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epa Research

Framework for Characterising Oligotrophic (3110 and 3160) Lakes Using Practical Methods and Assessment Tools

Authors: Heather T. Lally, Martin Gammell, Emma Gray, Giovanni Cappelli and Cilian Roden

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The EPA is assisted by advisory committees who meet regularly to discuss issues of concern and provide advice to the Board.

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Authors: Heather T. Lally, Martin Gammell, Emma Gray, Giovanni Cappelli and Cilian Roden

Lead organisation: Atlantic Technological University

Identifying pressures

Oligotrophic lake habitats are protected freshwater habitats in Ireland. They are unproductive environments where it can be difficult to sustain life. These lake habitat types are characterised using the presence of plant communities. However, other organisms, such as algae and macroinvertebrates, also show potential for characterising these lake habitats and could aid in assessing their conservation condition. This project aimed to investigate this potential through (i) characterising the water profile and plant and animal communities of oligotrophic lake habitats, (ii) evaluating what environmental conditions are needed to maintain these lake habitats in favourable conservation condition, (iii) assessing and recommending monitoring methods and assessment tools and (iv) proposing measures needed to maintain these lake habitats in favourable conservation condition.

Informing policy

We assessed water chemistry and data from plant communities, including macrophytes, algal communities (including desmids) and invertebrate communities, such as dragonflies, damselflies and beetles, from 24 water bodies within Atlantic blanket bog landscapes in western Ireland. We found all water bodies to be acidic with low alkalinity and conductivity and high water colour and organic matter content. Plant communities were sparse and species-poor and showed no distinct vegetation zonation patterns. A low plant species richness was observed across all water bodies sampled. Desmids (a type of algae) were the most species-rich group in the water bodies sampled, with oligotrophic lake habitats deemed important places for rare and vulnerable desmid species. In addition, the application of the desmid nature conservation value metric proved a useful monitoring tool, indicating the conservation value of the surveyed water bodies. Damselflies and predatory beetles were the most important macroinvertebrates differentiating oligotrophic lake habitat types. Furthermore, water bodies sampled hosted four Irish national red list species, highlighting the conservation value of these lake habitat types for invertebrate diversity.

Developing solutions

This research is important for the conservation of small water bodies (area ≤ 0.01 km^2) within Irish peatland landscapes. Such small water bodies would benefit from an updated National Peatlands Strategy implementation plan to safeguard their long-term monitoring and protection through financial supports and the implementation of conservation measures. Based on our research findings, we recommend that state agencies with responsibility for monitoring protected lake habitats in Ireland conduct a short "snapshot" field sampling programme to include a broader range of oligotrophic lake habitat types. This snapshot field sampling programme should collect data on water colour, pH, alkalinity and organic matter; maximum depth of macrophyte colonisation in the water body; dominant algal groups; and desmids and macroinvertebrates. It should also calculate the desmid nature conservation value metric and note rare species of all plants and animals. These findings will support the monitoring of favourable conservation conditions in oligotrophic lake habitats under the EU Habitats Directive.

EPA RESEARCH PROGRAMME 2021–2030

Framework for Characterising Oligotrophic (3110 and 3160) Lakes Using Practical Methods and Assessment Tools

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Prepared for the Environmental Protection Agency

by

Atlantic Technological University

Authors:

Heather T. Lally, Martin Gammell, Emma Gray, Giovanni Cappelli and Cilian Roden

ENVIRONMENTAL PROTECTION AGENCY
An Ghníomhaireacht um Chaomhnú Comhshaoil
PO Box 3000, Johnstown Castle, Co. Wexford, Ireland

Telephone: +353 53 916 0600 Fax: +353 53 916 0699
Email: info@epa.ie Website: www.epa.ie

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DISCLAIMER

This report is based on research carried out/data from September 2020 to February 2024. More recent data may have become available since the research was completed.

The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

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Project Partners

Dr Heather T. Lally
Department of Natural Resources and the Environment
School of Science and Computing
Atlantic Technological University
Galway City
Ireland
Tel.: +353 9 174 2484
Email: heather.lally@atu.ie

Dr Martin Gammell
Department of Natural Resources and the Environment
School of Science and Computing
Atlantic Technological University
Galway City
Ireland
Tel.: +353 9 174 2363
Email: martin.gammell@atu.ie

Dr Emma Gray
Department of Natural Resources and the Environment
School of Science and Computing
Atlantic Technological University
Galway City
Ireland
Tel.: +353 9 174 2181
Email: emma.gray@atu.ie

Dr Giovanni Cappelli
Marine and Freshwater Research Centre
Department of Natural Resources and the Environment
School of Science and Computing
Atlantic Technological University
Galway City
Ireland
Email: giocapp91@gmail.com

Dr Cilian Roden
Roden Ecology
Kinvara
Co. Galway
Ireland
Tel.: +353 86 171 3795
Email: cilianroden@icloud.com

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Executive Summary

Oligotrophic isoetid lake habitat (lake habitat code 3110) and acid oligotrophic lake habitat (lake habitat code 3160) are protected freshwater habitats under the European Union Habitats Directive (Directive 92/43/EEC). Ireland is a stronghold for both oligotrophic lake habitats in Europe; however, their conservation condition is bad (declining) and inadequate (stable), respectively. The *Interpretation Manual of European Union Habitats* focuses mainly on the phytosociological communities and a few physico-chemical conditions of each lake habitat. However, several other biological elements, such as phytoplankton and macroinvertebrates, have potential for use in characterising these lake habitat types and could aid in monitoring and assessing conservation condition. This project aimed to investigate this potential.

This research project had four main objectives:

1. to characterise the physico-chemical and biological elements of oligotrophic lake habitats 3110 and 3160 and their natural variations;
2. to evaluate the environmental conditions necessary to maintain oligotrophic lake habitats 3110 and 3160 in favourable conservation condition;
3. to assess and recommend monitoring methods and assessment tools; and
4. to propose measures needed to maintain oligotrophic lake habitats 3110 and 3160 in favourable conservation condition.

Key Findings

Data from this research provide specific baseline information on 24 water bodies within Atlantic blanket bog landscapes in western Ireland, specifically Connemara Bog Complex Special Area of Conservation (SAC) and Owenduff/Nephin SAC, and offers insights into regional and environmental factors influencing the characterisation of oligotrophic isoetid lake habitat 3110 and acid oligotrophic lake habitat 3160 within these landscapes.

Based on the 24 water bodies surveyed, oligotrophic isoetid lake habitat 3110 (12 water bodies) and acid oligotrophic lake habitat 3160 (12 water bodies) have similar biological communities and physico-chemical conditions that do not clearly distinguish them from each other in terms of lake habitat type. A strong regional distinction was observed in the water chemistry and all biological (macrophyte, desmids, Odonata and Coleoptera) datasets between Owenduff/Nephin SAC and Connemara Bog Complex SAC.

All lakes and pools sampled were in favourable conservation condition and naturally dystrophic, with acidic waters, low buffering capacity and conductivity, and high colour and organic matter content; however, it is acknowledged that oligotrophic isoetid lake habitat 3110 is also considered to exist in more rocky catchments, which were not sampled. The water chemistry parameters alkalinity, pH, true colour and dissolved organic matter were most influential in determining the regional biological communities (macrophytes, desmids, Odonata and Coleoptera) of the water bodies surveyed.

The ecological functioning of the water bodies sampled was driven by dissolved organic matter and mixotrophic algae rather than macrophytes, whose communities were relatively sparse and species-poor and who, in the water bodies surveyed, showed no distinct vegetation zonation patterns. In general, a low macrophyte species richness was observed across all water bodies sampled.

Desmids were the most species-rich group in both planktonic and benthic water samples and, based on the water bodies sampled, both oligotrophic lake habitats are important refuges for rare and vulnerable red-listed desmid species. In addition, moderate to high conservation values, determined using the desmid nature conservation value metric, demonstrated the conservation value of these water bodies for desmids.

Odonata of the family Coenagrionidae, including the species *Ischnura elegans* and *Pyrrhosoma nymphula,* dominated the water bodies classified as oligotrophic

isoetid lake habitat 3110, while predatory Coleoptera from the family Gyrinidae, including the species *Gyrinus minutus* and *Gyrinus aeratus*, dominated those classified as acid oligotrophic lake habitat 3160. Furthermore, water bodies sampled hosted four Irish national red list species – three near-threatened Coleoptera species and one endangered Odonata species – demonstrating the conservation value of these oligotrophic lake habitats for invertebrate diversity.

Priority Recommendations

A short "snapshot" field sampling programme of a broader range of oligotrophic isoetid lake habitat 3110 and acid oligotrophic lake habitat 3160 water bodies is recommended to capture regional variations and distinctions, including water bodies likely to be of unfavourable conservation condition owing to threats and pressures in their catchments. This snapshot field sampling programme should:

- collect data on maximum depth of macrophyte colonisation of the water body to further elucidate relationships between water chemistry and macrophytes;
- sample and identify, to species level, planktonic and benthic desmids of oligotrophic lake habitat types;
- identify all algal groups within the phytoplankton and monitor changes in dominant mixotrophic algal groups over time;
- record the physico-chemical parameters pH, alkalinity, dissolved oxygen, dissolved organic matter and water colour, in association with biological elements, to help improve understanding of ecological functioning within the water bodies;
- identify all macroinvertebrate taxa, to family level, to provide information on community composition;
- note species rarity (number of rare species) for macrophytes, desmids and invertebrates, as water bodies sampled hosted species of high conservation value; and
- utilise new and existing desmid data within Ireland to adapt and calculate the nature conservation value desmid metric and advance the development of condition assessments methods.

1 Introduction

1.1 Background

Oligotrophic isoetid lake habitat (lake habitat code 3110) and acid oligotrophic lake habitat (lake habitat code 3160) are protected freshwater habitats under the European Union (EU) Habitats Directive (Directive 92/43/EEC). Ireland is a stronghold for both oligotrophic lake habitats in Europe (O Connor, 2015); however, their conservation status is bad (declining) and inadequate (stable), respectively (NPWS, 2019).

Lake habitat 3110 is described by the *Interpretation Manual of European Union Habitats* (EC, 2013) as oligotrophic waters containing very few minerals of sandy plains (*Littorelletalia uniflorae*) and is characterised as shallow oligotrophic waters with few minerals and base-poor, with aquatic to amphibious low perennial vegetation of the order Littorelletalia uniflorae on oligotrophic (peaty) soils of lake and pool banks. Vegetation is dominated by *Littorella uniflora*, *Lobelia dortmanna* or *Isoetes* sp. In Ireland, the national working interpretation (O Connor, 2015) described lake habitat 3110 as oligotrophic isoetid lake habitat commonly found on sheltered, gently sloping shorelines, associated with peatland areas with soft, base-poor (pH < 6.5), nutrient-poor waters on acid bedrock catchments (i.e. granite and/or old red sandstone) overlain by peatlands. They are dominated by isoetids.

Lake habitat 3160 is described by the *Interpretation Manual of European Union Habitats* (EC, 2013) as natural dystrophic lakes and ponds, and characterised by naturally occurring lakes and ponds with brown (peat and humic acids) waters on peaty soils in bogs and heath (EC, 2007, 2013; EEA, 2013). pH is low (3–6) and plant communities are typically of the order Utricularietalia. The Irish working interpretation (O Connor, 2015) described lake habitat 3160 as acid oligotrophic lake habitat that is species-poor and dominated by aquatic *Sphagnum* (*Sphagnum cuspidatum* and *Sphagnum auriculatum*) mosses in small lakes and ponds in Atlantic and upland blanket bogs and wet heath. A rich invertebrate diversity, including Chydorid Cladocera, Coleoptera, Trichoptera and Heteroptera, has also been observed (Drinan, 2012).

Overall, the descriptions of lake habitats 3110 and 3160, as defined by the EU (EEA, 2013), rely heavily on macrophyte community data, with little consideration given to other biological elements. This has, in turn, led to differences in the interpretation of lake habitats by EU Member States. In addition, similar lake communities can be found in more than one environmental scenario (O Connor, 2015). This high degree of variation in habitat characteristics and differences in interpretation can make it difficult to confidently assign an individual lake to one habitat type.

Under the EU Habitats Directive there is no requirement for lake habitats to be continuously monitored; therefore, Member States assess the national conservation status of range, area and structure and function using a combination of "expert opinion", "extrapolation of limited data", "complete surveys" or "statistically robust estimates" (EEA, 2019). In general, range and area can be estimated and extrapolated using remote techniques (e.g. satellite imagery), whereas the evaluation of structure and function requires field data on their distribution, characteristics and environmental drivers, which are often limited (EEA, 2019; O Connor, 2015). In Ireland, where macrophyte community composition data are available they are used to determine the range, area and structure and function of lake habitats (NPWS, 2013, 2019).

The *Interpretation Manual of European Union Habitats* focuses mainly on the phytosociological communities and limited physico-chemical conditions of each lake habitat. However, several other biological elements, especially in the case of standing waters, such as phytoplankton, zooplankton and macroinvertebrates, have potential for characterising lake habitat types and could aid in monitoring and assessing conservation condition (Cappelli, 2024). In Ireland, a concerted effort is needed to gather the necessary baseline field data required to inform the overall conservation condition of oligotrophic lake habitats 3110 and 3160 under the EU Habitats Directive.

A comprehensive literature review, "A review of dystrophic lake and pool habitat in Europe: an Irish perspective", was published in the *Journal for Nature Conservation* (Gray *et al*., 2022).

1.2 Objectives

This research project had four main objectives:

1. to characterise the physico-chemical and biological elements of oligotrophic lake habitats 3110 and 3160 and their natural variations;
2. to evaluate the environmental conditions necessary to maintain oligotrophic lake habitats 3110 and 3160 in favourable conservation condition;
3. to assess and recommend monitoring methods and assessment tools; and
4. to propose measures needed to maintain oligotrophic lake habitats 3110 and 3160 in favourable conservation condition.

1.3 Study Sites

Connemara Bog Complex Special Area of Conservation (SAC) (site code IE0002034), County Galway, and Owenduff/Nephin Complex SAC (site code IE0000534), County Mayo (Figure 1.1), contain both oligotrophic lake habitats 3110 and 3160 in favourable conservation condition (O Connor, 2015; NPWS, 2020). To ensure sites of favourable conservation condition were targeted for study, both SACs underwent pre-screening using satellite imagery (Google Earth Pro, version 7.3.4.8642). This process involved the rejection of water bodies located inside conifer forestry, where peat cutting was evident, and within catchments with other anthropogenic impacts (e.g. agriculture or roads). Since the effect of past grazing pressure is generally not assessable by satellite imagery, this was evaluated using the Commonage Framework Planning (CFP) reports (NPWS, 2013). Sites were also rejected where the CFP reports indicated any level of damage (low to high). Final selection of water bodies was determined based on nearby river water quality status (2013–2018) (EPA, 2022), with only sites within proximity to good or high river water bodies (based on Water Framework Directive River Waterbody Status 2013–2018 national assessment) retained. In total, 24 water bodies were selected for study, with lakes greater than 0.01 km^2 expected to contain lake habitat

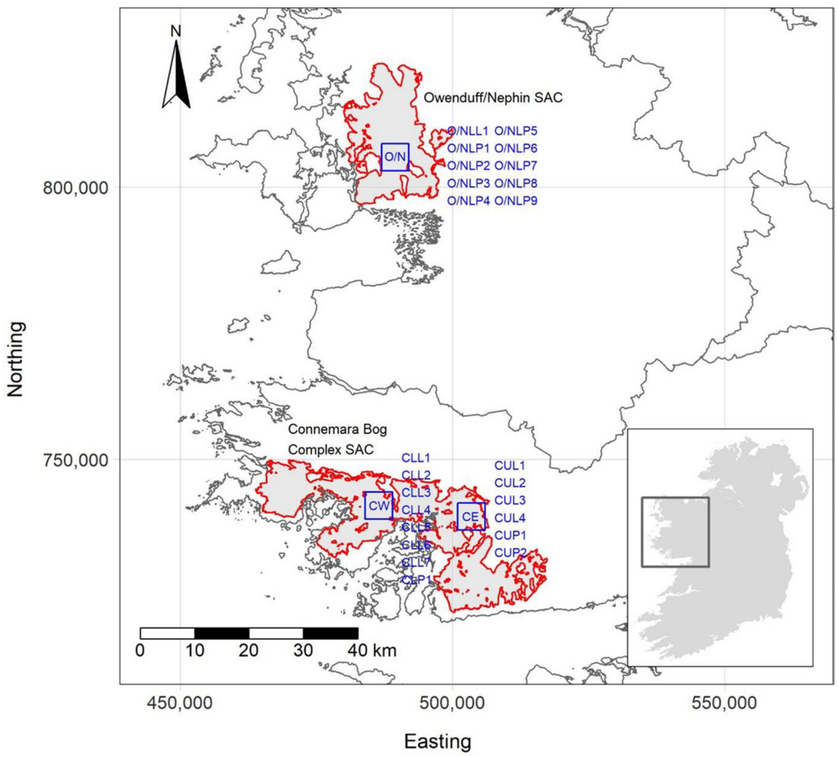

Figure 1.1. Map of study sites showing Owenduff/Nephin (O/N) SAC and Connemara Bog Complex SAC (red polygon contours). Sampling sites for each region, O/N, Connemara west (CW) and Connemara east (CE), are listed in blue. Inset: map of Ireland with sampling location in the west of Ireland highlighted. LL, lowland lake; LP, lowland pool; UL, upland lake; UP, upland pool.

