Environmental RTDI Programme 2000–2006

WATER FRAMEWORK DIRECTIVE

Identification of Reference – Status for Irish Lake Typologies Using Palaeolimnological Methods and Techniques (IN-SIGHT)

(2002-W-MS-17)

Synthesis Report

Prepared for the Environmental Protection Agency
by
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DISCLAIMER

WATER QUALITY

The Water Quality Section of the Environmental Research Technological Development and Innovation (ERTDI) Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in this area. The reports in this series are intended as contributions to the necessary debate on water quality and the environment.

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Executive Summary

This report synthesises findings from the EPA/ERTDI-funded research project *Identification of Reference-Status for Irish Lake Typologies using Palaeolimnological Methods and Techniques* (IN-SIGHT, project 2002-W-MS-17).

IN-SIGHT commenced on 1 January 2003 with the aim of assisting the Government of Ireland meet some of its obligations under the EU Water Framework Directive (WFD). In particular, the project aimed to test the ecological status of a representative selection of Candidate Reference Lakes (CRLs), or lakes that potentially provide extant examples of reference (or anthropogenically little disturbed) conditions. The project also aimed at reconstructing biological reference conditions for examples of the main types of impacted lakes.

The project was entirely located within the Irish EcoRegion (EcoRegion number 17). EcoRegions are relatively large extents of land and water that contain characteristic and geographically distinct assemblages of plants and animals and their habitats. The Irish EcoRegion comprises the island of Ireland and proximate smaller islands.

Work Package (WP) 1 of IN-SIGHT reviewed existing relevant information and sediments relating to lakes in the Irish EcoRegion and identified a representative selection of 35 lakes from a total of 76 CRLs.

WP2 determined the presence or absence of anthropogenic pressures at the selected CRLs. Sediment cores were obtained from the deepest part of each of the 35 CRLs during the summer of 2003 and dated according to down-core variations in Spheroidal Carbonaceous Particle (SCP) concentrations. SCPs are produced solely by fossil-fuel burning. Variations in the amounts of SCPs accumulating in lake sediments over time provide a relatively cheap and reliable means of dating those sediments, because they can be related to documented variations in industrial activity. Sediment core samples were also analysed for their diatom content and chemistry.

Sediment core samples were assessed using a variety of techniques to determine the nature of biological and chemical changes at each site. The degree of biological change between a core top sample (associated with present-day conditions) and a core bottom sample (associated with pre-industrial reference conditions) from each sampled CRL was assessed. In cases where biologically important floristic changes were evident from the diatom data, sediment chemistry and CORINE land cover data were used to identify possible human-induced drivers. In particular, the processes of acidification, eutrophication and sediment inwash were examined.

Reference status was confirmed for 11 (32%) of the CRLs for which diatom data were available. Core bottom samples in four of the 11 CRLs dated to c. 1850 or before (L. Bunny, L. Keel, L. Nahasleam and L. Upper). The estimated age of core bottom samples in the other seven cores was

c. 1850 to c. 1950 (L. Doo, L. Dunglow, L. Kiltooris, L. McNean and L. Veagh). In two cases (L. Barfinnihy and L. O'Flynn), establishing the age of core bottom samples proved impossible.

Twenty three (68%) of the CRLs sampled showed biologically important deviations from reference conditions. Acidification and nutrient enrichment were apparently the main causes of change. Catchment disturbance, notably peat erosion possibly linked to recent afforestation, also appeared to have been a factor in some cases. Recent climate changes may also have had an impact.

WP3 mainly aimed to establish pre-impact conditions for a selection of lakes in the Irish EcoRegion that had been impacted by human activity, notably agriculture. A multi-proxy approach was adopted, based on analyses of sediment chemistry and fossil remains (diatoms, cladocera and pollen) in cores of sediment collected from seven lakes in 2004. The cores of sediment were dated radiometrically, using Lead and Caesium radioactive isotopes. A transfer function was developed that enabled the reconstruction of past near-surface Total Phosphorous (TP) concentrations which provide a guide to lake productivity. The results indicate that all but one of the study sites are in a far more productive state compared with the beginning of the sediment core record. The results also indicate there has been a shift in the functioning of the lakes from systems characterised by benthic-littoral taxa to those in which planktonic forms are far more prominent. Furthermore, nutrient enrichment has accelerated after c. 1980 at five of the lakes (L. Ballybeg, L. Crans, L. Egish, L. Mullagh, and L. Sillan). The uppermost samples from the core from L. Atedaun also showed evidence of eutrophication, although at this site the onset of eutrophication could not be accurately dated.

Two of the lakes studied in WP3 show long-term enrichment, in one case starting in the late 19th century. Both eutrophication and oligotrophication occurred at three sites. The results obtained in WP2 and WP3 demonstrate that lakes in the Irish EcoRegion often have complex and locally specific histories.

WP3 also utilised the Modern Analogue Technique (MAT) to determine the degree of similarity between modern diatom assemblages in core top samples from a selection of moderate and high alkalinity CRLs sampled as part of WP2 and sediment core bottom samples from impacted lakes cored as part of WP3.

Sediment core bottom samples from only two of the seven impacted lakes were found to have a close modern analogue among the CRL dataset.

The potential of MAT in the Irish EcoRegion is limited by the size of the training set currently available and by the narrow range of biological proxies traditionally employed in palaeolimnological research. Future investment aimed at expanding the training set and number of biological proxies should enable the modern analogue approach to make a significant contribution to implementing the WFD in the Irish EcoRegion.

Introduction

Incorporation of Directive 2000/60/EC (the EU Water Framework Directive, WFD) to national legislation throughout the EU has established a new legislative framework for European waters. The fundamental aims of the WFD are: the sustainable use of water resources; maintenance of high status waters where they exist and the prevention of deterioration in the existing status of waters; and achievement of, at least, good status in relation to all waters by 2015. The adoption of agreed protocols and definitions underpins the current implementation phase of the WFD. Specifically with regard to surface waters in River Basin Districts (RBDs, the basis for water management under the WFD), member states are required to identify, delimit and differentiate water bodies and to establish hydromorphological, physiochemical and biological type-specific reference conditions (Anon 2000: L327/27). According to Table 1.2, Annex V, of the WFD and to REFCOND (2003: 5), biological reference conditions equate to high ecological status and show no or very minor deviation as a result of human activity. Biological reference conditions can be established through several pathways: (1) spatially, through comparisons with extant examples of the same type of water bodies which are judged undisturbed; (2) modelling, using predictive or hindcasting methods and historical, palaeoecological or other available data; (3) a combination of (1) and (2); and (4) expert judgment (Anon 2000; Andersen *et al.,* 2004). In the absence of long-term data, the WFD states that reference conditions based on modelling may be derived using hindcasting methods, such as palaeolimnology, the scientific study of past conditions in freshwater bodies (Anon 2000). Specifically Annex II of the WFD requires the identification of Candidate Reference Lakes (CRLs) or lakes which may represent type reference conditions; Annex V requires the development of tools for determining reference conditions and current status.

IN-SIGHT tested the current ecological status of a representative selection of CRLs in Ireland and reconstructed biological reference conditions for examples of the main types of impacted lakes in the country via a predominantly palaeolimnological approach. Palaeolimnology is a well-established science in many European and North American countries. IN-SIGHT utilised the remains of diatoms (single-celled, siliceous algae), preserved in sediments, as biological indicators of limnological change. Diatoms are commonly used in palaeolimnology in this way, because of their sensitivity to a wide variety of environmental variables and their good preservation in sediments (Stoermer and Smol, 1999), and their use has been enhanced through the development of transfer functions which enable water quality parameters, notably total phosphorus (TP) and pH, to be derived from diatom assemblages (Ramstack *et al*., 2003; Reid 2005). Weighted averaging (WA) regression and calibration (ter Braak and van Dam 1989) and its extension WA partial least squares (WA-PLS) (ter Braak and Juggins, 1993) are the most widely used techniques for deriving past environmental variables from biological assemblages (Birks, 1998). IN-SIGHT also made use of sediment chemistry and the sediment-based remains of cladocera (zooplankton) and pollen in the reconstruction of past aquatic and catchment conditions.

IN-SIGHT was divided into three work packages (WPs). The first of these, WP1, comprised a review of existing relevant information relating to freshwater lakes in the Irish EcoRegion (EcoRegion 17) and the identification of a representative selection of 35 CRLs (out of a total of 76 identified by the EPA) for subsequent palaeolimnological study in WP2. The decision over which 35 CRLs to sample was made first on the basis of a working typology, and second according to expert advice on a range of factors including, for example, ease of access. The CRLs sampled were divided among the eight most populated of a total of 12 classes in the working typology.

WP2 comprised a test of the current status of the sampled CRLs, based on down-core (generally sediment core top sample-bottom sample) differences in proxies of lake water quality and catchment conditions. Statistical techniques in the form of squared chord distance (SCD), detrended correspondence analysis (DCA) and TP and pH transfer functions enabled quantification of the nature and degree of biological and chemical changes at the CRLs studied in WP2. Concentrations of spheroidal carbonaceous particles (SCP) provided a means of estimating the age of core bottom samples. Sediment chemistry and CORINE land cover data were used to identify possible human-induced drivers, in particular processes of acidification, eutrophication and sediment inwash, in those cases where biologically important floristic changes were evident from the diatom data.

Palaeolimnological techniques were used in WP3 to reconstruct pre-human impact conditions in a selection of lakes from types for which there were likely to be few, if any, extant examples of reference conditions. These lakes were moderately to highly alkaline and generally in intensively farmed catchments. Analyses of sediment chemistry and fossil remains (diatoms, cladocera and pollen) were carried out on sediment samples from cores obtained from seven lakes and were facilitated by chronological control based upon radiometric analyses. A transfer function enabled the reconstruction of past epilimnetic TP concentrations. The Modern Analogue Technique (MAT) was used to determine the degree of similarity between modern diatom assemblages in core top samples from a selection of moderate and high alkalinity CRLs sampled as part of WP2 and sediment core bottom samples from impacted lakes cored as part of WP3.

The following sections of this synthesis report summarise the techniques, results and conclusions drawn from IN-SIGHT. More detailed treatment of these, and of WP1 deliverables, is provided in the full, final report to the EPA (Taylor *et al.,* 2006b). More detailed accounts of the testing of CRL status and of the reconstruction of past variations in water quality at currently impacted lakes have recently been published in, respectively, Leira *et al.* (2006) and Taylor *et al.* (2006a).

Testing of CRL Status

Testing the current status of a representative selection of CRLs (35 lakes in total) largely involved the analysis of sediment core top and bottom samples, although sediment cores from some sites were analysed at a higher resolution. Focusing on the differences between sediment core top and bottom samples provides a relatively efficient and effective means of establishing temporal changes at a large number of sites and is based on the assumption that sediment core top and bottom samples represent, respectively, the date of coring and pre-human impact background, or reference, conditions.

Methods

Cores of sediment, generally 20 to 40 cm long, were collected from the deepest part of each of the 35 CRLs selected using a gravity (Renberg) corer (Renberg, 1991) during the summer of 2003 (Table 1). Coring of the selected CRLs generally followed an extensive bathymetric survey. Sediment cores were sub-sampled in the field at 0.5 cm intervals for the upper 5 cm, and at 1 cm intervals thereafter.

