History, nutrients and water quality: a study of the lakes and catchments of Loughs Carra and Mask

Kenneth Irvine, Ian Donohue, Valerie McCarthy, Manel Leira and William Hobbs.
Centre for the Environment, School of Natural Sciences, Trinity College, Dublin 2, Ireland.

INTRODUCTION

It is a statement of the obvious that intensification of human activities puts pressures on the environment, and can lead to habitat degradation and loss of species. A major impact on freshwaters arises from increased nutrient loads; typically from point-source industrial outflows and domestic sewage, or diffuse movement from intensified agriculture. These pressures have led to a steady decline in the quality of freshwater habitats throughout Europe. In Ireland, point sources provide a relatively low proportion of nutrient loads compared with agriculture (Allott *et al*., 1998). Diffuse sources of nutrients are, however, often difficult to quantify. While this has led to considerable debate surrounding the actual contribution from agriculture, there is a large and convincing literature attributing degradation of water quality as a consequence of diffuse movement of nutrients from agricultural land to water (e.g. McGarrigle *et al.* 1993; Sharpley *et al*., 1994, 2000; Foy *et al*, 1995; Gibson *et al*., 1995; Heckrath *et al.*, 1995; Moss *et al.*, 1996; Pote *et al.*, 1996; Haygarth and Jarvis, 1997; Tunney *et al.*, 1998, 2000; Lucey *et al.*, 1999; Hooda *et al*., 2000). This is also reflected in the ongoing vibrant discussions relating to nitrate action plans, agricultural opposition to the Nitrates Directive (91/676) and the E.U. pending action against Ireland, E.U. judgement finding against Ireland for failure to establish controls on phosphorus emissions under the Dangerous Substances Directive (76/464) and widespread mobilisation of action under the Water Framework Directive (2000/60).

The Great Western Lakes of Counties Mayo and Galway are renowned for their high quality environment and wild salmonid fisheries, but given the general trend in Ireland of intensification of land use since the 1950s (Tunney *et al*., 1997), it is not surprising that these have also received steady increases in nutrient loads. This was shown very clearly for Lough Conn in the 1980s (McGarrigle *et al*., 1993) and suggested for Lough Corrib in the 1990s. The loss of Arctic Char from Corrib (McCarthy *et al.*, 2001) also hints at nutrient enrichment. Throughout the 1990s there was anecdotal evidence of increased algal biomass in Loughs Carra and Mask. However, anecdotal evidence is seldom sufficient to elicit a response from the responsible agencies. Monitoring of nutrients and algal biomass (measured as the concentration of the pigment chlorophyll *a*) in the open water of the western lakes has occurred for two decades, but, as in Lough Conn (McGarrigle *et al*., 1993), may not be sensitive to early changes in lake ecology; or reflect only a low level of change. The Great Western Lakes are, however, of sufficiently high international status to merit particular attention to their protection. Lough Carra is one of the few remaining examples of a high quality shallow calcareous lake in Europe. It is, however, easy to ignore the value of one's own heritage.

We describe here recent work that has estimated phosphorus loadings to Lough Carra, and the results obtained from examination of a core of sediment extracted from each of the lake's basins.

METHODS

Study Site

Lough Carra (grid reference: 53º 42' N, 9º 13' W, Fig. 1) has an area of just over 16 km^2, a mean depth of about 1.75 m and a maximum depth of 20 m. It is the largest marl lake in Ireland, a Special Area of Conservation under the EU Habitats Directive (92/43/EEC), and is one of the few remaining wild brown trout calcareous lakes in Europe. It has a catchment area of 114 km^2, which drains into Lough Mask, and comprises predominantly calcareous bedrock overlain with mostly grey-brown podzolics and brown earths. Land-use is mainly grassland used for sheep grazing, with some areas farmed more intensively for cattle, pigs and silage. Nutrients have been monitored since the 1970s and a recent summary is given in King and Champ (2000). There are no major point sources of nutrients in the lake catchment. At the southwestern end of the lake the Keel River is the sole outflow.

