Recent histories of six productive lakes in the Irish Ecoregion based on multiproxy palaeolimnological evidence

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Abstract

Palaeolimnological data from six mesotrophic, eutrophic and hypertrophic lakes in the Irish Ecoregion, in the form of radiometrically-dated microfossil (cladocera, diatoms and pollen) and sediment chemistry data from sediment cores, are used to reconstruct past variations in lake water quality and catchment conditions. Basal sediments from the six sites range in age from the late 18th century to the early 20th century. Interpretations of the sediment-based data were facilitated through the use of a transfer function, developed specifically for this project, to infer total epilimnetic phosphorus and recourse to documentary evidence. The results indicate that all but one of the sites studied are in a far more productive state at present compared with the beginning of the sedimentary record and that those same five lakes have experienced accelerated enrichment post c. 1980. Two of the sites demonstrate long-term enrichment, in one case beginning in the late 19th century, while both eutrophication and oligotrophication have occurred at three sites. The results demonstrate that productive lakes in the Irish Ecoregion have complex, locally-specific and often long histories of enrichment and may not be responsive to reduced external loadings of P and, as a result, restoration will prove particularly challenging.

Key words: Eutrophication, oligotrophication, palaeoecology, phosphorus, reference, WFD

Introduction

The *EU Water Framework Directive* (WFD, Directive 2000/60/EC) requires member states, *inter alia*, to establish type-specific reference conditions for a range of surface and ground water bodies (Anon, 2000: L327/27). Reference conditions, showing no or minimal anthropogenic impact can be established in several ways (Andersen *et al.,* 2004). It has been generally agreed in the UK that *c.* 1850 is a suitable primary reference date for the assessment of anthropogenically-driven aquatic impacts (Battarbee 1999; Bennion *et al.,* 2004), although in many parts of northwestern Europe, including Ireland, profound human impacts pre-date the mid 19th century (see Bradshaw (2001), for example). High fertiliser application rates were not a feature of agriculture in Ireland until intensification commenced in the 1950s (Tunney 1990), and *c.* 1950 maybe an appropriate secondary reference baseline in intensively farmed catchments.

A combination of spatial and palaeolimnological approaches has recently confirmed that some lakes in the Irish Ecoregion meet the criteria for reference status (Leira *et al.,* in press). The reference sites are generally oligotrophic and meso-oligotrophic, however, and do not include lakes in catchments that support intensive agriculture (Leira *et al.*, in press). The current situation raises two important questions, both relevant to the WFD. First, how far removed from biological reference conditions are lakes in impacted catchments? Second, how variable has the trophic status of such lakes been over the last c. 100-200 years (i.e. up to and during the main period of agricultural intensification and urbanisation and following the implementation of measures aimed at addressing eutrophication)? Both questions are particularly relevant to the management of impacted lakes, while the second invites evaluation of past management initiatives, including reduced phosphorus (P) inputs from point sources, and a test of the assumption that naturally eutrophic lakes do not exist in the Irish Ecoregion.

Eutrophication is most commonly associated with increased availability of P (Ulén & Kalisky, 2005; Smith *et al.*, 2005) or nitrogen (Bergstrom *et al.*, 2005) and is now considered the principal pressure on lake water quality in the Irish Ecoregion (EHS, 2000; Jennings *et al.*, 2003). Increased loadings of P to lakes (e.g., Battarbee, 1978; Anderson, 1990, 1997; Anderson & Rippey, 1994; Gibson *et al.*, 1995; Bowman & Clabby, 1998; Linnane & Murray, 2000; Foy *et al.,* 2003; Jordan & Rippey, 2003; Leira *et al*., in press) are commonly attributed to discharges of municipal and industrial waste (Smith *et al*., 1999) and agricultural intensification, with diffuse agricultural sources often considered the main contributor (Lucey *et al.*, 1999; EHS, 2000; Smith *et al.,* 2005). Eighteen percent of a total of 492 lakes in the Republic of Ireland surveyed during the period 2001-2003 were assigned a eutrophic or hypertrophic status (Toner *et al.*, 2005), while more than 50% of c. 600 lakes in Northern Ireland surveyed in the 1980s and 1990s were classed as eutrophic (HMSO, 1990; Gibson *et al.*, 1995).

Aside from a few studies, mainly in the north of the Irish Ecoregion, little attention has been paid to long-term temporal dynamics of loadings of P, to conditions pre-nutrient enrichment (Jennings *et al*., 2003), or to the possibility that naturally productive lakes may exist in the Irish Ecoregion, as elsewhere (e.g., Murphy *et al.*, 1983; Moss *et al.,* 1994; Bennion *et al.*, 2004; Räsänen *et al.*, in press), or to post-enrichment oligotrophication (Anderson *et al*., 2005). The research presented here provides information on ecological responses to long-term variations in aquatic pressures, such as P, and in so doing addresses the two questions raised previously. It achieves this through the application of multi-proxy, palaeolimnological and related approaches to six lakes in the Irish Ecoregion.

Study sites

No single agreed typology currently exists for lakes in the Irish Ecoregion, although a working typology has been established based upon physico-chemical and hydromorphic characteristics (Leira *et al.,* in press). The six sites in this study cover the main types of lakes within agriculturally productive catchments (Figure 1; Tables 1-3). The relatively low sampling frequency of waters normally precludes the application in Ireland of the trophic classification scheme proposed by the OECD (OECD, 1982). As a consequence, a modified version of this scheme has been adopted, based on annual maxima in chlorophyll concentration, which includes a subdivision of the eutrophic category. Thus, according to Toner *et al.* (2005): Ballybeg is strongly eutrophic; Egish is hypertrophic; Inchiquin is mesotrophic; and Mullagh and Sillan are both highly eutrophic. According to data presented in Gibson (1991), Crans is strongly eutrophic according to chlorophyll-a and hypertrophic according to TP (both single measurements made in August 1987). Improved pasture is the predominant land cover in all of the study catchments with the exception of Inchiquin, which is largely peatland. Deciduous woodland and conifer plantations are also present in the Inchiquin catchment. Urbanisation has impacted the Ballybeg catchment over the last two decades, with several houses now located close to the lakeshore. Urban and industrial developments have also encroached upon the Egish and Sillan catchments: a creamery is located in the former, while a meat-processing factory is situated in the latter. A caravan site is located close to the shoreline of Sillan, and the lake also receives treated sewerage from the nearby town of Sherlock. A small area of deciduous woodland is located close to Crans, and the catchment for this lake was included in a major arterial drainage development scheme constructed in the 1980s (Anon, 1997). Evidence of early human manipulation of the environment exists in the form of archaeological remains, such as a promontory fort at Mullagh and crannogs at Crans and Egish.

Methods

Field methods

Fieldwork took place during August and September 2004. Bathymetric surveys were used to locate the deepest part of each lake. Three cores were collected from coring sites c. 1 m apart in the deepest part of each of the six lakes using a gravity (Renberg) corer (Renberg, 1991). Cores were sliced (0.5 cm-thick for the uppermost 5 cm and 1 cm-thick thereafter) in the field immediately following collection and sediment slices were bagged in zip-lock bags, labelled and stored in a refrigerator for subsequent laboratory-based analyses. Samples from the three cores collected from each lake were separately used to determine: (a) the rate of sediment accumulation; (b) lithostratigraphic and sediment chemistry properties; and (c) microfossil content (diatoms, cladocera and pollen).

Laboratory methods

Chronological control in the current research is based upon radiometrically-determined sediment accumulation rates (Robbins *et al.,* 1978). Relative concentrations of ^{210}Pb (a naturally occurring isotope), ^{241}Am and ^{137}Cs in ten to fourteen samples per core were analysed, with background concentrations assumed to equate to measured levels in the basal sample from each core. Accumulation rates were used to calculate age using the constant rate of supply (CRS) and constant initial concentration (CIC) of ^{210}Pb, and were verified using measurements of ^{241}Am and ^{137}Cs activity. Limited resources meant that only one core per lake could be dated in this way, with chronological control extended to other cores from the same lake using down-core variations in sediment properties.

Wet sediment density and percentage water content were determined on all samples from the cores used for lithostratigraphic and sediment chemistry analyses. Wet sediment density was determined from the weight of known volumes of fresh sediment samples, while percentage water (as dry weight density) and organic (loss on ignition (LOI), measured at 1 cm intervals) contents were established thermogravimetrically (Hilton *et al.*, 1986). Total sediment chemistry concentrations of P, iron (Fe), manganese (Mn), calcium (Ca), sodium (Na) and potassium (K) were assessed using ICP-OES following sequential acid digestion (Jordan *et al.*, 2001). Additonally, uranium (U), cadmium (Cd) and boron (B) were determined by ICP-MS for sediments from Crans and Ballybeg. Sedimentary P was analysed to support microfossil data, while analyses of major cations were included to assist in the reconstruction of phases of catchment inwash (Fe, Mn, Ca, Na, K) and internal cycling (Fe and Mn)

(Mackereth, 1966; Engstrom & Wright, 1984). Uranium and Cd 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 inputs to freshwater (Neal *et al.*, 2005). These 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.

Three groups of microfossils (diatoms, cladocera and pollen and spores) were used to reconstruct historical lake water quality and catchment conditions. The remains of diatoms (Bacillariophyceae) preserved in sediments have been widely used as biological indicators of water quality (Stoermer & Smol, 1999; Battarbee *et al.*, 2001), an approach that utilises robust relationships between diatom assemblages and parameters such as pH (Battarbee, 1984; Jones *et al.*, 1986; Anderson & Korsman, 1990) and P (Hall & Smol, 1992; Bennion *et al.*, 1996). Several species of Cladocera that 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 & Riva, 1982; Ravera & Zarini, 1987): Daphniidae and Bosminidae tend to be planktonic, while the Chydoridae are mainly benthic/littoral. Pollen and spores are commonly used in studies of recent environmental changes (Bennett & Willis, 2001) and here are used to estimate changing terrestrial plant cover (e.g., Edwards & Whittington, 2001).

Microfossils were enumerated in seven to nine samples per core for diatoms and two samples per core for cladocera and pollen and spores. Where possible the microfossil content of core top and bottom samples was established. This approach assumes that the top and bottom samples in a sediment core integrate, respectively, conditions at the time of coring and site-specific reference conditions (Smol, 2002). For diatoms, samples were prepared and analysed using standard methods (Battarbee *et al.*, 2001), and Krammer and Lange-Bertalot (1986, 1988, 1991a,b) for identification. For cladocera and pollen and spores, 1 cm-thick samples of core sediment were used. Cladocera were concentrated using a modified version of the standard method described by Frey (1986) and identified following Frey (1959, 1960, 1962a, 1962b, 1964), Goulden & Frey (1963) and Alonson (1996). Pollen and spores were concentrated in unit volumes of sample following the standard laboratory protocol described in Bennett & Willis (2001)and through reference to type material. The relative abundances of all diatom and cladoceran species (including unidentified forms) were established on the basis of the total count per sample. Diatom abundances were also expressed in concentration (cells

g^{-1}) and accumulation rate (cells cm^{-2} yr^{-1}) forms and were used to infer down-core variations in TP. Two sums were used in percent calculations for pollen and spores: total, which excludes damaged and partially concealed grains but which includes unknowns, and tree, which comprises pollen from arboreal taxa (including *Pinus*-type [comprising pollen from *Pinus* and morphologically similar types from other conifers]).

Methods of data analysis

Down-core differences in diatom assemblages and water quality were quantified through: diatom inferred-total phosphorous (DI-TP) reconstructions; indices of diversity; and ordination. DI-TP transfer functions were developed using an Irish Ecoregion training set of 73 lakes (range in measured TP = 0-675 µg TP l^{-1}, mean = 33 µg TP l^{-1}, median = 10 µg TP l^{-1}) assembled specifically for the current study, the standard numerical technique of weighted averaging (WA) (Birks *et al.*, 1990a,b; Korsman & Birks, 1996; Koster *et al.*, 2004) and the computer software package C2 version 4 (Juggins, 2003). Reconstructions of DI-TP were based on harmonised data and produced using a WA partial least squares two-component (WA-PLS) model (ter Braak & Juggins, 1993; Birks, 1995), the performance statistics of which compared well with similar models developed for other parts of Europe (Table 4). Two diversity indices - Shannon (Pielou, 1975) and taxonomic distinctness (Clarke & Warwick, 1998) - were also calculated. Detrended correspondence analysis (DCA) (Hill & Gauch, 1980) was performed on diatoms with a relative abundance of >2% in at least two samples using CANOCO version 4.5 (ter Braak & Šmilauer, 2002) and square root transformed data.

Results

Lake sediment cores ranged in length from 27cm to 41cm. In general, there was good agreement between results of the CRS, CIS and ^{137}Cs-based analyses, 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) (Table 5).

Sediment samples generally contained abundant, well-preserved microfossils. At least 300 valves and 70-100 chydorids were enumerated in each sediment sample analysed for its diatom and cladocera content respectively. DI-TP 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. Most WA models produce DI-TP values that underestimate measured TP in highly productive lakes (Hall *et al.*, 1997), possibly because diatom species composition changes little as epilimnetic P concentration increases above 100-200 µg TP L^{-1}

(Anderson *et al.*, 1993; Bradshaw & Anderson, 2001). Furthermore, wide fluctuations in epilimnetic TP concentrations in highly productive lakes (Bennion & Smith, 2000; Bradshaw *et al.* 2002) are unlikely to be fully represented in a relatively few field measurements. Although lake trophic status represents a continuum and fluctuates seasonally, because the remains of diatoms in lake sediments reflect an integration of water quality parameters over time and for ease of interpretation, DI-TP values are discussed below in the context of the OECD (1982) scheme of trophic assessment (oligotrophic 0-10 μg l^{-1} TP; mesotrophic >10-35μg l^{-1} TP; eutrophic >35-100 μg l^{-1} TP; hypertrophic > 100 μg l^{-1} TP).

Cladocera counts usually required 0.1 to 0.3 ml of concentrated sample, although surface samples from Crans, Inchiquin and Egish required far larger volumes owing to low concentrations of cladocerans (1.6 ml of concentrate in the case of Crans). Counts of identifiable pollen and spores (i.e. excluding those rendered unidentifiable owing to damage or debris on the microscope slide) ranged from 141 to 397 (mean = 286) per sample. Preservation was poorest in samples from Ballybeg (material from core top and bottom samples from this site yielded, respectively, 141 and 203 grains). Problems in extracting sufficient quantities of pollen and spores from core top samples were also experienced on occasion: the uppermost samples analysed for their pollen and spore content in the sediment cores from Crans, Egish, Mullagh and Sillan were, respectively, 10-11cm, 5-6cm, 10-11 and 15-16cm. Pollen and spore data are provided in percentage form in Table 6.

Ballybeg

Close agreement was found between the three models used to establish chronological control: decreasing ^{210}Pb activity with depth (Figure 2a) is consistent with a constant rate of sediment accumulation, while the two peaks in ^{137}Cs concentration presumably equate to Chernobyl and weapons fallout. The proportion of organic matter is highly variable (Figure 3), whereas DMAR shows only minor down-core variations, as is the case for sediment chemistry accumulation rates. Sedimentary Fe, K, Mn, Na and TP concentrations increased markedly from c. 1970. By comparison, increases in Cd and U concentrations were later (from c. 1980).

The seven samples analysed yielded 102 diatom taxa (Figure 4a). Diatom concentrations and accumulation rates are highest in the core bottom and top samples. The top sample had substantially reduced diversity. Changes in diatom assemblages record a shift from a benthic-dominated (e.g. *Gomphonema pumilum*, *G. lateripunctatum, Pseudostaurosira brevistriata* and *Staurosira construens*) to a planktonic (e.g., *Asterionella formosa*, *Aulacoseira subarctica, Stephanodiscus hantzschii* and *S. parvus*) assemblage. DI-TP was relatively constant and in the mesotrophic range to c. 1980, after which date it increased to the extent that the core top sample represents hypertrophic conditions. Increased DI-TP concentrations from c. 1980 reflect increasing percentages of *Stephanodiscus hantzschii* and *S. parvus*. Planktonic cladocerans dominate both top and bottom samples, with relative increases of the planktonic *Chydorus sphaericus* (Műller, 1776) in the top sample compared with greater prevalence of the benthic *Acroperus harpae* (Baird, 1836) in the bottom sample (Figure 5a). Pollen from deciduous woodland taxa (*Alnus* [alder], *Corylus* [hazel], *Fagus* [beech], *Quercus* [oak], *Salix* [willow] and *Ulmus* [elm]) was less abundant in the core top than in the core bottom, while the reverse was true for *Pinus*-type and Poaceae pollen (Table 6).

