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The past and future of phytoplankton in the UK's largest lake, Lough Neagh

J. Alex Elliott[a,*], Yvonne R. McElarney[b], Michelle Allen[b]

[a] *Centre for Ecology & Hydrology, Lancaster, Library Avenue, Bailrigg, Lancashire LA1 4AP, UK*
[b] *Agri-Food and Biosciences Institute, 18a Newforge Lane, Belfast, Northern Ireland BT9 5PX, UK*

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ABSTRACT

Lough Neagh is the largest lake in the UK and has been extensively monitored since 1974. It has suffered from considerable eutrophication and toxic algal blooms. The lake continues to endure many of the symptoms of nutrient enrichment despite improvements in nutrient management throughout the catchment, in particular a permanently dominant crop of the cyanobacterium *Planktothrix agardhii*. This study examines the historical changes in the Lough, and uses the PROTECH lake model to predict how the phytoplankton community may adapt in response to potential future changes in air temperature and nutrient load. PROTECH was calibrated against 2008 observations, with a restriction on the maximum simulated mixed depth to reflect the shallow nature of the lake and the addition of sediment released phosphorus throughout the mixed water column between 1 May and 1 October (with an equivalent in-lake concentration of 2.0 mg m^{-3}). The historical analysis showed that phytoplankton biomass (total chlorophyll *a*) experienced a steady decline since the mid-1990s. During the same period the key nutrients for phytoplankton growth in the lake have shown contrasting trends, with increases in phosphorus concentrations and declines in nitrate concentrations. The modelled future scenarios which simulated a temperature increase of up to 3 °C showed a continuation of those trends, i.e. total chlorophyll *a* and nitrate concentrations declined in the surface water, while phosphorus concentrations increased and *P. agardhii* dominated. However, scenarios which simulated a 4 °C increase in air temperature showed a switch in dominance to the cyanobacteria, *Dolichospermum* spp. (formerly *Anabaena* spp.). This change was caused by a temperature related increase in growth driving nutrient consumption to a point where nitrate was limiting, allowing the nitrogen-fixing *Dolichospermum* spp. to gain sufficient advantage. These results suggest that in the long term, one nuisance cyanobacteria bloom may only be replaced by another unless the in-lake phosphorus concentration can be greatly reduced.

1. Introduction

In the latter half of the twentieth century, anthropogenic nutrient enrichment of freshwater lakes has been widespread and often damaging to ecosystems. The largest lake in the United Kingdom (UK), Lough Neagh has been no exception to this trend and forms the focus of this study. This polymictic, naturally mesotrophic lake has become much enriched as a result of anthropogenic eutrophication, most of which occurred in the last century (Wood and Smith, 1993). Despite the recent changes in nutrient loading the lake is still currently classed as hypereutrophic with annual mean chlorophyll *a* and total phosphorus concentrations of 46 mg m^{-3} and 108 mg m^{-3}, respectively in 2014.

While many algal taxa are present in the Lough, for example the diatoms *Stephanodiscus* spp. and *Aulacoseira* spp. which have their peak biomass in spring, the phytoplankton is dominated by the cyanobacteria *Planktothrix agardhii* and *Pseudanabaena* spp. which form a perpetual large crop. These cyanobacteria have the potential to produce toxins which pose a risk to both human and animal health (Briand et al., 2003; Codd et al., 2005). Cyanobacteria may also pose problems in water treatment works with some toxins difficult to remove, especially during bloom periods (Hitzfeld et al., 2000). Furthermore, in a future with a warmer climate, cyanobacteria are predicted to become more prevalent (Carey et al., 2012; Elliott, 2012). As Lough Neagh is the most important drinking water reservoir in Northern Ireland, supplying daily drinking water to approximately 1 million people, it is useful to understand and predict the behaviour of these cyanobacteria.

* Corresponding author at: Lake Ecosystems Group, Centre for Ecology & Hydrology, Lancaster, Library Avenue, Bailrigg, Lancashire LA1 4AP, UK. Tel.: +44 01524 595842; fax: +44 01524 61536.
E-mail address: alexe@ceh.ac.uk (J.A. Elliott).

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The Water Framework Directive (WFD) (EU, 2000) is the major driver of water quality legislation for European States. It is based on a holistic approach to water management and describes target biological elements, one of which is phytoplankton, which must be protected and/or improved through a required Programme of Measures. According to the Directive, Lough Neagh is considered a Heavily Modified Water Body due to water level control, however, it still must achieve ecological improvement through a management plan. In order to achieve a sustained reduction in cyanobacteria biovolume it is essential to make predictions regarding the response of lake phytoplankton to future changes in temperature and nutrient loading as temperature in the Lough is increasing and nitrogen loading from the catchment is decreasing (McElarney et al., 2015b). In order to help inform the WFD Programme of Measures, we used a computer model called PROTECH (Elliott et al., 2010). PROTECH (**P**hytoplankton **R**esp**O**nses **T**o **E**nvironmental **CH**ange) simulates the responses of up to 10 species of lake phytoplankton to seasonal changes at a daily time step. It has been applied in over 35 peer reviewed studies and is one of the most cited lake models in the world (Trolle et al., 2012).