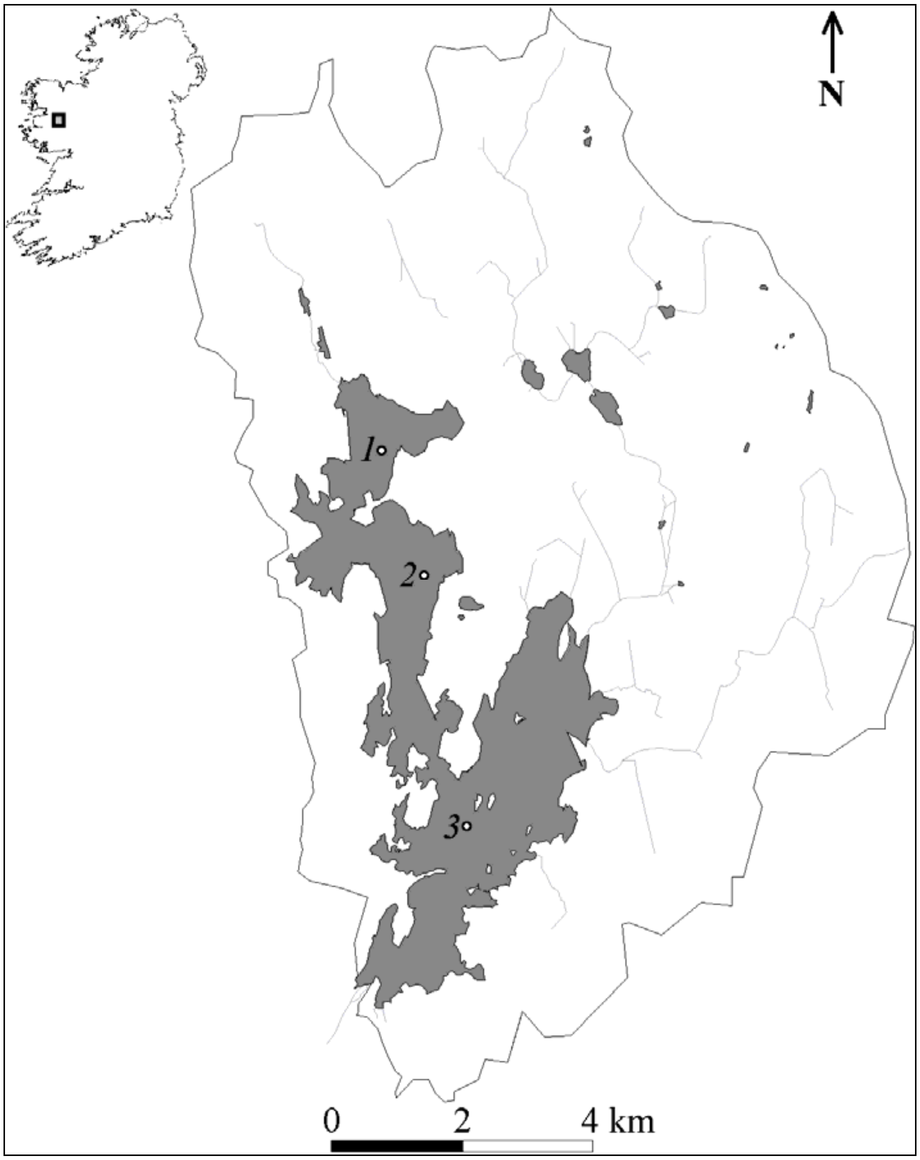

Fig.. 1. Lough Carra and surrounding catchment, showing the three sampling sites; Castleburke = North (1), Castlecarra = Mid (2), Twin Islands basin = South (3)

Sampling water and sediment cores

Monitoring of the three principal influent rivers to Lough Carra, which comprise approximately 95% of the total surface water inflow to the lake (Donohue, unpublished data), and the open waters of Lough Carra was done biweekly from July 2001 to July 2002, and monthly thereafter until July 2003. Vertically integrated water samples were taken using a 5 cm diameter plastic tube, 6 m in length. Conductivity, pH and temperature were measured on site using WTW meters. Water was analysed in triplicate for soluble reactive phosphorus (SRP), total dissolved phosphorus (TDP), total phosphorus (TP), nitrate, total nitrogen (TN), chlorophyll *a*, total suspended solids (SS), dissolved organic carbon (DOC), turbidity, colour and alkalinity, following standard methods (Eisenreich *et al*. 1975; Grasshoff *et al*. 1983; Standing committee of analysts *1980*; Mackereth *et al*. 1978).