3110 and pools of less than 0.01 km^2 expected to contain lake habitat 3160 (O Connor, 2015).

The Connemara Bog Complex SAC is a large site dominated by lowland Atlantic blanket bog with deep peat lying on igneous bedrock (NPWS, 2015). The eastern region is dominated by granite rock, while the central and western regions are dominated by gabbroic and quartz-dioritic layers (GSI, 2022). An average monthly rainfall of 116.1 mm was recorded for the SAC during the study (recorded at Mace Head, March 2021 to February 2022) (Met Éireann, 2022). Fourteen water bodies across two regions were selected for study in the Connemara Bog Complex SAC. In Connemara west, seven lakes classified as habitat 3110 and one habitat 3160 pool were studied (NPWS, 2015b), while in Connemara east four habitat 3110 lakes and two habitat 3160 pools were sampled (Figure 1.1).

Water bodies within the Owenduff/Nephin SAC were located in the Owenduff river catchment and were surrounded by an extensive area of active blanket bog with metasedimentary quartzites and schists (GSI, 2022; NPWS, 2017). An average monthly rainfall of 135.9 mm was recorded for the SAC during the study (recorded at Furnace, Newport) (Met Éireann, 2022). Ten water bodies, comprising one habitat 3110 lake and nine habitat 3160 pools, were selected (NPWS, 2017). Table 1.1 provides a summary of the study site characteristics.

1.4 Methods and Materials

Full details of the sampling methods employed and materials used throughout this research can be found in our field assessment methodologies manual, available at https://peatlakes.wordpress.com/publications/.

Table 1.1. Summary of study site characteristics

Site name[a]	Location coordinates (latitude, longitude)	Lake habitat assigned[b]	Habitat type	Altitude (m ASL)	Lake area (km²)	Catchment area (km²)	Approximate distance from the sea (km)
O/NLL 1	53.998153, –9.687078	3110	Lake	151	0.0106	0.0349	7.5
O/NLP 1	53.994844, –9.688436	3160	Pool	150	0.0016	0.0256	7.3
O/NLP 2	53.995578, –9.689233	3160	Pool	150	0.0018	0.0023	7.3
O/NLP 3	53.995231, –9.687850	3160	Pool	151	0.0011	0.0121	7.3
O/NLP 4	53.995900, –9.690250	3160	Pool	149	0.0028	0.0061	7.2
O/NLP 5	53.997781, –9.685533	3160	Pool	153	0.0008	0.0057	7.6
O/NLP 6	53.995317, –9.690158	3160	Pool	149	0.0033	0.0076	7.2
O/NLP 7	53.994808, –9.691239	3160	Pool	148	0.0005	0.0019	7.1
O/NLP 8	53.992481, –9.690792	3160	Pool	147	0.0060	0.0123	7.1
O/NLP 9	53.991833, –9.690694	3160	Pool	147	0.0003	0.0004	7.0
CLL 1	53.420597, –9.718833	3110	Lake	27	0.0887	1.4507	4.6
CLL 2	53.427989, –9.712903	3110	Lake	41	0.0326	0.1538	5.3
CLL 3	53.427628, –9.709103	3110	Lake	42	0.0108	0.0303	5.4
CLL 4	53.426244, –9.706181	3110	Lake	40	0.0403	0.3457	5.2
CLL 5	53.419497, –9.702053	3110	Lake	28	0.0389	0.2517	4.4
CLL 6	53.416375, –9.702503	3110	Lake	32	0.0105	0.0747	4.2
CLL 7	53.416917, –9.709889	3110	Lake	26	0.0830	3.8928	4.7
CLP 1	53.425897, –9.714419	3160	Pool	40	0.0089	0.0339	5.1
CUL 1	53.395814, –9.443747	3110	Lake	190	0.0170	0.0875	6.7
CUL 2	53.402194, –9.445675	3110	Lake	200	0.0406	0.3311	6.5
CUL 3	53.399700, –9.432550	3110	Lake	202	0.0191	0.2724	7.4
CUL 4	53.390725, –9.436958	3110	Lake	166	0.0244	0.7959	7.2
CUP 1	53.392850, –9.436911	3160	Pool	173	0.0006	0.0080	7.2
CUP 2	53.401578, –9.433133	3160	Pool	208	0.0011	0.0134	7.3

[a]Lowland sites are less than 150 m ASL, while upland sites are more than 150 m ASL (Fossitt, 2000). Lakes have a surface area greater than 0.01 km^2, while pools have a surface area less than 0.01 km^2 (O Connor, 2015).

[b]As assigned in NPWS (2015b, 2017).

ASL, above sea level; LL, lowland lake; LP, lowland pool; UL, upland lake; UP, upland pool.

2 Water Chemistry Characterisation

2.1 Introduction

The European Commission (EC, 2013) provides limited information on the expected chemical characterisation of lake habitats 3110 and 3160, with the only guidance being that their waters are nutrient-poor and pH is low. Thus, few data exist on the chemical thresholds and favourable reference values of these lake habitats.

The water chemistry of oligotrophic isoetid lake habitat 3110 is expected to be clear (true colour between 10 and 30 mg/L, Platinum-Cobalt scale (Pt-Co)), oligotrophic (low in phosphorus and nitrogen nutrients), with low turbidity and organic matter, and base-poor, with acidic to circum-neutral pH (pH > 5.5–7) (Borowiak *et al*., 2020; EC, 2013; EEA, 2016a; Free *et al*., 2009; Murphy, 2002; O Connor, 2015). In contrast, acid oligotrophic lake habitat 3160 is defined as small lake and pond water bodies that are brown in colour, with low transparency due to high concentrations of dissolved organic matter (DOM), low in nutrients and base-poor, with an acidic pH (pH 3–6), and are often oxygen limited (EC, 2013; EEA, 2016b; Gray *et al*., 2022; Murphy, 2002). Both lake habitats are considered nutrient-poor and, in Ireland, should have oligotrophic (0.005–0.01 mg/L) or ultra-oligotrophic (< 0.005 mg/L) total phosphorus levels, based on Water Framework Directive (WFD) (Directive 2000/60/EC) standards (O Connor, 2015), to be considered in favourable conservation condition. However, for acid oligotrophic lake habitat 3160, which is considered dystrophic in nature, water chemistry parameters such as colour and pH are more important descriptors of habitat condition (EC, 2013), with colour levels expected to be below 50 mg/L Pt-Co (O Connor, 2015).

To date, much of the physico-chemical data on oligotrophic lake habitats 3110 and 3160 have been gathered using broader research on peatland lakes and pools (Drinan, 2012). Data have been collected from these sources for very different purposes and, in most instances, lake habitat type is not distinguished. In addition, it is difficult to define favourable reference values for physico-chemical parameters without knowledge of their undisturbed state (Louette *et al*., 2011; O Connor, 2015). In Ireland, many peatland lakes have been subjected to multiple stressors (Drinan, 2012; NPWS, 2015; O Connor, 2015, 2016) that have altered their natural chemistry.

Overall, a general lack of water chemistry data from oligotrophic lake habitats 3110 and 3160 has hampered both the identification of characteristic structure and function features of these lake habitats and the detection of site-level changes in their conservation condition over time. This prevents appropriate evaluation of their conservation status at a national level (Gray *et al*., 2022; O Connor, 2015). Therefore, to improve and strengthen confidence in assessments, *in situ* monitoring and assessment of a variety of physico-chemical elements were required.

2.2 Objectives

The research objectives of this work package were to:

1. characterise the water chemistry of favourable oligotrophic lake habitats 3110 and 3160; and
2. investigate the effects of regional variations, seasonal patterns and catchment on the water chemistry of oligotrophic lake habitats.

2.3 Methods and Materials

Full details of the water chemistry methods and materials, statistical analysis, results and discussion can be obtained from our publication "Physico-chemical characterisation of protected lake habitats: a matter of dystrophy" (Cappelli *et al*., 2023).

2.4 Results

2.4.1 Characterise the water chemistry of favourable oligotrophic lake habitats 3110 and 3160

All water bodies sampled, whether classified as lake habitat 3110 or 3160, were oligotrophic in nature, with low nutrient concentrations, acidic waters (pH ≤ 7), average-medium true colour and DOM, low silica and alkalinity (≤ 10 mg/L $CaCO_3$) and very low conductivity, with oxygen-saturated surface waters (Table 2.1).

Table 2.1. Annual mean (± standard deviation), median and range for each water chemistry parameter recorded in oligotrophic lake habitats 3110 and 3160. Only parameters with values greater than the limits of detection are presented. Mann–Whitney U tests with *p*-values (significant values in bold) comparing each water chemistry parameter between oligotrophic isoetid lake habitat 3110 (*n* = 12) and acid oligotrophic lake habitat 3160 (*n* = 12)

Parameter	Mean and standard deviation		Median		Range		Mann–Whitney statistic
	3110	3160	3110	3160	3110	3160	
Alkalinity (mg/L $CaCO_3$)	0.21 ± 1.06	–0.62 ± 0.89	0.015	–0.64	–2.08–4.79	–6.43–2.42	U = 123, *p*-value = **0.003**
Ammonium (mg/L)	0.017 ± 0.009	0.016 ± 0.006	0.014	0.014	0.010–0.062	0.010–0.055	U = 81, *p*-value = 0.60
Chloride (mg/L)	13.38 ± 3.13	12.62 ± 3.75	13.85	12.30	5.41–22.10	5.410–35.00	U = 86, *p*-value = 0.42
Conductivity (µS/cm)	42.66 ± 10.31	40.44 ± 9.46	41.85	40.00	19.02–67.85	23.42–65.30	U = 91, *p*-value = 0.27
Dissolved organic matter (QSU)	44.40 ± 20.29	27.22 ± 16.91	41.45	25.34	2.60–116.34	3.20–69.70	U = 125, *p*-value = **0.002**
Dissolved oxygen (% saturation)	97.91 ± 6.16	93.56 ± 12.10	99.12	97.64	66.80–123.2	32.38–103.9	U = 109, *p*-value = **0.03**
Orthophosphate[a] (mg/L)	0.005 ± 0.005	0.006 ± 0.007	0.004	0.005	0.003–0.040	0.003–0.060	U = 61, *p*-value = 0.56
pH	5.70 ± 0.54	5.07 ± 0.44	5.71	4.91	4.63–6.79	4.54–6.61	U = 123, *p*-value = **0.003**
Silica[a] (mg/L)	0.10 ± 0.11	0.04 ± 0.02	0.07	0.04	0.02–0.68	0.01–0.14	U = 124.5, *p*-value = **0.002**
Temperature (°C)	12.19 ± 5.19	11.81 ± 5.16	12.65	11.79	3.60–26.31	3.84–24.79	U = 89, *p*-value = 0.33
Total phosphorus (mg/L)	0.010 ± 0.005	0.011 ± 0.006	0.010	0.011	0.003–0.044	0.004–0.069	U = 42, *p*-value = 0.09
True colour (mg/L Pt-Co)	52.61 ± 27.97	33.57 ± 21.82	43.20	28.80	13.10–134.0	4.70–109.0	U = 116, *p*-value = **0.01**
Turbidity (FNU)	0.78 ± 1.11	0.91 ± 1.30	0.50	0.66	0.20–9.48	0.20–14.70	U = 57.5, *p*-value = 0.43

[a]Data refer to 6 months of sampling.
FNU, formazin nephelometric unit; QSU, quinine sulphate unit.

These results suggest that both oligotrophic lake habitats 3110 and 3160, when in favourable conservation condition, are naturally dystrophic where they have acidic waters with low buffering capacity and conductivity and high colour and organic matter content. True colour, DOM, pH, alkalinity, silica and dissolved oxygen (DO) values were significantly higher in those lakes with a preliminary classification of oligotrophic isoetid lake habitat 3110 than in those classified as acid oligotrophic lake habitat 3160 (Table 2.1).

2.4.2 *Investigate the effects of regional variation, seasonal patterns and catchment on the water chemistry of oligotrophic lake habitats*

Regional variation

Principal component analysis showed that water chemistry data separated the water bodies into three significant groupings, reflecting the three different regions sampled (permutational multivariate analysis of variance (PERMANOVA) tests: Owenduff/Nephin ≠ Connemara west, pseudo-F = 28.67, $R^2 = 0.64$, $p < 0.01$; Owenduff/Nephin ≠ Connemara east, pseudo-F = 19.96, $R^2 = 0.59$, $p < 0.01$; and Connemara east ≠ Connemara west, pseudo-F = 5.25, $R^2 = 0.30$, $p < 0.01$). Water bodies in Connemara west ($n = 8$) were associated with higher levels of ammonium, those of Connemara east ($n = 6$) with higher pH, alkalinity and silica levels, and those of Owenduff/Nephin SAC ($n = 10$) with higher turbidity, orthophosphate and total phosphorus (Figure 2.1).

The water chemistry profiles of Connemara east and Connemara west differed from those of Owenduff/Nephin SAC in terms of median levels of DOM ($\chi^2 = 16.50$, $p < 0.001$), pH ($\chi^2 = 17.14$, $p < 0.001$) and alkalinity ($\chi^2 = 16.75$, $p < 0.001$) (Figure 2.2). Regional differences predominantly reflected the small pool water bodies surveyed in the Owenduff/Nephin SAC, where 9 out of 10 water bodies were assigned to acid oligotrophic lake habitat 3160 based on lake area (< 0.01 km^2). These pools have significantly lower

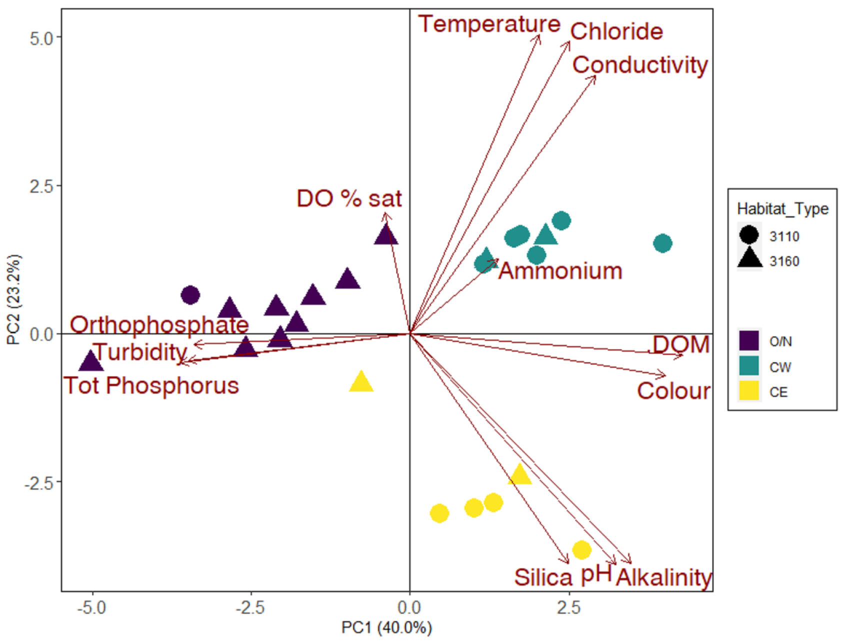

Figure 2.1. Principal component analysis of annual mean water chemistry data for oligotrophic lake habitats 3110 and 3160. Length of arrows (loadings) represents the contribution of the environmental variable to that grouping output. Lake habitat types are denoted as octagons (3110) and triangles (3160). Owenduff/Nephin sampling sites are denoted in purple (*n*=10); Connemara west sites in green (*n*=8); and Connemara east sites in yellow (*n*=6). Tot phosphorus, total phosphorus.

median levels of DOM, pH and alkalinity than water bodies in Connemara west (where only one water body was assigned acid oligotrophic lake habitat 3160) and Connemara east (where two water bodies were assigned acid oligotrophic lake habitat 3160), which were predominantly lakes with a surface area greater than 0.01 km^2.

Seasonal patterns

Most water chemistry parameters showed seasonal variation, with all water bodies experiencing an increase in true colour and DOM and a decrease in conductivity in autumn (Figure 2.3) due to increased rainfall delivering more organic matter from the surrounding catchment.

