Upper Lough Erne wetland landscape

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Geographical setting

Lough Erne, from the Irish *Loch Éirne*, comprises two large low-lying lakes fed and in turn linked by the slow-flowing River Erne: the Lower Lough (also known as Broad Lough) and the Upper Lough. The lower Lough and a substantial portion of the Upper Lough system are located in County Fermanagh, Northern Ireland with the latter extending south-eastwards into the Republic of Ireland. The southern part of the Lough Erne catchment lies on Ordovician and Silurian strata and in the northern catchment (especially in Northern Ireland) the system is situated over Carboniferous limestone. For the most part these formations are overlain by Late Midlandian till deposited during the last glaciation (Gibson et al. 1980; Gibson et al. 1995).

The Lower Lough has a surface area of 109.5 km^2 and is the third largest lake in Britain and Ireland. It is considerably deeper than the Upper Lough with average and maximum water depths of 11.9 m and 69 m respectively. The Upper Lough is situated in a drowned drumlin landscape (**Figure 1**) and consists of a main Lough (average depth 2.3 m, maximum depth 27 m) covering an area of 34.5 km^2, and a network of 100+ much smaller, shallower (<3 m) satellite loughs. As a consequence of the drumlin swarms, the main Upper Lough has several small islands and a highly intricate shoreline. Many of the satellite loughs are linked to the main Lough by channels or small rivers, while others are entirely isolated, except during extreme winter flood events.

Biological communities

Due to its shallowness and morphological complexity, the Upper Lough Erne network supports a diverse aquatic flora with over 50 recorded species of submerged and floating aquatic plant (Goldsmith et al. 2008). Rare water plants present in the loughs include Narrow-leaved Water-plantain *Alisma lanceolatum*, Long-stalked Pondweed *Potamogeton praelongus*, Reddish Pondweed *Potamogeton alpinus*, Needle Spike-rush *Eleocharis acicularis*, Frogbit *Hydrocharis morsus-ranae* and Rugged Stonewort *Chara rudis*. The Upper Lough also supports a number of Irish Red Data water beetles (*Donacia aquatica, Donacia bicolora, Gyrinus distinctus, Gyrinus natator* and *Hydroporus glabriusculus*) as well as the White-clawed Crayfish *Austropotabius pallipes* which is now exceptionally rare across all parts of its native European range (Füreder et al. 2010). The wetland habitat of Upper Lough Erne supports one of the strongest UK populations of Eurasian Otter *Lutra lutra* and many migratory aquatic birds. As a consequence of its important biological communities Upper Lough Erne has been designated as an Area of Special Scientific Interest (ASSI), RAMSAR site and also as Special Area of Conservation (SAC) under the EC Habitats Directive

(Article 3) and as a Special Protection Area (SPA) under the EC Birds Directive (Article 4).

In contrast to many shallow lakes in the UK lowlands which either lack aquatic macrophytes, or support species-poor plant communities due to eutrophication (Madgwick et al. 2011), most shallow areas of the main Lough and the vast majority of the satellite loughs are macrophyte-filled waterbodies. Typically the satellite loughs and quieter bays of the main Lough are surrounded by a thick fringe of reedswamp (**Figure 2**) often including Common Reed *Phragmites australis*, Water Horsetail *Equisetum fluviatile* and Common Club-rush *Schoenolectus lacustris*, succeeding to lake edge communities dominated by Yellow Water-lily, Duckweeds and in some cases Water Soldier *Stratiotes aloides* with open water communities often supporting several pondweed (Potamogetonaceae) and stonewort (Characeae) species.