Sediment cores were collected in July 2002. One core per basin was taken from an area of known maximum depth, using a 5 cm diameter modified Livingston core sampler. Each core was taken ashore following its extraction and segmented into 1 cm intervals. Samples were stored in individual zip lock polyethylene bags and refrigerated at 4 ^{o}C. Dry weight of sediments was calculated after drying at 105ºC for 24 hours. Quantification of total phosphorus was done following Murphy and Riley (1962) after nitric acid digestion in a CEM® MDS-2000 microwave. Percent organic matter (OM) was determined by loss-on-ignition following Allen (1989). Triplicate samples and quality control standards were used in all analyses, and were within acceptable ranges (± 3%) in each case.

Diatom slides were prepared following Battarbee (1986), with 300-400 valves counted per slide. Between 8 and 11 subsamples were analysed per core. Results of the diatom analyses were used to infer historic epilimnetic TP concentrations in Lough Carra using European Diatom Database software for palaeoenvironmental reconstructions (Juggins, 2001). Match analogue technique (Birks *et al.*, 1990; Jones & Juggins, 1995) was used to identify the datasets with the closest matches for the fossil sample. Diatom valves from the Mid Basin core exhibited a high degree of dissolution and breakage, which affected mainly the small and weakly silicified diatom frustules (e.g. *Cyclotella comensis*). This lack of preservation could have lead to a significant bias in the final counting and a subsequent unreliable estimation of the diatom inferred TP. Lake water TP concentrations for the period spanned by the core were reconstructed using locally-weighted weighted averaging (LWWA,) following Birks *et al.* (1990) and Juggins (2001).

Historical estimates of livestock and humans within each sub-catchment were obtained from data provided by the Central Statistics Office of Ireland for the period 1841–2002, with a mean of eight years between each census (range = 3-15 years), and weighted accordingly to account for differences in boundaries of District Electoral Division (DED) and Rural District (RD), following Donohue *et al.* (submitted). Estimation of historic TP loads were made by the application of the export coefficient model of Johnes *et al.* (1996). Previous work (Irvine *et al.*, 2003) found that the application of export coefficient models to the Lough Carra catchment overestimated the actual loading to the lake by approximately three times. Further work has, however, shown that the application of these models to the catchment works extremely well if only the subcatchments of the three main inflows to the lake, which together contribute about 95% of the total surface hydraulic load to the lake (Irvine *et al.*, 2003), are considered. For these reasons, the model of Johnes *et al.* (1996) was applied only to these areas. Dating of cores was done for the North Basin core using radioactive isotopes ^{137}Cs, ^{241}Am and ^{210}Pb (Appleby & Oldfield, 1983; Appleby *et al.*, 1986).

Results

Mean in-lake TP concentration (± 95% C.I., Fig. 2) of Lough Carra measured in the sampling period was 11.9 ± 1.3 µg l^{-1}; *n* = **123**. The application of the model of Foy (1992) to calculate average in-lake TP concentrations from weighed mean measurements from inflowing streams to Lough Carra predicted a mean concentration of 15.8 µg l^{-1}. Mean in-lake Nitrate_N for the same period was 0.18 ± 0.04 mg l^{-1}, *n* = 120**,** but with a strong seasonal pattern, falling to very low or undetectable concentrations in mid summer and with winter maxima (Fig 3). Concentration of chlorophyll *a* (Fig. 4), a measure of open-water phytoplankton biomass, had maxima in mid summer and winter in all basins, but was always less than 9 µg l^{-1} and sometimes (late spring) less than 1 µg l^{-1}. Mean concentrations across all basins was 2.7 ± 0.3 µg l^{-1}, n = 123**.**