Catchment influences

Catchment area and slope were important determinants of DOM, silica concentrations and true colour. Regression analysis showed there was a significant relationship between silica and catchment slope, DOM and catchment area, and true colour and catchment area for oligotrophic lake habitats 3110 and 3160 (Figure 2.4). In particular, for oligotrophic isoetid lake habitat 3110, levels of true colour and DOM were higher in lakes with larger catchments.

2.5 Conclusion

Water chemistry data suggest that, in the water bodies sampled, both oligotrophic lake habitats 3110 and 3160, when in favourable conservation condition, are naturally dystrophic where they have acidic waters with low buffering capacity and conductivity and high colour and organic matter content. A strong regional difference was reflected in the sampling areas, where small ombrotrophic pools less than 0.01 km^2 were predominantly located in the Owenduff/Nephin SAC, while larger lakes (surface area greater than 0.01 km^2) with large catchment size were found in the Connemara Bog Complex SAC. DOM and true colour showed seasonal patterns, with autumn noted as an important time of year for increased DOM and true colour in both oligotrophic lake habitats, reflecting increased rainfall and thus surface run-off. These were also influenced by catchment area, with higher levels of DOM and true colour in water bodies with larger catchment areas. Consequently, this research found that monitoring water colour alone and classifying and assessing lake habitat type based on colour is not

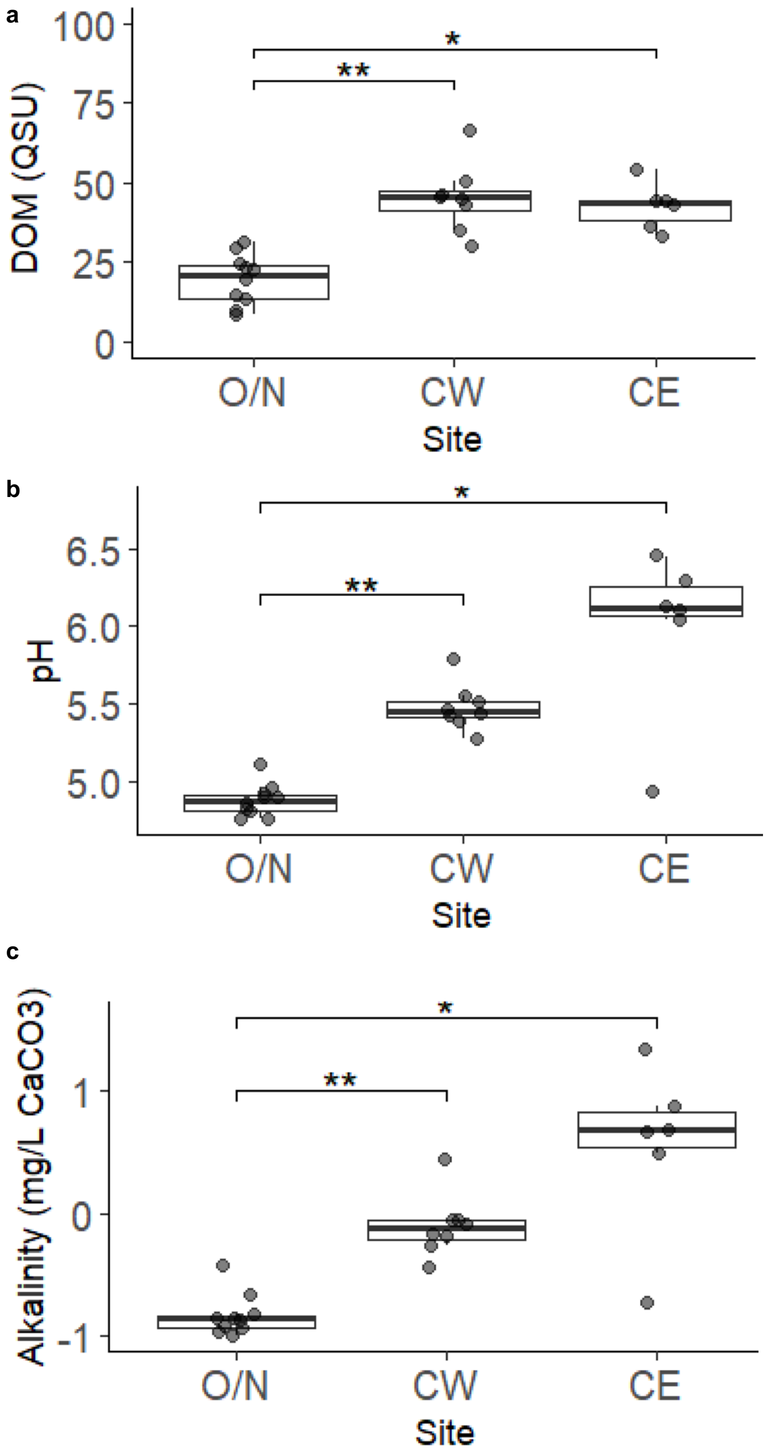

Figure 2.2. Box plots of regional median values (with 25th and 75th percentiles) for water chemistry parameters (a) DOM, (b) pH and (c) alkalinity. Significant differences between regions are indicated by asterisks (*$p<0.05$ and **$p<0.01$). Points represent all monthly measures within an assigned category, with those beyond the end of the whiskers considered outliers. O/N, Owenduff/Nephin ($n=120$); CW, Connemara west ($n=96$); CE, Connemara east ($n=72$).

advisable due to the confounding influence of region, season and catchment area. Additional parameters for monitoring are suggested, such as DOM, pH, conductivity, alkalinity and DO, as together they may reflect oligotrophic lake habitat type and conservation condition.

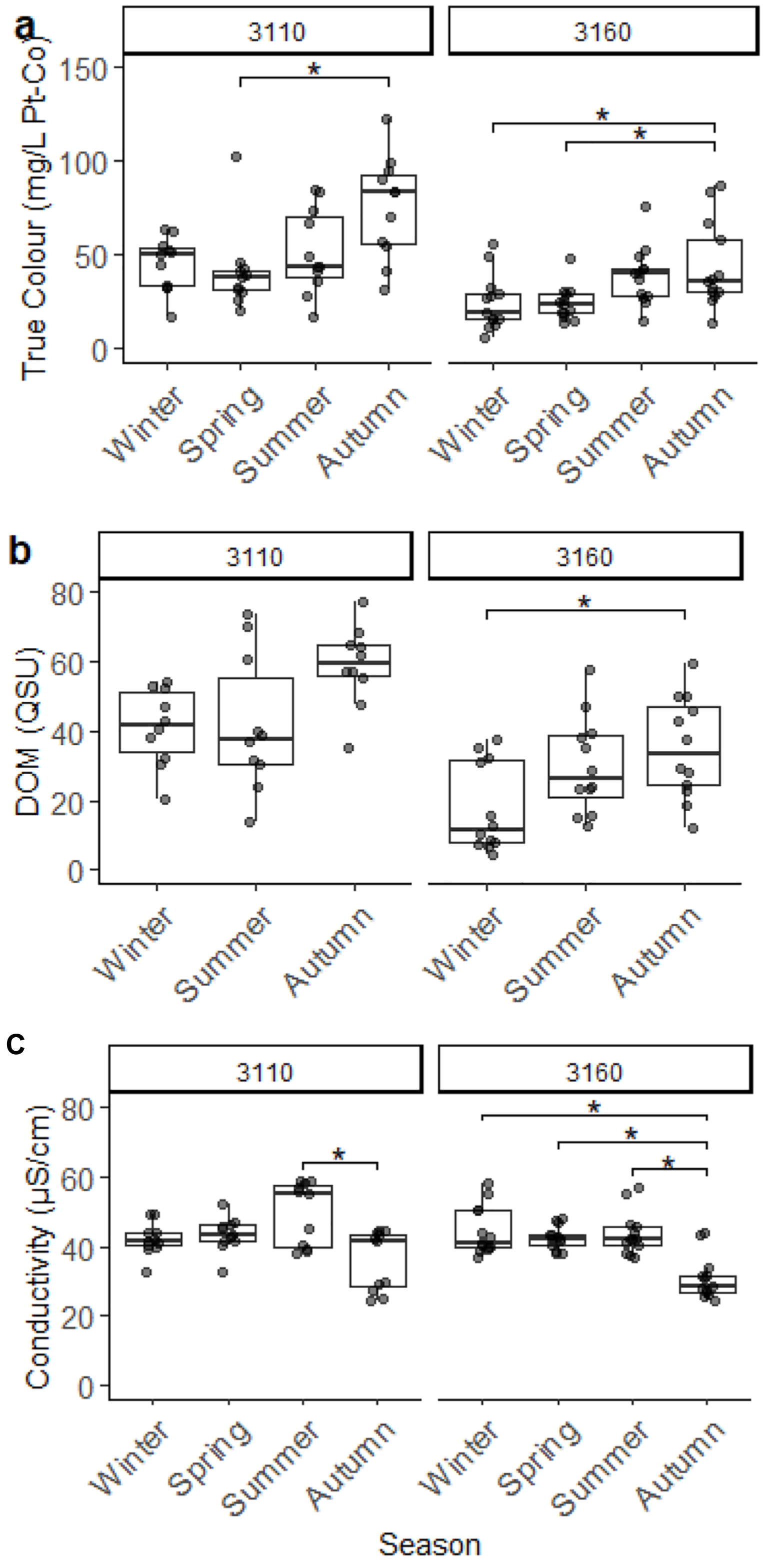

Figure 2.3. Box plots of seasonal median values (with 25th and 75th percentiles), by lake habitat type, for water chemistry parameters (a) true colour, (b) DOM and (c) conductivity. Significant differences between seasons are indicated by asterisks (*$p < 0.05$). Points represent all median monthly measures ($n = 3$) within an assigned category, with those beyond the end of the whiskers considered outliers. Winter ($n = 36$), spring ($n = 36$), summer ($n = 36$) and autumn ($n = 36$) for each lake habitat type.

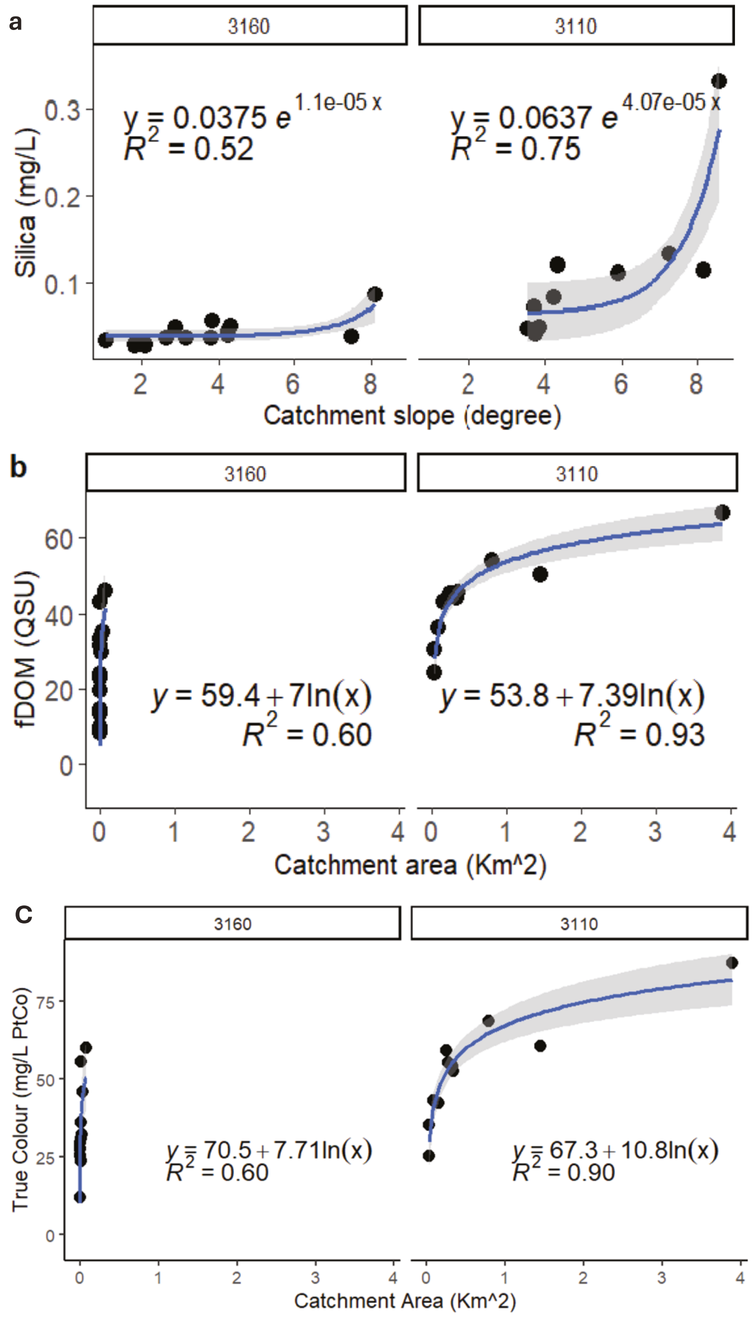

Figure 2.4. Regression models showing annual mean values of the two lake habitat types for water chemistry parameters (a) silica and slope of catchment, (b) DOM and catchment area, and (c) true colour and catchment area.

3 Biological Characterisation

3.1 Introduction

Defining oligotrophic lake habitat ecology is achieved by monitoring biological components. Here we investigated the use of macrophytes, algae (desmids) and macroinvertebrates (Odonata and Coleoptera) as monitoring indicators for oligotrophic lake habitats 3110 and 3160.

3.1.1 Macrophytes

Oligotrophic isoetid lake habitat 3110 communities belong to the Littorelletalia uniflorae order and, in Ireland, include characteristic species such as *Isoetes lacustris, Isoetes echinospora, Littorella uniflora, L. dortmanna, Eriocaulon aquaticum, Juncus bulbosus, Potamogeton polygonifolius, Sparganium angustifolium, Deschampsia setacea* (in Connemara), *Subularia aquatica, Pilularia globulifera, Nitella translucens, Nitella opaca, Nitella confervacea, Myriophyllum alterniflorum, Nymphaea alba, Nuphar lutea, Potamogeton natans, Utricularia intermedia, Utricularia minor* and *Eleogiton fluitans* (NPWS, 2019). Acid oligotrophic lake habitat 3160 is considered species-poor botanically and, in Ireland, is characterised by *Sphagnum* (*S. cuspidatum*, *S. auriculatum*) and the Utricularietalia phytosociological order, including *U. minor* and *U. intermedia* agg. alongside *J. bulbosus, Menyanthes trifoliata*, *P. polygonifolius, Cladium mariscus, E. fluitans, M. alterniflorum, Nitella flexilis, N. translucens, N. alba,* and *S. angustifolium* (NPWS, 2019). A full list of typical species found in oligotrophic lake habitats 3110 and 3160 can be viewed in EC (2007, 2013), EEA (2016a,b) and O Connor (2015).

3.1.2 Algae

Knowledge of algal community composition in oligotrophic lake habitats is derived from peatland research, where lake habitat type is not defined. Specific to acid oligotrophic lake habitat 3160, the phytoplankton community comprises cryptophytes, chrysophytes, diatoms, dinoflagellates, green algae, desmids and some small colonies of cyanobacteria (Herbich, 2004). Desmids are particularly abundant in peatland pool and lake systems with an optimal pH ranging between 5 and 8 (Free *et al*., 2006; Lally *et al*., 2012; Štěpánková *et al*., 2008, 2012). Furthermore, Coesel and Meesters' (2007) extensive research categorised 241 desmid species as being oligotrophic and acidophilic, while extensive desmid surveys conducted in peatland lakes in western Ireland by West (1892) and John and Williamson (2009) recorded a total of 476 desmid species and 706 subspecies.

Phytoplankton species have not been incorporated into the descriptions of oligotrophic lake habitats 3110 and 3160 under the EU Habitats Directive despite their suitability for determining habitat structure, function and conservation condition due to their restricted distribution in peatland lakes. Furthermore, at present, there is no desmid monitoring tool specifically for assessing the conservation condition of oligotrophic lake habitats in Ireland. This is despite their known reliable occurrence in acidic water bodies and existing historical records of desmids in the region (Brook, 1957; John and Williamson, 2009; Lind and Pearsall, 1944; Pearsall and Lind, 1942; Round and Brook, 1959; West, 1892) and an existing nature conservation value (NCV) metric based on desmid populations (Coesel, 2001).