Table 1 **Summary of locational, hydromorphological and physico-chemical information provided by the EPA of Ireland for the 35 lakes that had their CRL status tested through IN-SIGHT. Water quality data were provided by the EPA and are annual means.**

Lake name	Irish Grid Ref.	Lake code	Typology class	Altitude (m amsl)	Lake area (ha)	Max. depth (m)	pH	Conductivity (μS cm^{-1})	Alkalinity (mg l^{-1} CaCO$_3$)	TP μg l^{-1}	% Land cover in catchment					
											Urban	Forestry	Pasture	Agriculture	Bogs	Other
Annaghmore	M 900 837	ANN	10	46	53.1	5.7	8.46	351	159.4	6	0.00	0.00	91.44	0.00	00.0	8.56
Arderry	L 995 457	ARD	4	37	81.1	11.6	6.33	84	6.14	6	0.00	9.51	0.00	0.00	90.49	0.00
Ballynakill (Gorumna)	L 856 225	BAL	6	13	23.9	16.4	7.1	244	20.02	5	-	-	-	-	-	-
Bane	N 550 712	BAN	12	112	75.4	16.9	8.43	297	132.5	5	0.00	0.00	94.94	4.68	0.00	0.39
Barfinnihy	V 850 768	BAF	3	249	13.6	16.7	6.84	56	4.2	4	0.00	0.00	0.00	0.00	95.30	4.70
Barra	B 935 120	BAR	2	90	62.6	6.0	6.31	54	3.80	5	0.00	0.00	1.78	0.00	62.04	36.18
Bunny	R 375 967	BUN	10	17	102.9	11.6	8.47	361	156.2	5	0.00	0.00	36.70	0.74	1.22	61.33
Cloonaghlin	V 610 709	CLO	4	109	127.7	29.4	6.82	62	2.0	5	0.00	0.00	0.00	0.00	70.41	29.59
Cullaun	R 315 905	CUL	12	16	49.7	20.1	8.40	393	172.0	6	0.00	0.00	72.15	5.44	0.41	22.01
Dan	O 150 40	DAN	4	200	102.9	33.5	5.11	42	-0.1	6	0.00	8.75	1.01	0.00	51.79	38.45
Doo	C 359 394	DOO	3	283	9.0	6.8	5.88	78.1	2.05	12	0.00	0.00	0.00	0.00	100.00	0.00
Dunglow	B 782 117	DUN	2	13	61.2	6.1	5.73	100	59.63	6	0.00	0.00	1.31	4.37	93.83	0.49
Easky	G 442 225	EAS	2	180	119.2	11.0	6.53	48	4.04	7	0.00	0.00	0.00	0.00	100.00	0.00
Fad Inishowen East	C 539 439	FAD	3	233	12.3	13.6	6.35	80.9	5.02	7	0.00	0.00	0.00	0.00	49.08	50.92
Fee	L 790 613	FEE	4	47	173.7	31.5	6.55	62	3.06	9	0.00	14.02	0.00	0.00	72.46	13.51
Feeagh	F 965 000	FEA	4	11	394.8	43.0	7.39	86	9.60	8	0.00	22.69	0.10	1.62	63.95	11.65
Keel (Rosses)	B 847 162	KEE	1	136	11.4	10.5	5.3	135	2.4	8	0.00	0.00	0.00	0.00	99.91	0.09
Kiltooris	G 676 972	KIL	6	7	43.5	13.5	7.18	205	27.43	14	0.00	0.00	47.87	10.73	17.97	23.42
Kindrum	C 185 430	KIN	8	8	60.8	11.0	8.27	318	69.47	11	0.00	0.00	18.49	22.16	59.34	0.00
Kylemore	L 770 552	KYL	4	35	132.2	25.1	6.59	72	6.99	6	0.00	11.87	0.00	0.24	66.61	21.28
Lene	N 510 685	LEN	12	93	416.2	19.7	8.46	250	104.9	6	0.00	0.00	78.92	11.62	0.00	9.46
McNean	H 040 400	MCN	8	50	977.8	16.9	7.60	116	23.6	17	0.00	13.39	26.36	20.64	22.72	16.89
Muckanagh	R 370 925	MUC	12	17	96.1	17.8	8.53	462	208.6	5	0.00	0.00	55.29	9.18	21.74	13.79
Nahasleam	L 971 244	NAH	1	33	28.1	1.4	6.5	100.8	9.59	7	0.00	5.86	0.00	0.00	92.75	1.39
Nambrackkeagh	L 821 603	NAB	1	65	6.7	8.8	5.98	101	2.26	10	0.00	44.21	0.00	0.00	53.32	2.47
Naminn	C 396 419	NAM	1	150	15.0	7.8	6.55	112	7.0	10	0.00	0.00	0.00	0.00	100.00	0.00
Naminna	R 176 710	NAN	1	169	20.2	8.4	6.02	77	0.7	8	0.00	36.55	0.00	0.00	63.45	0.00
O'Flynn	M 585 795	OFL	10	77	137.5	3.4	8.51	333	138.9	10	0.52	0.00	54.12	0.00	42.04	3.32
Oorid	L 930 460	OOR	4	45	60.5	12.0	6.40	65	8.06	7	0.00	3.10	0.00	4.73	92.17	0.00
Rea	M 615 155	REA	12	81	301.1	20.9	8.54	308	128.5	6	3.07	0.00	86.73	10.20	0.00	0.00
Shindilla	L 960 460	SHI	4	38	70.2	23.0	6.45	73	6.17	4	0.00	5.69	0.00	0.00	94.31	0.00
Talt	G 398 150	TAL	8	130	97.3	23.0	8.01	190	85.09	8	0.00	0.81	26.12	0.00	73.07	0.00
Tay	O 160 75	TAY	4	250	50.0	32.8	5.12	40	-0.3	8	0.00	0.58	0.00	0.00	59.09	40.34
Upper	V 900 817	UPE	4	18	169.9	36.1	6.41	58	2.8	5	0.00	6.30	0.44	2.50	83.72	7.04
Veagh	C 022 215	VEA	4	40	260.9	28.0	6.30	33	2.16	0	0.25	3.15	0.00	0.00	65.19	31.41

Variations in concentrations of SCP, determined on five samples per core using the method described in Rose and Theophile (2004), provided chronological control. Concentrations of SCP in samples of lake sediments record fossil fuel combustion in the region, and down-core variations in these have been shown to provide a reliable and relatively cheap dating method (Rose *et al.,* 1995). The start of the SCP record in lake sediments at many sites across Europe is c. 1850, while c. 1950 marks the start of a rapid increase in concentrations, resulting from increased electricity generation, which peaked c. 1980.

Limited funding meant that only one (diatoms) of a range of potential biological indicators was used in the testing of CRL status. Sediment samples from the 35 CRLs cored were prepared and analysed for diatoms using standard methods (Battarbee *et al.,* 2001). Two levels of resolution were employed: two samples (top and bottom) per core were analysed for 28 of the cores; a higher resolution (four or five samples per core, including top and bottom samples) was adopted for cores where there was particular interest in the magnitude, rate and direction of change and where the SCP-based chronology was most robust (seven sites in total). At least one example from each of the major types of CRLs was analysed at higher resolution. Generally, core samples contained abundant, well-preserved diatoms. Poor preservation at Fad East precluded diatom-based reconstructions at this site.

The degree of change between diatom assemblages in core top and bottom sediment samples was assessed using SCD (Overpeck *et al.,* 1985). SCD scores range from 0 to 2, with 0 indicating that two samples have exactly the same species composition, and 2 that their compositions are entirely different. A decision was made to use an SCD score of 0.4 (approximating to the 2.5 percentile) as the cut-off point in deciding whether CRL status was verified or refuted. This decision was based on an examination of data from over 200 UK lakes; comparisons between diatom assemblages in core top and bottom samples from un-impacted lakes in this dataset generally have SCD scores ≤ 0.4. DCA (Hill and Gauch 1980) was used to identify the main patterns of variation in the diatom data, and to establish the directions and magnitude of changes in biological conditions at each coring location. Version 4.5 of CANOCO was employed in the DCA-based ordination of diatom data (ter Braak and Šmilauer, 2002). In the absence of direct measurements of epilimnetic pH and TP, diatom-inferred pH and TP (DI-pH and DI-TP) values were established using standard weighted averaging (Birks *et al.*, 1990a, b; Korsman and Birks 1996; Koster *et al.,* 2004). All diatom-inferred values were established using the C2 computer software package (Juggins 2003) and a training set comprising diatom counts for surface sediment samples and several years of measurements of lake water quality for oligotrophic and oligomesotrophic lakes in the Irish EcoRegion. The difference between current DI-TP and reference DI-TP was used to derive a qualitative estimate of change in nutrient status.

Wet sediment density and percentage water content were determined on core samples as a preliminary stage in sediment chemistry analyses. As chronological control was particularly problematic for Lene, O'Flynn and Tay, analysis of sediment chemistry was restricted to 32 CRLs. Wet sediment density was determined from the weight of known volumes of fresh sediment samples, while percentage water (as dry weight density) content was established thermogravimetrically (Hilton *et al.,* 1986). Total sediment chemistry concentrations of calcium (Ca), iron (Fe), manganese (Mn), phosphorous (P), potassium (K) and sodium (Na) were also assessed. Levels of sedimentary TP were used to assist interpretations of changes in diatom assemblages (Rippey and Anderson, 1996), while those of Ca, K and Na can indicate periods of catchment erosion. Fe and Mn in sediments are indicators of fine sediment ingress to lakes but can also be vectors for mobilisation of TP in anoxic sediments (Mackereth 1966). Sediment chemistry in each core was determined in the majority of cases on the top five 0.5 cm- and the bottom five 1 cm-thick slices and followed the technique described in Boyle (2001). Additional sediment samples were analysed between the uppermost and lowermost sets of samples in cores of sediment which had relatively robust SCP-based chronological control and which represented the major types of CRLs. Chemical concentrations (mg g^{-1}) were determined on diluted HNO_3 using an ICP-OES (Jordan *et al.,* 2001).

Results

Down core variations (generally core top-bottom comparisons) in diatoms and DI-pH and DI-TP and the estimated ages for core bottom samples are summarised in Table 2, while DCA results are portrayed in Figure 1. SCD scores between diatom assemblages in core top and bottom samples ranged from 0.05 (Upper) [least change] to 1.78 (Feeagh) [greatest change]. Eleven (32%) of the 34 sites for which top-bottom comparisons in diatom assemblages were possible generated SCD scores < 0.4, indicating little or no change. These 11 cases were distributed among the different CRL typology classes sampled, although none were in typology class 12 (deep, large, high alkalinity lakes). Aside from CRLs in typology class 12, where differential preservation of diatom frustules may have been a factor influencing the results, large, deep, low alkalinity lakes (typology class 4) most consistently showed biologically important deviations from reference. Eighty two percent of CRLs within this class tested generated SCD scores > 0.4. Many of the moderate to high alkalinity CRLs studied were also shown to have experienced important biological changes, based on the SCD scores, although differential preservation of diatom frustules may have been an important factor influencing the results in some of these cases. In general, the sediment chemistry data indicate stable catchments, and more or less stable or falling exogenic inputs of sediment to the CRLs studied, including sedimentary TP (see Figure 2, as an example).