Crans

Good agreement was found between the three models used for chronological control: an apparently exponential decline in $^{210}Pb_{excess}$ meant that equilibrium with ^{210}Pb was reached at c. 20 cm, and two well-resolved ^{137}Cs peaks were evident at 14.5 and 6.5 cm (Figure 2b). The estimated sediment accumulation rate suggests that all three cores date to at least the mid 19th century (Table 5). Only small variations in organic matter were found (Figure 6), while DMAR declined from the base of the core to c. 1880, after which date it stabilised at about 0.025 g cm^{-2} yr^{-1}. Concentrations and, to a lesser extent, accumulation rates of Cd, Fe, K, Na and U were much higher before c. 1880 than after, while the reverse is true for sedimentary Ca, Mn and TP.

The eight samples analysed yielded 95 diatom taxa (Figure 4b) and a plankton-dominated flora (e.g., *Aulacoseira ambigua*, *A. subarctica*, *Asterionella formosa* and a variety of small *Stephanodiscus* spp.). Non-planktonic taxa were, however, relatively abundant (~ 25%) in the basal sample and the DI-TP data record a transition from a mesotrophic to a hypertrophic state by the late 19th century. Reduced DI-TP, although still hypertrophic, was evident from the mid-20th century with further increases post-c. 1980. The onset of hypertrophic conditions also coincides with major peaks in diatom concentration and accumulation rate data. Lower abundances of planktonic cladocerans, including *Chydorus sphaericus,* and greater abundance of *Alonella nana* (Baird, 1843) were found in the bottom sample (Figure 5b). Poor pollen and spore preservation necessitated analysis of a sample from 10-11cm (c. 1960). Differences in pollen and spores indicate a decline in deciduous woodland taxa (*Betula* [birch], *Corylus* and *Fagus*) that is partially masked by increased pollen from *Alnus, Fraxinus* [ash], *Quercus* and *Salix* (Table 6). Levels of Poaceae and *Pinus*-type pollen increased substantially.

Egish

The CRS model accommodated a hiatus between 6.5 and 8.5 cm depth (Figure 3c), possibly due to sediment slumping. The LOI profile (Figure 7) shows three distinct peaks in organic matter, the uppermost one preceding the hiatus in the ^{210}Pb profile. DMAR shows little variation before a major increase from the c. 1980s. Sedimentary accumulation rates of all elements closely matched DMAR. Fe, Mn and TP concentration data show a similar pattern of variation, with the rise in concentrations c. 1950. Concentrations of Ca, Na and K were much more variable, with several pre-1950s peaks evident.

The eight samples analysed yielded 182 diatom taxa. Periphyton (mainly small *Achnanthes* and *Fragilaria*, and a few planktonic species, e.g. *Aulacoseira subarctica*) were common in the core bottom sample (Figure 4c). The abundances of planktonic diatoms, generally low in the core bottom, increased markedly from c. 1980 and, particularly, post c. 1990. Diatom diversity was relatively low in the core top sample, and two taxa were largely responsible for the increased abundances of planktonic forms: *Cyclostephanos dubius* and, post c. 1990, *Stephanodiscus parvus*. DI-TP data record a transition during the 1980s from a mesotrophic to eutrophic state with marked spikes in diatom concentration and accumulation rates. Cladoceran assemblages changed from being characterised by chydorids in the core bottom to one characterised by *Daphnia* and *Bosmina* in the core top (Figure 5c). Species shifts include a major decline in *Alona rustica* Scott, 1895 and increases in *Alona quadrangularis* (Műller, 1776) and *Chydorus sphaericus*. Comparison of the pollen and spore content in the core bottom with the sample from 5-6 cm (c. 1992) indicated the replacement of hazel woodland by more closed-canopy forms of deciduous woodland (containing *Quercus* and *Ulmus*), conifers and grassland (Table 6).

Inchiquin

The ^{210}Pb and ^{137}Cs activity profiles were in close agreement (Figure 2d), indicating relatively high sediment accumulation overall (Table 5). The mean supply rate of $^{210}\text{Pb}_{\text{excess}}$ is high compared with the other cores, suggesting a more substantial contribution from the catchment. There was little change in the proportion of organic matter to c. 1970 (Figure 8); DMAR and sediment accumulation rate data, with the exception of TP, were also largely constant to c. 1970, at which point they increased before declining from c. 1990. The profile of sedimentary TP accumulation rate was similar to DMAR to c. 1990, after which date the TP accumulation rate increased before declining from c. 2000. No clear link between DMAR and sediment chemistry concentration data is evident, however, with the latter either showing an overall increase (Fe, Mn, TP) or relatively little variation (Ca, K, Na) to c. 2000, after which date they declined.

Diatom assemblages in the eight samples analysed comprised 137 taxa and show a transition, c. 1980, from an assemblage dominated by benthic (e.g., *Amphora pediculus*) to planktonic (e.g., small *Cyclotella* and *Stephanodiscus*) taxa (Figure 4d). DI-TP, indicative of mesotrophy throughout the core, approached the OECD (1982) lower threshold for the eutrophic category during the 1990s, with peak DI-TP values correlating with spikes in diatom concentration and accumulation rate data. Planktonic cladocera were more abundant in the core top sample compared with the core bottom sample, although the species remained largely unchanged (Figure 5d). According to the pollen and spore data (Table 6), only relatively minor changes in woodland composition and a small increase in grassland cover has occurred since c. 1920.

Mullagh

A broad peak in the ^{137}Cs data precluded the construction of a ^{137}Cs-based chronology (Figure 2e). However, the CRS model of the ^{210}Pb profile indicates an overall rate of sediment accumulation of 0.04 g cm yr^{-1}, which compares well with the published rate (0.03 g cm yr^{-1}) for a core previously collected from Mullagh (Nowlan *et al*., 2000) (Table 5). The proportion of organic matter varied little to c. 1975, rising to a peak in the core top (Figure 9). DMAR showed little variation to the 1970s, declined during the late 1970s, remained virtually constant during the 1980s and 1990s, and then increased moderately from c. 2000. Down-core variations in sediment chemistry accumulation rates are similar to those for DMAR, although the peak during the 1970s is less evident in Mn and TP. Sedimentary Mn and TP concentrations initially declined before increasing from the 1970s and particularly from c. 2000. Ca concentrations increased to c. 1990 and then declined, while K and N concentration data showed a similar pattern of fluctuating levels before reaching a peak in the late 1970s and early 1980s after which there was a decline. Only the Fe accumulation rate and concentration profiles concur, although the 1970s peak was much more subdued in the latter.

The nine samples analysed for their diatom content yielded a total of 114 taxa, with assemblages showing a marked change from the late 1960s and particularly from post c. 1990. Benthic and epiphytic taxa, particularly *Fragilaria pseudoconstruens*, *Staurosira elliptica* and *Staurosirella pinnata* (Figure 4e), were replaced primarily by planktonic taxa, such as *Asterionella formosa, Aulacoseira granulata* var. *angustissima*, *A. ambigua* and the small centrics *Cyclotella* and *Stephanodiscus*. DI-TP increased exponentially, passing from oligo-mesotrophic levels at the base of the core into the eutrophic range during the 1980s and approaching hypertrophic conditions post-2000. Overall diatom productivity was generally highest in samples from before c. 1970. However, diatoms were also relatively abundant, although diversity was low, following the development of highly eutrophic conditions. Comparisons between core top and bottom samples show only relatively minor differences in cladocera (Figure 5e), although *Chydorus piger* Sars, 1862 was more common and planktonic taxa far less abundant in the core bottom than in the top sample. Comparisons between the pollen and spore assemblages in the core bottom sample and the sample from 10-11 cm (c. 1985) reflect a decline in pollen from deciduous woodland taxa and marked increases in Poaceae and the aquatic *Myriophyllum* (Table 6).

Sillan

$^{210}Pb_{excess}$ levels remain constant with depth to c. 12 cm before declining, while the ^{137}Cs profile shows a broad peak (Figure 2f). Sediment accumulation rate was estimated at 0.053 g cm^{-2} yr^{-1}, implying that basal sediments in the cores used for sediment chemistry and microfossil analyses date to the beginning of the 20th century (Table 5). Basal sediments are relatively inorganic (Figure 10); DMAR fluctuated throughout the core, but was highest from the start of the record to the late 1950s and from the late 1970s/early 1980s. Sedimentary TP (both accumulation rates and concentrations) exhibited a sharp increase from the 1940s to the 1960s, and again from the 1980s. Ca and Mn both showed an overall increase from the base to the core top, with Mn showing a distinct peak in the late 1980s, while Fe remained more or less constant throughout the core (although the accumulation rate data show a distinct overall increase from c. 1980). K and Na concentrations showed a steady decline from the base of the core. A similar trend is apparent from the accumulation rate data for these two elements to the late 1970s, after which date the trend was reversed.

The eight samples analysed for their diatom content yielded a total of 149 taxa with only slight down-core differences (Figure 4f). The planktonic *Aulacoseira* was prominent throughout the core and benthic and epiphytic taxa most abundant in the core bottom sample. DI-TP indicates enrichment from the beginning of the sedimentary record (c. 1900), becoming eutrophic by c. 1930. A peak in diatom concentration occurred c. 1950 followed by a decline in the 1980s before rising again in the 1990s. The chydorid *Alona quadrangularis* showed a marked increase between core bottom and top (Figure 5f) and there was also an increase in the planktonic/littoral ratio. Comparisons between the pollen and spore contents of the core bottom sample and a sample from 15-16 cm (c. 1971) indicate a decline in woodland taxa, including conifers, concomitant with a rise in grasses (Table 6).

Ordination

The examination of down-core variations in diatom assemblages was facilitated through DCA. Core top (2004) samples from each of the six study sites are labelled on Figure 11; fossil samples from deeper in the same core are linked with a connecting line. The two main axes of variation explain 20.7 % (axis 1) and 9.6 % (axis 2) of the total variance (respectively, λ_1=0.359 and λ_2=0.167). Comparisons between top and bottom samples for cores from all six lakes indicate similar trajectories – although different magnitudes – of difference and suggest common ecological pressure or pressures. Small diatoms of *Pseudostaurosira brevistriata* and the genus *Staurosira* characterise core bottom samples, while planktonic *Aulacoseira* and *Stephanodiscus* species are characteristic of core top samples.

Discussion

Results from the six study sites reveal some inter-site commonalities but also several important differences. One trend that is clear from DI-TP variations at all sites, with the exception of Inchiquin, is accelerated enrichment post c. 1980, which 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 exports of P from point sources during the same period (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 cause of increased sedimentary TP (Boyle, 2001). One factor that could have contributed to rapid increases in DI-TP post c. 1980 are increased inputs of P from soils that have become saturated with P as a result of agricultural practices (Foy *et al.*, 2003). Enhanced eutrophication may also be due to processes within the lake, such as the release of P from sediments (Søndergaard *et al.,* 1999; Jordan & Rippey, 2003; Phillips *et al.*, 2005).

Background reference conditions

All six lakes were oligo-mesotrophic or mesotrophic at the beginning of the sedimentary records analysed, with the results indicating that all except Inchiquin are today in a far more productive state. Pre-enrichment, i.e. reference, assemblages were characterised by a relatively diverse diatom flora in which benthic and epiphytic types are prominent, diverse littoral cladoceran assemblages indicative of abundant aquatic macrophyte cover, and by pollen indicators of a mosaic of deciduous woodland and grassland. According to the microfossil and DI-TP reconstructions, Crans and Sillan have been nutrient-enriched since, respectively, the late 19th and early 20th centuries. The trophic status of Inchiquin has remained comparatively stable, in keeping with recent and current land use practices in the catchment and the minor landcover changes apparent in the CORINE and pollen data.

Relative trophic stability could have been facilitated by the relatively remote location of this site and by a greater insensitivity to enrichment afforded by its high alkalinity (Irvine *et al.*, 2001; Hobbs *et al.*, 2005).

Long-term variations in trophic status

None of the six lakes appear to be naturally eutrophic, based on the data presented here, although enrichment at Crans and Sillan has a relatively long history: all six 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. Abrupt falls in diatom productivity following enrichment may be due to grazing by filter-feeding zooplankton, as has been reported elsewhere (Sandilands & Hann, 1995). Five of the study lakes show evidence of substantial nutrient enrichment (>50 $\mu g\ l^{-1}$ TP), with Crans and Egish showing the greatest level of increased TP (> x10) over the time covered by the sedimentary records analysed. 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, indicating nutrient enrichment. Similarities also exist in the direction of changes in catchment vegetation (towards reduced deciduous tree cover in most cases), evident in the pollen and spore data, with the actual onset of deforestation probably predating the oldest sediments analysed. At Crans and Egish changes in pollen appear to represent the development of a more stable tree cover in woodland remnants involving the shading-out of taxa associated with more open forms of woodland. Pollen from Ballybeg, Crans and Egish also indicate an expansion of conifer plantations during the period covered by the sedimentary records, although, because *Pinus*-type pollen may be transported long distances, this expansion may not have been local.

One notable difference between the lake histories presented here is that while three lakes (Ballybeg, Egish and Mullagh) show a unidirectional trend of increased TP beginning in the 1960s-1980s, often in association with evidence of catchment disturbance, and particularly from the 1990s, the other sites (Crans, Inchiquin and Sillan) have more complex histories. These comprise periods of both eutrophication and oligotrophication. Thus there is evidence that catchment disturbance and nutrient enrichment commenced at Crans at a very early date (late 19th century), with the lake becoming hypertrophic by the turn of the 20th century. This finding ties-in with other results from Northern Ireland: eutrophication commenced in the late 19th century at loughs 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 levels were reduced at Crans around the 1950s, but increased again from the 1980s, presumably as a response to local P supply and/or transport limitations. Decreases in P sedimentary efficiency have also been noted elsewhere in small lakes in Northern Ireland (Rippey & Anderson, 1996; Rippey *et al.*, 1997) and attributed to internal P loading and losses through the lake outflow. If this is a feature of the sedimentary P profile in Crans it appears, from the DI-TP data, that internal loading did not influence lake productivity. A similar trend of relatively early initial eutrophication (although not as early as at Crans), followed by recovery and a second phase of nutrient enrichment is also evident at Sillan (with eutrophication, commencing early in the 20th century, followed by oligotrophication in the 1970s and 1980s and a second period of nutrient enrichment post c. 1990). Nutrient enrichment is later still at Inchiquin, beginning post c. 1990 (although there are minor variations before this date), with oligotrophication, apparently unreversed, dating to the late 1990s. It is not immediately obvious why the trophic histories of Crans, Inchiquin and Sillan should be more complex than Ballybeg, Egish and Mullagh, although locally varying factors, notably environmental conditions and history, are likely to have been important.

Evidence from Crans and to a lesser extent Sillan of a long history of modification support the argument that the "only realistic 'background' state, from a lake management perspective, is probably a very recent one, immediately prior to 1950" (Anderson, 1997: 438). Moreover, the results presented in this paper provide evidence that productive lakes in the Irish Ecoregion have complex, locally-specific trophic histories and represent significant deviation from reference conditions. It is widely known that the water quality of eutrophic lakes can be resistant to changes in P inputs (e.g, Anderson *et al.,* 2005), and this is likely to prove a particular challenge to managers charged with the responsibility of implementing the WFD more generally.

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References

Alonso, M. (1996) Crustacea, Branchiopoda. *Fauna Ibérica*, 7. Museo Nacional de Ciencias Naturales. CSIC. Madrid.