3.1.3 Macroinvertebrates

Macroinvertebrates are commonly found in peatland lakes and ponds (Ozoliņš *et al*., 2021), and their distribution and the occurrence of rare species is well documented, with Coleoptera and Odonata on the red list in Ireland, the UK, Poland and Europe (Daguet *et al*., 2008; Foster, 2010; Foster *et al*., 2009; Kalkman *et al*., 2010; Nelson *et al*., 2011; Pawłowski *et al*., 2002). However, the typical community composition of oligotrophic lake habitats 3110 and 3160 within Ireland is not well understood. Oligotrophic isoetid lake habitat 3110 is expected to host Ephemeroptera, Plecoptera, Crustacea and Gastropoda (Beadle *et al*., 2015), while acid oligotrophic lake habitat 3160 is expected to have higher abundances of Trichoptera and Chironomidae (order: Diptera) (Kesti *et al*., 2022). The order Odonata is mentioned in association with acid oligotrophic lake habitat 3160 by the *Interpretation Manual of European Union Habitats* (EC, 2013), and this lake habitat may indeed be important for several rare dragonfly species, such as *Cordulia aenea* and *Somatochlora arctica* (Beadle *et al*., 2015; Nelson *et al*., 2011). In Ireland, the Irish working interpretation (O Connor, 2015) also includes Odonata *Aeshna juncea* and *Pyrrhosoma nymphula*, the Ephemeroptera *Leptophlebia vespertina* and predatory aquatic Coleoptera of the Dytiscidae family (diving beetles), including species such as *Acilius sulcatus*, *Dytiscus marginalis*, *Hydroporus obscurus*, *Hydroporus erythrocephalus*, *Ilybius aenescens* and *Nebrioporus assimilis,* as typical species of acid oligotrophic lake habitat 3160 (Drinan, 2012; O Connor, 2015; Towers, 2004). Macroinvertebrates may be good indicators of structure and function, with the potential to act as a tool for assessing conservation condition within oligotrophic lake habitats.

3.2 Objectives

The research objectives of this work package were to:

1. characterise the biological communities (macrophytes, algae (desmids) and invertebrates (Odonata and Coleoptera)) of favourable oligotrophic lake habitats 3110 and 3160;
2. evaluate the influence of physico-chemical elements on the biological communities;
3. investigate the effects of regional variation and seasonal patterns on the biological communities of oligotrophic lake habitats; and
4. assess the use of biological metrics as a tool to support the conservation condition assessment of oligotrophic lake habitats.

3.3 Methods and Materials

Full details of the sampling methods employed and materials used throughout this research can be found in our field assessment methodologies manual, available at https://peatlakes.wordpress.com/publications/.

3.4 Results

3.4.1 Macrophytes

A total of 24 macrophyte species were identified, 22 species in water bodies classified as oligotrophic isoetid lake habitat 3110 and 15 species in those

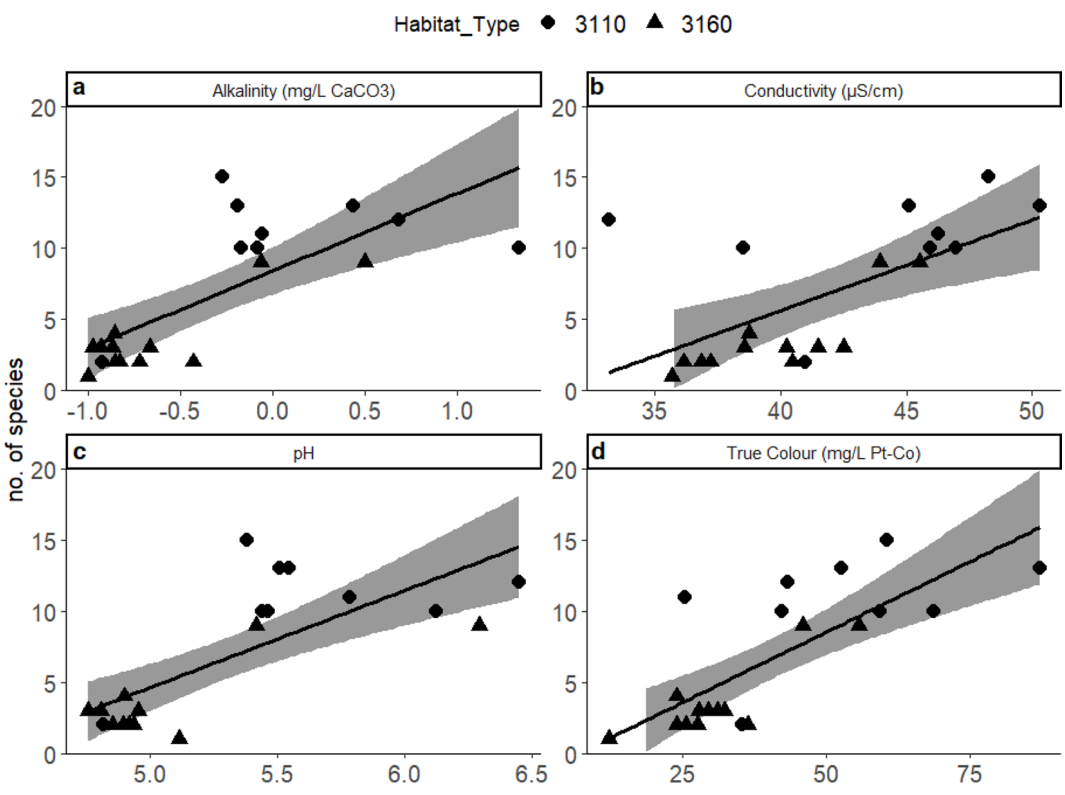

Figure 3.1. Spearman correlation models showing the correlation between site species richness and environmental factors (a) alkalinity; (b) conductivity; (c) pH; and (d) true colour. Points represent site species richness classified according to oligotrophic lake habitat type (lake habitat 3110: circles (*n*=9), lake habitat 3160: triangles (*n*=12)).

classified as acid oligotrophic lake habitat 3160. Overall, acid oligotrophic lake habitat 3160 recorded lower median species richness (3 ± 2.64, Wilcoxon signed-rank test $W = 95.5$, $p = 0.003$) and Shannon Diversity Index (0.95 ± 0.57, Wilcoxon $W = 94.5$, $p = 0.004$) than oligotrophic isoetid lake habitat 3110 (species richness $= 11 \pm 4.09$; Shannon Diversity Index $= 2.18 \pm 0.78$), reflecting the species-poor assemblages and dominance of a few species in acid oligotrophic lake habitat 3160. Spearman correlation analysis found significant relationships between four environmental parameters (alkalinity, pH, conductivity and true colour) and site species richness. Specifically, species richness per site was positively correlated with alkalinity ($R = 0.72$, $p < 0.001$), conductivity ($R = 0.63$, $p < 0.01$), true colour ($R = 0.69$, $p < 0.001$) and pH ($R = 0.69$, $p < 0.001$) for all water bodies sampled (Figure 3.1). Further partial correlation analysis considering the potential confounding effects of lake area between the four significant environmental parameters and site species richness revealed that the relationship between site species richness and pH (Spearman $W = 2.8$, $p = 0.01$), alkalinity (Spearman $W = 2.7$, $p = 0.01$) and true colour (Spearman $W = 2.8$, $p = 0.01$) was not influenced by lake area; however, the relationship between conductivity and site species richness was influenced by lake area (Spearman $W = 1.5$, $p = 0.1$).

The macrophyte communities of both oligotrophic lake habitats were sparse and showed no distinct

Table 3.1. Presence of macrophyte species and their occurrence, based on the number of water bodies the macrophyte species was present in for each oligotrophic lake habitat type

	Indicator species analysis				Oligotrophic isoetid lake habitat 3110 ($n = 9$)	Acid oligotrophic lake habitat 3160 ($n = 12$)
Species	Lake habitat type	Indicator value	*p*-value	Red list species[a]	Occurrence (no. of water bodies)	
Carex lasiocarpa					2	
Cladium mariscus	3110	0.67	0.030		4	
Elatine hexandra				Near-threatened	2	1
Eleocharis multicaulis	3110	0.80	0.010		7	2
Eriocaulon aquaticum	3110	0.90	0.002	Near-threatened	8	1
Isoetes echinospora				Near-threatened	2	1
Isoetes lacustris	3110	0.70	0.040		5	1
Eleogiton fluitans	3110	0.70	0.040		5	1
Juncus bulbosus					6	8
Littorella uniflora	3110	0.70	0.046		5	1
Lobelia dortmanna	3110	0.87	0.005		8	2
Menyanthes trifoliata	3160	0.91	0.002			10
Myriophyllum alterniflorum					2	
Nitella translucens					1	
Nymphaea alba	3110	0.84	0.003		7	1
Phragmites australis	3110	0.94	0.002		8	
Potamogeton natans					5	2
Potamogeton polygonifolius					1	
Ranunculus flammula	3110	0.67	0.020		4	
Schoenoplectus lacustris					1	
Sparganium angustifolium					2	3
Sparganium emersum	3110	0.82	0.002		6	
Utricularia intermedia				Data deficient	4	2
Utricularia minor	3160	0.76	0.020			7

The results of indicator species analysis highlight the macrophyte species that characterise each lake habitat type.
[a]Denotes red list species by Jackson *et al*. (2016).

vegetation zonation patterns. Overall, a low macrophyte species richness was observed in both oligotrophic lake habitats (Table 3.1). Non-metric multidimensional scaling (NMDS) community analysis showed that the macrophyte communities of the two oligotrophic lake habitats differed significantly (PERMANOVA $F = 9.8$, $R^2 = 0.3$, $p = 0.002$).

In particular, the isoetids *E. aquaticum, I. lacustris, Littorella uniflora, L. dortmanna* and species *Eleocharis multicaulis, E. fluitans, N. alba, Ranunculus flammula* and *Sparganium emersum* were associated with larger water bodies (i.e. lakes typically greater than 0.01 km^2 and assigned to oligotrophic isoetid lake habitat 3110) and higher levels of conductivity, true colour, alkalinity and pH (Figure 3.2). Indicator species analysis highlighted *C. mariscus, E. multicaulis, E. aquaticum, I. lacustris, E. fluitans, Littorella uniflora, L. dortmanna, N. alba, Phragmites australis, R. flammula* and *S. emersum* as indicator plants associated with oligotrophic isoetid lake habitat 3110. While these species separate the two oligotrophic lake habitats, many of the indicator plants listed for oligotrophic isoetid lake habitat 3110 are common to other lake habitat types, e.g. oligotrophic to mesotrophic standing waters with vegetation of the *Littorelletea uniflorae* and/or *Isoeto-Nanojuncetea* (lake habitat 3130). Two species were associated with acid oligotrophic lake habitat 3160 based on indicator species analysis – *M. trifoliata* and *U. minor*. Both *M. trifoliata* and *U. minor* are easily identified in the field, providing a rapid field-based method for identifying acid oligotrophic lake habitat 3160.

Species quality scores (SQSs) are a measure of species rarity and the metric is based on the number of 10 km squares (hectads) a species is recorded in using the Irish national grid. Data on the macrophyte species frequency at a national level were obtained for all periods, excluding Plant Atlas 2020 data, from the

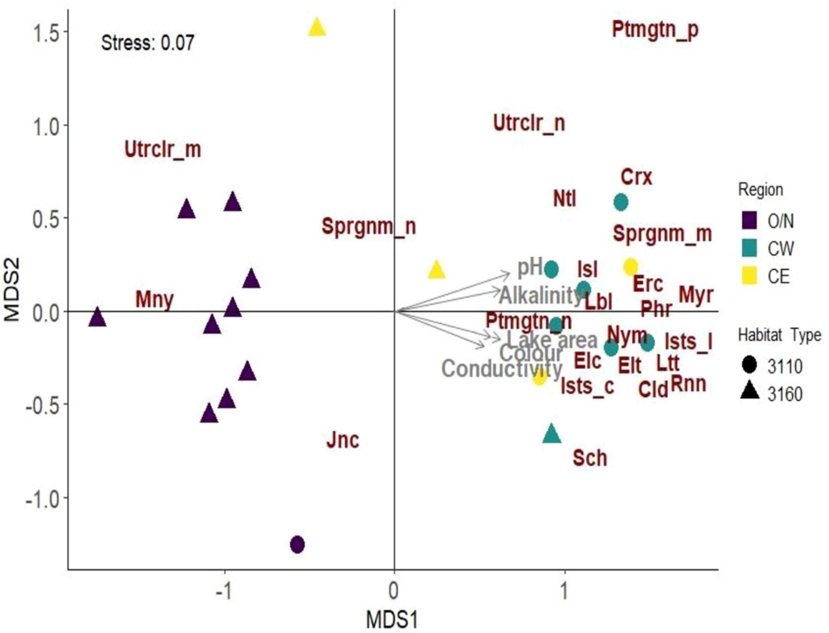

Figure 3.2. NMDS ordination of the 21 study sites by lake habitat type and region with macrophyte species labels. Significant environmental parameters are demonstrated as overlays. Circles indicate lake habitat type 3110 (*n* = 9) and triangles indicate lake habitat type 3160 (*n* = 12). Colours indicate region of sampling: purple, O/N (*n* = 10); yellow, CE (*n* = 6); and green, CW (*n* = 8). Crx, *Carex lasiocarpa*; Cld, *Cladium mariscus*; Elt, *Elatine exandra*; Elc, *Eleocharis multicaulis*; Erc, Eriocaulon aquaticum; Ists_c, *Isoetes echinospora*; Ists_l, *Isoetes lacustris*; Isl, *Isolepis fluitans* (syn. *Eleogiton fluitans)*; Jnc, *Juncus bulbosus*; Ltt, *Littorella uniflora*; Lbl, *Lobelia dortmanna*; Mny, *Menyanthes trifoliata*; Myr, *Myriophillium alterniflorum*; Ntl, *Nitella translucens*; Nym, *Nymphaea alba*; Phr, *Phragmites australis*; Ptmgtn_n, *Potamogeton natans*; Ptmgtn_p, *Potamogeton polygonifolius*; Rnn, *Ranunculus flammula*; Sch, *Schoenoplectus lacustris*; Sprgnm_m, *Sparganium emersum*; Sprgnm_n, *Sparganium angustifolium*; Utrclr_n, *Utricularia intermedia*; Utrclr_m, *Utricularia minor*.

National Biodiversity Data Centre (2023). The SQS rarity metric ranges from 1 (indicating very common species) to 10 (indicating very rare species). The SQSs were calculated using the recorded macrophyte species list. The average SQS for the 24 macrophyte species recorded was low (2.8 ± 1.4), indicating that the water bodies surveyed in this study hosted common macrophyte species overall, with only two macrophyte species having a moderate SQS of 5 (*E. aquaticum* and *I. echinospora*) and one macroalgae with a SQS of 6 (*N. translucens*). The overall mean SQS for the 21 water bodies was also low, at 2.2 (± 0.7) (Figure 3.3), with no significant difference detected in median SQSs between oligotrophic isoetid lake habitat 3110 (2.6 ± 0.6) and acid oligotrophic lake habitat 3160 (2.0 ± 0.8) (Wilcoxon W = 12, $p = 0.1$).

A second metric, the Floristic Rarity Index (FRI), was also applied and considered the overall rarity of species found in a sample and the alpha diversity of the whole community (Perrin, 2019). FRI was calculated using the average SQS of each site and multiplying by the square root of the number of species found in the same site (Perrin, 2019).

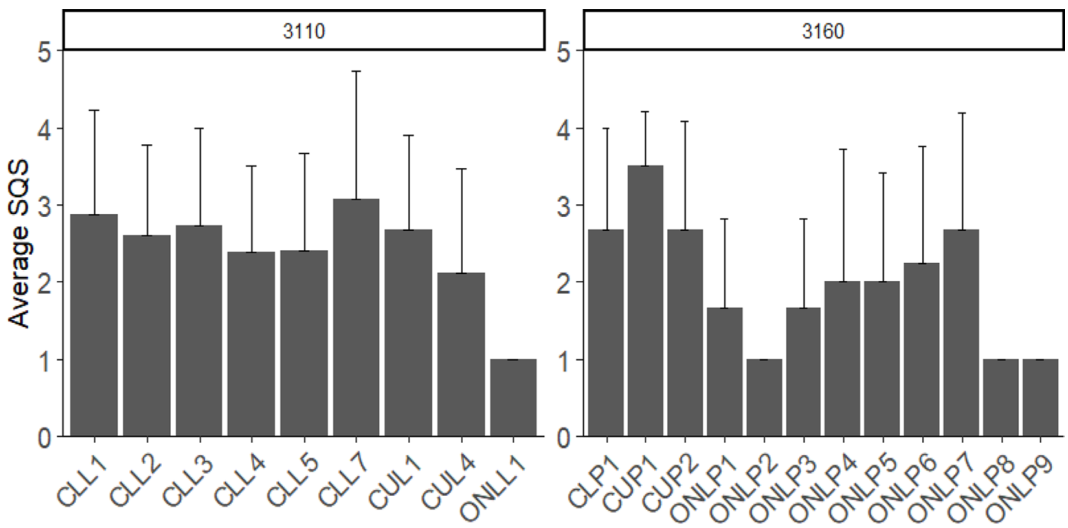

Figure 3.3. Mean SQS and standard deviation for the 21 water bodies where macrophyte surveys were conducted and defined by their lake habitat type.