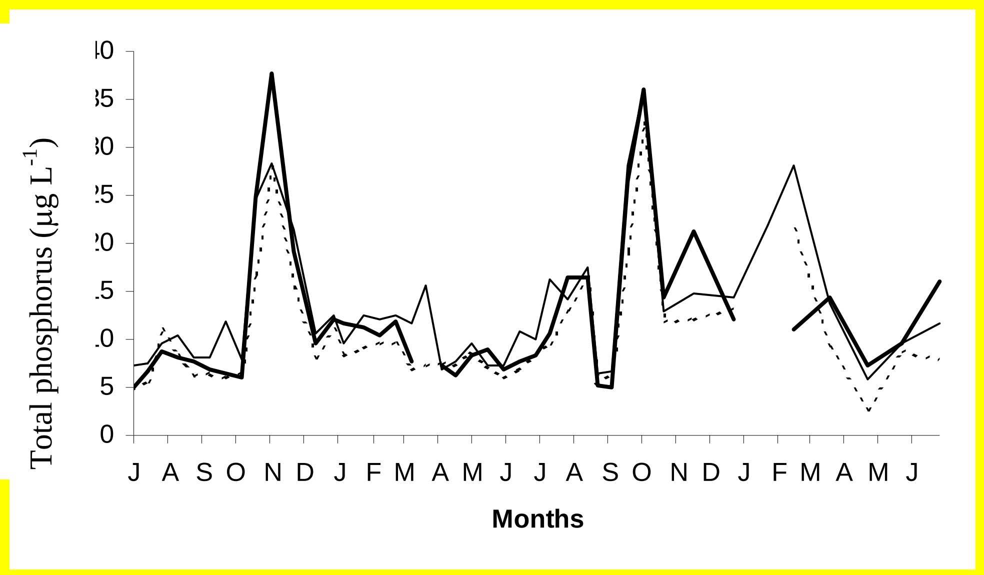

Fig. 2 Total phosphorus concentration for Lough Carra**,** July ’01 – June ’03.

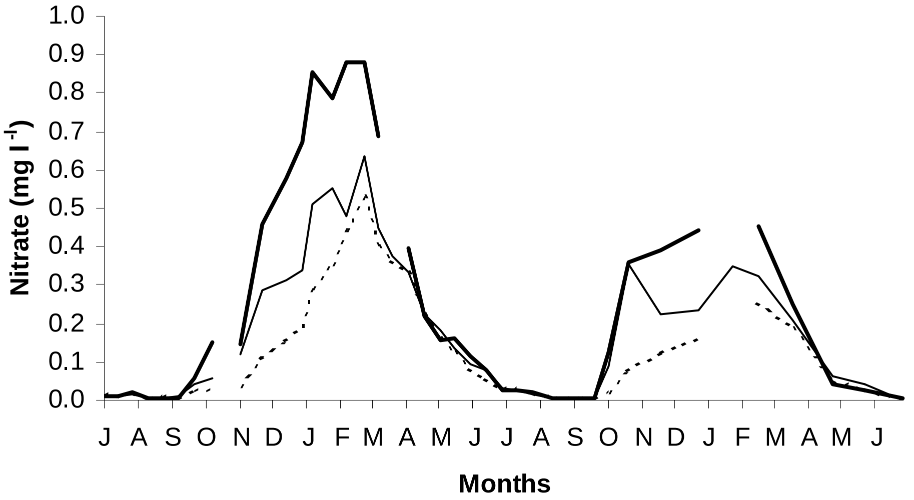

Fig. 3. Nitrate concentration for Lough Carra, July ’01 – June ’03.

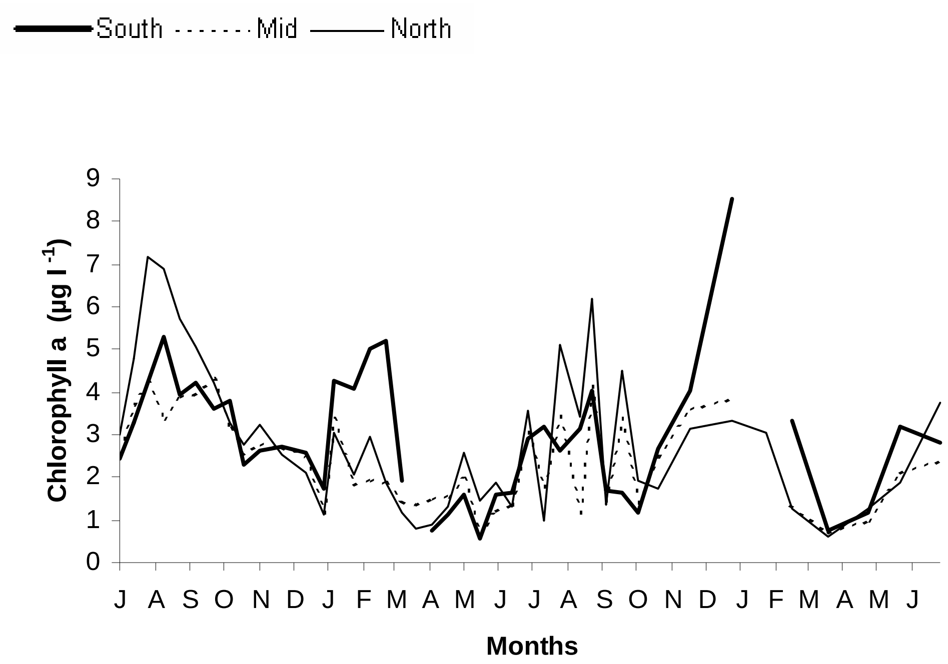

Fig. 4. Chlorophyll *a* concentration for Lough Carra, July 2001 – June 2003.