Andersen, J.H., Conley, D.J. & Hedal, S. (2004) Palaeoecology, reference conditions and classification of ecological status: the EU Water Framework Directive in practice. *Marine Pollution Bulletin*, 49, 283-290.

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 v anthropogenic change in lakes: the role of the sediment record. *Trends in Ecology Evolution*, 8, 356-361.

Anderson, N.J. (1995) Naturally eutrophic lakes: reality, myth or myopia? *Trends in Ecology and Evolution*, 10, 137-138.

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

Anderson, N.J., Jeppesen, E. & Søndergaard, M. (2005) Ecological effects of reduced nutrient loading (oligotrophication): an introduction. *Freshwater Biology*, 50, 1589-1593.

Anderson, N.J. & Korsman, T. (1990). Land-use change and lake acidification: Iron Age de-settlement in northern Sweden as a pre-industrial analogue. *Philosophical Transactions of the Royal Society, London*, B 327: 373-376.

Anderson, N.J. & Odgaard, B.V. (1994) Recent palaeolimnology of three shallow Danish lakes. *Hydrobiologia*, 275/276, 411-422.

Anderson, N.J. & Rippey, B. (1994) Monitoring lake recovery from point-source eutrophication: the use of diatom-inferred epilimnetic total phosphorus and sediment chemistry. *Freshwater Biology*, 32, 625-639.

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

Anon (1997) *Blackwater Catchment Rural Development Strategy*. Unpublished report. Brady Shipman Martin, Kirk McClure Morton, Minnock Barron, Belfast

Anon (2000) Directive 2000/60/EC of the European Parliament and of the council of 23 October 2000 establishing a framework for Community action in the field of water policy. *Official Journal of the European Communities*, 1-327

Battarbee, R.W. (1978) Observations on the recent history of Lough Neagh and its drainage basin. *Philosophical Transactions of the Royal Society of London B*, 281, 303-345.

Battarbee, R.W. (1984). Diatom analysis and the acidification of lakes. *Philosophical Transactions of the Royal Society, London, B* 305: 451-477.

Battarbee, R.W. (1986) 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*, 86B, 141-168.

Battarbee, R.W. (1999) The importance of palaeolimnology to lake restoration. *Hydrobiologia*, 395/396, 149-159.

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

Bennett, K.D. & Willis, K.J. (2001). Pollen. In: J.P. Smol, H.J.B. Birks & W.M. Last (eds) *Tracking Environmental Change Using Lake Sediments. Volume 3 Terrestrial, Algal and Siliceous Indicators.* Kluwer Academic Publishers, Amsterdam, pp 5-32

Bennion, H. (1994) A diatom-phosphorous transfer function for shallow, eutrophic ponds in southeast England. *Hydrobiologia*, 275/276, 391-410.

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

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

Bennion, H. & Smith, M.A. (2000) Variability in the water chemistry of ponds in south-east England, with special reference to the seasonality of nutrients and implications for modelling trophic status. *Hydrobiologia*, 436, 145-158.

Bennion, H., Wunsam, S., & Schmidt, R. (1995) The validation of diatom-phosphorus transfer functions: an example from Mondsee, Austria. Freshwater Biology, 34, 271-283.

Bergstrom, A.K., Blomqvist, P., Jansson, M. (2005) Effects of atmospheric nitrogen deposition on nutrient limitation and phytoplankton biomass in unproductive Swedish lakes. *Limnology and Oceanography*, 50(3), 987-994.

Birks, H.J.B. (1995) Quantitative palaeoenvironmental reconstructions. *Statistical Modelling of Quaternary Science Data* (eds. D. Maddy & J.S. Brew), pp 161-254. QRA, Cambridge.

Birks, H.J.B., Juggins, S. & Line, J.M. (1990a) Lake surface-water chemistry reconstructions from palaeolimnological data. *The Surface Waters Acidification Programme* (ed B.J. Mason), pp. 301-313. Cambridge University Press, Cambridge.

Birks, H.J.B., Line, J.M., Juggins, S., Stevenson, A.C. & ter Braak, C.J.F. (1990b) Diatoms and pH reconstruction. *Philosophical Transactions of the Royal Society of London Series B-Biological Sciences*, 327, 263-278

Boyle, J.F. (2001) Inorganic geochemical methods in palaeolimnology. In: W.M. Last & J.P. Smol (eds) *Tracking Environmental Change Using Lake Sediments Volume 2 Physical and Geochemical Methods*, pp 83-141. Kluwer Academic Publishers, Amsterdam.

Bowman, J.J. & Clabby, K.J. (1998) Water quality of rivers and lakes in the Republic of Ireland. In: J.G. Wilson (ed.) *Eutrophication in Irish Waters*. Royal Irish Academy, Dublin, 55-63.

ter Braak, C.J.F. & Juggins, S. (1993) Weighted averaging partial least square regression (WA-PLS) : an improved method for reconstructing environmental variables from species assemblages. *Hydrobiologia*, 269/270, 485-502

ter Braak, C.J.F. & Šmilauer, P. (2002) *CANOCO 4.5*. Biometris, Wagenigen.

Bradshaw, E.G. (2001) *Linking land and lake. The response of lake nutrient regimes and diatoms to long-term land-use change in Denmark*. PhD Thesis, University of Copenhagen.

Bradshaw, E.G. & Anderson, N.J. (2001) Validation of a diatom-phosphorus calibration set for Sweden. *Freshwater Biology*, 46, 1035-1048.

Bradshaw, E.G., Anderson, N.J., Jensen, J.P. & Jeppesen, E. (2002). Phosphorus dynamics in Danish lakes and the implications for diatom ecology and palaeoecology. *Freshwater Biology*, 47, 1963-1975.

Clarke, K.R. & Warwick, R.M. (1998) A taxonomic distinctness index and its statistical properties. *Journal of Applied Ecology,* 35, 523-531.

EHS (Environment and Heritage Service) (2000) *Managing the water environment in Northern Ireland 2000*. EHS, Belfast.

Edwards, K.J. & Whittington, G. (2001) Lake sediments, erosion and landscape change during the Holocene in Britain and Ireland. *Catena,* 42 (2-4), 143-173.

Engstrom, D.R. & Wright, H.E. (1984) Chemical stratigraphy of lake sediments as a record of environmental change. In: E.Y. Hawarth & J.G.W. Lund (eds) *Lake sediments and environmental history.* Leicester University Press, Leicester*,* 11-67

De Eyto, E., Irvine, K., Free, G. (2002) The use of members of the family Chydoridae (Anomopoda, Branchiopoda) as an indicator of lake ecological quality in Ireland. *Biology and Environment: Proceedings of the Royal Irish Academy* 102B (2): 81-91

Foy, R.H., Lennox, S.D. & Gibson, C.E. (2003) Changing perspectives on the importance of urban phosphorus inputs as the cause of nutrient enrichment in Lough Neagh. *The Science of the Total Environment*, 310, 87-99.

Frey, D.G. (1959) The taxonomic and phyolgenetic significance of the headr pores of the genus Chydoridae (Cladocera). *Internationale Revue der Gesamten Hydrobiologie* 44: 27-50.

Frey, D.G. (1960) The ecological significance of cladoceran remains in lake sediments. *Ecology,* 41, 684-699.

Frey, D.G. (1962a) Cladocera from the Eemian interglacial of Denmark. *Journal of Paleontology* 36: 1133-1154.

Frey, D.G. (1962b) Supplement to: The taxonomic and phylogenetic significance of the head pores of the Chydoridae (Cladocera). *Internatl Rev Ges Hydrobiol* **47**: 603-609

Frey, D. G. (1964) Differentiation of *Alona costata* SARS from two related species (Cladocera, Chydoridae). *Crustaceana* 8: 159-173.

Frey, D. G. (1986) Cladocera analysis. In: B.E. Berglund (ed.), Handbook of holocene palaeoecology and palaeohydrology. Whiley & sons, London, 667-701.

Gibson, C.E. (1991) Contributions to the regional limnology of Northern Ireland: (4) the lakes of Co. Tyrone. *The Irish Naturalists' Journal,* (23)11, 430-436.

Gibson, C.E., Wu, Y., Smith, S.J., & Wolfe-Murphy, S.A. (1995). Synoptic limnology of a diverse geological region; catchment and water chemistry. *Hydrobiologia*, 306, 213-227.

Goulden, C.E. & Frey, D. G. (1963) The Occurrence and Significance of Lateral Head Pores in the Genus *Bosmina* (Cladocera). *Internationale Revue der Gesamten Hydrobiologie,* 48, 513-522

Hall, R.I., Leavitt, P.R., Smol, J.P. & Zirnhelt, N. (1997) Comparison of diatoms, fossil pigments and historical records as measures of lake eutrophication. *Freshwater Biology*, 38(2), 401-417.

Hall, R.I. & Smol, J.P. (1992) A weighted-average regression and calibration model for inferring total phosphorus concentration from diatoms in British Columbia (Canada) lakes. *Freshwater Biology,* 27, 417-434.

Hill, M.O. & Gauch, H.G. (1980) Detrended Correspondence Analysis, an improved ordination technique. *Vegetatio*, 42, 47-58.

Hilton, J., Lishman, J.P. & Millington, A. (1986) A comparison of some rapid techniques for the measurement of density in soft sediments. *Sedimentology*, 33, 777-781.

HMSO (Her Majesty's Stationary Office) (1990) *Environmental Issues in Northern Ireland*. House of Commons Environment Committee, First Report, London.

Hobbs, W., Irvine, K. & Donohue, I. (2005) Using sediments to assess the resistance of a calcareous lake to diffuse nutrient loading. *Archiv Fur Hydrobiologie*, 164, 109-125.

Irvine, K., Allott, N., Caroni , R., Eyto, E. de, Free, G. & White, J. (2001) The Ecological Assessment of Irish Lakes: the development of a new methodology suited to the needs of the EU Directive for surface waters. EPA, Wexford.

Jennings, E., Mills, P., Jordan, P., Jensen, J-P., Søndergaard, M., Barr, . A., Glasgow, G. & Irvine, K. (2003) *Eutrophication from agricultural sources Seasonal patterns & effects of phosphorous*. Final Research Report (2000-LS-2.1.7-M2). EPA, Wexford.

Jones, V.J., Stevenson, A.C. & Battarbee, R.W. (1986). Lake acidification and the land-use hypothesis: a mid-post-glacial analogue. *Nature,* 322: 157-158.

Jordan, P. & Rippey, B. (2003) Lake sedimentary evidence of phosphorus, iron and manganese mobilisation from intensively fertilised soils. *Water Research*, 37, 1426-1432.

Jordan, P., Rippey, B. & Andersen, N.J. (2001) Modelling diffuse phosphorus loads from land to freshwater using the sedimentary record. *Environmental Science & Technology,* 35(5), 815-819.

Juggins, S. (2003) *C2 Software for ecological and palaeoecological data analysis and visualisation. User guide Version 1.3*. Newcastle University, Newcastle upon Tyne.

Korsman, T. & Birks, H.J.B. (1996) Diatom-based water chemistry reconstructions from northern Sweden: a comparison of different reconstruction techniques. *Journal of Paleolimnology* 15, 65-77.

Koster, D., Racca, J.M.J. & Pienitz, R. (2004) Diatom-based inference models and reconstructions revisited: methods and transformations. *Journal of Paleolimnology*, 32, 233-246.

Krammer, K. & Lange-Bertalot, H. (1986-91) Bacillariophyceae. 1-4 Teil. *Süßwasserflora von Mitteleuropa*. Gustav Fischer-Verlag, Stuttgart.

Leira, M., Jordan, P., Taylor, D., Dalton, C., Bennion, H., Rose, N. & Irvine, K. (in press) Assessing the ecological status of candidate reference lakes in Ireland using palaeolimnology. *Journal of Applied Ecology*.

Linnane, S. M. & Murray, D. A. (2000) Assessment of changes within the sediments of Lough Derg (Ireland) using selected pigments as biomarkers. *Verhandlungen Internationale Vereinigung fur Limnologie,* 28, 1050-1055.

Lotter, A.F., Birks, H.J.B., Hofmann, W. & Marchetto, A. (1998) Modern diatom, cladocera, chironomid and chrysophyte cyst assemblages as quantitative indicators for the reconstruction of past environmental conditions in the Alps. II. Nutrients. *Journal of Palaeolimnology*, 19, 443-463.

Lucey, J., Bowman, J.J., Clabby, K.J., Cunningham, P., Lehane, M., MacCártaigh, M., McGarrigle, M. & Toner, P.f. (1999). *Water Quality in Ireland*. EPA, Wexford.

Mackereth, F.J. (1966) Some Chemical Observations of Post-Glacial Lake Sediments. *Philosophical Transactions of the Royal Society of London Series B-Biological Sciences*, 250, 165-213.

Moss, B., McGowan, S. & Carvalho, L. (1994) Determination of phytoplankton crops by top-down and bottom-up mechanisms in a group of English lakes, the West Midland meres. *Limnology and Oceanography*, 39, 1020-1029.

Murphy, T., Hall, K. & Yesaki, I. (1983) Coprecipitation of phosphate with calcite in a naturally eutrophic lake. *Limnology and Oceanography*, 28, 58-69.

Neal, C., House, W.A., Jarvie, H.P., Neal, M., Hill, L. & Wickham, H. (2005) Phosphorus concentrations in the River Dun, the Kennet and Avon Canal and the River Kennet, southern England. *Science of the Total Environment*, 344, 107-128

Nowlan, N.V., Mitchell, P.I., Murray, D.A., Leon Vintro, L. & Seymore, E. (2000) Measurement and interpretation of lead-210 and caseium-137 profiles in relation to recent sedimentation in some Irish lakes. *Verhandlungen Internationale Vereinigung fiir Theoretische und Angewandte limnologie*, 27, 2303-2306

OECD (Organisation for Economic Cooperation and Development) (1982) *Eutrophication of Waters, Monitoring, Assessment and Control*. OECD, Paris.

Parise, G. & Riva, A. (1982) Cladocera remains in recent sediments as indices of cultural eutrophication of Lake Como. *Schweiz Z. Hydrol*, 44, 277-278

Phillips, G., Kelly, A., Pitt, J-A., Sanderson, R. & Taylor, E. (2005) The recovery of a very shallow eutrophic lake, 20 years after the control of effluent derived phosphorus. *Freshwater Biology*, 50, 1628-1638.

Pielou, E.C. (1975) *Ecological Diversity*. Wiley Interscience, New York.

Räsänen, J., Kauppila, T. & Salonen, V.-P. (in press) Sediment-based investigation of naturally or historically eutrophic lakes – implications for lake management. *Journal of Environmental Management*

Ravera, O. & Zarini, S. (1987) A century variations in some zooplankton and zoobenthos organisms in Lake Comabbio (Northern Italy) "read" from their remains in the lake sediment. *Schweiz. Zeit. Hydrol.*, 49, 93-101

Renberg, I. (1991) The HON-Kajak sediment corer. *Journal of Paleolimnology*, 6, 167-170.

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

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 and increased internal loading. *Canadian Journal of Fisheries and Aquatic Sciences*, 54, 2637-2646.

Robbins, J. A., Edgington, D.N. & Kemp, A.L.W. (1978) Comparative 210Pb, 137Cs, and pollen geochronologies of sediments from Lakes Ontario and Erie. *Quaternary Research*, 10, 256-278.

Sandilands, K.A. & Hann, B.J. (1995) *The effect of macrophyte removal and nutrient addition on zooplankton abundance in a prairie wetland*. UFS (Delta Marsh) Annual Report, 30, 38-42.

Smith, R.J., Wolfe-Murphy, S.A., Enlander, I., & Gibson, C.E. (1991) *The Lakes of Northern Ireland: an annotated inventory*. HMSO, Belfast.

Smith, V.H., Tilman, G.D. & Nekola, J.C. (1999) Eutrophication impacts of nutrient inputs to freshwater, marine and terrestrial ecosystems. *Environmental Pollution*, 100, 179-196.

Smith, R.V., Jordan, C. & Annett, J.A. (2005) A phosphorus budget for Northern Ireland: inputs to inland and coastal waters. *Journal of Hydrology*, 304, 193-202.

