1.35	1987	10	2	0.23	0.51	31
8.0	2.08	1983	14	3	0.16	0.46	24
10.0	2.72	1978	19	4	0.11	0.38	22
12.0	3.37	1973	25	6	0.14	0.39	31
14.0	4.07	1968	29	8	0.18	0.48	35
16.0	4.89	1964	33	10	0.22	0.37	39
18.0	5.68	1957	40	13	0.13	0.26	44
20.0	6.39	1948	49	14	0.079	0.23	33
22.0	7.05	1940	57	15	0.076	0.23	28
24.0	7.71	1931	66	16	0.076	0.22	28
26.0	8.39	1922	75	17	0.076	0.21	28
28.0	9.15	1912	85	19	0.076	0.21	28
30.0	9.91	1902	95	21	0.076	0.20	28

Table 8 ^{210}Pb chronology of Upper Lough MacNean core MACU1

Depth		Chronology			Sedimentation Rate		
cm	g cm^{-1}	Date AD	Age y	±	g cm^{-2} y^{-1}	cm y^{-1}	±
0.0	0.00	1996	0	0			
2.0	0.26	1995	1	2	0.29	2.4	12
4.0	0.50	1994	2	2	0.28	2.1	14
6.0	0.78	1993	3	2	0.28	1.9	13
8.0	1.08	1992	4	2	0.28	1.8	11
10.0	1.42	1991	5	2	0.30	1.5	11
12.0	1.83	1990	6	2	0.27	1.4	13
14.0	2.24	1988	8	3	0.30	1.3	13
16.0	2.68	1986	10	3	0.23	0.88	15
18.0	3.14	1983	13	4	0.13	0.52	15
20.0	3.57	1978	18	4	0.11	0.38	15
22.0	4.07	1973	23	5	0.10	0.35	19
24.0	4.60	1967	29	6	0.09	0.34	23
26.0	5.15	1961	35	8	0.08	0.33	25
28.0	5.71	1955	41	10	0.08	0.32	26
30.0	6.28	1949	48	12	0.10	0.33	36
32.0	6.87	1943	54	14	0.10	0.33	47

Table 9 ^{210}Pb chronology of Lower Lough MacNean core MACL1

Depth		Chronology			Sedimentation Rate		
		Date	Age				
cm	g cm^{-1}	AD	y	±	g cm^{-2} y^{-1}	cm y^{-1}	±
0.0	0.00	1996	0	0			
1.0	0.28	1985	11	2	0.027	0.079	13.2
2.0	0.65	1972	24	4	0.027	0.079	13.2
3.0	1.01	1958	38	6	0.027	0.079	13.2
4.0	1.37	1944	52	8	0.027	0.079	13.2
5.0	1.71	1932	64	10	0.027	0.081	13.2
6.0	2.02	1920	76	11	0.027	0.086	13.2
7.0	2.33	1908	88	13	0.027	0.090	13.2