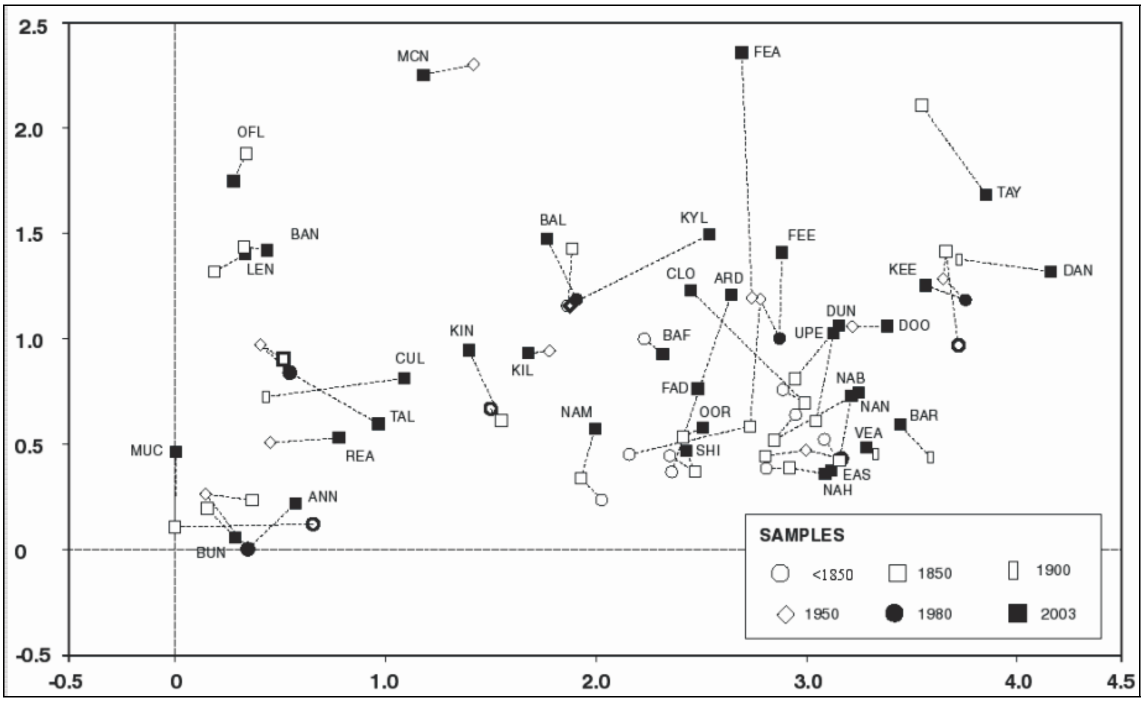
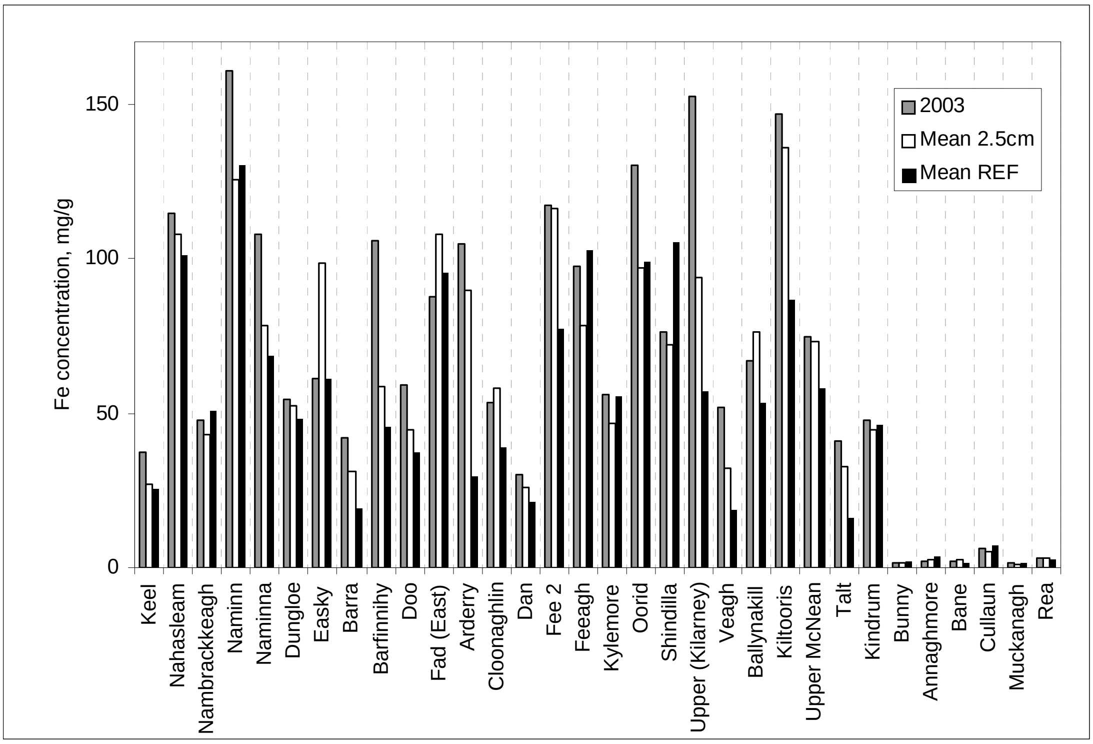


Figure 1 DCA biplot combining lake sediment core bottom and top samples, as well as mid-core samples where available. Lines connect samples from the same sediment core. The orientation of the line provides an indication of the direction of floristic change and its length is a measure of floristic difference (species turnover) (units=Hill's SD). See Table 1 for explanation of lake codes. Chronological control provided by down-core variations in SCP concentrations – see text for details.

Table 2 Summary of down-core variations in biological and inferred parameters for the 35 CRLs studied in IN-SIGHT. Data comprise estimated age of core bottom samples (based on SCP concentrations), SCD scores for pairs of core bottom and samples from 34 of the 35 CRLs, along with Hill's SD units and intra-core differences in DI-pH and DI-TP. 'Prop change in DI-TP' = the proportion of change in DI- TP in the core top sample compared with the core bottom, or reference, where for example 0.8 = 20% decrease, 1.2 = 20% increase, *etc.,* CRLs with SCD scores ≤ 0 .4 are highlighted. NB < 1850 = pre 1850 and > 1850 = post 1850; no SCD score based on an intra-core comparison was calculated for Fad Inishowen East because of an absence of well-preserved diatoms from below 2 cm depth in the core.

Lakes	Typology class	SCP-based estimated age for core bottom sample	SCD	SD Hill's units	Change in DI-pH units	Prop. change in DI-TP
Annaghmore	10	1834	0.835	1.118	0.11	0.95
Arderry	4	< 1850?	0.859	1.797	-0.08	1.31
Ballynakill	6	1831	0.509	1.24	-0.09	1.09
Bane	12	< 1850	0.557	1.112	0.21	1.01
Barfinnihy	3	< 1850?	0.139	0.731	0.03	1.04
Barra	2	1905	0.409	0.986	-0.01	1.01
Bunny	10	1833	0.351	0.94	0.03	0.90
Cloonaghlin	4	< 1850	1.599	1.416	0.39	1.31
Cullaun	12	< 1850	1.302	1.376	-0.29	1.18
Dan	4	1909	0.410	0.806	-0.43	0.96
Doo	3	1944	0.259	1.139	-0.21	1.02
Dunglow	2	1885	0.171	1.176	-0.08	0.97
Easky	2	1838	1.034	1.1	-0.47	1.08
Fad	3	1850-1950	-	-	-	-
Fee	4	< 1850	0.967	1.494	-0.09	2.05
Feeagh	4	1926	1.769	1.822	-0.19	1.89
Keel	1	1788	0.319	1.1	-0.14	1.31
Kiltooris	6	1944	0.288	1.171	-0.02	1.03
Kindrum	8	1776	0.423	1.26	0.25	1.25
Kylemore	4	< 1850?	1.044	1.551	-0.76	0.91
Lene	12	> 1850	0.478	1.001	0.06	1.01
McNean	8	1950	0.148	1.056	0.15	1.14
Muckanagh	12	< 1850	0.458	0.884	-0.12	1.10
Nahasleam	1	< 1850	0.296	0.787	-0.10	1.03
Nambrackkeagh	1	1789	0.75	0.984	0.12	1.25
Naminn	1	1804	0.562	1.205	-0.05	1.09
Naminna	1	< 1850	0.735	1.123	-0.30	0.92
O'Flynn	10	> 1850	0.327	1.045	0.19	0.83
Oorid	4	< 1850?	0.987	1.715	-0.19	1.08
Rea	12	< 1850	0.472	1.554	-0.25	1.02
Shindilla	4	1775	0.416	1.039	0.10	1.20
Talt	8	1830	0.96	1.508	-0.25	0.99
Tay	4	> 1850	1.169	1.069	-0.58	0.58
Upper	4	1840	0.046	1.019	-0.09	0.98
Veagh	4	1850-1950	0.245	0.923	0.05	1.01



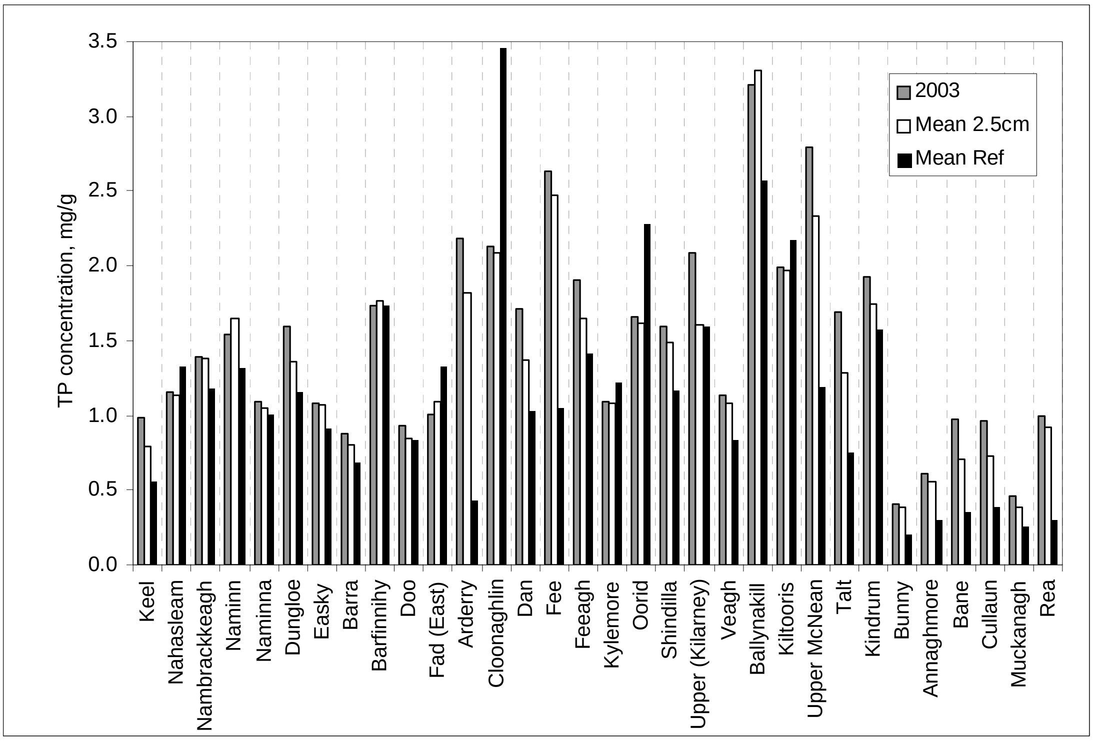


Figure 2 **Examples of sedimentary chemistry data: Intra-core differences in Fe (top) and TP concentrations (below) for the 32 CRLs sampled for which there is tightest chronological control. '2003' = core top sample; 'Mean 2.5 cm' = mean value for top 5 cm of sediment in the core; 'Mean Ref.' = mean value for lowermost 5 cm of sediment in the core.**

Only four CRLs (Dan, Easky, Kylemore and Tay, all low alkalinity) showed a decline in DI-pH between core bottom and top samples greater than the estimated error of the model. Several CRLs appear to have experienced a reduction in DI-TP, but only at Tay (moderate alkalinity) was the reduction greater than the estimated error of the model used. By comparison, two low alkalinity CRLs (Fee and Feeagh) showed a statistically significant increase in DI-TP. According to results from those lakes where a relatively high temporal resolution was possible, low alkalinity lakes (*e.g.* Easky, Keel and Fee) showed the most striking changes in DI-pH and DI-TP. In one of the lakes (Keel), the increase in DI-TP takes place before c. 1850, and shows some stability since the mid-19th century. There is also evidence of acidification at Fee, Feeagh and Naminna, although the DI-pH changes, including those for Keel, are not significant. Only relatively small changes in DI-pH and DI-TP between core top and bottom samples are evident at sites within the moderate (*e.g.* Ballynakill) and high (*e.g.* Annaghmore and Muckanagh) alkalinity classes. It should be noted that the sediment core bottom samples from Annaghmore, Ballynakill and Muckanagh appear to pre-date c. 1850.