Smol, J.P. (2002) *Pollution of Lakes and Rivers: A Paleoenvironmental Perspective*. Arnold Publishers, London; Co-published by Oxford University Press, New York.

Søndergaard, M., Peder, J.P. & Jeppesen, E. (1999) Internal phosphorus loading in shallow Danish lakes. *Hydrobiologia*, 408/409, 145-152

Stoermer, E.F. & Smol, J.P. (1999) *The Diatoms. Applications for the Environmental and Earth Sciences*. Cambridge University Press, Cambridge, UK.

Toner, P., Bowman, J., Clabby, K., Lucey, J., McGarrigle, M., Concannon, C., Clenaghan, C., Cunningham, P., Delaney, J., O'Boyle, S., MacCárthaigh, M., Craig, M. & Quinn, R. (2005) *Water Quality in Ireland 2001-2003*. EPA, Wexford.

Tunney, H. (1990) A note on a balance sheet approach to estimating the phosphorus fertiliser needs in agriculture. *Irish Journal of Agricultural Research*, 29, 149-154.

Ulén, B. M. & Kalisky, T. (2005) Water erosion and phosphorus problems in an agricultural catchment – need for natural research for implementation of the EU Water Framework Directive. *Environmental Science & Policy*, 8, 477-484

Wunsam, S. & Schmidt, R. (1995) A diatom-phosphorus transfer function for alpine and pre-alpine lakes. Memoria Istituto Italiano. *Idrobiologia*, 53, 85-99.

Zhou, Q., Gibson, C.E. & Foy, R.H. (2000) Long-term changes of nitrogen and phosphorus loadings to a large lake in north-west Ireland. *Water Research*, 34, 922-926.

Zielinski, R.A., Asher-Bolinder, S., Meier, A.L., Johnson, C.A. & Szabo, B.J. (1997) Natural or fertilizer-derived uranium in irrigation drainage: a case study in southeastern Colorado, USA. *Applied Geochemistry*, 12(1), 9-21.

Figures

Figure 1: *Location of the six productive lakes in the Irish Ecoregion (Ecoregion # 17) studied in the current research*

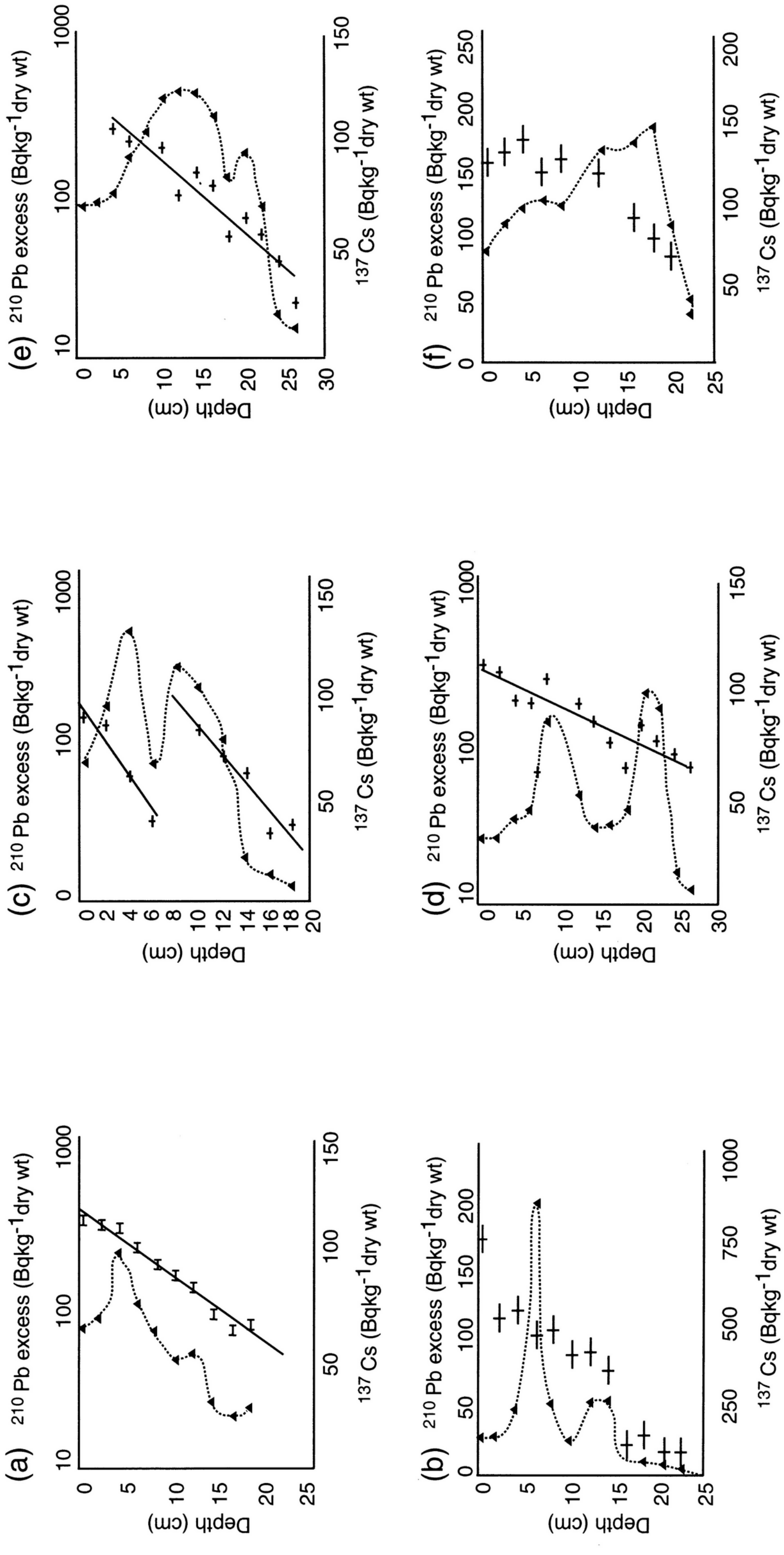


Figure 2: *Down-core variations in* ^{137}*Cs (dotted line) and* ^{210}*Pb*$_{excess}$ *(with 1SD error bars) (a) Ballybeg; (b) Crans; (c) Egish; (d) Inchiqin (e) Mullagh; (f) Sillan.*

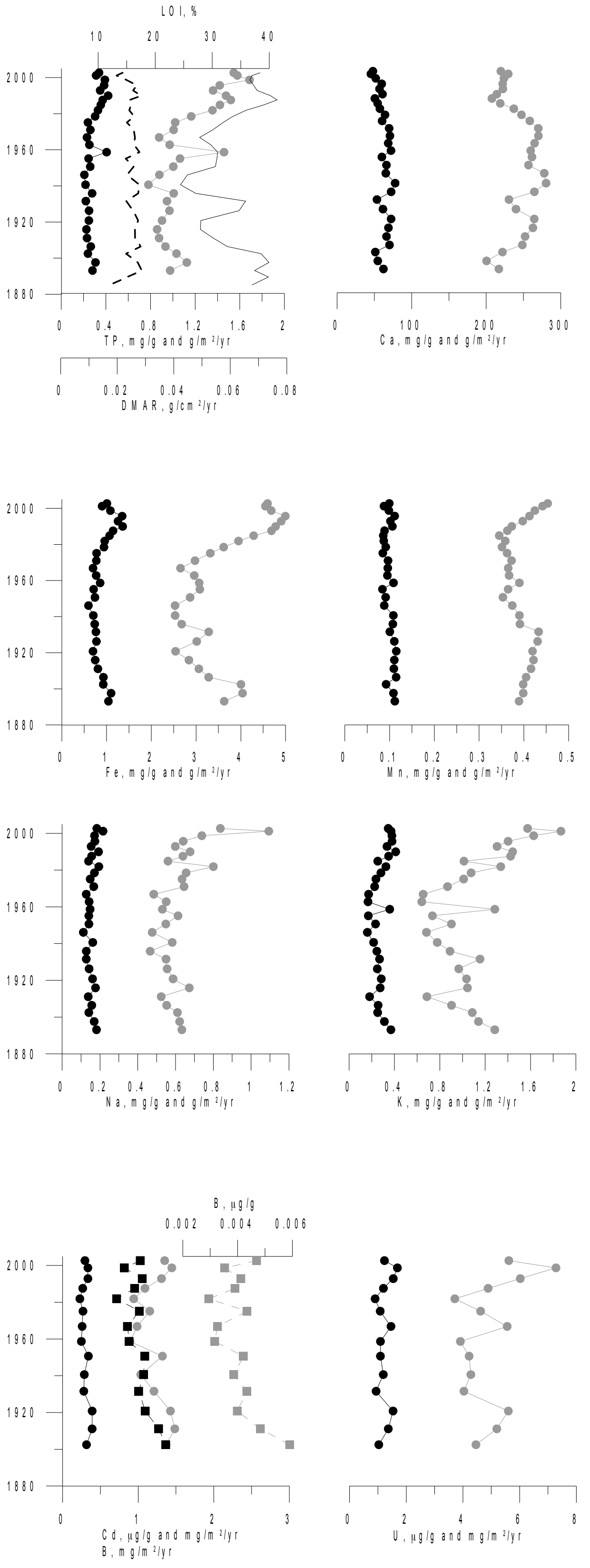
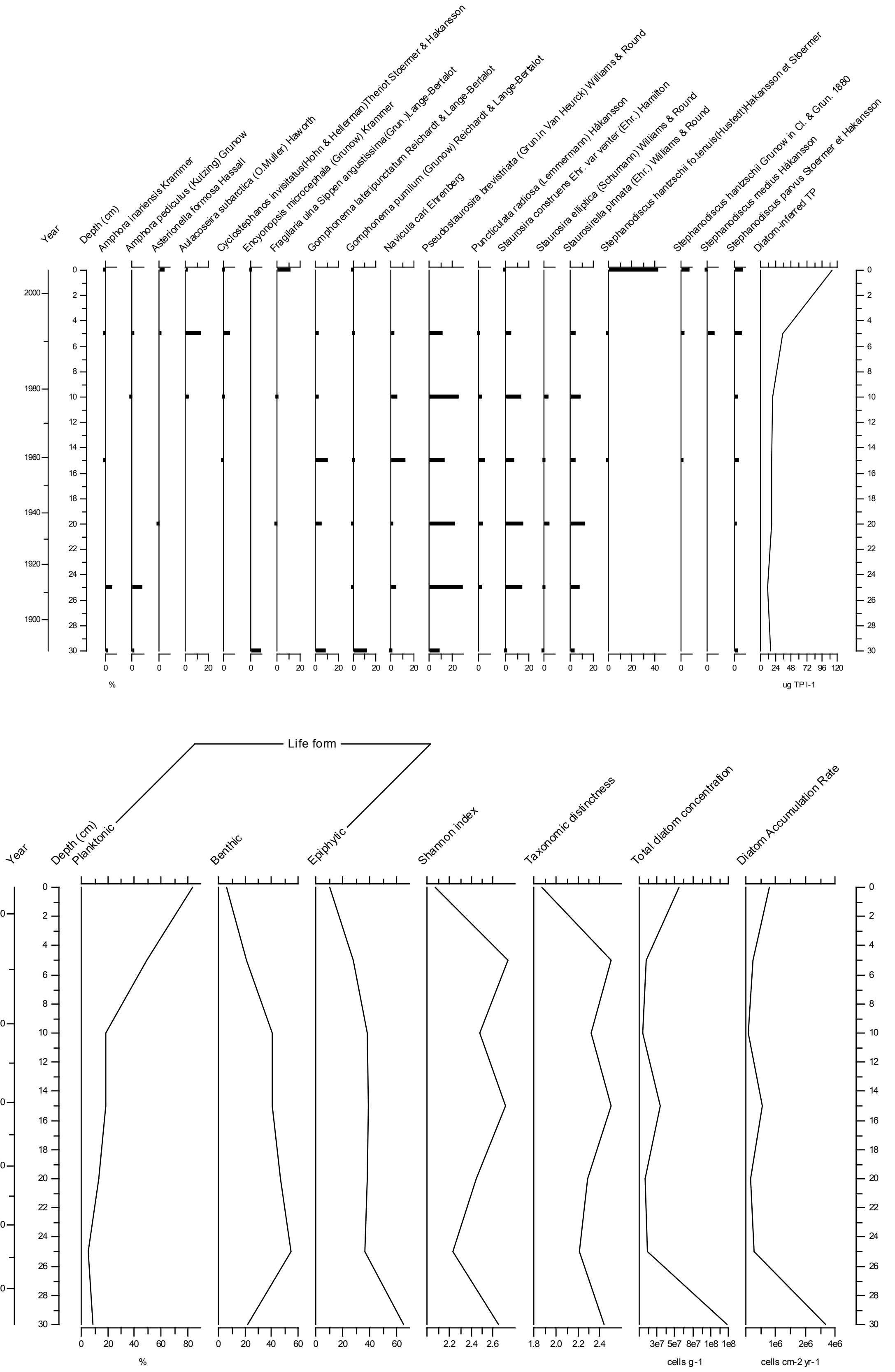
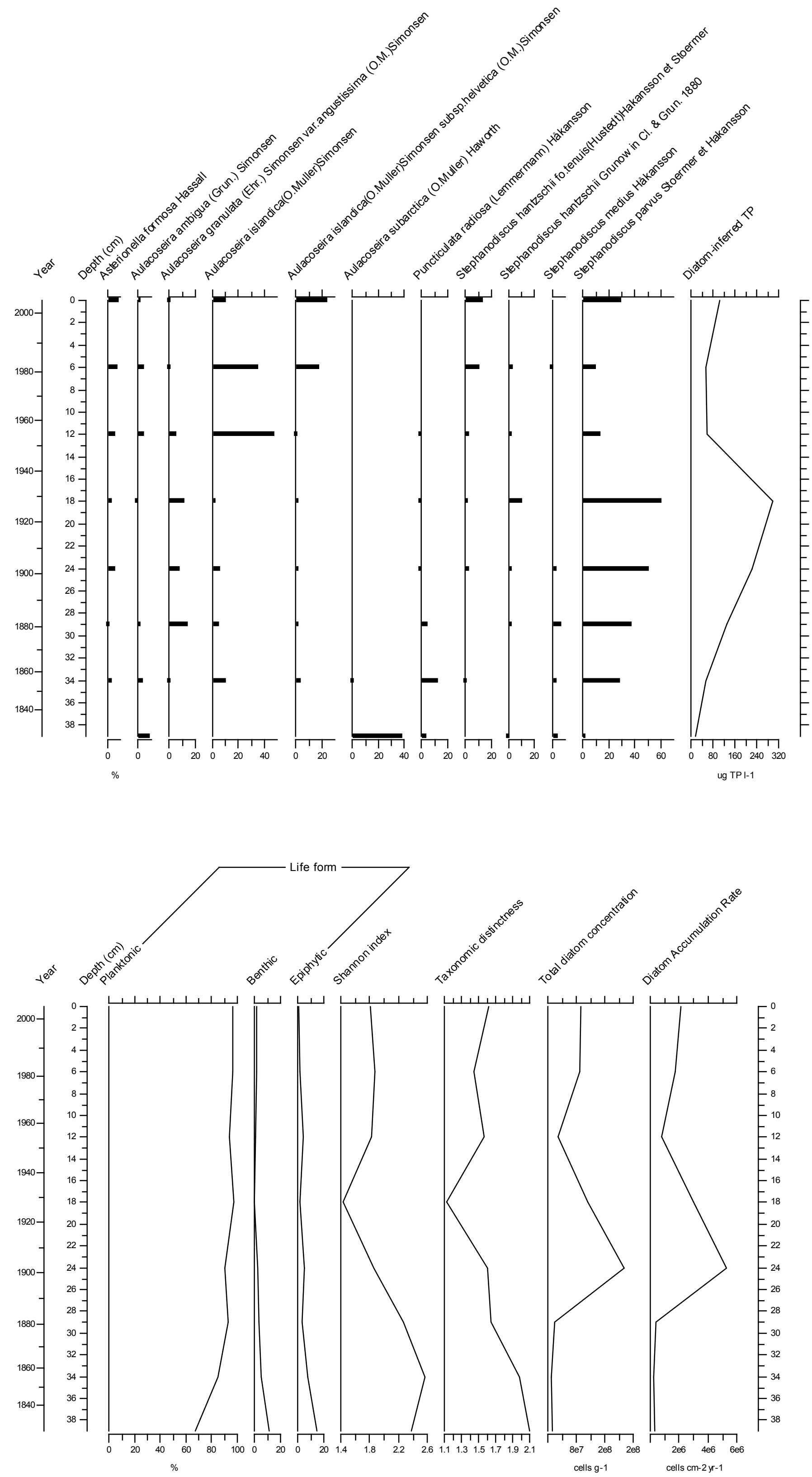