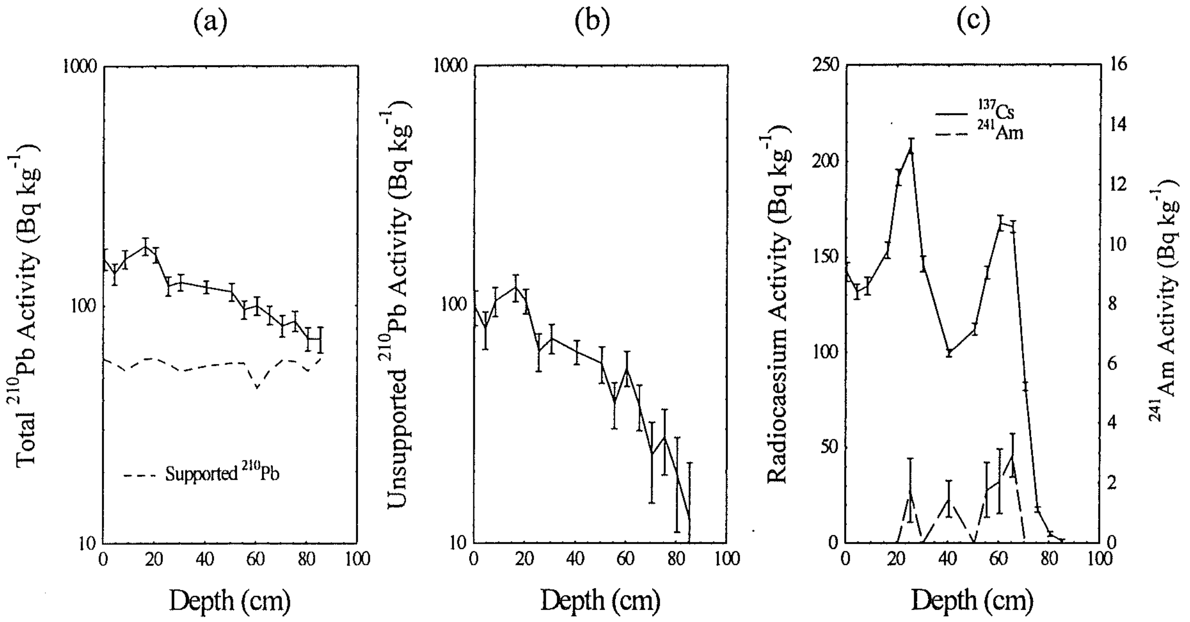

Figure 1. Fallout radionuclide concentrations in Oughter Lough OUGT1 showing (a) total and supported ^{210}Pb, (b) unsupported ^{210}Pb, (c) ^{137}Cs and ^{241}Am.

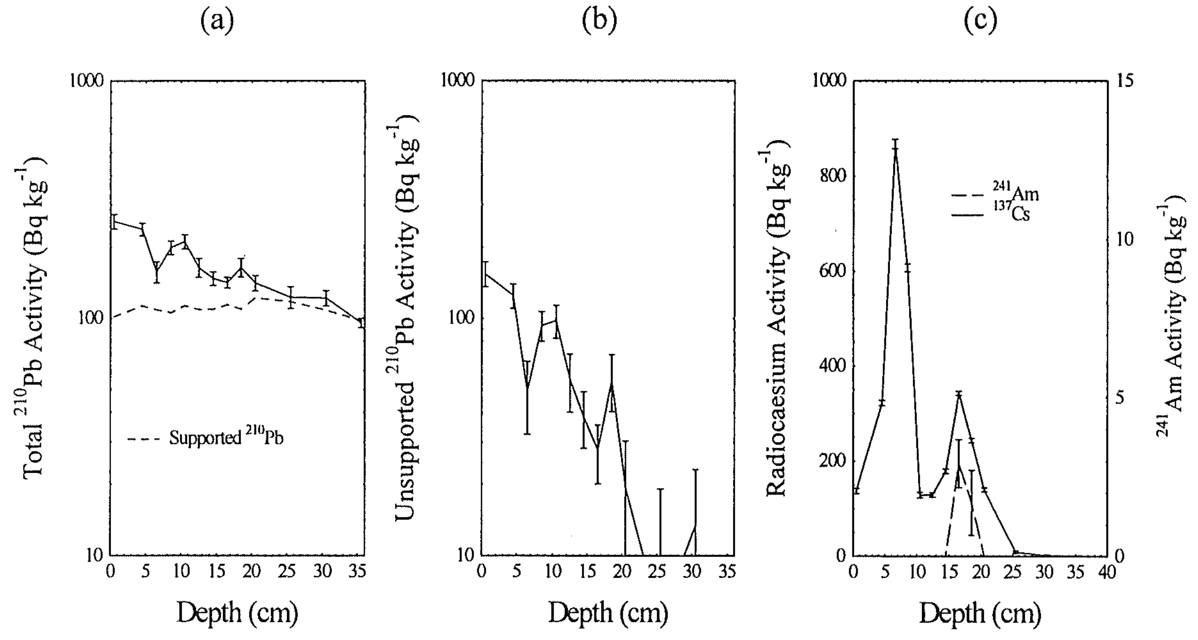

Figure 2. Fallout radionuclide concentrations in Allen Lough core ALLN1 showing (a) total and supported ^{210}Pb, (b) unsupported ^{210}Pb, (c) ^{137}Cs and ^{241}Am.