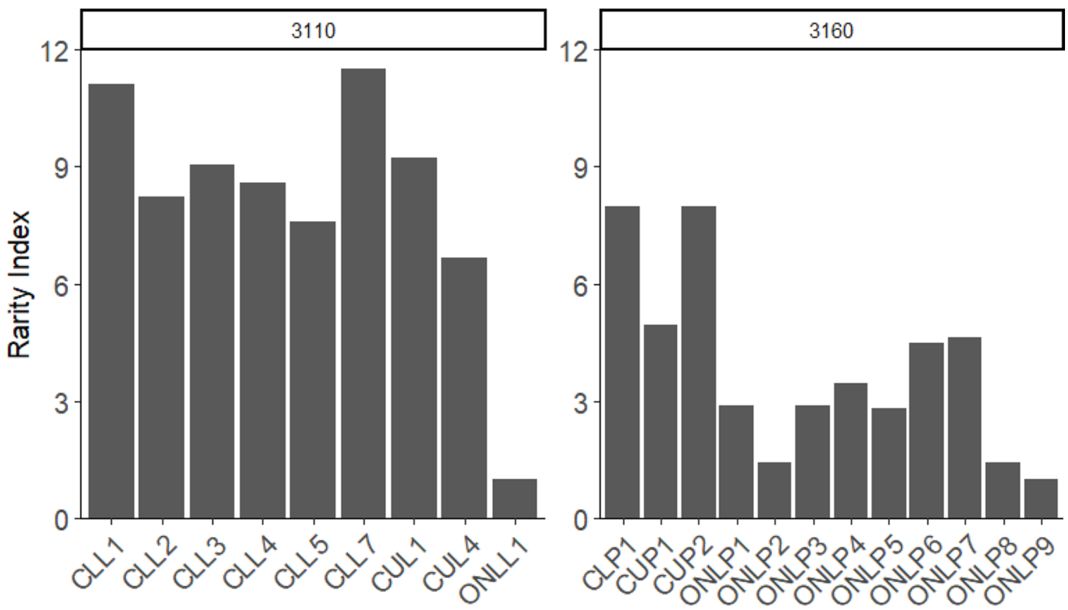

Figure 3.4. FRI for the 21 water bodies where macrophyte surveys were conducted and defined by their lake habitat type.

The overall mean FRI for the 21 water bodies surveyed (Figure 3.4) was 5.7 (±3.4), with a significant difference observed in median FRI between acid oligotrophic lake habitat 3160 (3.2) and oligotrophic isoetid lake habitat 3110 (8.6) (Wilcoxon W = 92.5, $p = 0.007$), reflecting the higher mean FRI in the lakes of the Connemara Bog Complex SAC.

3.4.2 Algae

NMDS community analysis showed no clear distinction in phytoplankton communities between oligotrophic isoetid lake habitat 3110 and acid oligotrophic lake habitat 3160 (Figure 3.5a). The phytoplankton communities of both oligotrophic lake habitats comprised a mixture of Bacillariophyceae, Chrysophyceae, Chlorophyceae, Cyanophyceae, Dinophyceae and Raphidophyceae (see https://peatlakes.wordpress.com/desmid-datasets/ for a full list of desmid species), with Chrysophyceae having the overall highest mean abundance for both the entire dataset and in spring and summer, respectively (Figure 3.6), driven by blooms of *Dinobryon divergens*. This mixotrophic community has a competitive advantage in these low-nutrient waters compared with autotrophic algal groups.

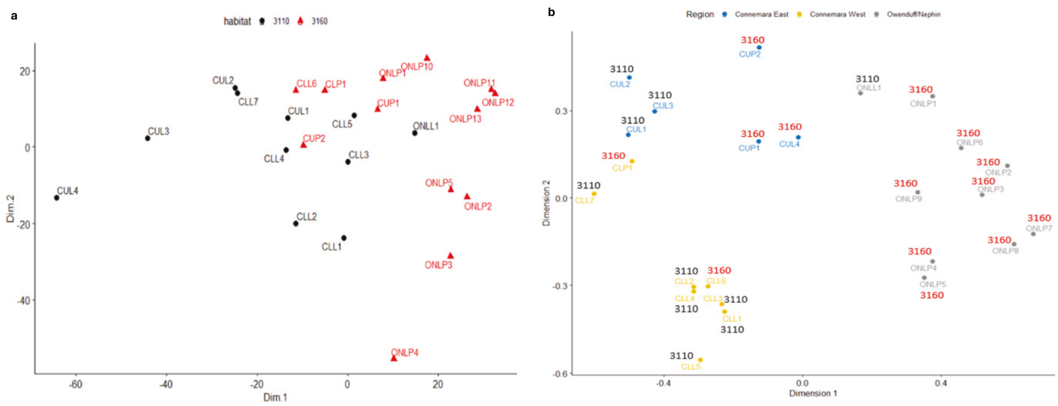

Figure 3.5. NMDS using (a) all phytoplankton count data for the 24 study sites by lake habitat type, where black circles indicate oligotrophic isoetid lake habitat 3110 (*n* = 12) and red triangles indicate acid oligotrophic lake habitat 3160 (*n* = 12); and (b) planktonic desmid data for the 24 study sites by region only, where blue circles indicate Connemara east (*n* = 8), yellow circles indicate Connemara west (*n* = 6) and grey circles indicate Owenduff/Nephin (*n* = 10).

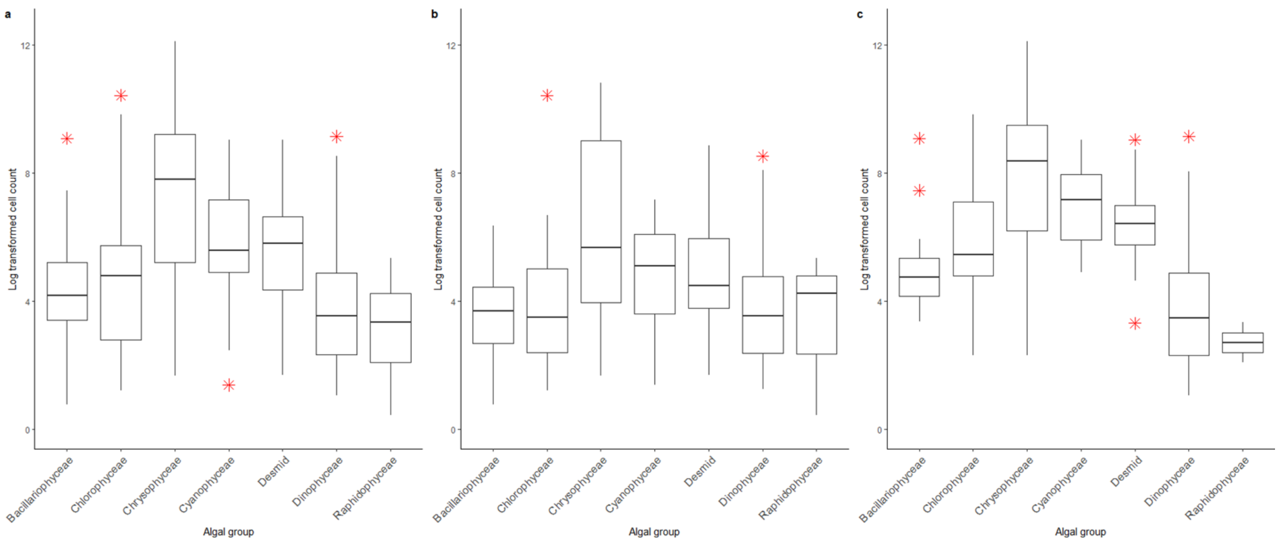

Figure 3.6. Logged mean cell abundance with 95% confidence interval of each algal group for (a) the entire dataset; (b) spring; and (c) summer. Red asterisks indicate outliers.

Desmids were the most species-rich group, with a total of 332 desmid species identified in planktonic and benthic samples across spring and summer 2021 (Figure 3.7). In addition, desmids were also present in all 24 water bodies regardless of lake habitat type. NMDS community analysis, based on a Bray–Curtis dissimilarity index, showed that planktonic desmids grouped the water bodies by region rather than habitat type, with Owenduff/Nephin SAC separating from the Connemara east and west regions (Figure 3.5b).

Desmid species richness also varied across the three sampling regions ($F = 8.516$, $p < 0.001$), with Connemara east ($p < 0.001$) and Connemara west ($p < 0.05$) recording a significantly higher number of desmid species than Owenduff/Nephin SAC (Figure 3.8).

A distance-based redundancy analysis (RDA) found that higher total phosphorus ($p < 0.01$) was significantly associated with the planktonic desmids of Owenduff/Nephin pools and that higher water colour ($p < 0.01$),

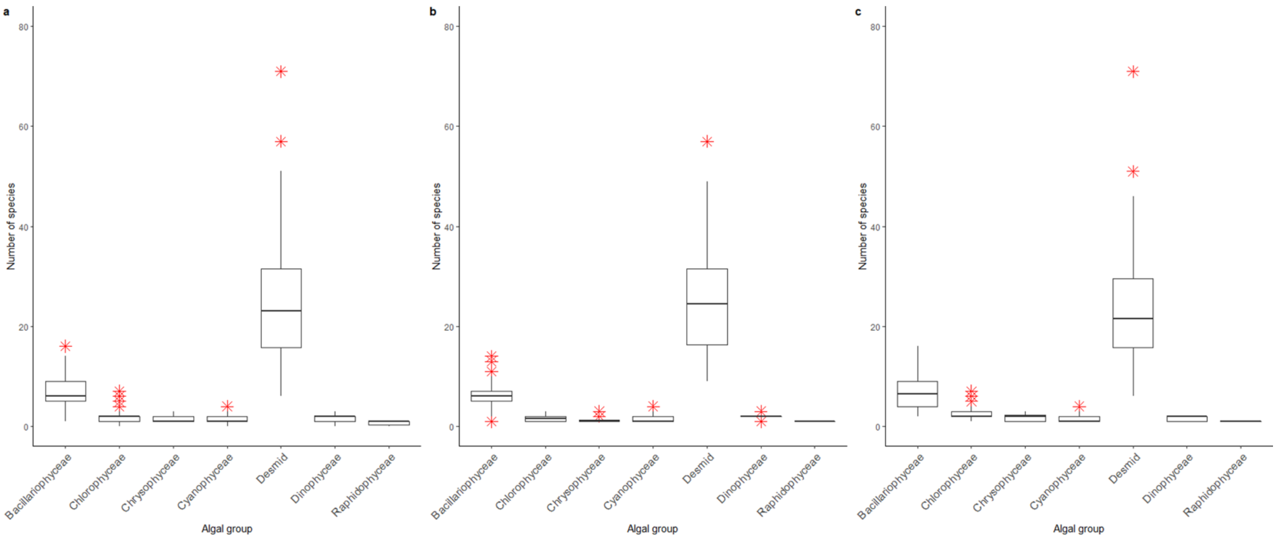

Figure 3.7. Number of species with 95% confidence interval of each algal group for (a) the entire dataset; (b) spring; and (c) summer. Red asterisks indicate outliers.

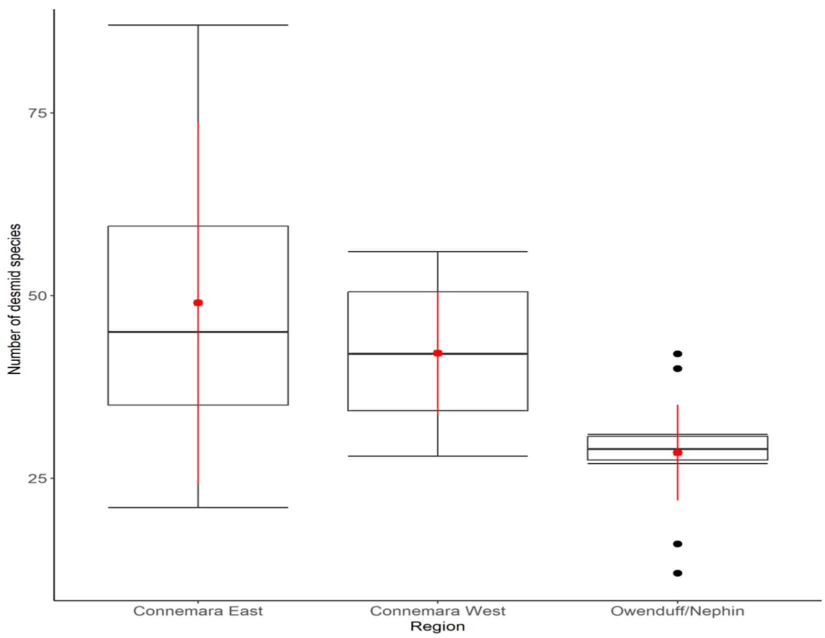

Figure 3.8. Box plot of the number of desmid species across the three sampling regions. Black circles indicate outliers, red squares represent the mean, and red lines indicate the 95% confidence interval.

pH ($p < 0.01$) and silica ($p < 0.05$) were significantly associated with planktonic desmids in Connemara east and west sites (Figure 3.9). A lower desmid species richness in Owenduff/Nephin is likely to be the result of lower pH levels (mean annual pH < 5) in the bog pools. *t*-test analysis showed a significant difference in species richness ($t = 4.66$; $p = < 0.0001$), where water bodies with a mean annual pH < 5 were typically bog pools located in Owenduff/Nephin SAC with a lower mean species richness (18) than water bodies with a mean annual pH ≥ 5 (33), which were predominantly lakes located in Connemara Bog Complex SAC.

All water bodies sampled contained rare desmid species of the UK and Ireland (John and Williamson, 2009), vulnerable species on the UK red list (Brodie *et al*., 2007) and vulnerable species on the Netherlands red list (Coesel, 2001) (see https://peatlakes.wordpress.com/desmid-datasets/ for a full list of desmid rarity species). Owenduff/Nephin SAC sites had fewer rare and vulnerable species, according to both the UK and Netherlands red lists, compared with the two regions in the Connemara Bog Complex SAC. Linear model analysis of water chemistry and catchment parameters as predictors of the number of rare species of the UK and Ireland (John and Williamson, 2009), vulnerable species on the UK red list (Brodie *et al*., 2007) and vulnerable species on the Netherlands red list (Coesel, 2001) found water colour was a significant parameter for explaining variance in the models (Table 3.2). However, only a small proportion of the variance (adjusted R^2 ranging from 0.351 to 0.518) was explained, indicating that alternative parameters need to be considered. In general, the higher the water colour, the higher the number of rare and vulnerable species according to both the UK and Netherlands red lists. Overall, the reliable presence of desmids in every water body sampled and their high species diversity make them a suitable indicator group for oligotrophic lake habitats in Ireland.

The desmid NCV metric (Coesel, 2001) is a quantitative method of determining the aquatic NCV of lentic systems. The metric uses species richness (indicative of internal structural and functional differentiation of the ecosystem), the occurrence of rare taxa (indicative of particular environmental conditions) and the presence of species (indicative of ecosystem maturity) as parameters in determining conservation value. The desmid NCV ranges from 1 (low conservation value) to 10 (high conservation value). For this study the desmid NCV was calculated for each water body using the “Desmid Value V1 tool” (Coesel and Meesters, 2007), with values for species rarity and maturity being available for 75% of desmid species identified. All water bodies assessed using planktonic desmids had a desmid NCV above 5, suggesting a moderate to high conservation value (Figure 3.10); however, at sites where benthic samples

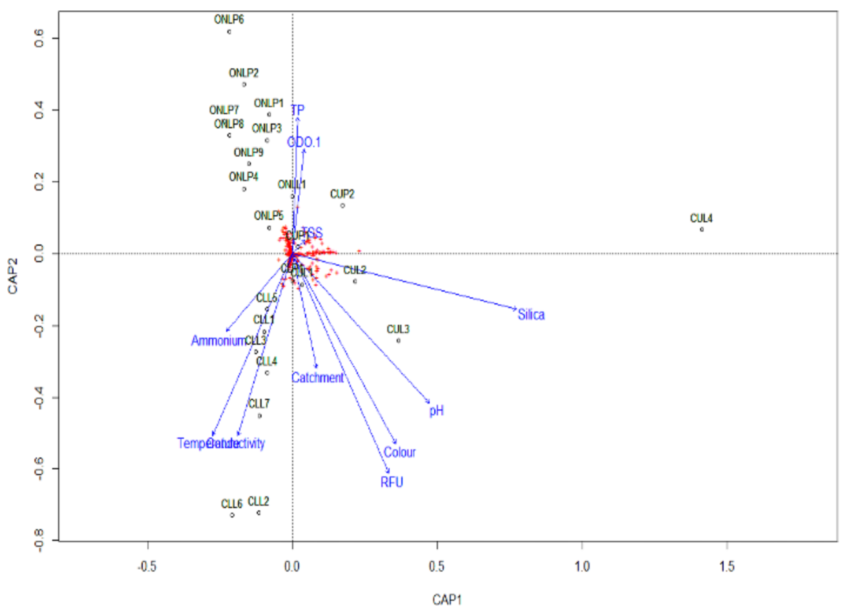

Figure 3.9. Distance-based RDA using planktonic desmids for the 24 study sites, with physico-chemical parameters as overlays. CAP, canonical analysis of principal coordinates.