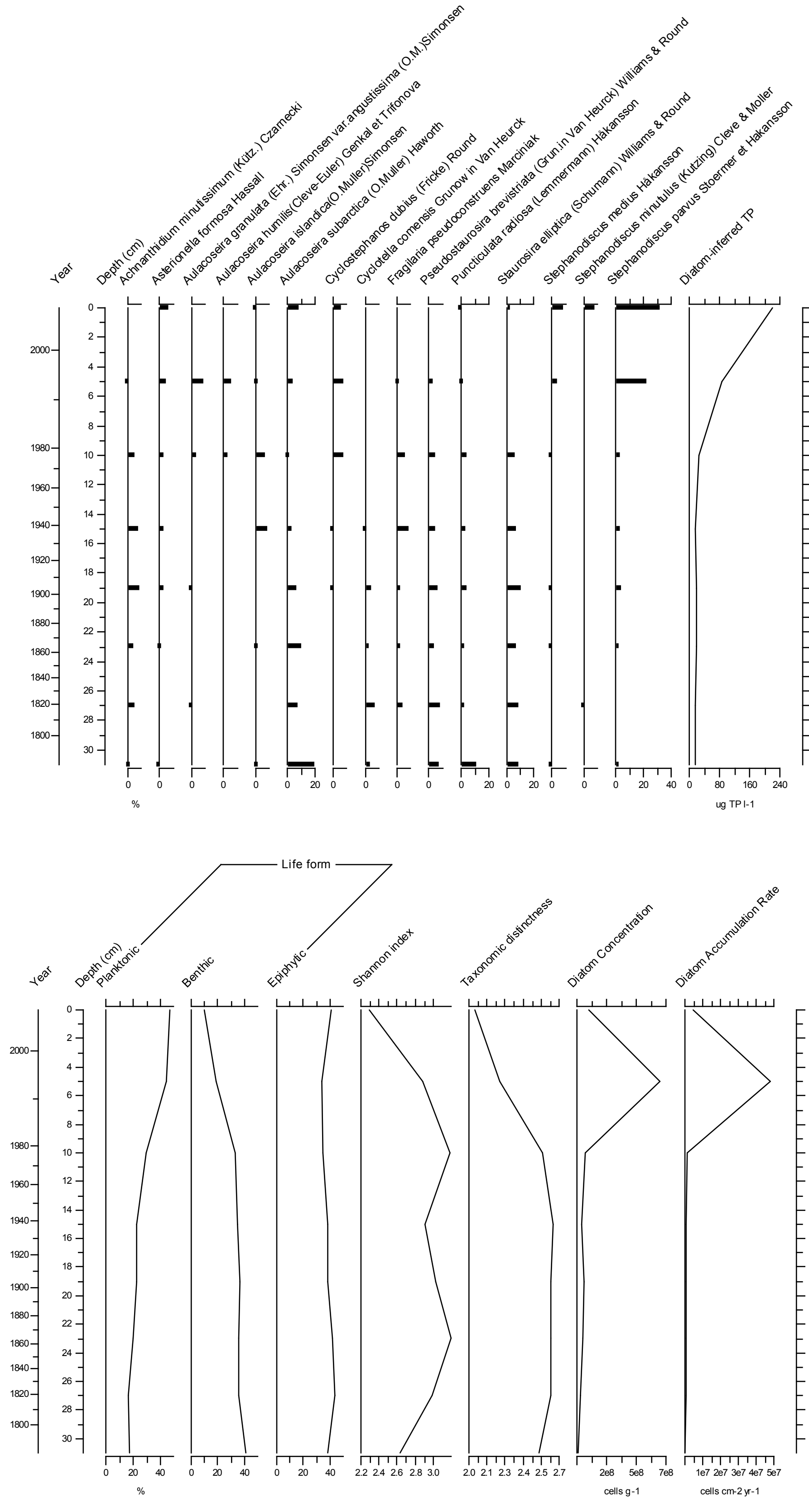
Figure 3: *Sedimentary chemistry profiles of Ca, Cd, Fe, K, Mn, Na, P and U from* ***Ballybeg****. Grey circles are chemical concentrations; black circles are chemical accumulation rates For B, black squares are chemical accumulation rates; grey squares are chemical concentration. In the top left, the dashed line is DMAR; and the unbroken line is LOI. Data are plotted on an age scale.*


Year
Depth (cm)
Amphora inariensis Krammer
Amphora pediculus (Kutzing) Grunow
Asterionella formosa Hassall
Aulacoseira subarctica (O.Muller) Haworth
Cyclostephanos invisitatus(Hohn & Hellerman)Theriot Stoermer & Hakansson
Encyonopsis microcephala (Grunow) Krammer
Fragilaria ulna Sippen angustissima(Grun.)Lange-Bertalot
Gomphonema lateripunctatum Reichardt & Lange-Bertalot
Gomphonema pumilum (Grunow) Reichardt & Lange-Bertalot
Navicula cari Ehrenberg
Pseudostaurosira brevistriata (Grun.in Van Heurck) Williams & Round
Puncticulata radiosa (Lemmermann) Håkansson
Staurosira construens Ehr. var venter (Ehr.) Hamilton
Staurosira elliptica (Schumann) Williams & Round
Staurosirella pinnata (Ehr.) Williams & Round
Stephanodiscus hantzschii fo.tenuis(Hustedt)Hakansson et Stoermer
Stephanodiscus hantzschii Grunow in Cl. & Grun. 1880
Stephanodiscus medius Håkansson
Stephanodiscus parvus Stoermer et Hakansson
Diatom-inferred TP
2000
1980
1960
1940
1920
1900
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
0 20
%
0 24 48 72 96 120
ug TP l-1
Life form
Planktonic
Benthic
Epiphytic
Shannon index
Taxonomic distinctness
Total diatom concentration
Diatom Accumulation Rate
0 20 40 60 80
%
0 20 40 60
0 20 40 60
2.2 2.4 2.6
1.8 2.0 2.2 2.4
3e7 5e7 8e7 1e8 1e8
cells g-1
1e6 2e6 4e6
cells cm-2 yr-1

(a)

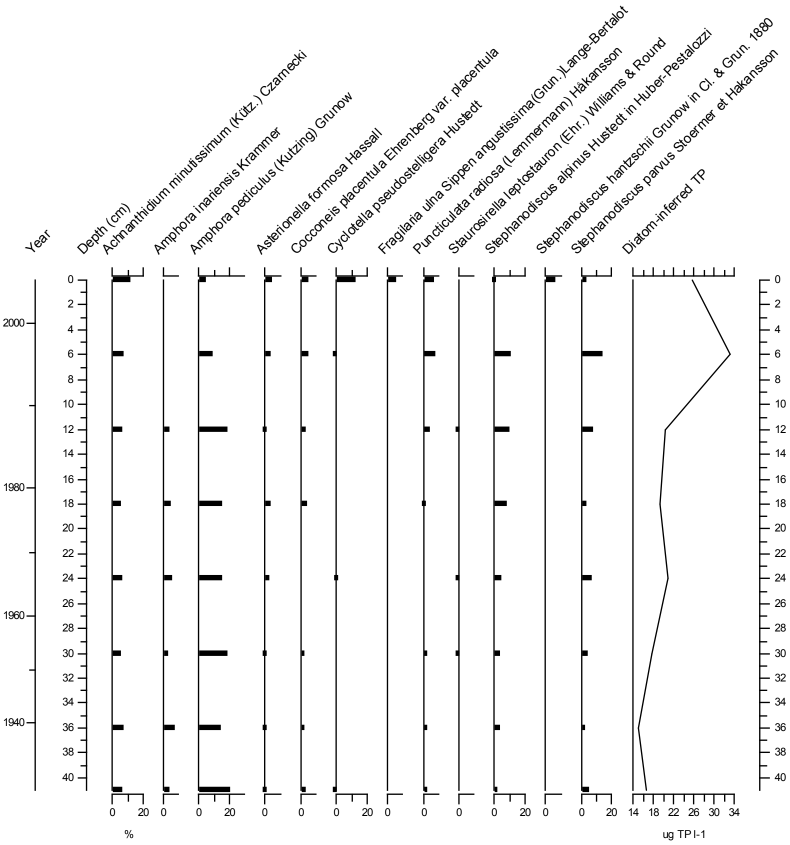

Year
Depth (cm)
Asterionella formosa Hassall
Aulacoseira ambigua (Grun.) Simonsen
Aulacoseira granulata (Ehr.) Simonsen var.angustissima (O.M.)Simonsen
Aulacoseira islandica(O.Muller)Simonsen
Aulacoseira islandica(O.Muller)Simonsen subsp.helvetica (O.M.)Simonsen
Aulacoseira subarctica (O.Muller) Haworth
Puncticulata radiosa (Lemmermann) Håkansson
Stephanodiscus hantzschii fo.tenuis(Hustedt)Hakansson et Stoermer
Stephanodiscus hantzschii Grunow in Cl. & Grun. 1880
Stephanodiscus medius Håkansson
Stephanodiscus parvus Stoermer et Hakansson
Diatom-inferred TP
2000
1980
1960
1940
1920
1900
1880
1860
1840
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
0 20 40 60
0 80 160 240 320
%
ug TP l-1
Life form
Planktonic
Benthic
Epiphytic
Shannon index
Taxonomic distinctness
Total diatom concentration
Diatom Accumulation Rate
0 20 40 60 80 100
1.4 1.8 2.2 2.6
1.1 1.3 1.5 1.7 1.9 2.1
8e7 2e8 2e8
2e6 4e6 6e6
cells g-1
cells cm-2 yr-1

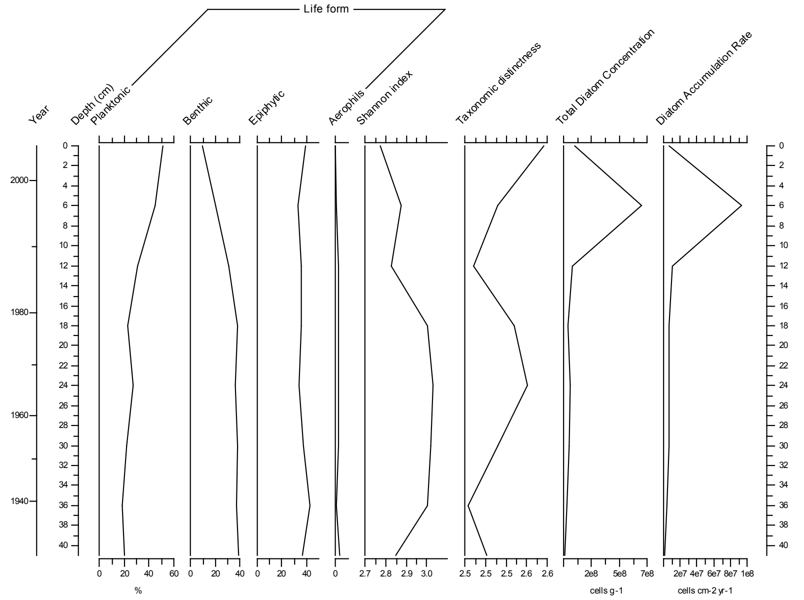
(b)



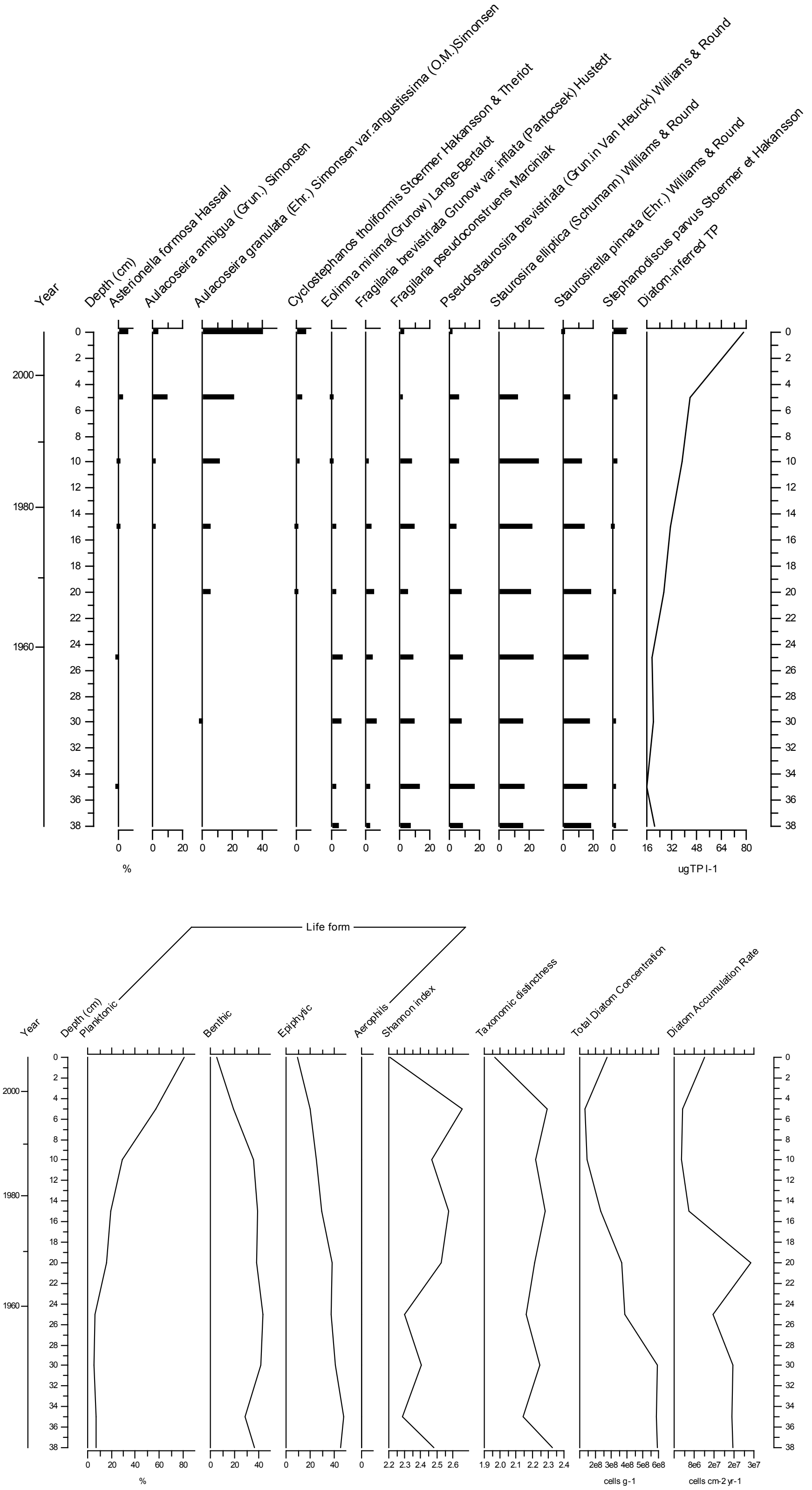
Year
Depth (cm)
Achnanthidium minutissimum (Kütz.) Czarnecki
Asterionella formosa Hassall
Aulacoseira granulata (Ehr.) Simonsen var.angustissima (O.M.)Simonsen
Aulacoseira humilis(Cleve-Euler) Genkal et Trifonova
Aulacoseira islandica(O.Muller)Simonsen
Aulacoseira subarctica (O.Muller) Haworth
Cyclostephanos dubius (Fricke) Round
Cyclotella comensis Grunow in Van Heurck
Fragilaria pseudoconstruens Marciniak
Pseudostaurosira brevistriata (Grun.in Van Heurck) Williams & Round
Puncticulata radiosa (Lemmermann) Håkansson
Staurosira elliptica (Schumann) Williams & Round
Stephanodiscus medius Håkansson
Stephanodiscus minutulus (Kutzing) Cleve & Moller
Stephanodiscus parvus Stoermer et Hakansson
Diatom-inferred TP
2000
1980
1960
1940
1920
1900
1880
1860
1840
1820
1800
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
0 20 40
0 80 160 240
%
ug TP l-1
Life form
Planktonic
Benthic
Epiphytic
Shannon index
Taxonomic distinctness
Diatom Concentration
Diatom Accumulation Rate
0 20 40
2.2 2.4 2.6 2.8 3.0
2.0 2.1 2.2 2.3 2.4 2.5 2.6 2.7
2e8 5e8 7e8
cells g-1
1e7 2e7 3e7 4e7 5e7
cells cm-2 yr-1