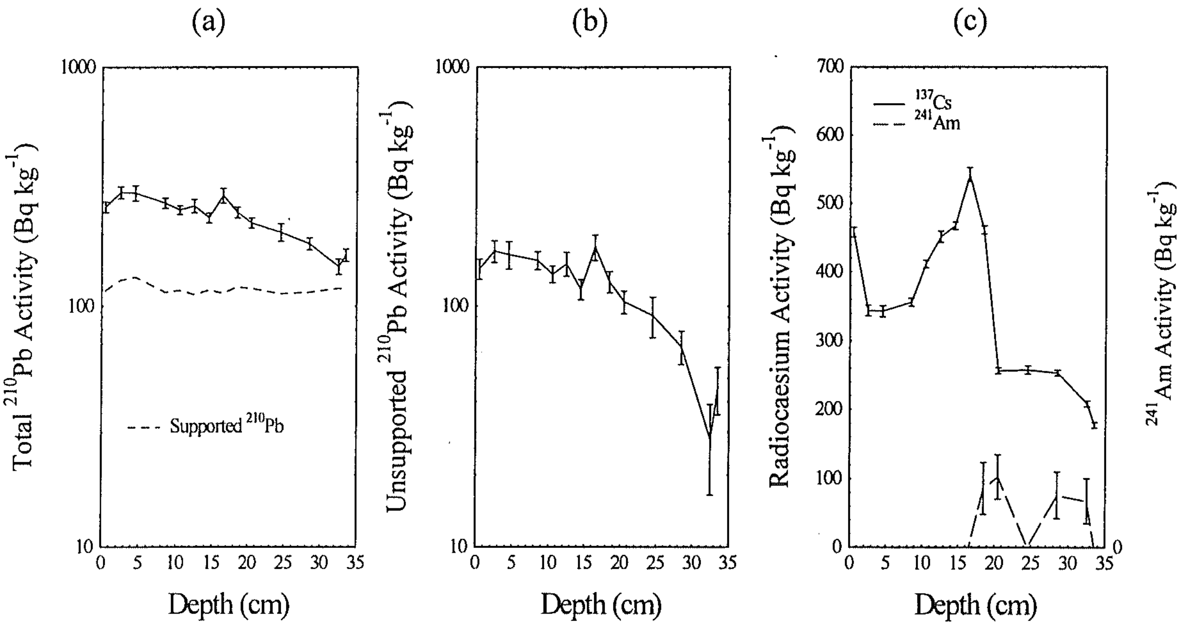

Figure 3. Fallout radionuclide concentrations in Upper Lough MacNean core MACU1 showing (a) total and supported ^{210}Pb, (b) unsupported ^{210}Pb, (c) ^{137}Cs and ^{241}Am.