Human-induced ecological change and palaeoecology

Despite its current high ecological importance, the Upper Lough Erne system has long been affected by human-induced pressures. Frequent flood events during the 1800s, due to an inability of the River Erne to discharge the incoming water back to the sea, led to a major drainage scheme between 1880 and 1890 (Price 1890; Cunningham 1992). In this period, channels associated with the main Lough were excavated to increase water depth and as consequence, water levels dropped from around 48 m to 46 m above sea level (Price 1890). Even despite these earlier efforts, recurrent flood events prompted a second attempt at water level regulation under the Erne Drainage and Development Act (Northern Ireland) in the early 1950's. At this time 30 km of channel was dredged between the Upper and Lower Lough Erne loughs, since which time water levels have been maintained between around 43-45 m above sea level (Mathers et al. 2002; Smith et al. 2005). Nevertheless, with the potential for prolonged periods of high rainfall in the region, the area is still prone to major winter flood events (e.g. 2009) which can cover huge areas of the system resulting in most of the satellite loughs (but not all) and the main Lough coalescing into one sheet of water (**Figure 2**).

Eutrophication has also been a major agent of ecological change for the whole Upper Lough Erne system, as revealed by palaeoecology and water chemistry monitoring. A number of diatom-based palaeo-studies suggest a gradual increase in nutrient enrichment since the 1900s with a further acceleration of this process after the 1950s-1960s in particular (Battarbee 1986; Gibson et al. 2003; Salgado et al. 2008a). Nutrient data collected over 1974 to 1997 further show that soluble reactive phosphorus (SRP) loading into Lough Erne increased by approximately 2.0 tonnes SRP yr^{-1} so that, over the same period, mean SRP in the inflow increased from 15 to 33 μg SRP l^{-1} (Zhou et al. 2000). Early eutrophication of Upper Lough Erne is thought to be have been due to domestic effluent inputs after storm drains were introduced to local towns (Battarbee 1986). The acceleration of eutrophication during the mid-twentieth century likely resulted from the interaction of various factors, including increased sewage inputs, intensification of agriculture, increased development of rural septic-tank sanitation and considerable drainage activity during the 1970s, when many streams and channels in the Erne catchment were dredged and straightened and when underfield drains were widely installed (Gibson et al. 2003). All of these factors would have increased nutrient influx to the lake system, whilst reducing wetland buffering.

A further major impact on the Upper Lough Erne system is the Zebra Mussel *Dreissena polymorpha* which invaded the system in the 1990s, most likely as a result of recreational boat movements (Minchin et al. 2003). This species, which originates from the Ponto-Caspian region of Europe and Asia, is a highly efficient filter feeder able to achieve exceptionally high densities on hard substrates in particular. As a consequence, the Zebra Mussel is conceptualised as an ecosystem engineer being able to substantially reduce phytoplankton abundance in lakes (Higgins & Vander Zanden, 2010) with cascading effects through the pelagic food web, affecting lake bed habitats and especially macrophytes which can often be promoted due to reductions in phytoplankton populations (Zhu et al. 2006). Currently, the impacts of Zebra Mussel invasion in the Upper Lough Erne system is incompletely understood, but mussel densities are known to be high in some areas and there is evidence of mussel-induced increases in water transparency (Maguire et al. 2006).

Recent palaeoecologcal work in the Upper Lough Erne main Lough and satellite loughs, has especially focused on plant macrofossil-based reconstructions of aquatic macrophyte community change, with particular reference to eutrophication and Zebra Mussel invasion. In particular, building on the previous work of Goldsmith et al (2008) and Salgado (2011), the recent NERC-funded Lake Biodiversity, Ecosystem Services and Sustainability (LakeBESS) project aimed to understand why, despite current high nutrient concentrations in the Upper Lough Erne network (mean annual total phosphorus and total nitrogen 29-383 μg L^{-1} and 0.22-2.25 mg L^{-1} respectively), macrophyte vegetation is both abundant and species-rich.