Table 3.2. Analysis of variance results with morphological and water chemistry parameters as predictors of the number of rare desmid species, number of vulnerable species on the Netherlands red list and number of vulnerable species on the UK red list

	Number of rare desmid species (John and Williamson, 2009)		Number of vulnerable species on the Netherlands red list (Coesel, 2001)		Number of vulnerable species on the UK red list (Brodie *et al.*, 2007)	
Predictors	**F-value**	***p*-value**	**F-value**	***p*-value**	**F-value**	***p*-value**
Total phosphorus (mg/L)	1.135	0.318	0.054	0.823	5.355	**0.049***
Orthophosphates (mg/L)	0.497	0.501	1.918	0.203	1.797	0.217
Ammonium (mg/L)	0.163	0.697	0.003	0.961	0.249	0.631
Turbidity (FNU)	2.555	0.149	1.059	0.334	2.261	0.171
Total suspended solids (g/L)	2.369	0.162	1.207	0.304	4.547	0.066.
Water colour (mg/L Pt-Co)	12.967	**0.007****	6.730	**0.032***	12.613	**0.007****
Dissolved organic matter (RFU)	0.165	0.695	0.010	0.923	0.065	0.805
pH	5.044	0.055	0.918	0.366	1.962	0.199
Alkalinity (mg/L $CaCO_3$)	0.252	0.629	0.058	0.816	0.091	0.770
Conductivity (µS/cm)	0.984	0.350	0.482	0.507	1.275	0.292
Silica (mg/L)	5.740	**0.043***	5.417	**0.048***	4.880	0.058.
Temperature (°C)	0.188	0.676	0.005	0.946	0.022	0.887
Dissolved oxygen (mg/L)	1.837	0.212	5.699	**0.044***	2.578	0.147
Lake area (km^2)	1.028	0.340	2.095	0.186	1.093	0.326
Catchment area (km^2)	1.171	0.311	1.810	0.215	0.954	0.357
***R*^{2}/*R*^{2} adjusted**	**0.819/0.478**		**0.774/0.351**		**0.832/0.518**	

Significant predictors are highlighted in bold with levels of significance: *< 0.001, **0.001, *0.01, .0.05.**
FNU, formazin nephelometric unit; RFU, relative fluorescence unit.

were also obtained, a desmid NCV greater than 7 was observed, indicating high conservation value (Figure 3.10).

3.4.3 Odonata and Coleoptera

Forty-four Odonata and Coleoptera species were found in oligotrophic isoetid lake habitat 3110 (median: 76 ± 21.8) and 34 species in acid oligotrophic lake habitat 3160, with significantly lower median species richness observed in acid oligotrophic lake habitat 3160 (median: 48 ± 10.36, Wilcoxon W = 116, $p = 0.01$). NMDS community analysis showed that the Odonata and Coleoptera communities of the oligotrophic lake habitats differed significantly from each other (PERMANOVA F = 4.55, $R^2 = 0.17$, $p < 0.01$) (Figure 3.11). Oligotrophic isoetid lake habitat 3110 comprised a mixture of Coenagrionidae, Dytiscidae, Gyrinidae, Libellulidae and Aeshnidae specimens (Table 3.3) and was associated with larger water bodies (i.e. lakes greater than 0.01 km^2), with higher levels of conductivity, pH and temperature in the Connemara Bog Complex SAC. Indicator species analysis highlighted Coleoptera species *Haliplus fulvus*, and Odonata species *Ischnura elegans*, *P. nymphula* and *Sympetrum striolatum* as indicative of oligotrophic isoetid lake habitat 3110. Acid oligotrophic lake habitat 3160 communities comprised a mixture of Gyrinidae, Coenagrionidae, Dytiscidae, Libellulidae and Lestidae specimens and were typically smaller pools with higher turbidity levels, located further from the sea and at higher altitudes within the Owendiff/Nephin SAC. Indicator species analysis highlighted Coleoptera species *A. sulcatus*, *Gyrinus aeratus* and *Gyrinus minutus* as indicator species of acid oligotrophic lake habitat 3160. Dytiscidae (Coleoptera) were the most diverse family in both oligotrophic lake habitats. The most common species found in both oligotrophic lake habitats were the Odonata *Enallagma cyathigerum*, followed by Odonata species *I. elegans* and *P. nymphula* in oligotrophic isoetid lake habitat 3110 and Coleoptera species *G. minutus* and *G. aeratus* in acid oligotrophic lake habitat 3160 (see https://peatlakes.wordpress.com/odonata-and-coleoptera-datasets/ for a full list of Odonata and Coleoptera species recorded).

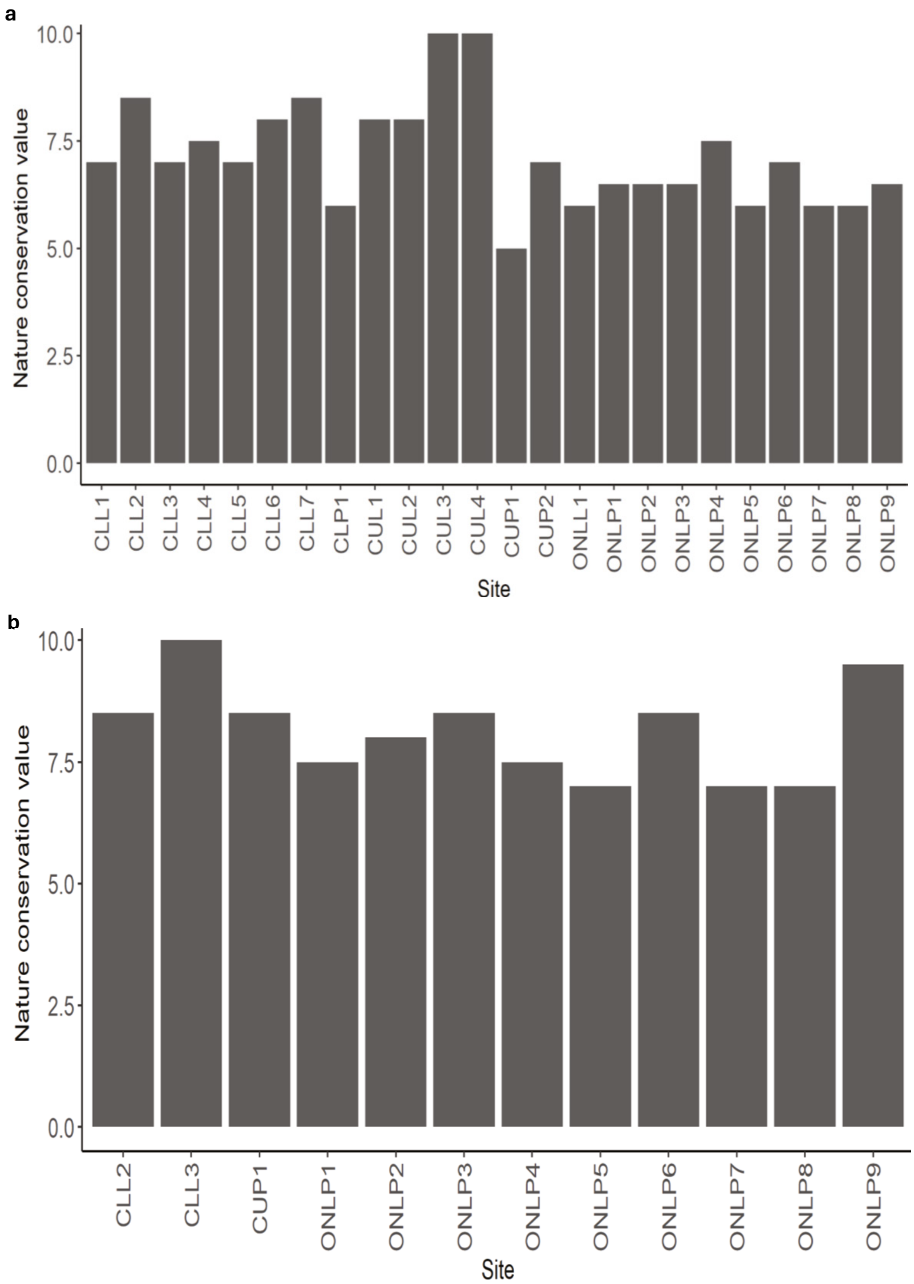

Figure 3.10. Desmid NCV scores for (a) all 24 sites with planktonic samples and (b) 12 sites with benthic samples.

Both oligotrophic lake habitats hosted four Irish national red list species: Coleoptera species *Agabus arcticus* (near-threatened), *Dytiscus lapponicus* (near-threatened), *Boreonectes multilineatus* (syn. *Stictotarsus multilineatus*, near-threatened) and Odonata species *C. aenea* (endangered) (Foster *et al*., 2009; Nelson *et al*., 2011). Sixty-two per cent of water bodies studied included at least one red list species, with *C. aenea* the most represented species. *C. aenea* has previously been associated with acid oligotrophic lake habitat 3160 (O Connor, 2015); however, this study recorded the species from water bodies classified as oligotrophic isoetid lake habitat 3110 located within Connemara Bog Complex SAC, corresponding with one of three known areas for the species in Ireland (Drinan *et al*., 2011; National Biodiversity Data Centre, 2023).

RDA modelling found that physico-chemical parameter turbidity significantly influenced the assemblages of acid oligotrophic lake habitat 3160 and indicator species *A. sulcatus*, while chloride, DO (percentage of saturation), pH, temperature and lake area significantly

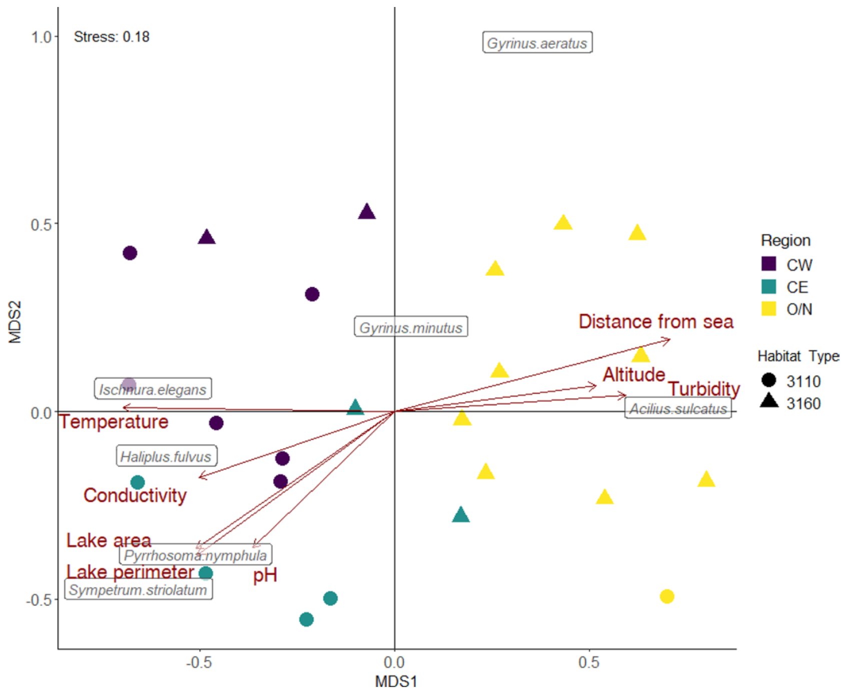

Figure 3.11. NMDS showing the 24 study sites by lake habitat type and region, with overlays of significant environmental parameters and lake habitat indicator species for Odonata and Coleoptera. Colours indicate region of sampling: yellow, O/N (n=10); purple, CW (n=6); and green, CE (n=8). Circles indicate lake habitat type 3110 (n=12) and triangles indicate lake habitat type 3160 (n=12). MDS, multidimensional scaling.

Table 3.3. Species richness, percentage diversity, total abundance (number of specimens) and percentage abundance of Odonata and Coleoptera families recorded for oligotrophic lake habitats

		Oligotrophic isoetid lake habitat 3110				Acid oligotrophic lake habitat 3160			
Order	Family	No. of species	% diversity	Total abundance	% abundance	No. of species	% diversity	Total abundance	% abundance
Odonata	Aeshnidae	3	6.8	63	4.4	2	5.9	30	3.6
Coleoptera	Chrysomelidae	1	2.3	1	0.1	1	2.9	1	0.1
Odonata	Coenagrionidae	3	6.8	898	62.5	3	8.8	191	22.6
Odonata	Corduliidae	1	2.3	15	1.0	1	2.9	7	0.8
Coleoptera	Dryopidae	1	2.3	12	0.8	1	2.9	20	2.4
Coleoptera	Dytiscidae	18	40.9	157	10.9	16	47.1	183	21.7
Coleoptera	Elmidae	1	2.3	3	0.2	0	0	0	0.0
Coleoptera	Gyrinidae	3	6.8	109	7.6	4	11.8	281	33.3
Coleoptera	Haliplidae	1	2.3	15	1.0	1	2.9	1	0.1
Coleoptera	Helophoridae	2	4.5	23	1.6	0	0	0	0.0
Coleoptera	Hydrophilidae	5	11.4	17	1.2	1	2.9	1	0.1
Odonata	Lestidae	1	2.3	17	1.2	1	2.9	57	6.8
Odonata	Libellulidae	4	9.1	106	7.4	3	8.8	72	8.5
Total		**44**	**100**	**1436**	**100**	**34**	**100**	**844**	**100**

influenced the assemblages of oligotrophic isoetid lake habitat 3110 and indicator species *I. elegans* and *P. nymphula* (Figure 3.12).

Odonata and Coleoptera species richness was similar across the three sampling regions. However, species composition differed, with the NMDS community

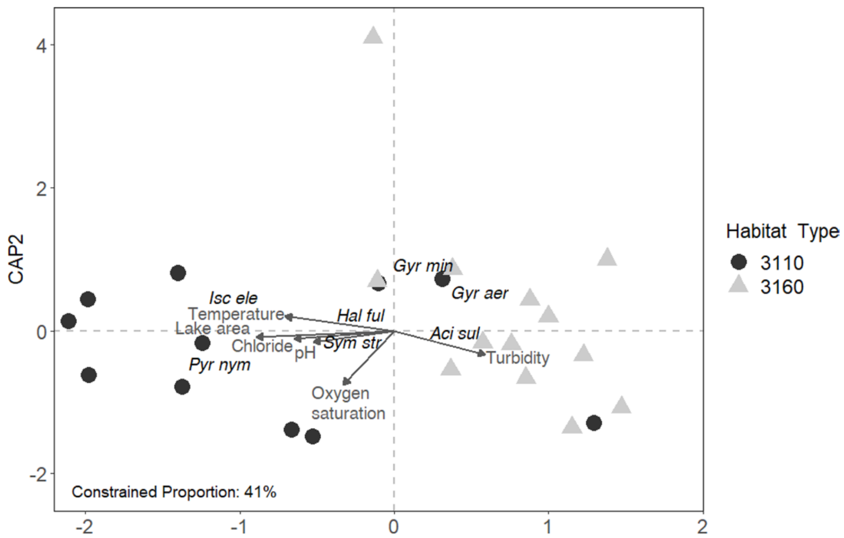

Figure 3.12. RDA with overlays of significant environmental parameters and seven significant indicator species for Odonata and Coleoptera. Points indicate lake habitat type, with black circles indicating oligotrophic isoetid lake habitat 3110 (n=12) and grey triangles indicating acid oligotrophic lake habitat 3160 (n=12). Aci sul, *Acilius sulcatus*; Gyr aer, *Gyrinus aeratus*; Gyr min, *Gyrinus minutus*; Hal ful, *Haliplus fulvus*; Isc ele, *Ischnura elegans*; Pyr nym, *Pyrrhosoma nymphula*; Sym str, *Sympetrum striolatum*.

analysis highlighting how Odonata and Coleoptera assemblages in Connemara west and east differed from those of Owenduff/Nephin SAC (PERMANOVA $F=7.05$, $R^2=0.24$, $p=0.0017$) (Figure 3.11). *E. cyathigerum*, *P. nymphula, A. juncea*, *H. obscurus* and *I. elegans* were the most abundant species in Connemara east, while *I. elegans, E. cyathigerum*, *G. minutus, G. substriatus* and *Libellula quadrimaculata* dominated in Connemara west (Table 3.4). *G. aeratus, H. obscurus, E. cyathigerum, Sympetrum danae* and *G. minutus* were the top five most abundant species found in Owenduff/Nephin SAC.