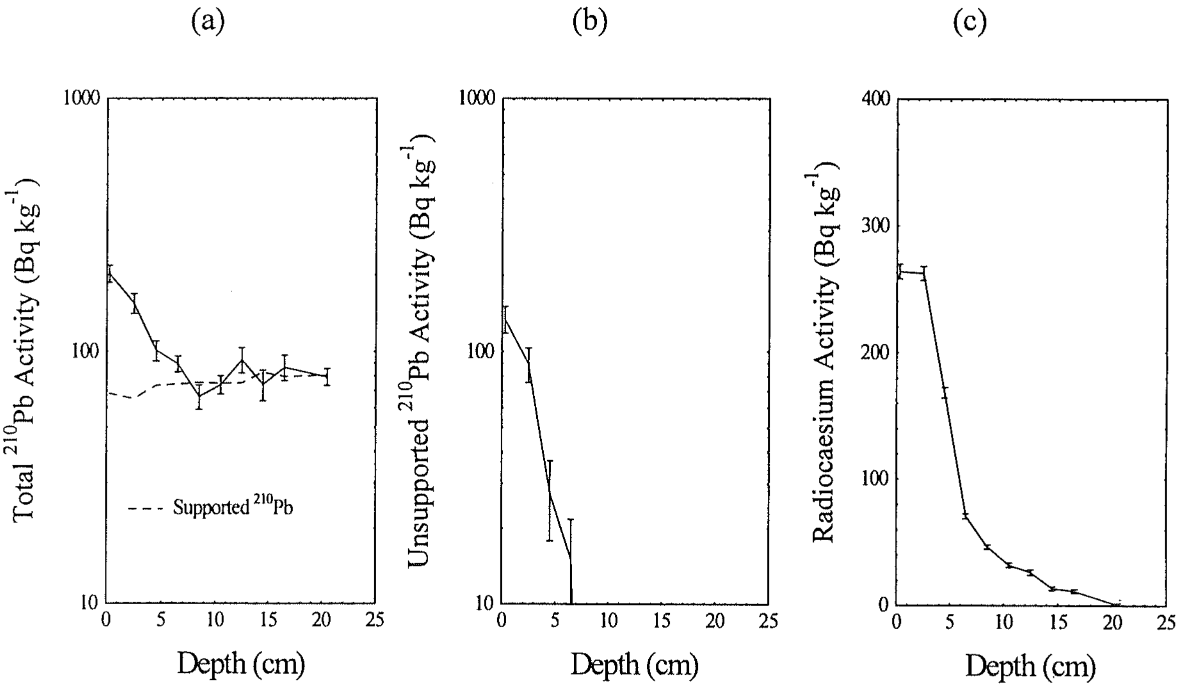

Figure 4. Fallout radionuclide concentrations in Lower Lough MacNean core MACL1 showing (a) total and supported ^{210}Pb, (b) unsupported ^{210}Pb, (c) ^{137}Cs.

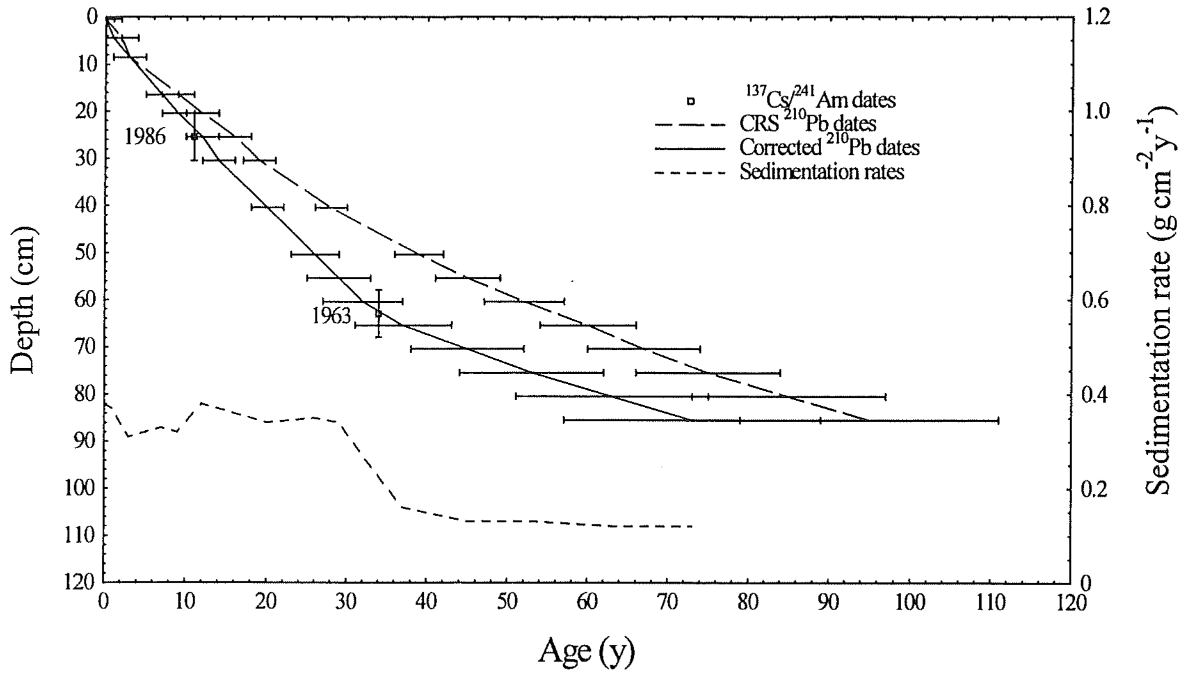

Figure 5 Radiometric chronology of Lough Oughter core OUGT1 showing CRS model ^{210}Pb dates together with dates determined from the ^{137}Cs and ^{241}Am stratigraphy. Also shown are corrected ^{210}Pb dates and sedimentation rates calculated using the ^{137}Cs/^{241}Am dates as reference levels.