Profiles of TP and organic matter in the sediment cores (Fig. 5) showed highest concentrations towards the top of the profile, with a secondary peak around the mid-nineteenth century. Highly significant correlations were found between TP and organic matter in each of the three cores (North Basin: r = 0.95, p <0.001; Mid Basin: r = 0.96, p <0.001; South Basin: r = 0.92, p <0.001). In addition, significant correlations between diatom-inferred epilimnetic TP (Fig. 5) and both TP and organic matter were found in the North and South Basin cores (r = 0.88 and 0.82; p <0.001 and <0.01, respectively, in each basin). Data from the Mid Basin was less reliable, with a lack of significant association between diatom-inferred epilimnetic TP and either TP or OM.

Highly significant Pearson Product-Moment correlations (n = 12 for the North and Mid Basins, n = 10 for the South Basin) were found between modelled historic TP loads and concentrations of each of TP (r = 0.81, p <0.01), organic matter (r = 0.784, p <0.01) and diatom-inferred epilimnetic TP (r = 0.93, p <0.001) in the North Basin are largely explained (56-77%) by historical changes in the numbers of humans and cattle in the catchment. In 1851, humans accounted for 52% and cattle 14% of TP loads, while in 2000, it was, respectively, 15% and 54%. During this time, the number of individual farms in the catchment decreased by 62%. This was accompanied by an increase in individual farm size; in 1851, only 8% of farms were >20 ha in area. In 2000, 43% of farms exceeded 20 ha. With the exception of the period preceding and during WW II, the proportion of ploughed land in the catchment has declined steadily since 1851.