(c)

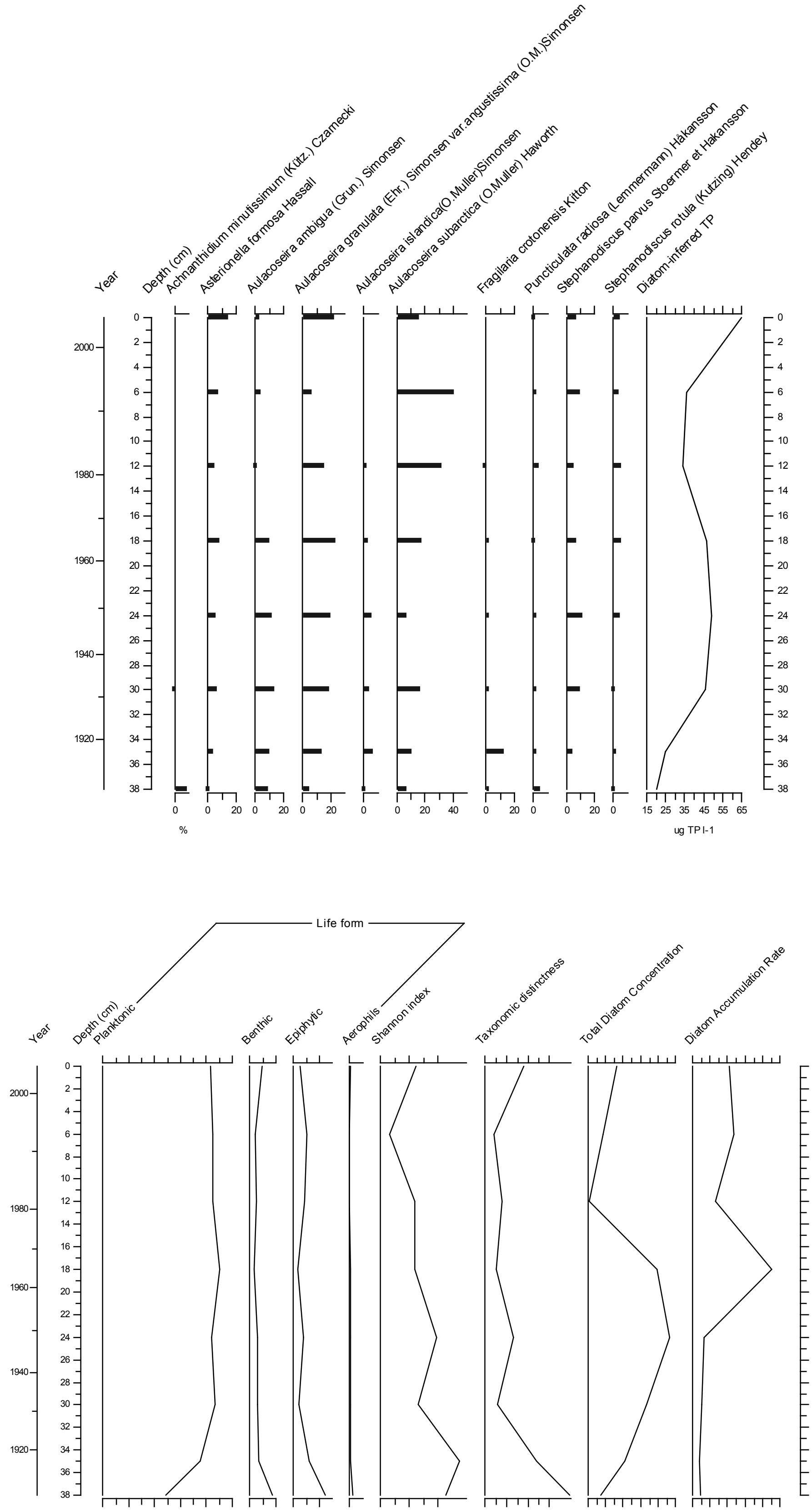

Year
Depth (cm)
Achnanthidium minutissimum (Kütz.) Czarnecki
Amphora inariensis Krammer
Amphora pediculus (Kutzing) Grunow
Asterionella formosa Hassall
Cocconeis placentula Ehrenberg var. placentula
Cyclotella pseudostelligera Hustedt
Fragilaria ulna Sippen angustissima(Grun.)Lange-Bertalot
Puncticulata radiosa (Lemmermann) Håkansson
Staurosirella leptostauron (Ehr.) Williams & Round
Stephanodiscus alpinus Hustedt in Huber-Pestalozzi
Stephanodiscus hantzschii Grunow in Cl. & Grun. 1880
Stephanodiscus parvus Stoermer et Hakansson
Diatom-inferred TP
2000
1980
1960
1940
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
0 20
%
14 18 22 26 30 34
16 20
ug TP l-1


Life form
Year
Depth (cm)
Planktonic
Benthic
Epiphytic
Aerophils
Shannon index
Taxonomic distinctness
Total Diatom Concentration
Diatom Accumulation Rate
2000
1980
1960
1940
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
0 20 40 60
%
0 20 40
0 20 40
0
2.7 2.8 2.9 3.0
2.5 2.5 2.5 2.6 2.6
2e8 5e8 7e8
cells g-1
2e7 4e7 6e7 8e7 1e8
cells cm-2 yr-1

(d)

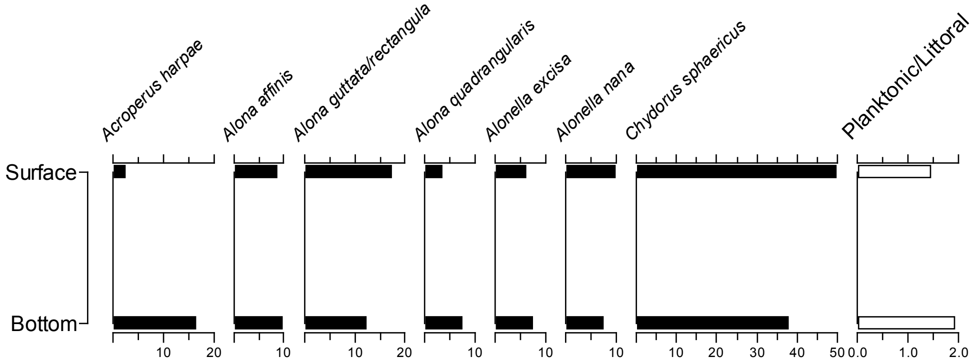

Year
Depth (cm)
Asterionella formosa Hassall
Aulacoseira ambigua (Grun.) Simonsen
Aulacoseira granulata (Ehr.) Simonsen var.angustissima (O.M.)Simonsen
Cyclostephanos tholiformis Stoermer Hakansson & Theriot
Eolimna minima(Grunow) Lange-Bertalot
Fragilaria brevistriata Grunow var.inflata (Pantocsek) Hustedt
Fragilaria pseudoconstruens Marciniak
Pseudostaurosira brevistriata (Grun.in Van Heurck) Williams & Round
Staurosira elliptica (Schumann) Williams & Round
Staurosirella pinnata (Ehr.) Williams & Round
Stephanodiscus parvus Stoermer et Hakansson
Diatom-inferred TP
2000
1980
1960
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38
0 20 40
16 32 48 64 80
%
ugTP l-1
Life form
Planktonic
Benthic
Epiphytic
Aerophils
Shannon index
Taxonomic distinctness
Total Diatom Concentration
Diatom Accumulation Rate
0 20 40 60 80
2.2 2.3 2.4 2.5 2.6
1.9 2.0 2.1 2.2 2.3 2.4
2e8 3e8 4e8 5e8 6e8
8e6 2e7 2e7 3e7
cells g-1
cells cm-2 yr-1

(e)

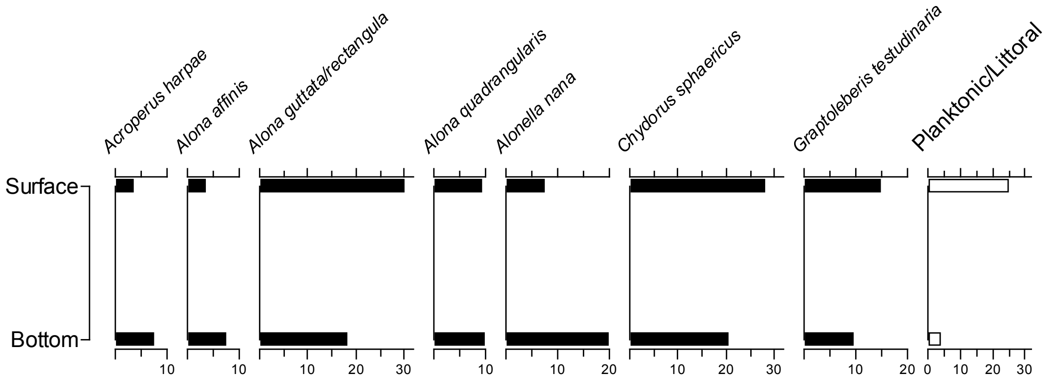


(f)

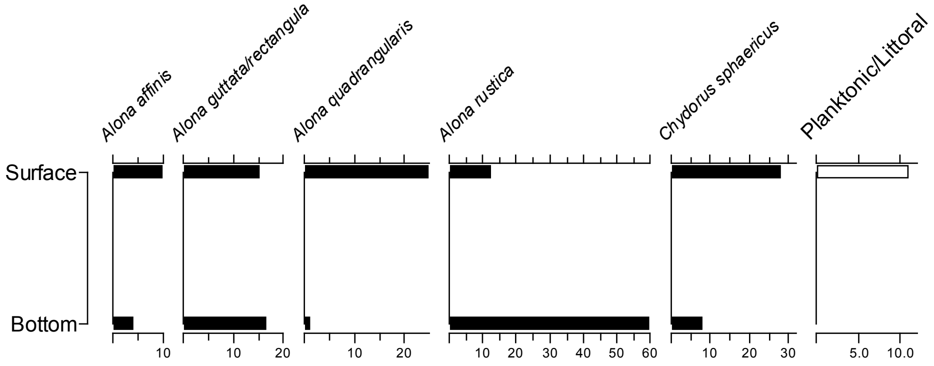
Figure 4: *Summary plots of the common diatom taxa and diatom-inferred TP (above) and diatom life form and variations in diversity and concentration/accumulation (below). Data are plotted on a depth and age scale ((a) Ballybeg; (b) Crans; (c) Egish; (d) Inchiqin (e) Mullagh; (f) Sillan)*


Acroperus harpae
Alona affinis
Alona guttata/rectangula
Alona quadrangularis
Alonella excisa
Alonella nana
Chydorus sphaericus
Planktonic/Littoral
Surface
Bottom
10 20
10
10 20
10
10
10
10 20 30 40 50
0.0 1.0 2.0

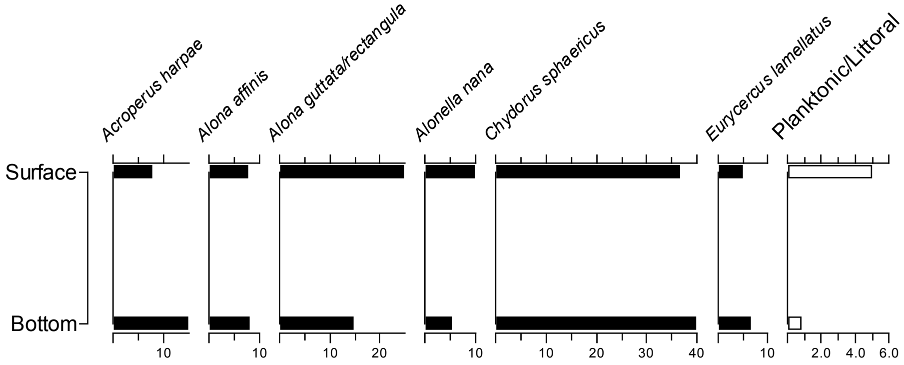
(a)


Acroperus harpae
Alona affinis
Alona guttata/rectangula
Alona quadrangularis
Alonella nana
Chydorus sphaericus
Graptoleberis testudinaria
Planktonic/Littoral
Surface
Bottom
10
10
10 20 30
10
10 20
10 20 30
10 20
0 10 20 30

(b)


Alona affinis
Alona guttata/rectangula
Alona quadrangularis
Alona rustica
Chydorus sphaericus
Planktonic/Littoral
Surface
Bottom
10
10 20
10 20
10 20 30 40 50 60
10 20 30
5.0 10.0

(c)


Acroperus harpae
Alona affinis
Alona guttata/rectangula
Alonella nana
Chydorus sphaericus
Eurycercus lamellatus
Planktonic/Littoral
Surface
Bottom
10
10
10 20
10
10 20 30 40
10
2.0 4.0 6.0

(d)

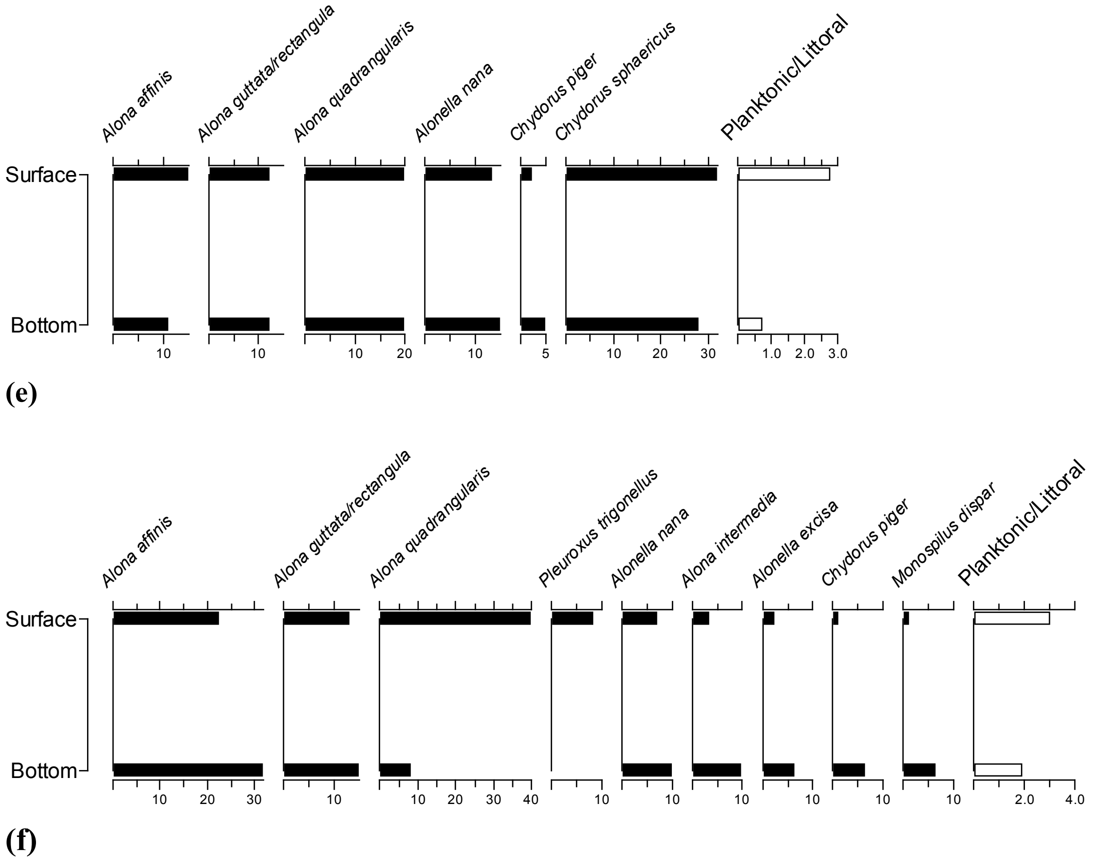


Figure 5: *Selected chydorid species in bottom (reference) and surface (c. 2004) sediment samples ((a) Ballybeg; (b) Crans; (c) Egish; (d) Inchiqin (e) Mullagh; (f) Sillan).*