The DCA results indicate similar trajectories of changes in diatom assemblages between core bottom and top samples for moderate to high alkalinity sites. Some lakes (*e.g.* McNean) appear to have experienced relatively little change, although in some cases this is because the time period between the lowermost samples analysed and the age of the core top sample (c. 2003) is comparatively short (about 53 years in the case of McNean). Core bottom samples from moderate alkalinity, shallow, large lakes (Ballynakill and Kiltooris) were characterised by the benthic diatoms *Achnanthidium minutissimum* and *Cocconeis placentula*. The relatively low SCD scores indicate that these lakes have not experienced more than slight levels of biological change. In contrast, core bottom diatom assemblages from moderate alkalinity, deep, large lakes, such as Talt, were largely characterised by planktonic taxa (*e.g. Cyclotella comensis*). The diatom data indicate considerable change at Talt (SCD score = 0.96). Surface samples from some high alkalinity lakes also show major deviations when compared with core bottom samples (*e.g.* the SCD scores for Annaghmore and Cullaun are, respectively, 0.84 and 1.30). Diatom assemblages in which *Amphora pediculus* and *Pseudostaurosira brevistriata* are abundant characterise the core bottom samples of these lakes, which in both cases appear to pre-date c. 1850. A largely planktonic diatom flora has replaced the non-planktonic diatom reference assemblage at Cullaun, while Annaghmore shows a shift from a non-planktonic diatom community, comprising *Eunotia arcus* and *Pseudostaurosira brevistriata*, to a flora characterised by *Amphora pediculus* and *Mastogloia lacustris*.

Reconstructions of Reference Conditions at Impacted Lakes

A multi-proxy palaeolimnological approach, based on three types of microfossils (cladocera, diatoms and pollen and spores), sediment lithology and geochemistry, enabled the reconstruction of reference conditions at seven impacted lakes in the Irish EcoRegion. Rather than concentrations of SCP, chronological control was provided by down core variations in the isotopes of lead (^{210}Pb) and Caesium (^{137}Cs). The statistical technique MAT (Juggins, 1994) was also trialled as a means of identifying whether extant examples of reference conditions existed for the seven impacted lakes among a selection of moderate and high alkalinity CRLs studied in an earlier phase of the research. This involved the application of MAT to diatom assemblages from surface sediment samples from the selected CRLs (forming the training set) and from core bottom samples from impacted lakes. The technique assumes that if close analogues are found to exist between modern and core bottom diatom assemblages then the similarities should extend to other, taxonomically unrelated groups (*e.g.* fish, benthic macro-invertebrates). To date MAT has been used in the UK to identify restoration targets for lakes based on diatoms (Flower *et al.,* 1997) and, more recently, based on both diatoms and cladocera (Simpson *et al.,* 2005).

Methods

The seven impacted lakes studied comprised: Atedaun, Ballybeg and Inchiquin in County Clare; Egish and Sillan in County Monaghan; Mullagh in County Cavan; and Crans in County Tyrone (Table 3). The lakes were selected based on knowledge of nutrient enrichment, lake typology classes, expert judgment and following consultation with EPA staff. All are from moderate and high alkalinity typology classes (5, 6, 7, 8, 9 and 12) and are generally located within catchments in which improved pasture is the predominant landuse: all are in the mesotrophic to hypertrophic range. Lakes were surveyed and cored during August and September 2004. Three cores were collected from coring sites c. 1 m apart in the deepest part of each lake using a Renberg corer (Renberg, 1991). Sampling of cores in the field followed the same procedure as for the CRLs, with samples from the three cores collected from each lake subsequently used separately to determine: (a) the rate of sediment accumulation; (b) lithostratigraphic and sediment chemistry properties; and (c) microfossil content (diatoms, cladocera and pollen).

Chronological control was based upon radiometrically determined sediment accumulation rates (Robbins *et al.,* 1978). Relative concentrations of ^{210}Pb (a naturally occurring isotope) and ^{137}Cs in ten to fourteen sediment samples per core were determined by high-resolution gamma spectrometry. Sediment chronologies and accumulation rates were used to calculate age using the constant rate of supply (CRS) of ^{210}Pb model, and were verified using

Table 3 Summary of information for seven impacted lakes studied in IN-SIGHT.

Lake	County	Grid Ref.	Geology	River Catchment	Altitude (m)	Mean depth (m)	Lake area (ha)	Catchment area (km^2)	Sample Date	pH	Alkalinity mg l^{-1} $CaCO_3$	TP µg l^{-1}	Chl *a*	Colour PTCo	Reference
Atedaun	Clare	R297885	Limestone	Fergus	22	1.43	37.99	282.50	2000	8.01	135.4	36.7	15.5	31	Wemaere, 2001
Ballybeg	Clare	R331738	Limestone	Fergus	10	2.69	19.73	4.14	2001	7.94	128.0	84.3			Wemaere, 2001
Crans	Tyrone	H711568	Limestone & Shale	Oona	95	6.67	8.50	n/a	1989/1990	8.82	2.45*	89.0	48.0		Gibson, 1991 & Northern Ireland Lake Survey Database (unpub)
Egish	Monaghan	H794134	Ordovician Shale & Quartzite	Erne	162	3.32	121.74	7.84	01/10/1996	7.25	78.6	675.0	3.2	35	Irvine *et al.*, 2001
Inchiquin	Clare	R270896	Limestone	Fergus	35	10.15	115.67	147.14	2001	8.21	161.8	19.3			Wemaere, 2001
									1996/1997	8.22	140	21	4.5	28	Irvine *et al.*, 2001
Mullagh	Cavan	N677854	Silurian Quartzite	Boyne	120	2.33	35.07	1.14	24/07/1996	7.61	58.4	57.0	8.1	29	Irvine *et al.*, 2001
Sillan	Monaghan	H709630	Silurian	Annalee	94	5.98	172.00	n/a	01/10/1996	6.98	37.6	141.0	9.3	36	Irvine *et al.*, 2001

** Alkalinity measured as* HCO_3

anthropogenic ^{137}Cs activity profiles.

Limited resources meant that only one core per lake could be dated in this way, with chronological control extended to other cores from proximate coring locations in the same lake basin.

Three groups of microfossils (cladocera, diatoms and pollen and spores) were used to hindcast a range of historical variations in lake water quality and catchment conditions. Several species of cladocera which preserve well and reflect the nutrient status and pH of lake water (Irvine *et al.,* 2000; de Eyto *et al.,* 2002) have been used in the reconstruction of aquatic conditions (Frey, 1960; Parise and Riva, 1982): *Daphniidae* and *Bosminidae* tend to be planktonic, while the *Chydoridae* are mainly benthic/littoral. The use of diatoms in palaeolimnology has previously been described in this report. Pollen and spores are also commonly used in studies of recent environmental changes (Bennett and Willis, 2001) and were used in IN-SIGHT to estimate changing terrestrial plant cover (*e.g.* Edwards and Whittington, 2001). Microfossils were enumerated in seven to nine samples per core for diatoms and, generally, two samples per core for cladocera and pollen and spores. Where possible the microfossil contents of core top and bottom samples were established. For diatoms, samples were prepared and analysed using the procedure outlined previously. For cladocera and pollen and spores, 1 cm thick slices of core sediment were used. Cladocera were concentrated using a modified version of the standard method described by Frey (1986). Pollen and spores were concentrated in unit volumes of sample following the standard laboratory protocol described in Bennett and Willis (2001).

Down-core differences in diatom assemblages and water quality were quantified through reconstructions of DI-TP, indices of diversity, and ordination. The DI-TP transfer functions developed for impacted lakes were based on a dataset which incorporated a broader range of measured TP values (range = 0.675 µg l^{-1}, TP mean = 33 µg l^{-1}, TP median = 10 µg l^{-1} TP) when compared with the dataset used in developing the version of the model applied to CRLs because the latter did not extend into the eutrophic and hypertrophic parts of the trophic gradient. Measures of diversity were also established for the diatom assemblages (Clarke and Warwick, 1998; Pielou 1975) (although the results must be treated with caution because of the potential problem of differential preservation over time). CANOCO version 4.5 (ter Braak and Šmilauer, 2002) was used to carry out DCA (Hill and Gauch 1980) of diatom data (root transformed with down-weighting of rare taxa).

Sediment chemistry and associated measurements of wet sediment density and percentage water content were determined using the procedures described above. Along with the same elements quantified for sediment samples from CRLs, uranium (U), cadmium (Cd) and boron (B) were determined for sediments from Crans and Ballybeg. Uranium and cadmium were included as proxies linked to signals of inorganic fertiliser inputs (Zielinski *et al.,* 1997) and B as a chemical proxy linked to sewage discharge to freshwater (Neal *et al.,* 2005). Chemical parameters were determined every 1 cm, except U, B and Cd, which were determined every 2 cm: chemical accumulation rates were generated based on the product of chemical concentration (mg g^{-1}) and dry mass accumulation rate (DMAR) and expressed as g m^{-2} yr^{-1}. Quality control was assured through repeat digests and the use of a batch digest method validated with certified reference material.

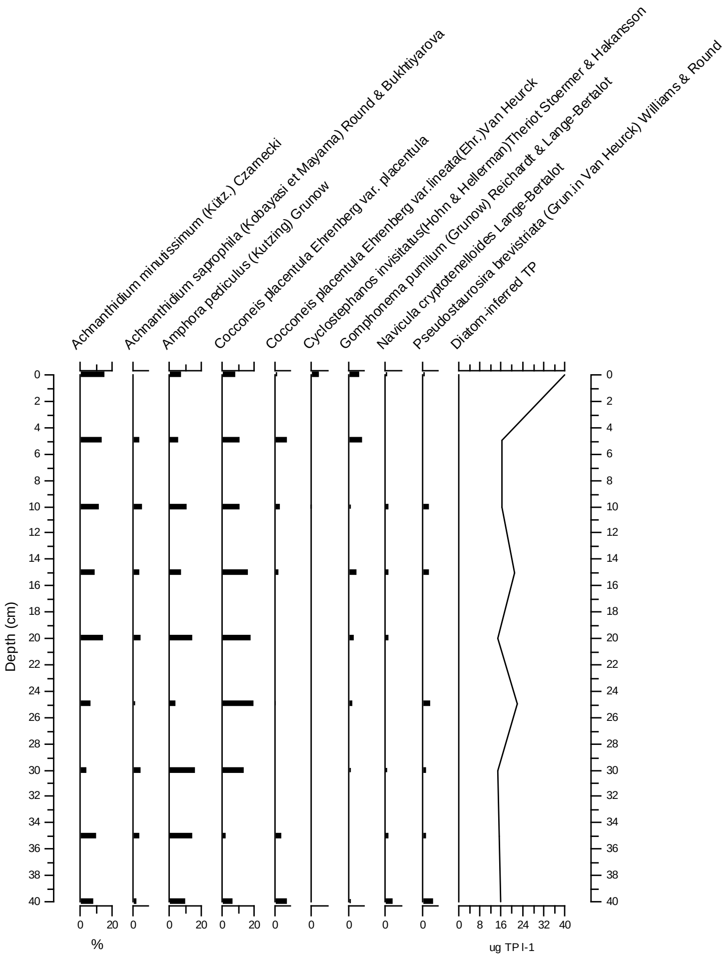
The MAT training dataset comprised diatom data from surface sediment (core top) samples from a total of 13 moderate and high alkalinity CRLs. SCD was used to determine the degree of similarity between diatom assemblages in the MAT training set and diatom assemblages in core bottom (reference) samples from the seven impacted lakes. A SCD score of 0.4 was viewed as the critical threshold in determining the level of similarity between two assemblages. Thus a SCD score > 0.4 meant that a surface sample from a CRL in the training dataset was too dissimilar to be considered a modern analogue for reference conditions in an impacted lake.