A key palaeoecological investigation in the Upper Lough Erne system was carried out by Salgado et al. (2018a) for Castle Lough (13 ha.) in the southern part of the system (**Figure 1**). Sediment cores from three basins of Castle Lough were analysed for plant macrofossils revealing a series of changes to the aquatic vegetation, likely due to eutrophication development (**Figure 3**). Prior to around 1930 Slender Naiad *Najas flexilis,* Quillwort *Isoetes lacustris* and bryophytes were dominant in the lough as is typical under oligo-mesotrophic conditions. After this time all of these plant components declined, with increases evident in canopy-forming *Potamogeton* taxa, especially in basins 2 and 3 (*P. praelongus. P. lucens*) and Millfoil *Myriophyllum* sp. in basin 1. Finally, after c. 1980, *Nitella* sp. oospores increased in basin 1 and remains of floating-leaved taxa such as Ivy-leaved Duckweed *Lemna trisulca,* Water Lily *Nymphaeaceae* and Bur-reed *Sparganium* sp. increased in all basins. This latter shift towards floating plant-dominance, as is evident in the present-day, reflects a further progression of eutrophication. Importantly, through comparison of compositional change trajectories across the multiple cores, the study showed a spatial convergence of macrophytes after the 1980s suggesting that, as eutrophication advances, a limited set of eutrophication-tolerant species became homogeneously distributed across the entire lough. Thus, an early sign of eutrophication in the Upper Lough system seems to be a reduction in broad-scale within-lake variation in plant communities.

A further study by Salgado et al. (2018b) combined the analysis of contemporary macrophyte data for 19 loughs and sediment core macrofossil data for 6 lough sites across the Upper Lough Erne system. A key hypothesis of LakeBESS was that high connectivity between loughs might, at least temporarily, buffer the effects of eutrophication on macrophytes. To this effect, Salgado et al. (2018b) showed that increasing water course connectivity resulted in higher macrophyte diversity and community heterogeneity, with an average of 5-6 more species present in connected loughs, compared to loughs isolated from the main Lough. In addition, it was inferred that dispersal and the exchange of macrophytes among hydrologically connected sites may ultimately maintain macrophyte species abundances that are sensitive to nutrient-enrichment within the system, with Zebra Mussel invasion adding to this eutrophication-buffering effect. Finally and importantly, Salgado et al. (2018b) concluded that, in the long-term, eutrophication impacts have ultimately been countering diversity-generating processes such as connectivity, such that, if high nutrient inputs continue, the conservation value of the Upper Lough system will eventually be greatly diminished, Zebra Mussel or not.

The Upper Lough Erne lake network is arguably the most biologically-rich and intact wetland landscape that remains in Britain and Northern Ireland. Urgent conservation action is needed to combat its growing problem of nutrient enrichment and to protect the loughs for future generations to enjoy. With agricultural intensification progressing at a pace throughout the region there could big troubles ahead (**Figure. 4**). It is crucial that the system is not allowed to degrade as occurred in eastern England's Norfolk and Suffolk Broads after the 1950s-60s. The warning siren has just sounded – who is hearing it?

a). **b).**

Figure 1. Thick and diverse marginal plant communities in the Upper Lough Erne main Lough (a) and in a satellite lough showing dominance of Common Club-rush *Schoenoplectus lacustris* and Yellow Water-lily *Nuphar lutea* (b). Photographs: Ben Goldsmith.