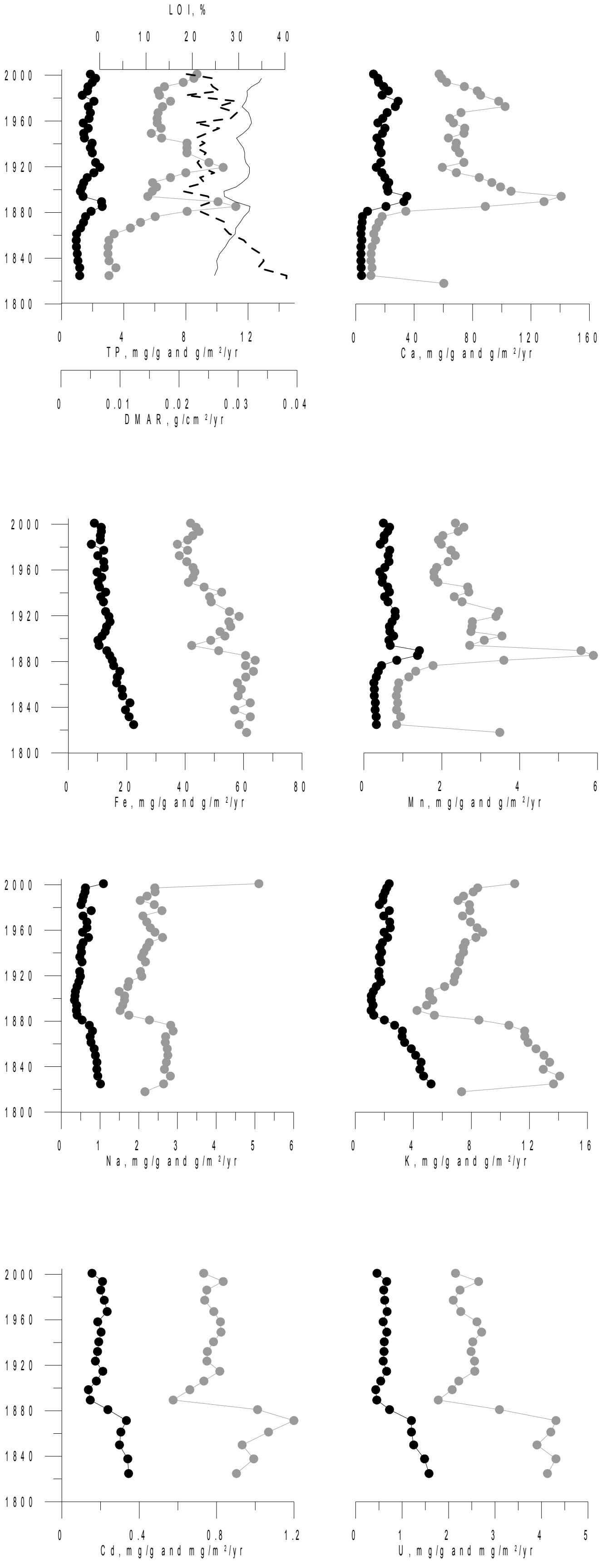


Figure 6: *Sedimentary chemistry profiles of Ca, Cd, Fe, K, Mn, Na, P and U from* ***Crans****. Grey circles are chemical concentrations; black circles are chemical accumulation rates. In the top left, the dashed line is DMAR; and the unbroken line is LOI. Data are plotted on an age scale.*

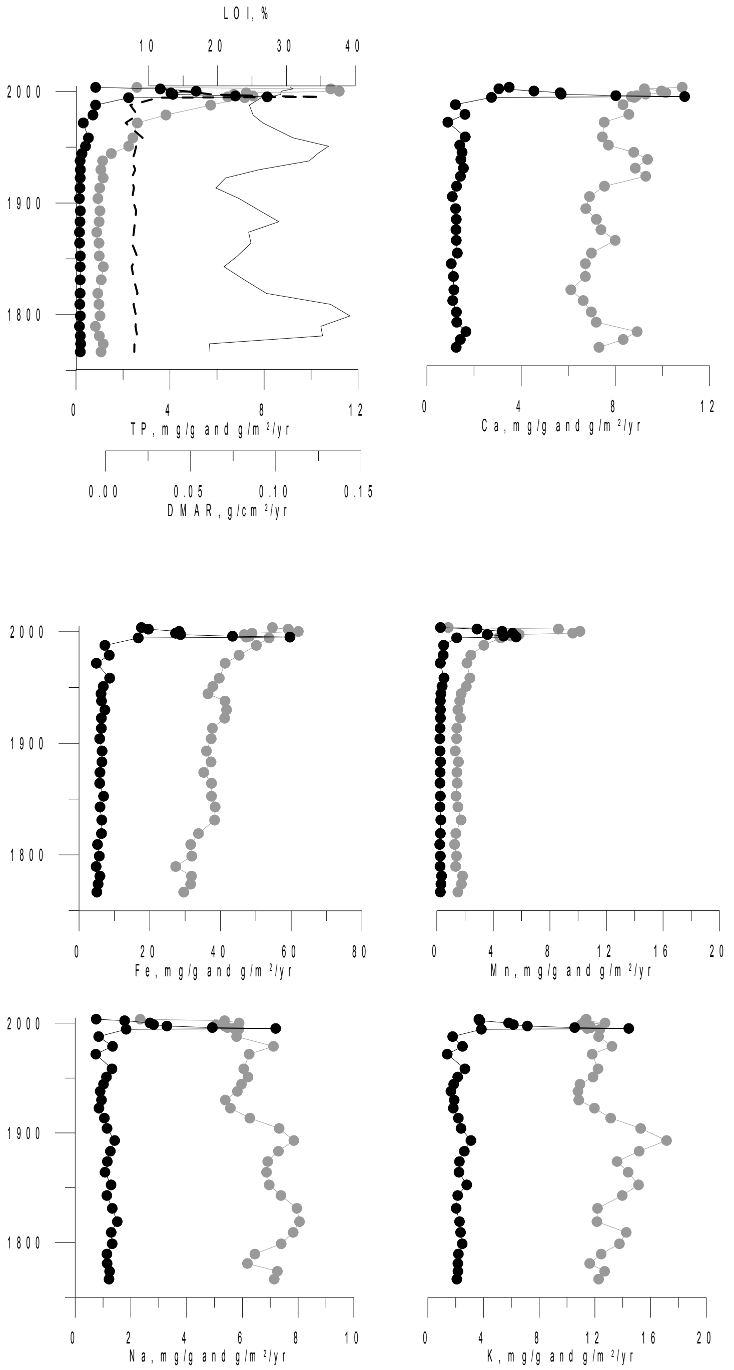


Figure 7: *Sedimentary chemistry profiles of Ca, Fe, K, Mn, Na and P from* ***Egish****. Grey circles are chemical concentrations; black circles are chemical accumulation rates. In the top left, the dashed line is DMAR; and the unbroken line is LOI. Data are plotted on an age scale.*

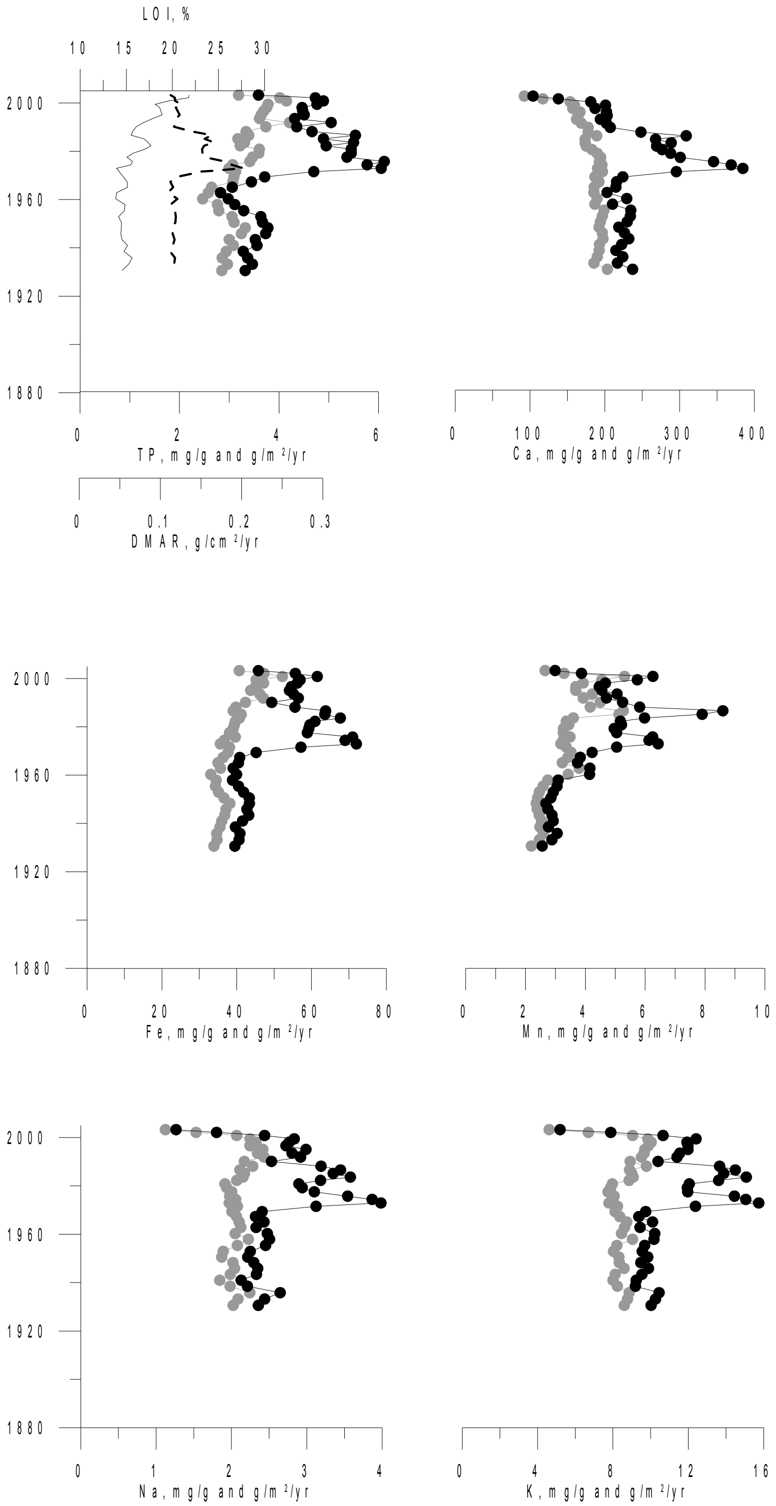


Figure 8: *Sedimentary chemistry profiles of Ca, Fe, K, Mn, Na and P from* ***Inchiquin****. Grey circles are chemical concentrations; black circles are chemical accumulation rates. In the top left, the dashed line is DMAR; and the unbroken line is LOI. Data are plotted on an age scale.*

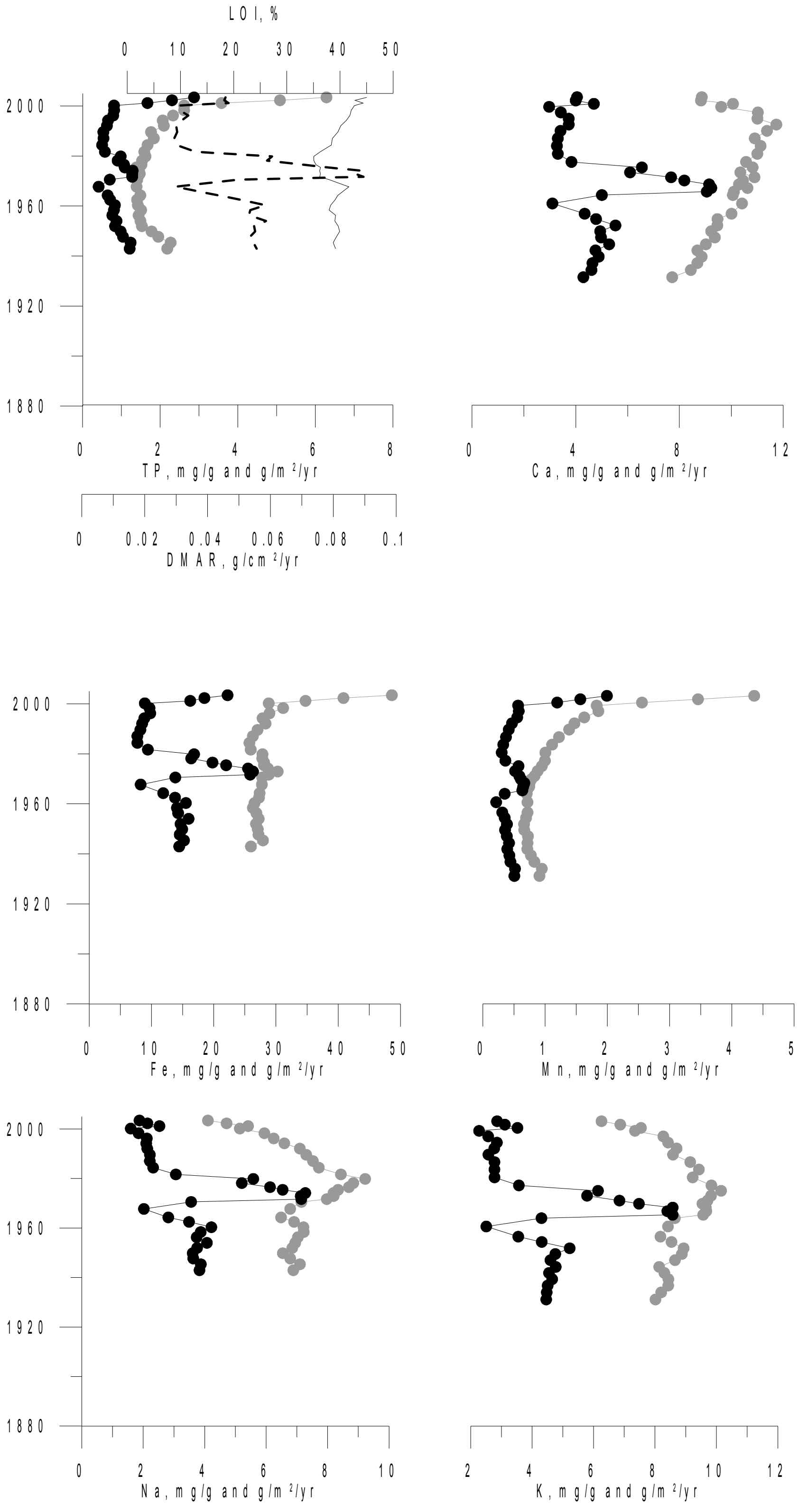


Figure 9: *Sedimentary chemistry profiles of Ca, Fe, K, Mn, Na and P from* ***Mullagh****. Grey circles are chemical concentrations; black circles are chemical accumulation rates. In the top left, the dashed line is DMAR; and the unbroken line is LOI. Data are plotted on an age scale.*