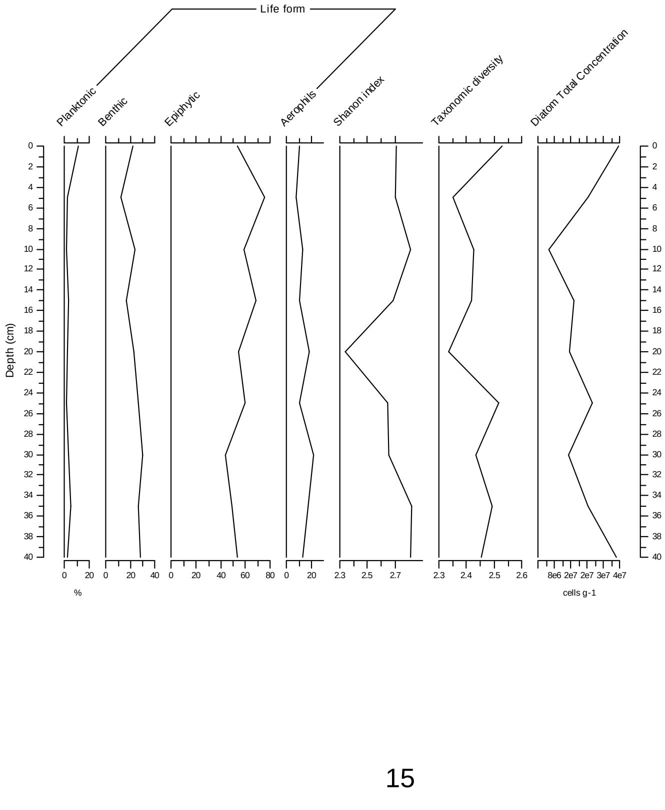
Results

Sediment cores from the impacted lakes ranged in length from 27 cm to 41 cm. In general, there was good agreement between results of the CRS and ^{137}Cs-based age models, with estimated rates of sediment accumulation varying from 0.017 ± 0.004 g cm^{-2} yr^{-1} (Egish) to 0.12 ± 0.02 g cm^{-2} yr^{-1} (Inchiquin) and estimated ages of core bottom samples ranging from the late 18th century (Egish) to the early 20th century (Inchiquin, Sillan and possibly Mullagh). Only at Atedaun were problems in dating irresolvable: an irregular ^{210}Pb concentration profile and an absence of noticeable peaks in the ^{137}Cs profile prevented the construction of a reliable chronological framework for this site.

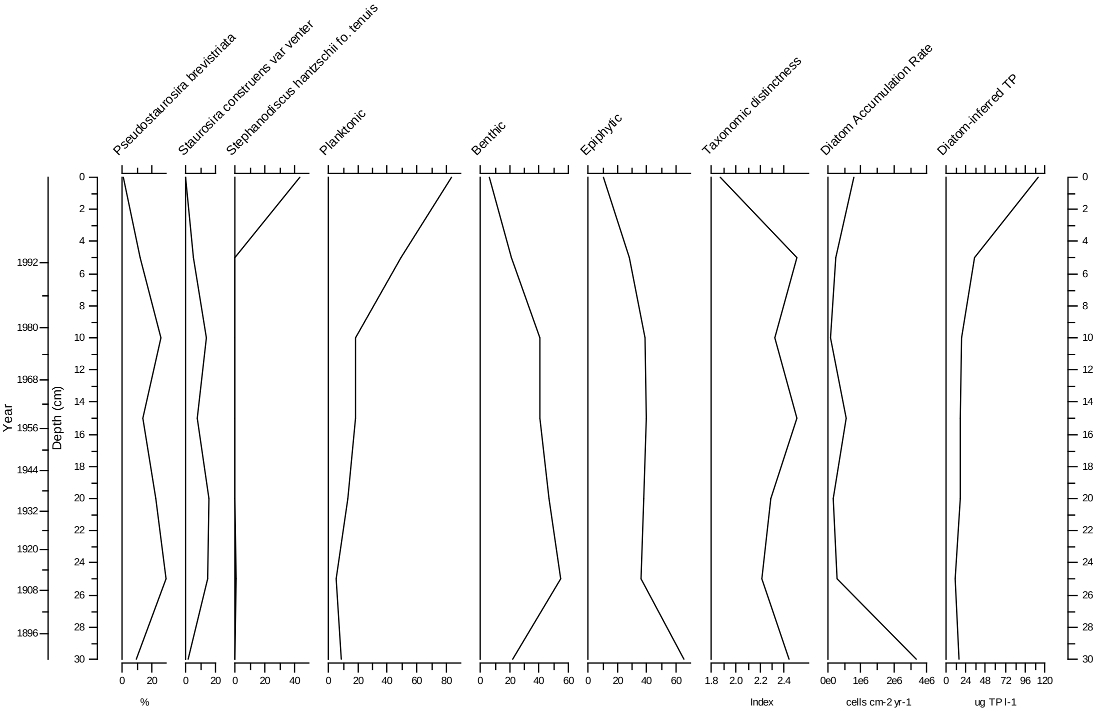
Down core variations in diatom and diatom-inferred data are summarised in Figure 3. Cladocera and pollen counts are summarised in, respectively, Table 4 and Table 5. Figure 4 provides an example of core-based sedimentary chemistry data (for Crans). Sediment samples generally contained abundant, well-preserved microfossils. Diatom species were assigned to habitat (aerophilic, benthic, epiphytic and planktonic) groups using contemporary data derived from different literature studies, but mainly Van Dam *et al.,* 1994. DI-TP from core top data and measured TP correlated well ($r^2 = 0.67$, p value < 0.01), although the model tended to underestimate the high values of TP measured at Egish and Sillan.

Inter-core comparisons of down-core variations in diatom assemblages were facilitated through DCA (Figure 5). Comparisons between top and bottom samples for cores from all seven lakes indicate similar trajectories – although different magnitudes – of difference and suggest common ecological pressure or pressures. The application of MAT indicated that Bane and Ballynakill in the CRL training dataset could potentially act as modern analogues for two of the seven impacted lakes (respectively, Ballybeg and Egish) (Table 6).

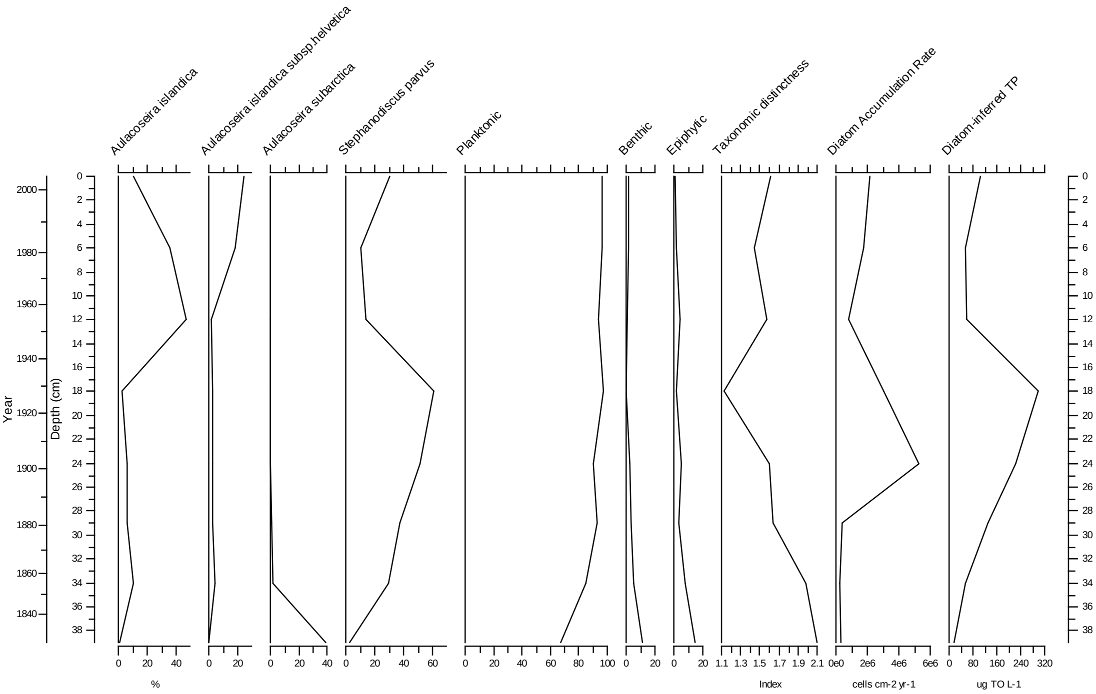

Achnanthidium minutissimum (Kütz.) Czarnecki
Achnanthidium saprophila (Kobayasi et Mayama) Round & Bukhtiyarova
Amphora pediculus (Kutzing) Grunow
Cocconeis placentula Ehrenberg var. placentula
Cocconeis placentula Ehrenberg var. lineata(Ehr.)Van Heurck
Cyclostephanos invisitatus(Hohn & Hellerman)Theriot Stoermer & Hakansson
Gomphonema pumilum (Grunow) Reichardt & Lange-Bertalot
Navicula cryptotenelloides Lange-Bertalot
Pseudostaurosira brevistriata (Grun.in Van Heurck) Williams & Round
Diatom-inferred TP
Depth (cm)
%
ug TP l-1
0
20
8
16
24
32
40


Life form
Planktonic
Benthic
Epiphytic
Aerophils
Shanon index
Taxonomic diversity
Diatom Total Concentration
Depth (cm)
%
cells g-1
2.3
2.5
2.7
2.4
2.6
8e6
2e7
3e7
4e7

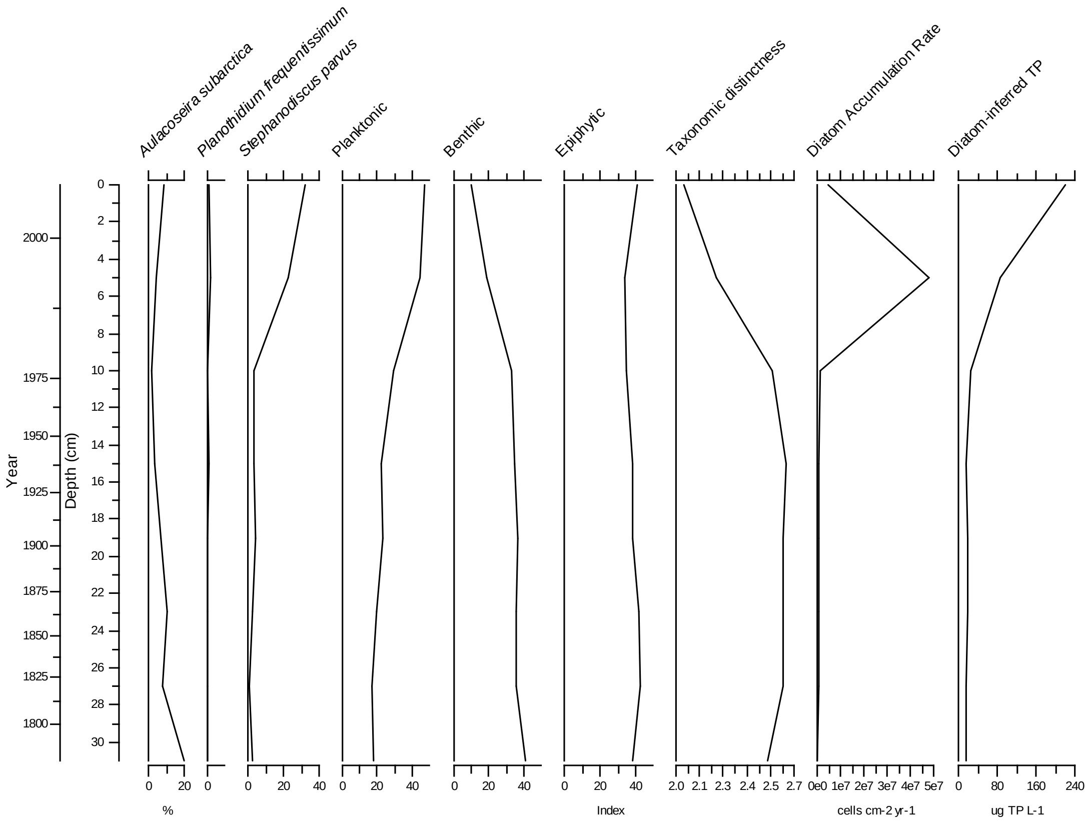
a)