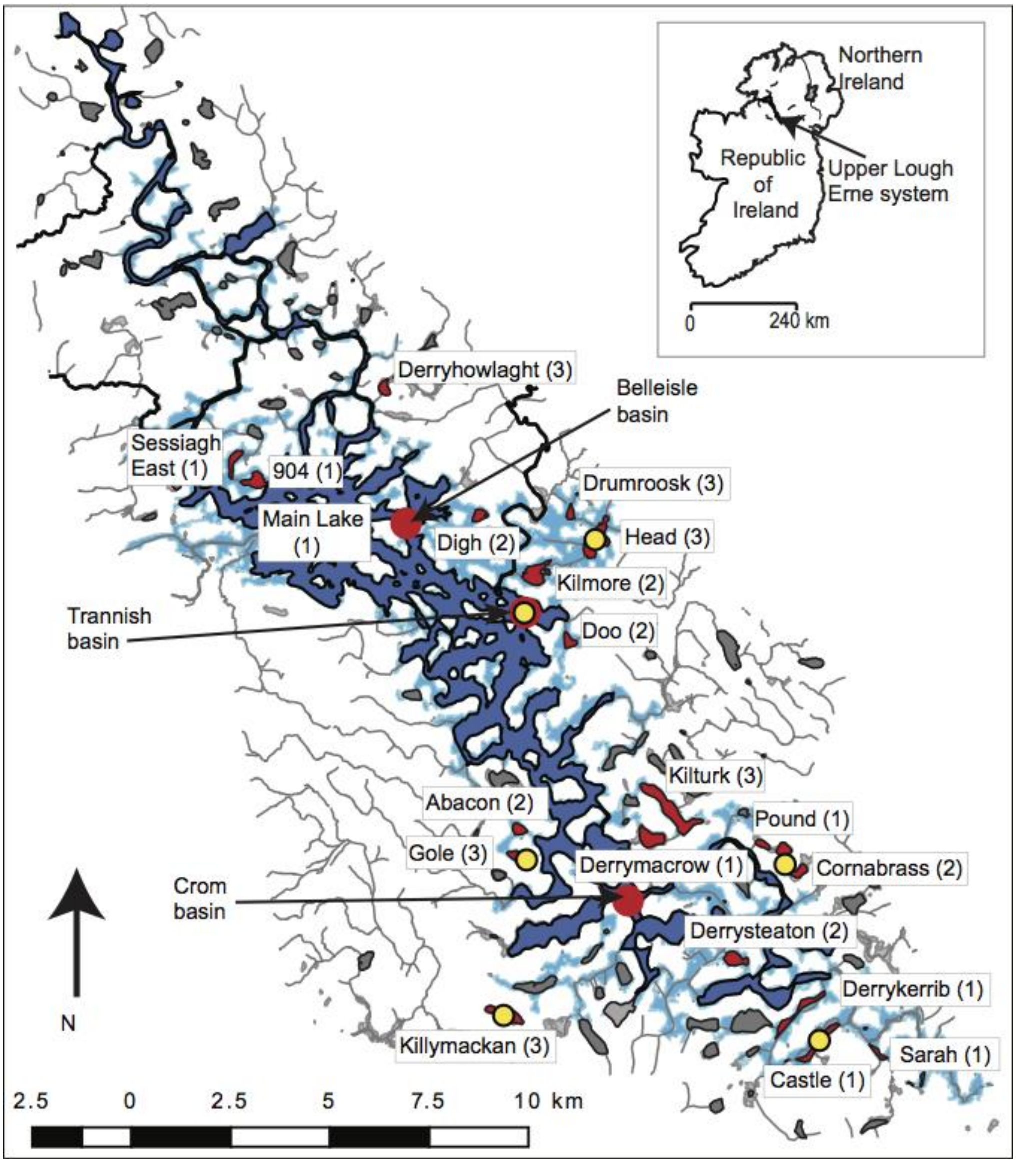

Figure 2. Map of the Upper Lough Erne system, Northern Ireland, illustrating key lough sites studied by Salgado et al. (2010b). The main Lough is indicated in dark blue and the studied satellite loughs are presented in red, with loughs having paleoecological data highlighted with a yellow circle. A number in parenthesis identifies three connectivity groups according to water flow direction. These are Group 1: loughs directly connected to the main Lough via the River Erne; Group 2: loughs with a direct lateral connection to the main Lough; and Group 3: loughs connected laterally to the main Lough via 1 or more intermediate loughs.