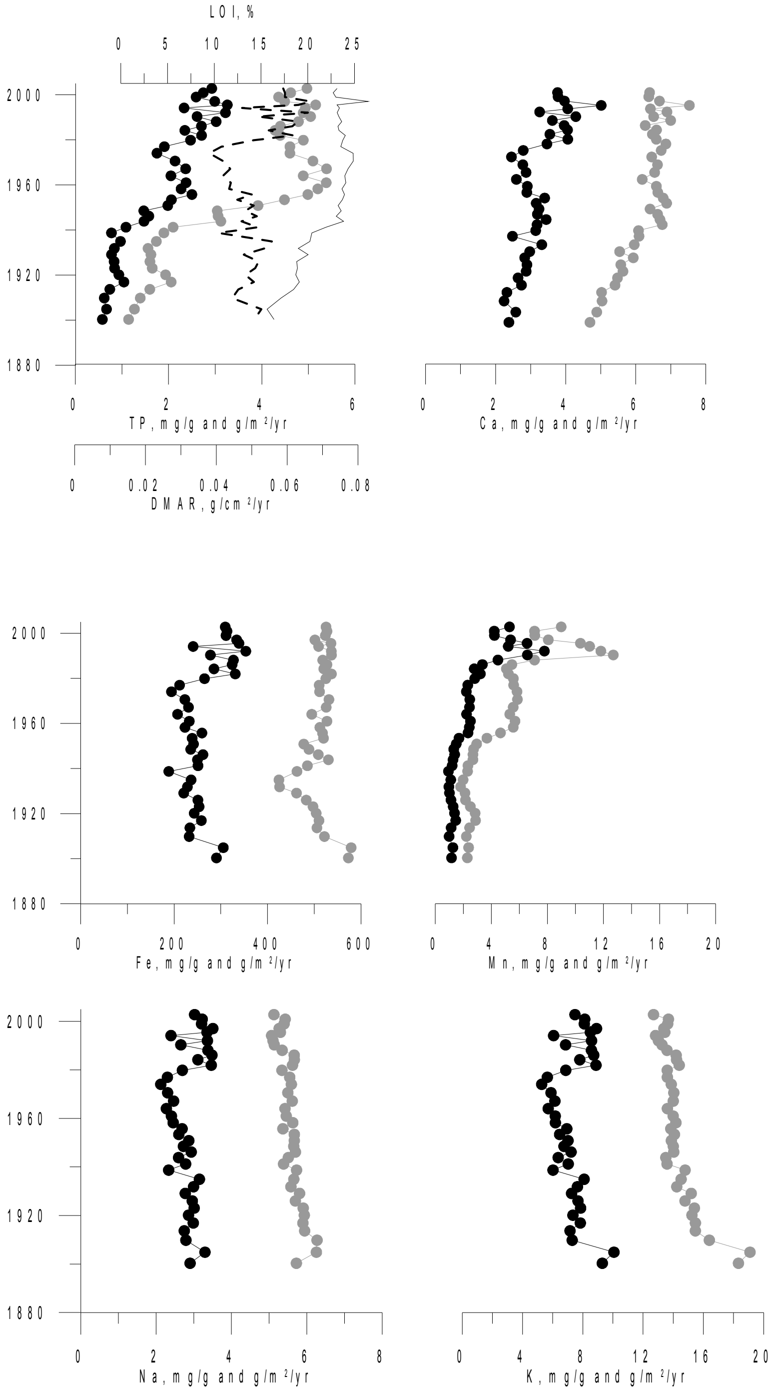


Figure 10: *Sedimentary chemistry profiles of Ca, Fe, K, Mn, Na and P from **Sillan**. Grey circles are chemical concentrations; black circles are chemical accumulation rates. In the top left, the dashed line is DMAR; and the unbroken line is LOI. Data are plotted on an age scale.*

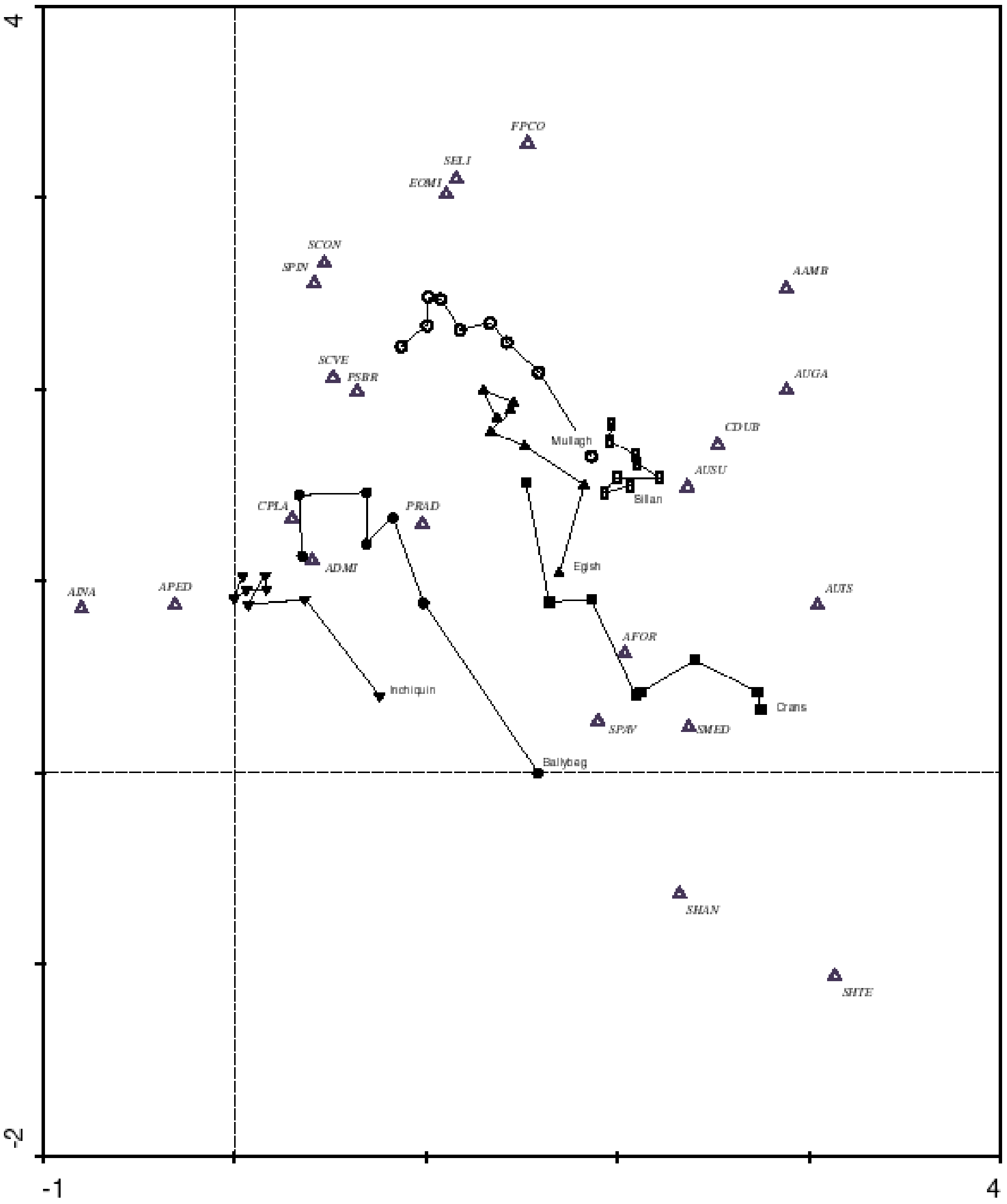


Figure 11: *DCA ordination results for diatom samples from six cores of sediment analysed in the current research. Names of the lakes are shown next to the core top sample from that lake. The four letter codes represent the following diatom taxa (see Figure 4 for authorities):* AAMB = *Aulacoseira ambigua*; ADMI = *Achnanthidium minutissimum*; AINA = *Amphora inariensis*; APED = *Amphora pediculus*; AUGA = *Aulacoseira granulata* var. *angustissima*; AUIS = *Aulacoseira islandica*; AUSU = *Aulacoseira subarctica*; CPLA = *Cocconeis placentula* var. *placentula*; EOMI = *Eolimna minima*; FPCO = *Fragilaria pseudoconstruens*; PRAD = *Puncticulata radiosa*; PSBR = *Pseudostaurosira brevistriata*; SCON = *Staurosira construens*; SCVE = *Staurosira construens;* SELI = *Staurosira elliptica*; SHAN = *Stephanodiscus hantzschii*; SHTE = *Stephanodiscus hantzschii* fo. *tenuis*; SMED = *Stephanodiscus medius*; SPAV = *Stephanodiscus parvus*; SPIN = *Staurosirella pinnata*.

Tables

.

Lake	County	Grid Ref.	River Catchment	Altitude (m)	Mean depth (m)	Lake area (ha)	Working typology*
Ballybeg	Clare	R331738	Fergus	4	2.7	19.7	9
Crans	Tyrone	H711568	Oona	95	6.7	8.5	7
Egish	Monaghan	H794134	Erne	162	3.3	121.7	6
Inchiquin	Clare	R270896	Fergus	24	10.2	115.7	12
Mullagh	Cavan	N677854	Moynalty/ Boyne	120	2.3	35.1	5
Sillan	Monaghan	H709630	Annalee	94	6.0	172.0	12

Table 1: *Summary of locational information and physical characteristics for the six study lakes. Working typology* is based on EPA Ireland approach in which typology class 5 = moderate alkalinity (20-100 mg l^{-1} $CaCO_3$), shallow (mean depth < 4m) and small (< 50 ha); class 6 = moderate alkalinity, shallow and large (> 50 ha); class 7 = moderate alkalinity, deep (mean depth > 4m) and small; class 9= high alkalinity (> 100 mg l^{-1} $CaCO_3$), shallow and small; and class 12 =high alkalinity, deep and large (and see Leira et al., in press).*

Lake	**pH**	**Alkalinity (mg $CaCO_3$ l^{-1})**	**Annual mean maximum Chlorophyll-a (µg l^{-1})***	**Predominant catchment geology**
Ballybeg	7.9	128.0	50.8 [mean of 8 samples in 2001]	Lower Carboniferous cherty limestone with crinoidal intervals
Crans	8.8	118**	43^{+} [single measurement in August 1987]	$^{\#}$Lower Carboniferous (Viséan Calp) limestone and shale***
Egish	7.3	78.6	36.0 [mean of 2 samples in 2001] 110.0 [mean of 2 samples in 2002] 84.0 [mean of 5 samples in 2003]	Ordovician shales and rhyolitic volcanic tuff (north) and Silurian (Llandovery) turbidites (south)***
Inchiquin	8.2	161.8	14.3 [mean of 10 samples in 2001]	Lower Carboniferous cherty limestone with crinoidal intervals
Mullagh	7.6	58.4	40.0 [mean of 10 samples in 2001] 56.0 [mean of 11 samples in 2002] 73.0 [mean of 11 samples in 2003]	Silurian (Llandovery) turbidites***
Sillan	?	140	40.2 [mean of 14 samples in 2001] 80.3 [mean of 12 samples in 2002] 47.8 [mean of 12 samples in 2003]	Silurian (Llandovery) turbidites***

Table 2: *Summary of chemical characteristics for the six study lakes. *Data from Toner* et al. *(2005). According to the modified OECD (1982) scheme based on annual maximum chlorophyll concentrations: oligotrophic = <8* µg l^{-1}*; mesotrophic = 8-25* µg l^{-1}*; moderately eutrophic = 25-35* µg l^{-1}*; strongly eutrophic =33-55* µg l^{-1}*; highly eutrophic = 55-75* µg l^{-1}*; hypertrophic = > 75* µg l^{-1}. *Data for Crans are*$^{+}$ *from Gibson (1991) and* $^{\#}$ *from Smith* et al. *(1991). All other data from Irvine* et al. *(2001). ** Alkalinity measured as* HCO_3. ** **underlying geology is largely blanketed by overlying glacial till.*

Lake	**Urban**		**Forest/ woodland**		**Pasture**		**Agriculture**		**Peatland**		**Other**	
	1990	**2000**	**1990**	**2000**	**1990**	**2000**	**1990**	**2000**	**1990**	**2000**	**1990**	**2000**
Ballybeg	0	10.9	15.7	22.6	70.9	53.7	0	4.0	0	0	13.4	8.8
Crans	NA	0	NA	15	NA	85	NA	0	NA	0	NA	0
Egish	0	2.7	0	0	89.3	86.4	10.7	10.9	0	0	0	0
Inchiquin	0	0	6.8	5.6	4.6	5.1	2.7	2.6	77.8	82.7	8.1	3.9
Mullagh	0	0	0	0	97.8	95.7	0.3	4.3	0	0	1.9	0
Sillan	0	1.3	0	0.9	99.6	79.8	0.4	18.0	0	0	0	0

Table 3: *Summary information of percentage of land cover in catchments of the six study lakes. Land cover information is from the CORINE (1990 & 2000) database and was provided by EPA Ireland.*

Reference	TP range μgTP l^{-1}	Lakes *n*	Apparent r^2	RMSE log μgTP l^{-1}	RMSEP log μgTP l^{-1}	Model
Anderson *et al*. (1993)	25-800	43	0.75/0.77	0.17/0.16		WA
Anderson & Rippey (1994)	15-800	49	0.80	0.19	0.24	WA
Anderson & Odgaard (1994)	25-1000	27	0.80	0.15		WA
Bennion (1994)	25-646	30	0.79	0.16	0.28	WA
Wunsan & Schmidt (1995)	2-266	86	0.61/0.65	0.12/0.22	0.35/0.36	WA
Bennion *et al.* (1995)	2-263	44	0.60	0.32	0.37	WA
Bennion *et al.* (1996)	5-1190	152	0.91	0.15	0.21	WA
Lotter *et al.* (1998)	6-520	72	0.93	0.11	0.19	WA-PLS
Bradshaw & Anderson (2001)	1-369	45	0.75/0.79	0.17/0.15	0.24/0.27	WA
This study	0-675	73	0.89	0.15	0.31	WA-PLS

Table 4: *Performance of different diatom-inferred TP datasets based on WA or WA-PLS models. The RMSEP values are based on either leave-one-out jacknifing or bootstrapping. n = number of lakes, WA = weigthed averaging, WA-PLS = weighted averaging partial least squares*.

Lake	$^{210}Pb_{excess}$ (Bq m^{-2} y^{-1})	^{137}Cs (Bq m^{-2})	Estimated average sediment accumulation rate (g cm^{-2} yr^{-1})	Estimated age of particular sample depths	
				Core dated directly (CRS chronology) (± 1 SD)	Core used for microfossil analyses (estimated age) (± 1 SD)
Ballybeg	90	784	0.026 ± 0.002	1944 ± 5 at 18-19cm	c. 1889 ± 11 at 29-30cm*
Crans	51	3500	0.028 ± 0.007	1916 ± 15 at 22-23cm	c. 1825 ± 37 at 38-39cm*
Egish	66	1400	0.017 ± 0.004	1913 ± 24 at 18-19cm	c. 1781 ± 50 at 30-31cm*
Inchiquin	320	2960	0.12 ± 0.02	1956 ± 4 at 25-26cm	c. 1931 ± 8 at 38-39cm*
Mullagh	90	1600	0.04 ± 0.01	1950 ± 4 at 26-27cm	Pre-1950 ± 4 at 37-38
Sillan	120	2600	0.053 ± 0.012	1954 ± 4 at 22-23cm	1905 ± 13 at 37-38cm*

Table 5: *$^{210}Pb_{excess}$ supply rates, ^{137}Cs inventories, estimated sediment accumulation rates, and extrapolated and estimated ages of selected core samples. NB Confidence intervals for extrapolated ages (*) were derived from estimated accumulation rates for the lowermost part of the core where there was evidence for varying sediment accumulation rates. An abrupt change in accumulation rate towards the base of the core from Mullagh made precise estimation of basal age impossible.*

Sample identifier and depth range (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)**
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

Table 6: *% pollen data. Data underlined are for core bottom samples. See text for information on pollen sums used. BA = Ballybeg, CR = Crans, EG = Egish, IN =Inchiquin, MU = Mullagh, SI = Sillan*