Pseudostaurosira brevistriata
Staurosira construens var venter
Stephanodiscus hantzschii fo. tenuis
Planktonic
Benthic
Epiphytic
Taxonomic distinctness
Diatom Accumulation Rate
Diatom-inferred TP
Year
Depth (cm)
1992
1980
1968
1956
1944
1932
1920
1908
1896
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
%
Index
cells cm-2 yr-1
ug TP l-1
1.8
2.0
2.2
2.4
0e0
1e6
2e6
4e6
24
48
72
96
120

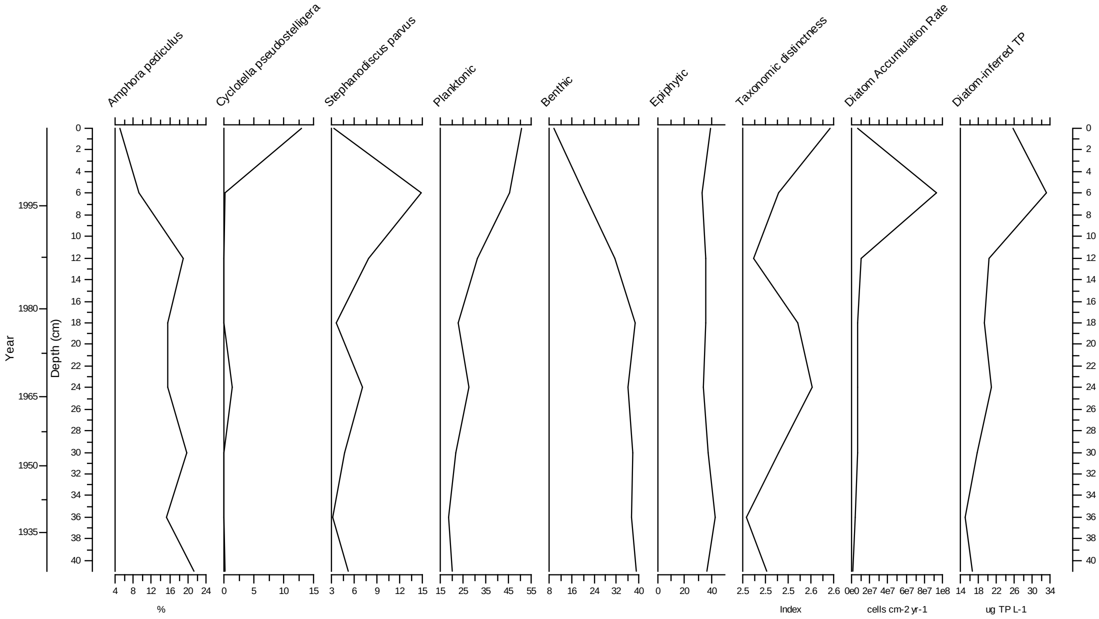
b)


Aulacoseira islandica
Aulacoseira islandica subsp.helvetica
Aulacoseira subarctica
Stephanodiscus parvus
Planktonic
Benthic
Epiphytic
Taxonomic distinctness
Diatom Accumulation Rate
Diatom-inferred TP
Year
Depth (cm)
2000
1980
1960
1940
1920
1900
1880
1860
1840
%
Index
cells cm-2 yr-1
ug TO L-1
1.1
1.3
1.5
1.7
1.9
2.1
0e0
2e6
4e6
6e6
80
160
240
320

c)


Aulacoseira subarctica
Planothidium frequentissimum
Stephanodiscus parvus
Planktonic
Benthic
Epiphytic
Taxonomic distinctness
Diatom Accumulation Rate
Diatom-inferred TP
Year
Depth (cm)
2000
1975
1950
1925
1900
1875
1850
1825
1800
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
0 20 0 0 20 40 0 20 40 0 20 40 0 20 40 2.0 2.1 2.3 2.4 2.5 2.7 0e0 1e7 2e7 3e7 4e7 5e7 0 80 160 240
%
Index
cells cm-2 yr-1
ug TP L-1

d)


Amphora pediculus
Cyclotella pseudostelligera
Stephanodiscus parvus
Planktonic
Benthic
Epiphytic
Taxonomic distinctness
Diatom Accumulation Rate
Diatom-inferred TP
Year
Depth (cm)
1995
1980
1965
1950
1935
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
4 8 12 16 20 24 0 5 10 15 3 6 9 12 15 15 25 35 45 55 8 16 24 32 40 0 20 40 2.5 2.5 2.5 2.6 2.6 0e0 2e7 4e7 6e7 8e7 1e8 14 18 22 26 30 34
%
Index
cells cm-2 yr-1
ug TP L-1

e)

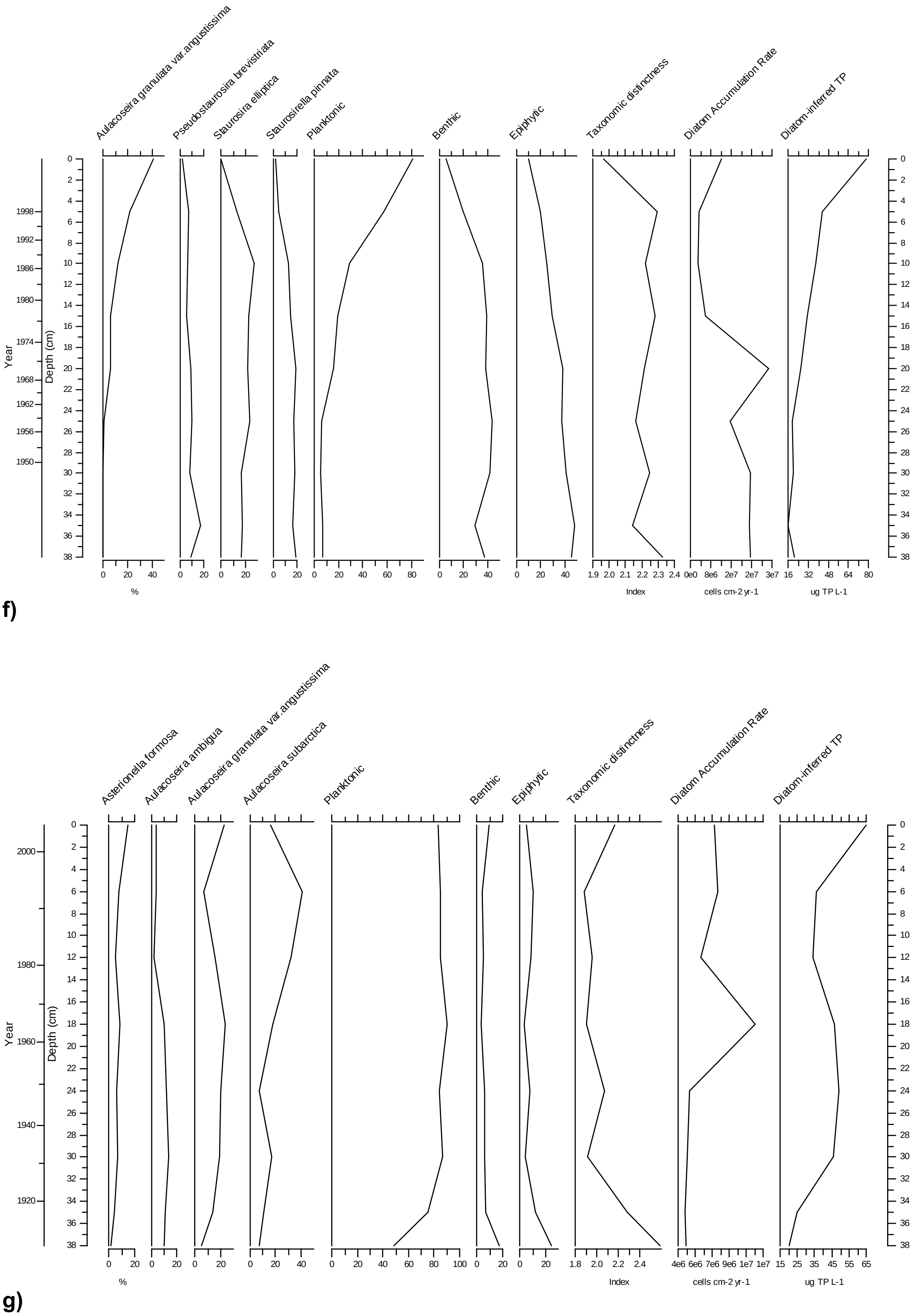


Figure 3 **Down-core variations in diatoms (commonly occurring taxa and grouped into life form categories) (% data) and other diatom-related parameters, including DI-TP and diatom accumulation rate. (a) Atedaun; (b) Ballybeg; (c) Crans; (d) Egish; (e) Inchiquin (f) Mullagh; (g) Sillan. All data are portrayed against both depth (cm) and estimated age, except Atedaun (data portrayed only against depth (cm)).**

Table 4 **Summary of planktonic and littoral cladocera and Shannon Diversity Index (H) of chydorid species for sediment core samples from the seven impacted lakes.**

Lake	Atedaun		Ballybeg		Crans		Egish		Inchiquin		Mullagh		Sillan	
Depth (cm)	**0-1**	**39-40**	**0-1**	**30-31**	**0-1**	**39-40**	**0-1**	**31-32**	**0-1**	**40-41**	**0-1**	**38-39**	**0-1**	**38-39**
% Planktonic	30	12	60	66	96	80	92	14	84	46	74	43	75	66
% Littoral	70	88	40	34	4	20	8	86	16	54	26	57	25	34
Planktonic/Littoral	0.43	0.14	1.48	1.94	25.27	4.12	11.02	0.16	5.07	0.86	2.80	0.75	3.03	1.94
Chydorid diversity (H)	2.44	2.47	2.07	2.36	2.08	2.33	2.26	1.78	2.38	2.25	2.14	2.43	2.41	2.57

Table 5 **% pollen data for sediment core samples from seven impacted lakes. Data underlined are for core bottom samples. See ext for information on pollen sums used. AT = Atedaun, BA = Ballybeg, CR = Crans, EG = Egish, IN =Inchiquin, MU = Mullagh, SI = Sillan**