The aims of this study were to examine the historical changes in the Lough, with particular emphasis on the phytoplankton and, through using the PROTECH model, to predict how the phytoplankton community may adapt in response to potential future environmental changes. The focus of these future scenarios was to assess the combined impact of increasing air temperature (predicted for this region of the UK to be between 1 and 4 °C over this century (Jenkins et al., 2009)) and reducing nutrient load, thus creating a range of potential scenarios likely to be seen in the 21st century.

2. Material and methods

2.1. Site description

Lough Neagh is located in Northern Ireland with a surface area of 383 km^2 and volume of 3.45 × 109 m^3. Hydraulic residence time is approximately 1.2 years (Foy et al., 2003), mean and maximum depth are 8.9 m and 34 m respectively. Six inflowing rivers drain 88% of the 4453 km^2 catchment. As well as being a drinking water reservoir, the lake has several conservation designations under the Ramsar convention (Ramsar Bureau, 2000), and the Habitats Directive (EU, 1997). The lake supports a commercial fishery, primarily exploiting the European eel (*Anguilla anguilla*). It is also part of the UK Environmental Change Network (ECN; Sier et al., in this issue). A more in-depth description of the lake and its catchment is provided in Wood and Smith (1993).

2.2. Sampling

Integrated water samples of 10 m were collected by boat at a central lake location (approximately N54 35.779, W6 23.1301) either weekly (1980–1993) or fortnightly (1993 to present) using a lead-weighted polythene tube.

2.3. Laboratory analyses

Water chemistry and biological parameters were determined using standard methodologies (Wood and Smith, 1993). Water chemistry methods for the entire time period were subject to internal Quality Control and external quality proficiency testing (Aquachecks) run by the Laboratory Government Chemists. Certified reference materials were used. The laboratory is also currently UKAS accredited to ISO17025 and test methods are validated to UKAS standards. Water samples were filtered using 0.45 μm pore size GFC filters and analysed for soluble reactive phosphorus (SRP), nitrate, silica and chlorophyll *a*. Chlorophyll *a* was extracted from the residue on the filter paper by being placed in tubes of 90% methanol in a water bath at 55 °C, the pigment was measured spectrophotometrically after centrifugation (Talling and Driver, 1963). Determination of soluble reactive P concentration followed the method of Eisenreich et al. (1975). Samples were not available for 2009. Silica concentration was determined by spectrometer according to Golterman et al. (1978). Analytical methods were consistent across the period with the exception of observations of nitrate concentration which, from 1980 to 2011, was determined by reduction to nitrite (Chapman et al., 1967) and from 2012 was determined according to Environmental Protection Agency (1993). Nitrate is reported as nitrate N. Phytoplankton samples were obtained from a composite water sample. They were counted and their biovolume estimated using an inverted microscope (Lund et al., 1958; CEN, 2006; Brierley et al., 2007; Mischke et al., 2012). A phytoplankton sample was counted for each month.

2.4. Flow and nutrient data for rivers

Nutrient loadings to the lake were calculated using monitoring results from the inflow of the major rivers. Weekly river water samples were obtained over the time series and analysed for SRP, nitrate and silica fractions as for lake water samples. Flow rates for the rivers were available from the Northern Ireland Rivers Agency in daily mean flows ($m^3\,s^{-1}$). Total phosphorus, silica and nitrate concentration entering the lake from each of the eight monitored inflowing rivers were calculated using nutrient-specific regression equations (Eq. (1)):

$$\log_{10}(C_{ij}) = a_j + b_j \log_{10}(Q_{ij}) \qquad (1)$$

where C_{ij} is the nutrient concentration ($\mu g\,l^{-1}$) for river j on day i, Q_{ij} is the river flow ($m^3\,s^{-1}$) for river j on day i and a_j and b_j are regression parameter estimates for river j in 2008.

Daily loads (kg), L_{ij}, were derived by multiplying the daily concentrations (Eq. (1)) by daily flow for river j on day i for 2008. The load, L_{ij}, was corrected for bias using Ferguson (1987) yielding L_{cij}, that is $L_{cij} = L_{ij} \times \exp(2.651 s_j^2)$ where s_j is the estimated standard error of Eq. (1) for river j. The daily, Ferguson corrected, total loading to the lake from all of the rivers was derived by Eq. (2):

$$L_{ci} = \sum_{j=1}^{r} L_{cij} \qquad (2)$$

where r is the number of rivers, L_{ci} is the Ferguson corrected total loading of a nutrient to the lake and L_{cij} is the Ferguson corrected daily load for river j.

2.5. Statistical analysis

Mann–Kendall tests were used to detect monotonic trends in water chemistry. This nonparametric test is based entirely on ranks and is robust against non-normality and censoring. Missing values are taken into account and the method can be extended to account for seasonality (Hirsch et al., 1982, 1991).

2.6. The PROTECH model

PROTECH simulates the responses of between 8 and 10 species of lake phytoplankton throughout a 1D vertical water column at daily time steps. A full description of the model's equations and concepts has been already published (Reynolds et al., 2001; Elliott et al., 2010) but the main biological component of the model can