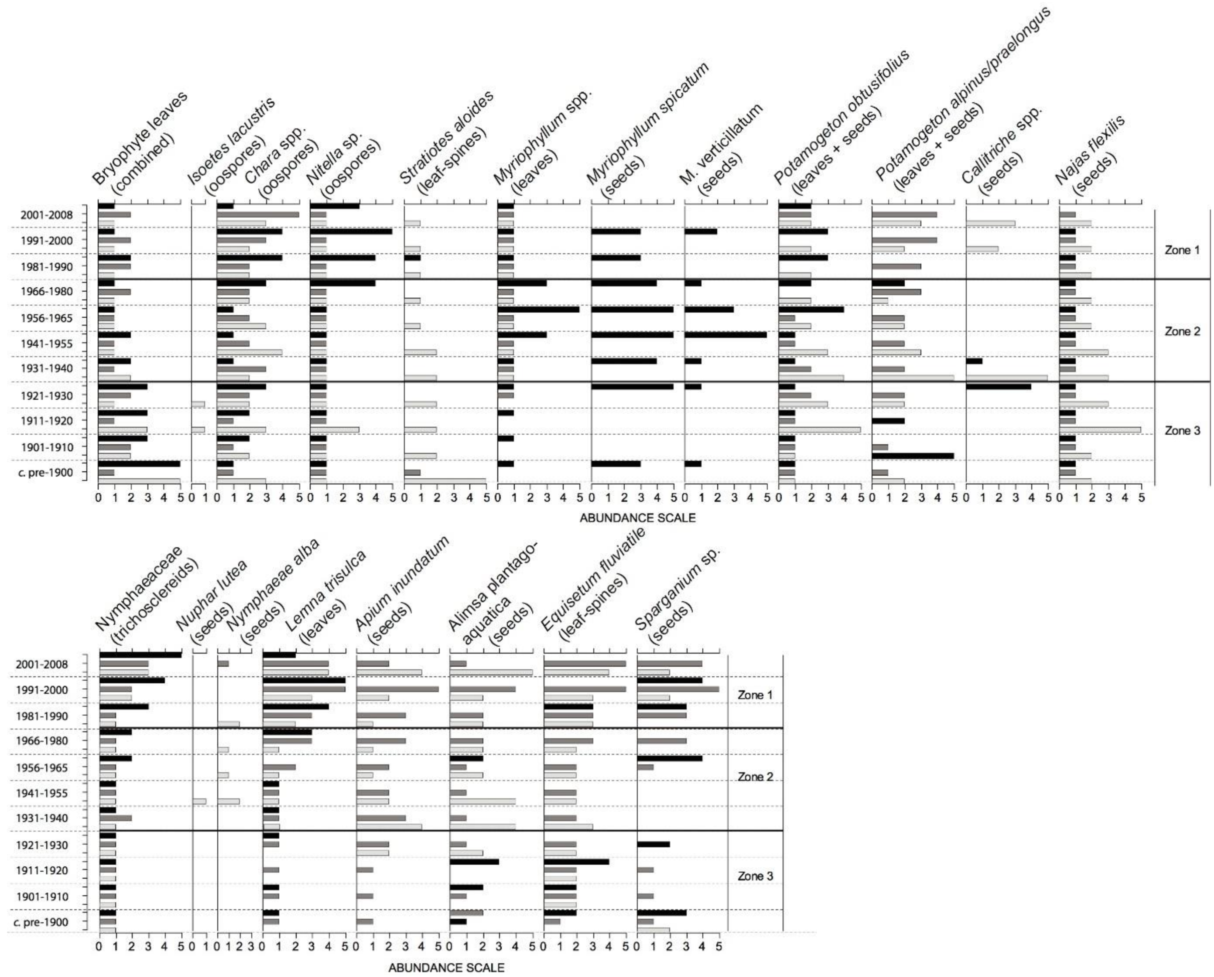

Figure 3. Plant-macrofossil stratigraphy for sediment cores from Castle Lough, Upper Lough Erne, Northern Ireland (see Fig. 2 for location). Cores NCAS1-basin 1 (black), NCAS2-basin 2 (dark grey), and NCAS3-basin 3 (light grey). Dotted lines represent a c. 10-year time-period. Solid black lines represent zones corresponding to c. pre-1900-1920, 1931-1980 and 1981-present (from Salgado et al. 2018a).

Figure 4. Slurry recently applied to grassland sloping down to an Upper Lough Erne satellite lough. Photo: Ben Goldmsith.

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