Sample id. & depth (cm)	Deciduous tree (% sum = total excluding damaged)	*Alnus* (% sum = tree pollen)	*Betula* (% sum = tree pollen)	Corylus (% sum = tree pollen)	*Fagus* (% sum = tree pollen)	*Fraxinus* (% sum = tree pollen)	*Pinus*-type (% sum = tree pollen)	*Quercus* (% sum = tree pollen)	*Salix* (% sum = tree pollen)	*Ulmus* (% sum = tree pollen)	Poaceae (% sum = total excluding damaged)	Ericaceae (% sum = total excluding damaged)	*Isoetes* (% sum = total excluding damaged)	*Myriophyllum* (% sum = total excluding damaged)
AT 00-01	46	5	6	61	1	1	16	5	1	3	23	0	0	0
AT 10-11	43	12	8	48	0	5	9	7	7	2	34	1	0	0
AT 39-40	35	17	5	42	0	0	9	18	3	6	34	3	0	0
BA 00-01	25	8	0	31	0	2	33	25	0	0	30	0	0	0
BA 30-31	30	20	0	33	2	0	6	34	3	2	38	0	0	0
CR 10-11	15	19	0	12	2	2	21	36	5	0	68	4	1	0
CR 39-40	34	15	10	28	7	1	7	28	1	3	41	3	1	0
EG 05-06	47	21	10	38	0	0	7	18	1	5	36	1	1	1
EG 31-32	62	30	6	47	0	0	2	12	1	2	13	7	2	3
IN 00-01	35	6	6	41	0	3	18	23	2	0	37	1	0	0
IN 40-41	36	4	3	48	0	0	16	26	2	1	32	1	0	0
MU 10-11	52	16	7	45	2	0	8	19	0	3	26	2	0	5
MU 38-39	70	16	7	47	0	0	6	20	0	4	15	1	0	1
SI 15-16	41	23	8	32	0	2	9	21	3	2	34	2	5	3
SI 38-39	49	22	7	33	0	0	11	24	0	2	21	2	5	7

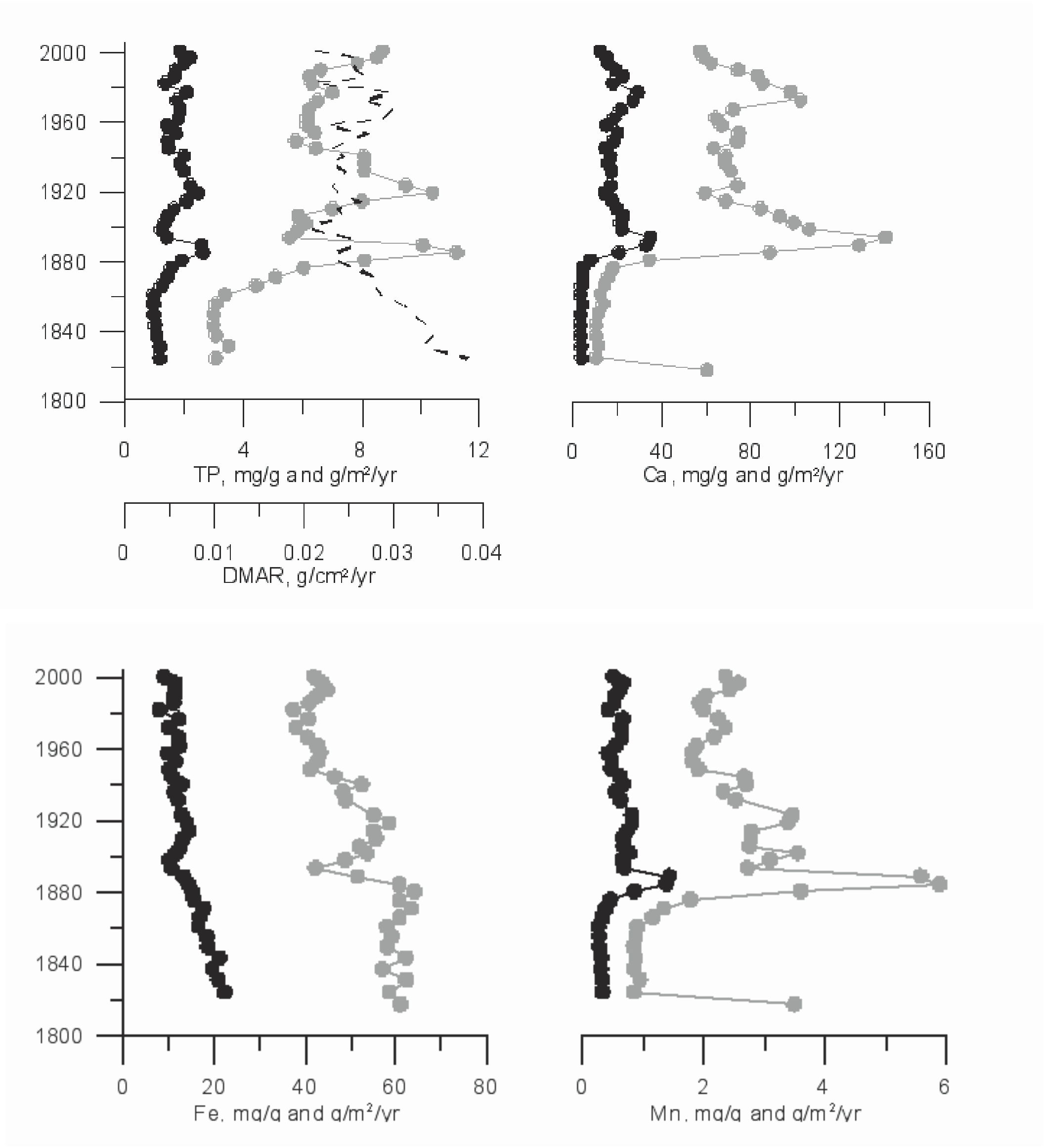


Figure 4 **Example of down-core variation in DMAR and selected sedimentary elements (Crans, County Tyrone). Grey circles are chemical concentrations; black circles are chemical accumulation rates. The dashed line in the top left panel is DMAR. Data are plotted on an age scale.**

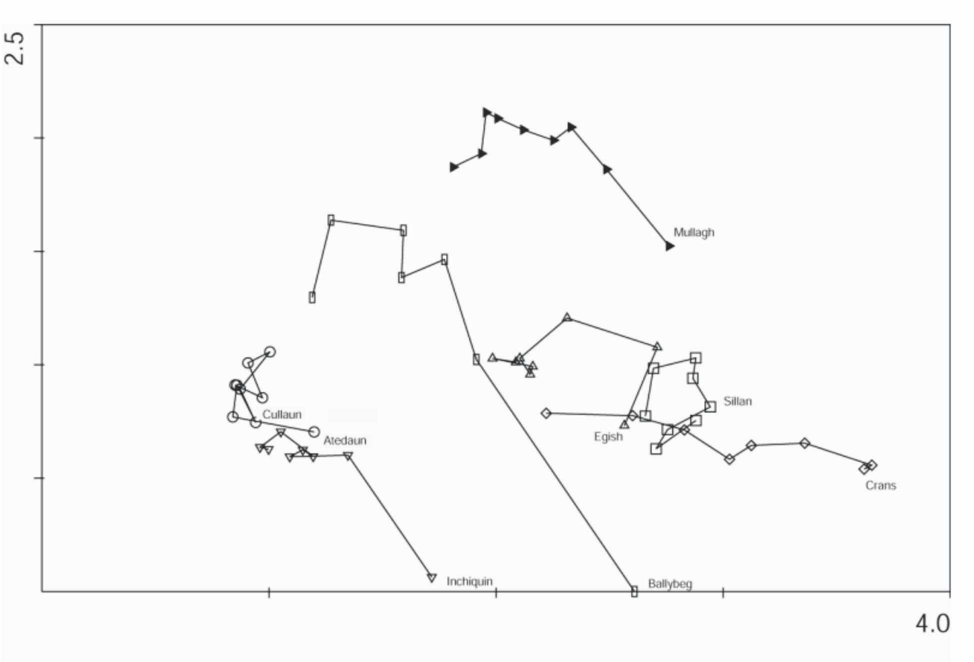


Figure 5 DCA biplot combining all sediment samples from seven impacted lakes. Lake names are given next to the core top sample from that lake; contiguous samples from the same core are linked with a connecting line. Units = SD.

Table 6 Summary of MAT results (SCD scores for core bottom samples from impacted lake and closest modern analogue among CRL training dataset of 13 core top [surface sediment] samples). Only diatom taxa with abundances > 2% have been included in analysis. SCD scores less than 0.4 are in bold in far right column.

Impacted lake	Closest modern analogue			Minimum SCD
	SCD < 0.40	SCD ≥ 0.40 to < 0.71	SCD ≥ 0.71	
Atedaun			Bunny	0.755
Ballybeg	Bane			**0.365**
Crans		Ballynakill		0.684
Egish	Ballynakill			**0.397**
Inchiquin		Bunny		0.663
Mullagh			Bane	1.021
Sillan		Ballynakill		0.623

Discussion

Testing of CRL status

According to intra-core comparisons, largely stable ecological conditions were observed for 11 CRLs (32% of the 34 CRLs for which data are available) over the period of time represented by their sediment cores. Basal samples from 10 of these sites pre-date c. 1950, or the onset of agricultural intensification and afforestation. For four of the sites (Bunny, Keel, Nahasleam and Upper) the core bottom sample dated to c. 1850 or earlier, while core bottom samples for five (Doo, Dunglow, Kiltooris, McNean and Veagh) dated to c. 1850 to c. 1950. Sediment core bottom samples for the remaining two CRLs (Barfinnihy and O'Flynn) proved impossible to date to an acceptable level of certainty using the SCP method, although they appeared considerably older (Barfinnihy) and somewhat younger (O'Flynn) than c. 1850.

Biologically important changes between core bottom and top samples were shown to exist for 23 (68%) of the CRLs studied. The main drivers of changes at these oligotrophic and meso-oligotrophic lakes appeared to be nutrient enrichment and increased acidity. Phosphorus transfer to freshwaters is a major cause of nutrient enrichment in Ireland at present, although no evidence of major increases in exogenic inputs was detected in the sediment cores. Increased TP transfer is not necessarily linked directly to increased soil loss, however, and both increased point sources, such as those associated with rural dwellings and septic tanks, and diffuse soluble P losses from P-saturated soils or inappropriate slurry spreading (*e.g.* during wet weather) (Jordan *et al.,* 2005) are possible drivers of changes in the diatom assemblages recorded here.

Of particular note is the comparatively high incidence of important deviations in biological conditions among the low alkalinity, large deep lakes (82% of CRLs in typology class 4 generated SCD scores > 0.4). Nutrient enrichment does not appear to have been the driver here as increases in DI-TP are relatively minor and are not generally supported in the sedimentary TP data. It could be, however, that epilimnetic TP concentrations are not in balance with sediment-based TP. Moreover, relatively small increases in TP concentrations in P-limited lakes may impact diatom populations before any increases are evident in sediment chemistry: rapid DI-TP change has been found in some historically oligotrophic lakes in Northern Ireland prior to increases in sediment TP (Jordan and Anderson unpublished data). Acidification appears to have been a factor at several of these lakes, however, notably Dan, Kylemore and Tay.

The more finely resolved sediment chemistry and diatom data from Keel and Talt are of particular interest. The sedimentary data for Keel indicate relatively little change between c. 1850 and the present-day. The rate of sedimentation at Keel was, however, low (0.19 cm yr^{-1}) and the base of the 41 cm-long core of sediment obtained dated to the late 18th century, based on an extrapolation of the

SCP chronology. Comparisons of diatom assemblages and DI-TP between the core bottom and top samples from this site indicate much larger changes than are evident since c. 1850, due to increased abundances of *Asterionella ralfsii* (a taxon that was not recorded in pre-c. 1850 sediments). The ecology of this taxon is not well known but appears to be indicative of peatland disturbance and nutrient enrichment (Liehu *et al.,* 1986). The results from Talt indicate a pattern of change which may be hidden in some of the less finely resolved core datasets, in the form of catchment disturbance after c. 1950 followed by stabilisation, but without a full recovery of diatom communities and pH levels.