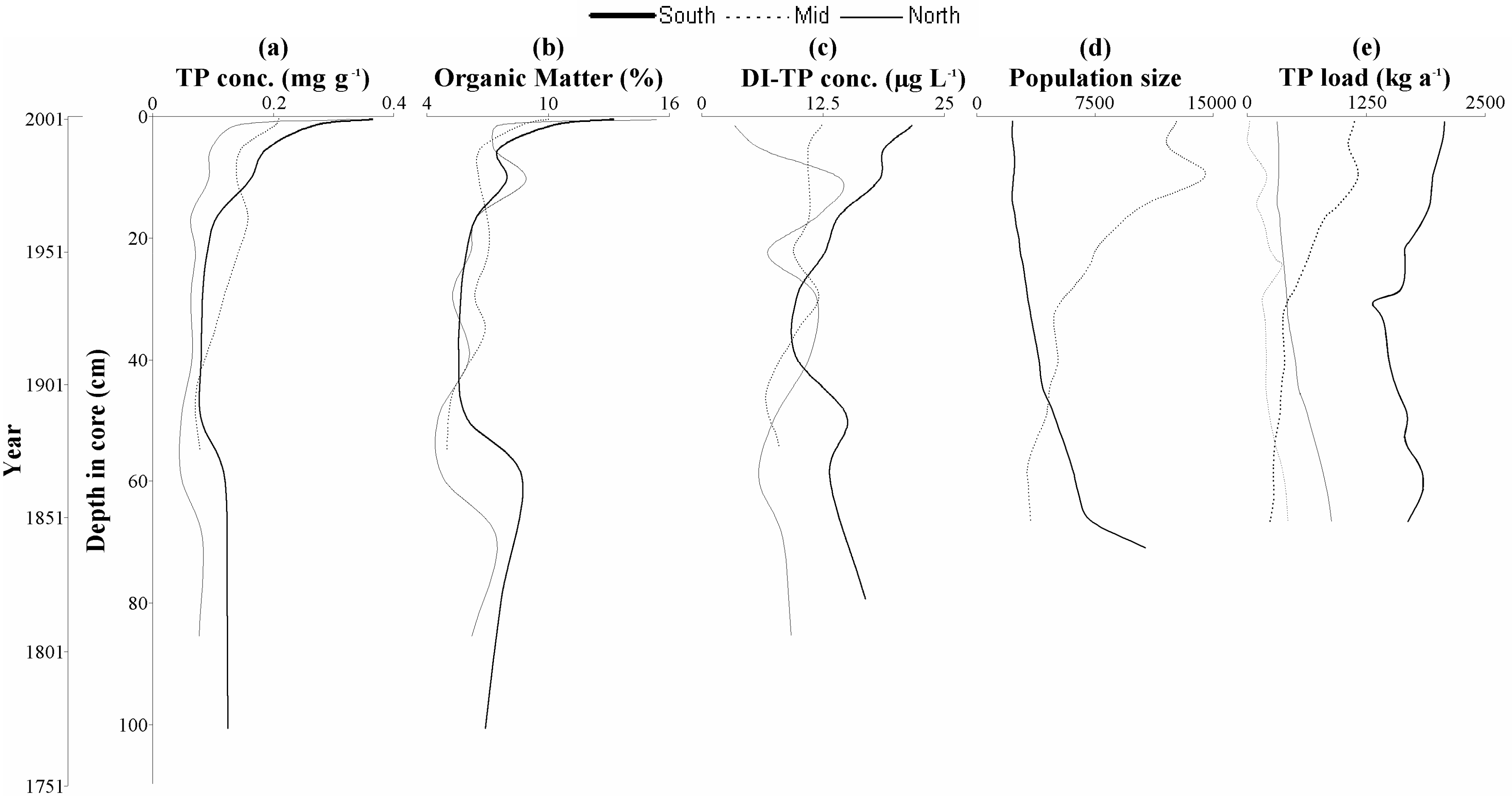

Fig. 5. Core profiles of TP (a), organic matter (b), and epilimnetic diatom-inferred TP concentrations (c) for the North (thick line), Mid (thin line) and South (dashed line) basins of Lough Carra (estimated dates refer to the North Basin only). Also shown are historical changes in populations of humans (thick line) and cattle (dashed line) (d) and modelled loads of TP (after Johnes *et al.*, 1996) to the lake (thick line), showing the loading attributable to humans (thin line), cattle (thick dashed line) and ploughed land (thin dashed line) (g).

Discussion

Monitoring of Lough Carra by the Fisheries Boards and the Environmental Protection Agency since 1975 suggests a gradual decline in water quality (McGarrigle *et al*., presented at this conference). Our results support this, showing high inputs of phosphorus over the winter period, and nitrogen limitation in mid summer. The high winter phosphorus loads are of particular concern as they can promote high spring populations of phytoplankton, and nutrients entering the lake can be recycled if not flushed out over the winter. Additional nitrogen entering during the summer will stimulate further algal growth. Concentrations of open-water phytoplankton are, however, still fairly modest and it is likely that binding of P to the surficial sediment provides a buffer to eutrophication. However, Hobbs et al. (2005) has shown that the buffering capacity in Carra may be limited because of increasing build up of P in the sediment. The elimination of such buffering capacity in a shallow lake such as Carra can lead to dramatic shifts in ecosystem state (Scheffer et al., 1993) resulting in high densities of phytoplankton, a loss of submerged plants and, very likely, shifts in fish composition and structure.

The data from the sediment cores provide very convincing evidence of accumulating phosphorus in the sediment and, through modelling using diatom remains, associated increases in the water column since the 1950s. This coincides with the agricultural intensification in Ireland that has occurred over the last half century (Tunney et al., 1997; Allott et al., 1998). It is not, however, the first time that land use has led to increased nutrient loading to the lake. The historical record from the sediment, supported with independent estimates of phosphorus loading from catchment nutrient export models (Johnes et al., 1996), indicates increased nutrient inputs to the lake in the period prior to the Irish famine. That period was characterised by high numbers of people in a, mainly, ploughed landscape. Since the depopulation that accompanied the famine, the extent of ploughed land has decreased, while cattle numbers and average size of farm has increased. This shift from a people dominated to a livestock dominated catchment, coupled with the knowledge of increased fertiliser application since the 1950s, provides compelling evidence that current nutrient loads to Lough Carra are from diffuse sources from, what is now, a predominantly grassland catchment.

Measures to restrict nutrient loads to the lake should be a high priority under the new Water Framework Directive's *Programme of Measures.* Failure to implement appropriate measures will likely result in further action by the E.U. against Ireland's poor record of environmental protection. Diffuse run-off of nutrients are, however, not the only concern. While there are no major sewerage outfalls to the lake, increasing housing development in the catchment provides an additional potential for nutrient enrichment and altered hydrology. Lough Carra is an asset of immense ecological and cultural importance and merits the instigation of measures to keep it from further degradation. The legal instruments and technical knowledge are there to safeguard the lake.

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