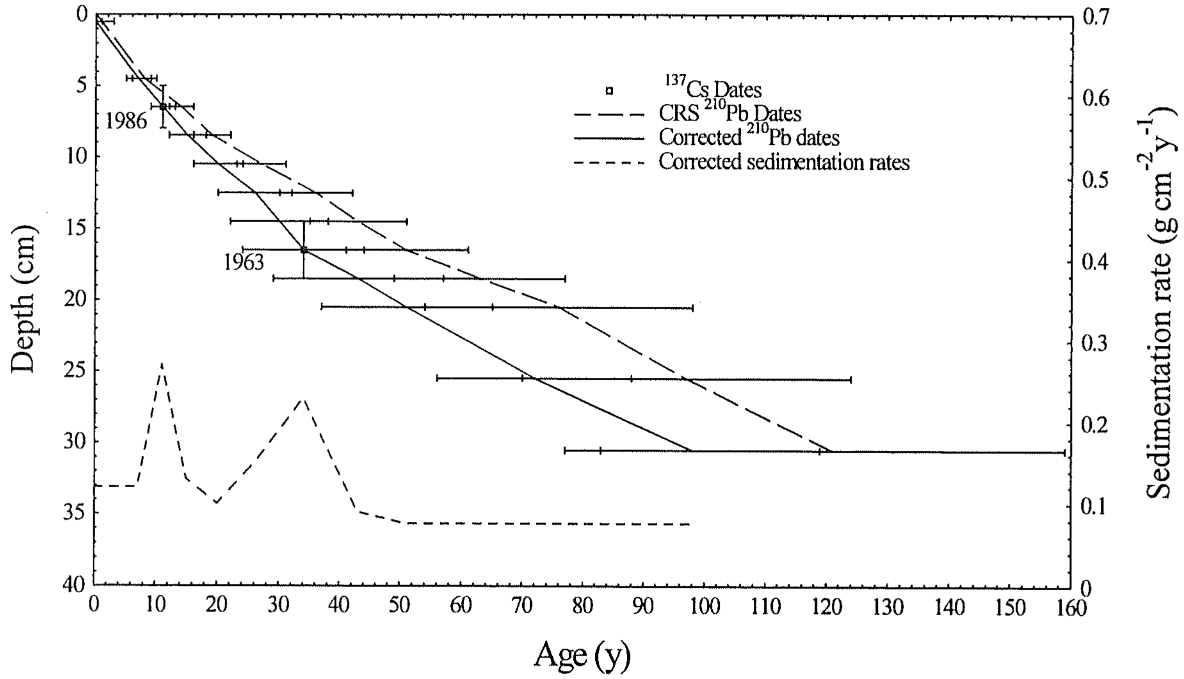

Figure 6 Radiometric chronology of Lough Allen core ALLN1 showing CRS model ^{210}Pb dates together with dates determined from the ^{137}Cs and ^{241}Am stratigraphy. Also shown are corrected ^{210}Pb dates and sedimentation rates calculated using the ^{137}Cs/^{241}Am dates as reference levels.