Analysis of the moderate and high alkalinity lakes, where dissolution of silica diatom frustules has caused interpretation problems, highlights the dangers of relying on diatoms as the sole proxy of biological conditions in these systems. As the sedimentary data which are available for sites within these classes show some deviation from reference conditions may have occurred, a separate study should focus specifically on these typology classes using biological indicators other than diatoms (*e.g.* chironomids, cladocera, ostracods, pigments). A further limitation of this investigation was that it was only possible to consider in any detail a restricted range of causes of variability, despite the potential role of other important influencing factors, notably climate change. A number of lakes in this study have experienced a rise in Cyclotella taxa when compared with reference conditions, which could not be related directly to human activities. Increased abundances of various *Cyclotella* species have been linked to climate change throughout the Canadian arctic (Karst-Riddoch *et al.,* 2005) as well as in temperate regions (Wolin and Stoermer, 2005) and recent climate changes are likely to have impacted oligotrophic and meso-oligotrophic lakes in Ireland.

Reconstruction of Reference Conditions at Impacted Lakes

All seven impacted lakes were oligo-mesotrophic or mesotrophic at the onset of the sedimentary records retrieved. Sediment core bottom samples ranged in age from the late 18th to possibly as recently as post-circa 1950 and were characterised by a relatively diverse diatom flora, in which benthic and epiphytic types were prominent, with DI-TP ranging from 12 to 21 mg l^{-1}, and diverse littoral cladoceran assemblages generally indicative of abundant aquatic macrophyte cover. Pollen and spores preserved in core bottom samples appear to reflect a mosaic of deciduous woodland and grassland in the catchments and therefore conditions post major human-induced changes in vegetation.

In the case of Atedaun, the core bottom diatom assemblage (estimated to be post-1950) was characterised by non-planktonic taxa. Overall the assemblage was very diverse and indicative of oligo-mesotrophic to mesotrophic conditions. The occurrence of taxa associated with epiphytic habitats suggests the presence of macrophytes. Remains of cladocera also indicate low to medium nutrient concentrations and an abundance of macrophytes. The core bottom diatom assemblage for Ballybeg dates to the late 19th century and is relatively diverse, with non-planktonic taxa predominant, and is typical of alkaline, shallow lakes of intermediate nutrient status. Cladocera remains recovered from the core bottom sample were also indicative of mesotrophic conditions.

Planktonic diatom taxa characterised the core bottom diatom assemblage for Crans, dating to the early to mid-19th century, and were indicative of alkaline, mesotrophic waters. Planktonic taxa were also abundant among the cladocera. The core bottom diatom assemblage from Egish, which may date to the late 18th century in age, was dominated by non-planktonic taxa and was indicative of shallow, oligo-mesotrophic conditions. Abundant epiphytic taxa suggest that macrophytes were extensive. The core bottom sample from Inchiquin dates to the c. 1930s and yielded diatom and cladocera assemblages indicative of mesotrophic conditions. The age of the core bottom diatom assemblage from Mullagh could not be determined to an acceptable level of certainty. However, it was similar in composition to the reference sample from Egish, which potentially dated to the late 18th century, being characterised by the non-planktonic taxa. Large numbers of benthic diatom and cladocera taxa indicate shallow waters, while the high percentage of epiphytic diatoms suggests that macrophytes were abundant.

The core bottom sample from Sillan dates to the early 20th century. Planktonic taxa were pre-dominant in this sample and indicative of relatively deep, mesotrophic waters. The abundance of epiphytic taxa in the core bottom sample suggests that macrophytes were more common than today. The remains of cladocera also indicate mesotrophic conditions; planktonic forms were abundant, and diversity levels were the highest among the impacted lakes studied. According to the MAT results and despite a relatively small training dataset of surface samples from CRLs, Ballynakill and Bane may today provide broad indications of reference conditions for two of the seven impacted lakes (Ballybeg and Egish). It should be pointed out, however, that SCD scores from intra-core comparisons in diatom assemblages for Ballynakill and Bane, at respectively 0.5 and 0.56, are the wrong side of the 0.4 threshold for verification of CRL status adopted in IN-SIGHT.

Long-term Variations in Trophic Status at Impacted Lakes

Sediment-based evidence from five of the seven impacted lakes (Ballybeg, Crans, Egish, Mullagh and Sillan) showed clear evidence of substantial nutrient enrichment (> 50 µg l^{-1} TP), and two of these (Crans and Egish) show a more than tenfold increase in DI-TP over the time covered by the sedimentary records analysed. Of the two lakes which did not show substantial nutrient enrichment, DI-TP levels for one (Atedaun) showed a change in trophic status (from mesotrophic to eutrophic). Similarities exist between sites in changes in diatom and cladocera assemblages, as is evident for diatoms in the DCA results: generally, the abundances of planktonic taxa increase up-core, replacing benthic and epiphytic taxa. All the lakes have experienced periods of catchment disturbance and nutrient enrichment, with steep increases in DI-TP associated with unsustained increases in diatom productivity and sharp falls in diversity. The microfossil and DI-TP reconstructions indicate that Crans and Sillan have been nutrient-enriched since, respectively, the late 19th and early 20th centuries, while the trophic status of Inchiquin remained comparatively stable. Relatively low population densities and the high proportion of unimproved or low intensity land use in the Inchiquin catchment (Irvine *et al.,* 2000; Wemaere, 2005) were no doubt important, and P-buffering due to high alkalinity of the lake may have facilitated the maintenance of a relatively stable nutrient status (Hobbs *et al.,* 2005). Large periodic flushing may, however, also be important for removal of phytoplankton from both the lake and sedimentary record. Allott (1990) found a much reduced summer mean chlorophyll a: winter TP ratio in Inchiquin compared with other lakes in the region.

Five of the sediment profiles indicate accelerated enrichment post c. 1980: the profile for Inchiquin remains relatively stable and in the mesotrophic range, while weak chronological control for the sediments from Atedaun precludes precise dating (although levels of DI-TP and diatom concentrations for this site indicate a rapid increase in productivity towards the top of the core). Accelerated enrichment post circa 1980 has also been reported for several lakes in Northern Ireland (Anderson, 1997; Zhou *et al.,* 2000; Jordan *et al.,* 2001; Foy *et al.,* 2003), despite reduced inputs of P from point sources during the same period (Foy *et al.,* 1995; EHS, 2000; Jennings *et al.,* 2003). Enrichment is also evident in levels of sedimentary TP, although the co-variance of sedimentary TP with DMAR, Fe and Mn suggests that enhanced catchment erosion was an important contributing factor to increased sedimentary TP (Boyle, 2001). Increased inputs of P from soils which have become saturated with P as a result of agricultural practices (Tunney *et al.,* 1997; Foy *et al.*, 2003) provide one explanation for enhanced enrichment. Recently increased internal P input as a result of the release of P from sediments (Søndergaard *et al.,* 1999; Jordan and Rippey, 2003; Phillips *et al.,* 2005) provides another, or complementary, explanation.

Catchment disturbance and nutrient enrichment at Crans, dating from the late 19th century, with the lake becoming hypertrophic by the turn of the 20th century, correspond with evidence from other lakes in Northern Ireland. Eutrophication commenced in the late 19th century at Heron (Anderson, 1997) and Neagh (Battarbee 1978; Foy *et al.,* 2003) and at the beginning of the 20th century at Upper Lough Erne (Battarbee 1986). Early cultural eutrophication was also reported for meres in central England (Anderson, 1995). Nutrient concentrations were reduced at Crans around the 1950s, but increased again from the 1980s. A similar trend of relatively early initial eutrophication followed by recovery and a second phase of nutrient enrichment was evident at Sillan, with eutrophication commencing early in the 20th century, followed by reduced nutrient status in the 1970s and 1980s and a second period of nutrient enrichment post c. 1990.

Conclusions

- Diatom assemblages in sediment core top samples from 11 (32%) of 34 CRLs showed relatively little deviation from those in sediment core bottom samples from the same lakes. The core bottom samples from ten of these sites appeared to pre-date c. 1950, or the onset of agricultural intensification and major afforestation in the catchments, with the basal sample from the eleventh site (O'Flynn) being imprecisely dated at younger than c. 1850. Assuming that the diatom assemblages reflect more general biological conditions, the 11 CRLs to have their reference status confirmed comprise: Barfinnihy (typology class 3); Bunny (typology class 10); Doo (typology class 3); Dunglow (typology class 2); Keel (typology class 1); Kiltooris (typology class 6); McNean (typology class 8); Nahasleam (typology class 1); O'Flynn (typology class 10); Upper (typology class 4); and Veagh (typology class 4).

- Large, deep, low alkalinity lakes (typology class 4) appear particularly prone to biological deviations from reference conditions over the periods of time represented by the sediment cores analysed (82% of this type of CRL studied showed biologically important deviations from reference conditions).

- Acidification and nutrient enrichment were important drivers of biological changes at those CRLs which did not have their reference conditions confirmed, while other factors, such as climate change, were probably also important, and may have contributed to biologically important deviations at some low alkaline lakes in particular.

- Reconstructions based on down-core variations in several proxies of lake and catchment conditions from seven impacted lakes, drawn from EPA typology classes 5, 6, 7, 8, 9 and 12, indicate complex and locally-specific trophic histories.

- The results of analyses of sediment core bottom (reference) samples from the seven impacted lakes suggest that reference conditions at these sites equate to oligo-mesotrophic or mesotrophic conditions. Diverse diatom flora in which benthic and epiphytic types were prominent are indicated, while reconstructed levels of DI-TP levels ranged from 12 to 21 µg l^{-1}. The analyses also revealed diverse littoral cladoceran assemblages indicative of abundant aquatic macrophytes and catchment vegetation cover characterised by a mosaic of deciduous woodland and grassland.

- Substantial nutrient enrichment (> 50 µg l^{-1} TP) and accelerated enrichment post c. 1980s characterised results from five of the impacted lakes (Ballybeg, Crans, Egish, Mullagh and Sillan), with two (Crans and Egish) showing a more than tenfold increase in DI-TP over the time covered by the sedimentary records analysed. Although chronological control was weak for Atedaun, the results also indicated that this lake had experienced nutrient enrichment, and that enrichment had been particularly intense during the most recent period.

- MAT has the potential to be a useful tool in the identification of appropriate restoration targets for impacted lakes. However, in order to allow the true potential of the technique to be realised a larger dataset than the one available to IN-SIGHT researchers is needed.

- Application of the palaeolimnological approach in IN-SIGHT has revealed significant shortfalls in the amount of relevant information currently available and the severe difficulties in setting a priori a *terminus ad quem* for type-specific reference conditions in the Irish EcoRegion.

- Palaeolimnology, although relatively under-developed as a science in Ireland, has great potential as a tool in the implementation phase of the WFD, and is therefore deserving of further investment. Future palaeolimnological research in Ireland aimed at facilitating implementation of the WFD would benefit from high resolution, multi-proxy based studies of radiometrically dated sediment cores and from close links with palaeolimnological research taking place in neighbouring EcoRegions. This research ought to focus on the establishment of reference conditions for those types of lakes without extant examples of high quality status, on the development of new sediment-based proxies of water quality and catchment conditions, and on understanding the links between ecological pressures and responses in aquatic ecosystems.

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Acronyms and Notation

AMSL	**Above Mean Sea Level**
CRL	**Candidate Reference Lakes**
DCA	**Detrended correspondence analysis**
DMAR	**Dry mass accumulation rate**
EPA	**Environmental Protection Agency (Ireland)**
EU	**European Union**
MAT	**Modern Analogue Technique**
RBD	**River Basin Districts**
SCD	**Squared chord distance**
SCP	**Spheroidal Carbonaceous Particle**
TP	**Total Phosphorus**
UCL	**University College London**
WA	**Weight Averaging**
WFD	**Water Framework Directive**
WP	**Work Package**