Odonata and Coleoptera communities also differed between spring and summer sampling for the two oligotrophic lake habitats. Odonata dominated within oligotrophic isoetid lake habitat 3110 during spring, with *E. cyathigerum* the most common species followed by *I. elegans* and *L. quadrimaculata* (Table 3.5). In summer, Odonata species *E. cyathigerum* and *I. elegans* remained prevalent alongside *P. nymphula* and Coleoptera species *Gyrinus substriatus* and *H. obscurus.* In acid oligotrophic lake habitat 3160, spring samples were also dominated by the Odonata species *E. cyathigerum* followed by Coleoptera species *G. aeratus* and *G. minutus*, while summer samples were dominated by Coleoptera species *G. minutus* and *G. aeratus* and Odonata species *E. cyathigerum, Lestes sponsa* and *H. obscurus*.

SQSs were also calculated using the Odonata and Coleoptera dataset. The mean SQS for the 53 Odonata and Coleoptera species dataset was low (3.0 ± 2.0), although high SQS values were observed for the Odonata *C. aenea* (7) and Coleoptera *D. lapponicus* (7), *A. arcticus* (6), *B. multilineatus* (6) and *Helochares punctatus* (6). The mean SQS value for the 24 water bodies surveyed was also low (2.6 ± 0.4), indicating that the water bodies contained similar species to each other (Figure 3.13), with no significant difference in median SQS values observed between oligotrophic isoetid lake habitat 3110 (2.3) and acid oligotrophic lake habitat 3160 (2.7) (Wilcoxon $W=43.5$, $p=0.1$).

3.5 Conclusion

This research identifies the characteristic biological communities, specifically the macrophytes, desmids and Odonata and Coleoptera, of oligotrophic lake habitats in favourable conservation condition.

The macrophyte communities of all water bodies sampled were sparse, species-poor and showed no distinct vegetation zonation patterns. A low macrophyte

Table 3.4. Top five most abundant Odonata and Coleoptera species, based on total number of individuals recorded and occurrence within water bodies for each sampling region

			Connemara east		Connemara west		Owenduff/Nephin	
Order	Family	Species	Occurrence (no. of water bodies)	Abundance (total no. of individuals)	Occurrence (no. of water bodies)	Abundance (total no. of individuals)	Occurrence (no. of water bodies)	Abundance (total no. of individuals)
Odonata	Aeshnidae	*Aeshna juncea* (Linnaeus, 1758)	5	57				
Odonata	Coenagrionidae	*Enallagma cyathigerum* (Charpentier, 1840)	8	415	6	172	8	63
Coleoptera	Gyrinidae	*Gyrinus aeratus* (Stephens, 1835)					3	77
Coleoptera	Gyrinidae	*Gyrinus minutus* (Fabricius, 1798)			2	100	9	29
Coleoptera	Gyrinidae	*Gyrinus substriatus* (Stephens, 1828)			3	88		
Coleoptera	Dytiscidae	*Hydroporus obscurus* (Sturm, 1835)	4	56			10	68
Odonata	Coenagrionidae	*Ischnura elegans* (Vander Linden, 1820)	6	39	2	214		
Odonata	Libellulidae	*Libellula quadrimaculata* (Linnaeus, 1758)			5	78		
Odonata	Coenagrionidae	*Pyrrhosoma nymphula* (Sulzer, 1776)	4	111				
Odonata	Libellulidae	*Sympetrum danae* (Sulzer, 1776)					9	30

Table 3.5. Top five most abundant Odonata and Coleoptera species, based on total number of individuals recorded for each oligotrophic lake habitat type during spring and summer 2021

			Habitat type 3110		Habitat type 3160	
Order	**Family**	**Species**	**Spring**	**Summer**	**Spring**	**Summer**
Odonata	Corduliidae	*Cordulia aenea*[a]	5			
Odonata	Coenagrionidae	*Enallagma cyathigerum*	103	378	84	85
Coleoptera	Gyrinidae	*Gyrinus aeratus*			34	83
Coleoptera	Gyrinidae	*Gyrinus minutus*			29	101
Coleoptera	Gyrinidae	*Gyrinus substriatus*		95		
Coleoptera	Dytiscidae	*Hydroporus obscurus*		90		49
Odonata	Coenagrionidae	*Ischnura elegans*	68	171		
Odonata	Lestidae	*Lestes sponsa*				56
Odonata	Libellulidae	*Libellula quadrimaculata*	23		28	
Odonata	Coenagrionidae	*Pyrrhosoma nymphula*	8	170		
Coleoptera	Dytiscidae	*Rhantus exsoletus*			17	

[a]Classified as an endangered species (Nelson *et al*., 2011).

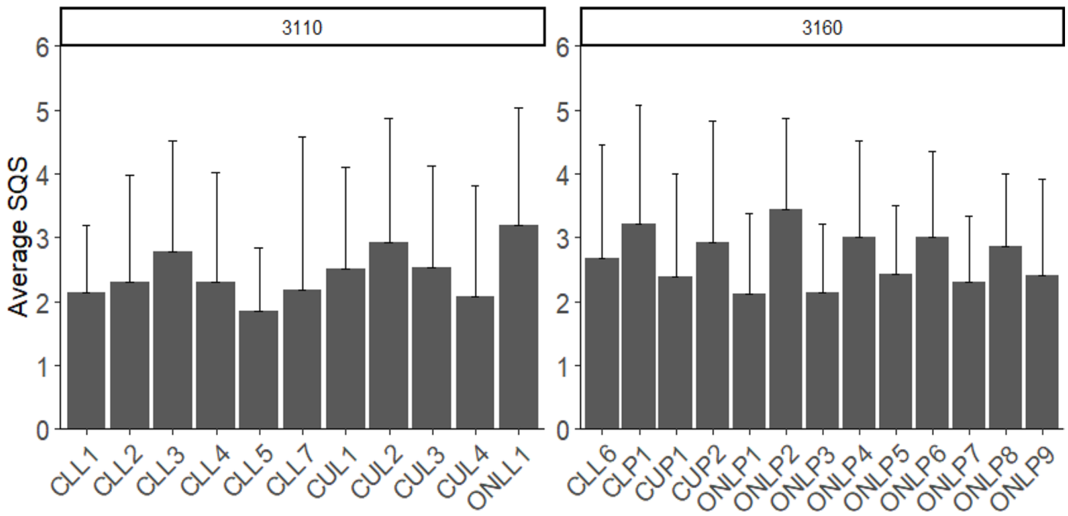

Figure 3.13. Mean Odonata and Coleoptera SQS and standard deviation for the 24 study sites as defined by their lake habitat type.

species richness was observed in all water bodies, with water chemistry parameters alkalinity, pH and true colour positively influencing site species richness. The macrophyte communities of water bodies classified as oligotrophic isoetid lake habitat 3110 differed from those of acid oligotrophic lake habitat 3160. Those classified as oligotrophic isoetid lake habitat 3110 were typically large lake water bodies (i.e. greater than 0.01 km^2) with higher levels of conductivity, true colour, alkalinity and pH. Water bodies classified as acid oligotrophic lake habitat 3160 were dominated by the presence of a few species: *M. trifoliata*, *J. bulbosus* and *U. minor*. *M. trifoliata* and *U. minor* were identified as key indicator species of acid oligotrophic lake habitat 3160 and are easily recognised and identified in the field, providing a rapid field-based method of identifying acid oligotrophic lake habitat 3160.

The phytoplankton communities of all water bodies sampled were similar, although regional differences were detected, with higher planktonic desmid richness in Connemara Bog Complex SAC than in Owenduff/Nephin SAC. Overall, the surveyed water bodies consistently showed high abundance of mixotrophic species comprising Bacillariophyceae, Chrysophyceae, Chlorophyceace, Cyanophyceae, Dinophyceae and Raphidophyceae. Desmids were the most species-rich taxa in both planktonic and benthic samples and in both spring and summer samples and were present in all 24 water bodies surveyed. These traits make them a suitable target indicator group for distinguishing individual water bodies as oligotrophic lake habitats in Ireland. pH was an important driver of regional differences in the planktonic desmid communities, where water bodies with a mean annual pH < 5 were typically bog pools located in Owenduff/Nephin SAC, whereas water bodies with a mean annual pH ≥ 5 (33) were predominantly lakes located in Connemara Bog Complex SAC. All water bodies sampled contained rare or vulnerable species on the UK and Netherlands red lists, highlighting the importance of these oligotrophic water bodies as a refuge for desmid species and ensuring their conservation protection. Water colour was a significant physico-chemical parameter for determining the presence of rare or vulnerable red-listed species, as the darker coloured waters of Connemara Bog Complex SAC resulted in a greater number of rare and vulnerable red list species. The consistently high diversity of desmids, in addition to their moderate to high conservation values, determined using the desmid NCV metric, confirms the assignment of favourable conservation condition within the studied water bodies and further highlights how desmids could be used as a bioindicator group for conservation condition in oligotrophic lake habitats.

Regional and seasonal differences were observed in the Odonata and Coleoptera communities of the study sites. In summary, Odonata and Coleoptera communities of oligotrophic isoetid lake habitat 3110 were species-rich, dominated by Odonata of the family Coenagrionidae (damselflies), with species *I. elegans* and *P. nymphula* dominating, while Dytiscidae, Gyrinidae, Libellulidae and Aeshnidae were also commonly occurring families. Odonata species *E. cyathigerum* and *I. elegans* were recorded in high numbers in both spring and summer sampling. Lake area, chloride, DO (percentage of saturation), pH and temperature were important parameters influencing the presence of communities in oligotrophic isoetid lake habitat 3110. In acid oligotrophic lake habitat 3160, predatory Coleoptera dominated from the family Gyrinidae, with species *G. minutus and G. aeratus* dominating in addition to Coenagrionidae, especially *E. cyathigerum*, and the commonly occurring Dytiscidae, Libellulidae and Lestidae families. The Odonata species *E. cyathigerum* and the Coleoptera species *G. aeratus* and *G. minutus* were prevalent in spring samples, but this changed to a dominance by *G. minutus* and *G. aeratus* in summer samples. Turbidity was the only physico-chemical parameter influencing the presence of communities in acid oligotrophic lake habitat 3160. In this study Coleoptera species *H. fulvus* and Odonata species *I. elegans*, *P. nymphula* and *S. striolatum* were indicative of oligotrophic isoetid lake habitat 3110, while Coleoptera species *A. sulcatus* and *G. aeratus* were indicator species of acid oligotrophic lake habitat 3160. Furthermore, both oligotrophic lake habitats hosted four Irish red list species: three near-threatened Coleoptera species, *A. arcticus*, *D. lapponicus* and *B. multilineatus* (syn. *S. multilineatus*), and one endangered Odonata species, *C. aenea,* demonstrating the conservation value of oligotrophic lake habitats. The presence of *C. aenea* in the Connemara Bog Complex SAC agrees with known areas for the species in Ireland; however, this study found the specimens in water bodies assigned to oligotrophic isoetid lake habitat 3110 and not acid oligotrophic lake habitat 3160. Further targeted surveys of known areas and water bodies for *C. aenea* are required to determine its association with specific lake habitat traits and physico-chemical preferences.

4 Framework for Monitoring Oligotrophic Lake Habitats

4.1 Key Findings

The collated physico-chemical and biological datasets from this research provide specific baseline data on 24 water bodies from blanket bog landscapes in western Ireland, specifically Connemara Bog Complex SAC and Owenduff/Nephin SAC, and offer insights into regional, seasonal and environmental factors influencing the characterisation of oligotrophic isoetid lake habitats 3110 and acid oligotrophic lake habitat 3160. Gathering these datasets requires highly trained personnel with specific skills in the identification of biological organisms to species level.

Key findings from this research indicate that:

- Based on the 24 water bodies surveyed, oligotrophic isoetid lake habitat 3110 (12 water bodies) and acid oligotrophic lake habitat 3160 (12 water bodies) have similar biological communities and physico-chemical conditions that are not clearly distinguishable from each other based on lake habitat type.
- A strong regional distinction was observed in the water chemistry and all biological (macrophyte, desmids, Odonata and Coleoptera) datasets between Owenduff/Nephin SAC and Connemara Bog Complex SAC.
- Water body size (lake area), where small ombrotrophic pools smaller than 0.01 km^2 are classified as acid oligotrophic lake habitat 3160 and lakes of surface area greater than 0.01 km^2 are classified as oligotrophic isoetid lake habitat 3110, appears to be a useful parameter for distinguishing between the two oligotrophic lake habitat types in peatland landscapes in Ireland and is appropriate for pre-determining acid oligotrophic lake habitat 3160 during desk-based analysis where these water bodies can be reliably and confidently identified using online mapping software programmes (e.g. Google Earth) and their range and area assessed.
- All 24 water bodies sampled were in favourable conservation condition and naturally dystrophic, with acidic waters, low buffering capacity and conductivity, and high colour and organic matter content; however, it is acknowledged that oligotrophic isoetid lake habitat 3110 is also considered to exist in more rocky catchments that were not sampled.
- Increased autumnal rainfall patterns resulted in greater DOM and true colour in both oligotrophic lake habitats, although patterns were most pronounced in oligotrophic isoetid lake habitat 3110 water bodies, which typically had larger catchment areas.
- Monitoring water colour alone and classifying lake habitat type based on colour is not advisable due to the confounding influence of region, season and catchment area. We suggest monitoring water colour in addition to the physico-chemical parameters alkalinity, DOM and pH, as together they can reflect the conditions needed to maintain the biological elements (specifically macrophytes and desmids) to support the favourable conservation condition of these oligotrophic lake habitat types.
- Ecological function within the favourable oligotrophic lake habitat water bodies sampled was driven by organic matter and mixotrophic algae.
- The macrophyte communities of all water bodies sampled were relatively sparse and species-poor and, in the water bodies sampled, showed no distinct vegetation zonation patterns.
- A low macrophyte species richness was observed across all water bodies sampled, although those classified as oligotrophic isoetid lake habitat 3110 did have a higher species richness than those classified as acid oligotrophic lake habitat 3160.
- Few macrophyte species (*M. trifoliata* and *U. minor*) were specific to acid oligotrophic lake habitat 3160; these indicator macrophytes can be easily recognised and identified in the field to identify acid oligotrophic lake habitat 3160.

- Water chemistry parameters alkalinity, pH and true colour positively influenced macrophyte site species richness.
- The phytoplankton communities of all water bodies were similar and consistently showed high mixotrophic species abundance.
- Desmids were the most species-rich group in both planktonic and benthic samples and, based on the water bodies sampled, are important refuges for rare and vulnerable red-listed desmid species.
- Regional differences were evident for planktonic desmid richness, with Connemara Bog Complex SAC recording higher desmid richness than Owenduff/Nephin SAC.
- pH with a threshold level of 5 was an important driver of regional differences in the planktonic desmid communities.
- The moderate to high conservation values determined using the desmid NCV metric demonstrated the conservation value of these water bodies and the importance of protecting oligotrophic lake habitats in favourable conservation condition.
- Desmids are a suitable target indicator group for distinguishing oligotrophic lake habitats in Ireland and could also be used as a bioindicator group for conservation condition in oligotrophic lake habitats.
- Water bodies sampled within the Connemara Bog Complex SAC and classified as oligotrophic isoetid lake habitat 3110 were dominated by Odonata of the family Coenagrionidae, with species *I. elegans* and *P. nymphula* dominating in both spring and summer sampling.
- Water bodies sampled in the Owenduff/Nephin SAC and classified as acid oligotrophic lake habitat 3160 were dominated by predatory Coleoptera from the family Gyrinidae, with species *G. minutus* and *G. aeratus* dominating in summer samples.
- Water bodies sampled hosted four Irish national red list species – three near-threatened Coleoptera species and one endangered Odonata species, demonstrating the conservation value of these oligotrophic lake habitats for invertebrate diversity.
- Water chemistry parameters alkalinity, pH, true colour and DOM were most influential in determining the regional biological communities (macrophytes, desmids, Odonata and Coleoptera) of the water bodies surveyed.

4.2 Objectives

The research objectives of this work package were to:

1. propose conservation measures needed to maintain oligotrophic lake habitats 3110 and 3160 in favourable conservation condition; and
2. recommend monitoring methods and assessment tools for oligotrophic lake habitats.