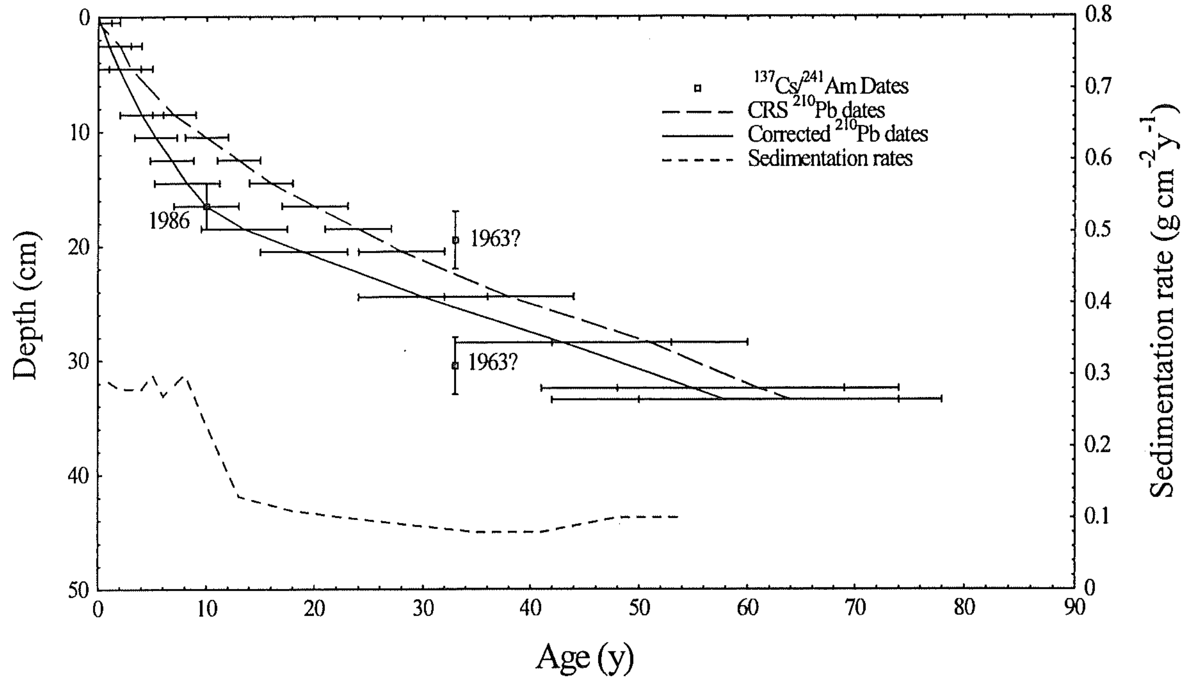

Figure 7 Radiometric chronology of Upper Lough MacNean core MACU1 showing CRS model ^{210}Pb dates together with dates determined from the ^{137}Cs and ^{241}Am stratigraphy. Also shown are corrected ^{210}Pb dates and sedimentation rates calculated using the ^{137}Cs/^{241}Am dates as reference levels.

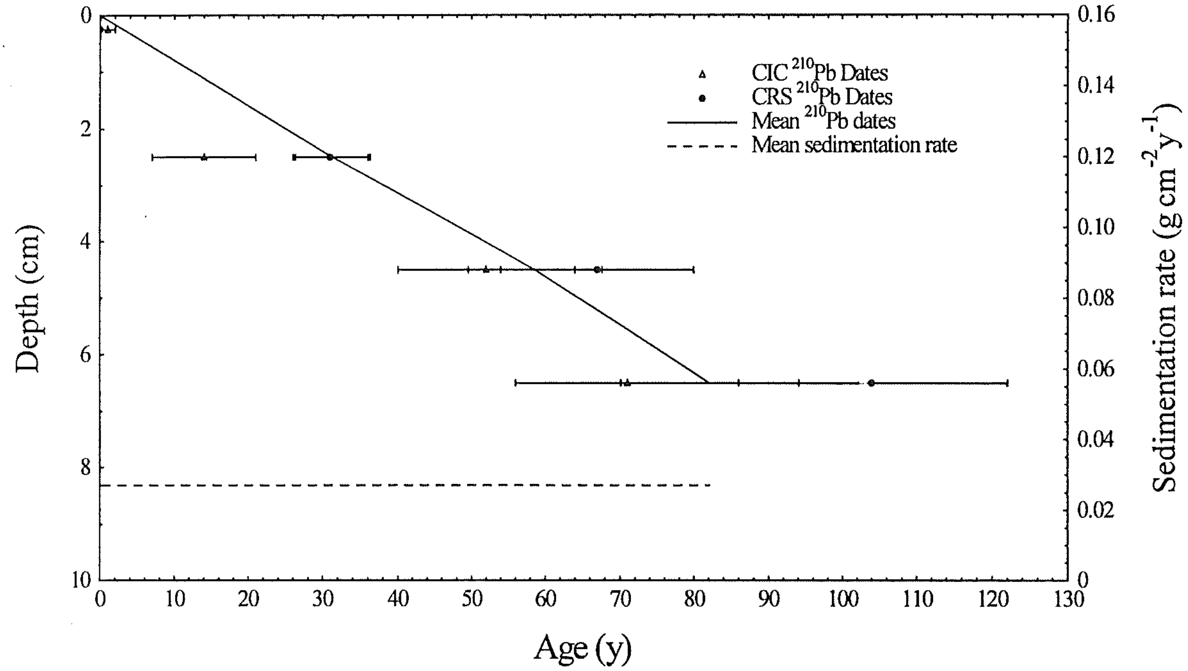

Figure 8 Radiometric chronology of Lower Lough MacNean core MACL1 showing CRS model ^{210}Pb dates together with dates determined from the ^{137}Cs and ^{241}Am stratigraphy. Also shown are sedimentation rates calculated using the CRS model.