4.3 Proposed Conservation Measures for Oligotrophic Lake Habitats 3110 and 3160

The water bodies surveyed during this research were pre-selected to be of favourable conservation condition and situated in areas of favourable Atlantic blanket bog located within protected areas, namely Connemara Bog Complex SAC, County Galway, and Owenduff/Nephin SAC, County Mayo. Pre-screening using satellite imagery (Google Earth Pro, version 7.3.4.8642) ensured the water bodies were located within intact blanket bog habitat where water body catchments contained no forestry and there was no evidence of peat cutting or other anthropogenic impacts (e.g. agriculture, aquaculture or road infrastructure). In addition, CFP reports (NPWS, 2013) were used to ensure catchments had low levels of past grazing damage. Finally, the WFD River Waterbody Status 2013–2018 national assessment ensured surrounding river water bodies and lakes were of good or high ecological status. Therefore, the 24 water bodies selected for study were located in favourable Atlantic blanket bog habitat with no or limited threats and pressures.

Key findings from this research now support the assertion that these water bodies are of favourable conservation condition (desmids) and of high conservation value in terms of national biodiversity (desmids, Odonata and Coleoptera). Based on the 24 water bodies sampled, both oligotrophic lake habitats in favourable conservation condition are naturally dystrophic (acidic waters with low alkalinity and conductivity and high colour and organic matter content). Their ecological function is driven by organic matter and mixotrophic algae, not macrophytes, which are sparse, and they have low species richness and lack a defined vegetation zonation pattern. It is acknowledged, however, that further investigation of oligotrophic isoteid lake habitat 3110 in sites less dominated by peat is necessary.

Desmids demonstrated the greatest potential to act as a biological indicator group for the oligotrophic lake habitats.

To maintain favourable conservation condition for these water bodies at a landscape level requires maintenance of favourable ecological conditions within the wider peatland mosaic of habitats (Atlantic blanket bog, wet heath, etc.). The oligotrophic lake habitats share many pressures (e.g. forestry, agriculture, including overgrazing and peat extraction) with the surrounding blanket bog habitat, although threats from these pressures may impact lake habitats in different ways and to varying degrees of intensity (NPWS, 2019). If measures are not in place to protect against these pressures and threats at a landscape level, water bodies are at risk of eutrophication and acidification and, thus, unfavourable conservation condition. Acid oligotrophic lake habitat 3160 is intricately linked to the surrounding peatland and, where associated actions from pressures such as drainage lead to a loss of the hydrological regime within the peatland, detrimental effects on the water levels of acid oligotrophic lake habitat 3160 will also occur. Therefore, to protect all peatland habitats, implementing conservation measures within peatland landscapes, including protected and non-protected lands, should be a priority. Where degraded peatland sites with the potential to develop oligotrophic water bodies, either oligotrophic isoetid lake habitat 3110 and/or acid oligotrophic lake habitat 3160, are selected for restoration or enhancement, determining appropriate restoration trajectories will require a better understanding of the structure and function element of water bodies in favourable conservation condition. Table 4.1 proposes conservation measures aimed at maintaining and restoring favourable conservation condition in these protected oligotrophic lake habitat types and the surrounding peatland landscape.

4.4 Recommended Practical Monitoring Methods and Assessment Tools for Oligotrophic Lake Habitats

The following practical monitoring methods and assessment tools are recommended for monitoring oligotrophic isoetid lake habitat 3110 and acid oligotrophic lake habitat 3160 and addressing data gaps identified in this study, helping to inform conservation condition assessments, in addition to providing scientific evidence on boundaries and transitions between oligotrophic and other protected lake habitat types.

A short “snapshot” field sampling programme of a broader range of oligotrophic isoetid lake habitat 3110 and acid oligotrophic lake habitat 3160 water bodies is recommended to capture regional variations and distinctions, including water bodies likely to be of unfavourable conservation condition owing to threats and pressures in their catchments. This snapshot field sampling programme should:

- Collect data on water bodies’ maximum depth of macrophyte colonisation to further elucidate relationships between water chemistry and macrophytes, enhancing our knowledge of regional distinctions and variations in catchments.
- Record physico-chemical parameters pH, alkalinity, DO, DOM and water colour in association with biological elements to help improve understanding of ecological functioning within the water bodies and of trophic gradients (oligotrophic and dystrophic state) from water bodies across various conservation condition.
- Sample and identify planktonic and benthic desmids, to species level, of oligotrophic lake habitat types. Their high species diversity makes them a suitable indicator group for distinguishing oligotrophic lake habitats and for assessing the conservation condition of these water bodies in Ireland.
- Identify all algal groups within the phytoplankton community and monitor changes in dominant mixotrophic algal groups over time, providing early warning of any reduction in water quality within the oligotrophic lake habitats.
- Utilise new and existing desmid data within Ireland to adapt and calculate the NCV desmid metric and advance the development of condition assessments methods. In addition, the NCV could act as a useful assessment tool for monitoring restoration efforts of degraded oligotrophic water bodies.
- Identify all macroinvertebrate taxa, to family level, to provide information on community composition.
- Note species rarity (number of rare species) for macrophytes, desmids and invertebrates, as both types of water body sampled hosted species of high conservation value, and this is an important measure of national biodiversity.

Table 4.1. Proposed conservation measures to maintain and restore favourable conservation condition in oligotrophic isoetid lake habitat 3110 and acid oligotrophic lake habitat 3160

	Oligotrophic isoetid lake habitat 3110		Acid oligotrophic lake habitat 3160	
Target parameters	**Maintain favourable conservation condition**	**Restore favourable conservation condition**	**Maintain favourable conservation condition**	**Restore favourable conservation condition**
Hydrology	Maintain hydrological connection with the catchment in general and especially the surrounding intact blanket bog and inlet waters and springs Prevent water abstraction in designated peatland catchments, which could cause a significant impact Prevent the discharge of wastewater treatment effluent, which could cause significant impacts	Drain blocking of the surrounding blanket bog, in particular, may be required to increase water levels and restore the hydrological regime Review and, where necessary, modify water abstraction licences in designated peatland catchments Review and, where necessary, modify wastewater treatment effluent discharge licences	Maintain hydrological connection with surrounding intact blanket bog	Drain blocking of the surrounding blanket bog, in particular, may be required to increase water levels and restore the hydrological regime
Organic matter, particulate and nutrient run-off	Assess and regulate new anthropogenic activities, including forestry, turf cutting and wind farms, within peatland catchments, which could negatively impact protected lakes	Assess the impact of and, where necessary, regulate current anthropogenic activities, including turf cutting and associated drainage activities, wind farms and associated access roads and aquaculture Remove forestry on peat soils using sensitive removal methods Apply for forestry licence derogation to replace conifer plantations on peat soils with native peatland regeneration options Restore degraded areas of blanket bog and wet heath within the catchments and sub-catchments of the lake habitats Remove access by livestock to the restoration site using fencing to allow vegetation recovery	Assess and regulate new anthropogenic activities, including forestry, turf cutting and wind farms, within peatland catchments, which could negatively impact protected lakes	Assess the impact of and, where necessary, regulate current anthropogenic activities, including turf cutting and associated drainage activities and wind farms and associated access roads Remove forestry on peat soils using sensitive removal methods Apply for forestry licence derogation to replace conifer plantations on peat soils with native peatland regeneration options Restore degraded areas of blanket bog and wet heath within the catchments and sub-catchments of the lake habitats Remove access by livestock to the restoration site using fencing to allow vegetation recovery
Biology		Reduce livestock stocking densities where there is evidence of overgrazing on the site or within the catchment to allow vegetation recovery. Deer management plans for SACs and the wider region should be implemented to allow vegetation recovery Select sites within proximity to natural oligotrophic lake and pool habitats, increasing opportunities for biological transfer within blanket bog catchments Reinstate buffer zones on inlet streams		Reduce livestock stocking densities where there is evidence of overgrazing on the site or within the catchment to allow vegetation recovery. Deer management plans for SACs and the wider region should be implemented to allow vegetation recovery Select sites within proximity to natural oligotrophic lake and pool habitats, increasing opportunities for biological transfer within blanket bog catchments
Invasive aquatic plants	Identify, manage and eradicate aquatic invasive species	Identify, manage and eradicate aquatic invasive species	Identify, manage and eradicate aquatic invasive species	Identify, manage and eradicate aquatic invasive species

4.5 Future Research

The following recommendations are aimed at improving our understanding of oligotrophic isoetid lake habitat 3110 and acid oligotrophic lake habitat 3160 and what information is required to inform conservation condition assessments. Further work is required to:

- Expand on the list of typical species for a range of biological elements (e.g. desmids, invertebrates, zooplankton, fish) at a national scale, including characteristic/recurrent species, keystone species for maintaining the structure and function of the lake habitats and sensitive indicator species of favourable conservation condition.
- Conduct targeted monitoring of planktonic and benthic desmids in oligotrophic lake habitat types of both favourable and unfavourable conservation condition, and develop a national desmid species rarity list. This will further inform their suitability as an indicator group for assessing the conservation condition of these water bodies and the full adoption of the NCV desmid metric in Ireland.
- Conduct targeted monitoring of macroinvertebrate taxa within functional feeding groups (e.g. shredders and filter feeders) associated with organic matter breakdown and internal nutrient cycling. This would provide information on the macroinvertebrate drivers of ecological functioning within the oligotrophic water bodies and inform the development of a macroinvertebrate assessment tool for these oligotrophic lake habitats.
- Understand the functional role of water colour within each oligotrophic lake habitat type, determine how it relates to the biological communities (e.g. desmids, macrophytes) within the water bodies and assess how it varies over wider geographical and environmental gradients.
- Demonstrate the efficacy of underwater drones in confidently and reliably surveying submerged macrophytes in oligotrophic water bodies.

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Abbreviations

CFP	Commonage Framework Planning
DO	Dissolved oxygen
DOM	Dissolved organic matter
NCV	Nature conservation value
NMDS	Non-metric multidimensional scaling
PERMANOVA	Permutational multivariate analysis of variance
Pt-Co	Platinum-Cobalt scale
RDA	Redundancy analysis
SAC	Special Area of Conservation
SQS	Species quality score
WFD	Water Framework Directive

An Ghníomhaireacht Um Chaomhnú Comhshaoil

Tá an GCC freagrach as an gcomhshaol a chosaint agus a fheabhsú, mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ar thionchar díobhálach na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialáil: Rialáil agus córais chomhlíonta comhshaoil éifeachtacha a chur i bhfeidhm, chun dea-thorthaí comhshaoil a bhaint amach agus díriú orthu siúd nach mbíonn ag cloí leo.

Eolas: Sonraí, eolas agus measúnú ardchaighdeáin, spriocdhírithe agus tráthúil a chur ar fáil i leith an chomhshaoil chun bonn eolais a chur faoin gcinnteoireacht.

Abhcóideacht: Ag obair le daoine eile ar son timpeallachta glaine, táirgiúla agus dea-chosanta agus ar son cleachtas inbhuanaithe i dtaobh an chomhshaoil.

I measc ár gcuid freagrachtaí tá:

Ceadúnú

- Gníomhaíochtaí tionscail, dramhaíola agus stórála peitril ar scála mór;
- Sceitheadh fuíolluisce uirbigh;
- Úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe;
- Foinsí radaíochta ianúcháin;
- Astaíochtaí gás ceaptha teasa ó thionscal agus ón eitlíocht trí Scéim an AE um Thrádáil Astaíochtaí.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil

- Iniúchadh agus cigireacht ar shaoráidí a bhfuil ceadúnas acu ón GCC;
- Cur i bhfeidhm an dea-chleachtais a stiúradh i ngníomhaíochtaí agus i saoráidí rialáilte;
- Maoirseacht a dhéanamh ar fhreagrachtaí an údaráis áitiúil as cosaint an chomhshaoil;
- Caighdeán an uisce óil phoiblí a rialáil agus údaruithe um sceitheadh fuíolluisce uirbigh a fhorfheidhmiú
- Caighdeán an uisce óil phoiblí agus phríobháidigh a mheasúnú agus tuairisciú air;
- Comhordú a dhéanamh ar líonra d'eagraíochtaí seirbhíse poiblí chun tacú le gníomhú i gcoinne coireachta comhshaoil;
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Dramhaíola agus Ceimiceáin sa Chomhshaol

- Rialacháin dramhaíola a chur i bhfeidhm agus a fhorfheidhmiú lena n-áirítear saincheisteanna forfheidhmithe náisiúnta;
- Staitisticí dramhaíola náisiúnta a ullmhú agus a fhoilsiú chomh maith leis an bPlean Náisiúnta um Bainistíocht Dramhaíola Guaisí;
- An Clár Náisiúnta um Chosc Dramhaíola a fhorbairt agus a chur i bhfeidhm;
- Reachtaíocht ar rialú ceimiceán sa timpeallacht a chur i bhfeidhm agus tuairisciú ar an reachtaíocht sin.

Bainistíocht Uisce

- Plé le struchtúir náisiúnta agus réigiúnacha rialachais agus oibriúcháin chun an Chreat-treoir Uisce a chur i bhfeidhm;
- Monatóireacht, measúnú agus tuairisciú a dhéanamh ar chaighdeán aibhneacha, lochanna, uiscí idirchreasa agus cósta, uiscí snámha agus screamhuisce chomh maith le tomhas ar leibhéil uisce agus sreabhadh abhann.

Eolaíocht Aeráide & Athrú Aeráide

- Fardail agus réamh-mheastacháin a fhoilsiú um astaíochtaí gás ceaptha teasa na hÉireann;
- Rúnaíocht a chur ar fáil don Chomhairle Chomhairleach ar Athrú Aeráide agus tacaíocht a thabhairt don Idirphlé Náisiúnta ar Ghníomhú ar son na hAeráide;
- Tacú le gníomhaíochtaí forbartha Náisiúnta, AE agus NA um Eolaíocht agus Beartas Aeráide.

Monatóireacht & Measúnú ar an gComhshaol

- Córais náisiúnta um monatóireacht an chomhshaoil a cheapadh agus a chur i bhfeidhm: teicneolaíocht, bainistíocht sonraí, anailís agus réamhaisnéisiú;
- Tuairiscí ar Staid Thimpeallacht na hÉireann agus ar Tháscairí a chur ar fáil;
- Monatóireacht a dhéanamh ar chaighdeán an aeir agus Treoir an AE i leith Aeir Ghlain don Eoraip a chur i bhfeidhm chomh maith leis an gCoinbhinsiún ar Aerthruailliú Fadraoin Trasteorann, agus an Treoir i leith na Teorann Náisiúnta Astaíochtaí;
- Maoirseacht a dhéanamh ar chur i bhfeidhm na Treorach i leith Torainn Timpeallachta;
- Measúnú a dhéanamh ar thionchar pleananna agus clár beartaithe ar chomhshaol na hÉireann.

Taighde agus Forbairt Comhshaoil

- Comhordú a dhéanamh ar ghníomhaíochtaí taighde comhshaoil agus iad a mhaoiniú chun brú a aithint, bonn eolais a chur faoin mbeartas agus réitigh a chur ar fáil;
- Comhoibriú le gníomhaíocht náisiúnta agus AE um thaighde comhshaoil.

Cosaint Raideolaíoch

- Monatóireacht a dhéanamh ar leibhéil radaíochta agus nochtadh an phobail do radaíocht ianúcháin agus do réimsí leictreamaighnéadacha a mheas;
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha;
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta;
- Sainseirbhísí um chosaint ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Ardú Feasachta agus Faisnéis Inrochtana

- Tuairisciú, comhairle agus treoir neamhspleách, fianaise-bhunaithe a chur ar fáil don Rialtas, don tionscal agus don phobal ar ábhair maidir le cosaint comhshaoil agus raideolaíoch;
- An nasc idir sláinte agus folláine, an geilleagar agus timpeallacht ghlan a chur chun cinn;
- Feasacht comhshaoil a chur chun cinn lena n-áirítear tacú le hiompraíocht um éifeachtúlacht acmhainní agus aistriú aeráide;
- Tástáil radóin a chur chun cinn i dtithe agus in ionaid oibre agus feabhsúchán a mholadh áit is gá.

Comhpháirtíocht agus Líonrú

- Oibriú le gníomhaireachtaí idirnáisiúnta agus náisiúnta, údaráis réigiúnacha agus áitiúla, eagraíochtaí neamhrialtais, comhlachtaí ionadaíocha agus ranna rialtais chun cosaint chomhshaoil agus raideolaíoch a chur ar fáil, chomh maith le taighde, comhordú agus cinnteoireacht bunaithe ar an eolaíocht.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil

Tá an GCC á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóir. Déantar an obair ar fud cúig cinn d'Oifigí:

1. An Oifig um Inbhunaitheacht i leith Cúrsaí Comhshaoil
2. An Oifig Forfheidhmithe i leith Cúrsaí Comhshaoil
3. An Oifig um Fhianaise agus Measúnú
4. An Oifig um Chosaint ar Radaíocht agus Monatóireacht Comhshaoil
5. An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tugann coistí comhairleacha cabhair don Ghníomhaireacht agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.