PROJECT MUSE®

Status of freshwater invertebrate biodiversity in Ireland's
rivers – time to take stock

Mary Kelly-Quinn, Hugh Feeley, Catherine Bradley

Biology and Environment: Proceedings of the Royal Irish Academy,
Volume 120B, Number 2, 2020, pp. 65-82 (Article)

Published by Royal Irish Academy

➔ For additional information about this article

<https://muse.jhu.edu/article/809360/summary>

STATUS OF FRESHWATER INVERTEBRATE BIODIVERSITY IN IRELAND'S RIVERS – TIME TO TAKE STOCK

Mary Kelly-Quinn, Hugh Feeley and Catherine Bradley

ABSTRACT

In recent years a growing number of publications have highlighted alarming biodiversity losses in freshwaters. Given the continuing pollution pressure on water quality in Ireland, it is now timely to take stock of the information base on freshwater invertebrate biodiversity in rivers. This paper interrogates available macroinvertebrate datasets and published results to determine the state of knowledge of freshwater invertebrate biodiversity in Ireland's rivers, what is known in terms of their threat status and what is the impact of pollution on riverine invertebrate biodiversity. Second, it investigates the potential use of surrogates to monitor biodiversity of macroinvertebrates in Irish rivers and concludes with a discussion of emerging threats to macroinvertebrate biodiversity, key knowledge gaps, and addressing monitoring of invertebrate biodiversity.

INTRODUCTION

Freshwater ecosystems occupy less than 1% of the Earth's surface and yet they provide a disproportionately high level of essential ecosystem services (Dudgeon *et al.* 2006) that enable life on land. Some of these are tangible, such as water for consumption and other uses including recreation, but there is growing recognition of the importance of less tangible values for human wellbeing such as sense of place and other physical and spiritual interactions with the natural environment. These benefits are underpinned by the species that occupy freshwaters and their ecological processes. Freshwaters are remarkably diverse, supporting up to 9.5% of all known animal species (Dudgeon 2019). In recent years a growing number of publications have highlighted alarming biodiversity losses in freshwaters; these losses are higher than in terrestrial and marine systems, threatening the delivery and sustainability of ecosystem services (Abell 2002; Strayer and Dudgeon 2010; Dudgeon 2014, 2019; WWF 2018; Reid *et al.* 2019). For example, the living Planet Freshwater Index (WWF 2018) highlights an 83% decline since the 1970s while Sánchez-Bayo and Wyckhuys (2019) highlight four key freshwater orders (Ephemeroptera, Plecoptera, Trichoptera and Odonata) that have lost a considerable number of species. Furthermore, Reid *et al.* (2019) consider the unprecedented loss of freshwater species as an invisible tragedy and stress the need to identify the greatest threats to freshwater biodiversity and opportunities for effective interventions. Here in Ireland most populations

of the protected pearl mussel *Margaritifera margaritifera* (Linnaeus, 1758), the largest and among the longest-lived invertebrate species, is at unfavourable-bad status with unfavourable habitat conditions. There is also evidence of decline in populations of the white-clawed crayfish *Austropotamobius pallipes* (Lereboullet, 1858) due to crayfish plague (NPWS 2019a).

The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services report (IPBES 2019) highlighted that freshwater ecosystems show among the highest rates of decline in condition. Reid *et al.* (2019) documented a range of well-known threats such as elevated nutrients and sediment, and twelve others that are new or that have been intensified such as emerging contaminants and microplastics. Such threats arise from a range of anthropogenic pressures that are yielding multiple interacting stressors. These include point and diffuse discharges from areas of agricultural and urban land uses, and commercial forestry and industrial operations as well as habitat degradation (hydromorphology) due to flow regulation, flood management, fragmentation by dams and other barriers, invasive species, diseases and overexploitation, all of which have intensified in the so-called 'Anthropocene' (Dudgeon 2014, 2019; Reid *et al.* 2019).

Climate change is set, in many instances, to exacerbate the threats and impacts on freshwater biodiversity through changes in flow and temperature regimes (Dudgeon 2019; Reid *et al.* 2019). Drier weather periods will also reduce a water body's capacity to assimilate pollutants, maintain oxygen

Mary Kelly-Quinn
(corresponding
author; email: mary.
kelly-quinn@ucd.ie.
ORCID iD: [https://
orcid.org/0000-
0002-0110-5360](https://orcid.org/0000-0002-0110-5360)),
School of Biology
& Environmental
Science and UCD Earth
Institute, University
College Dublin,
Belfield, Dublin 4; Hugh
Feeley, Environmental
Protection Agency,
McCumiskey House,
Richview, Clonskeagh
Rd., Dublin 14;
Catherine Bradley
Environmental
Protection Agency,
McCumiskey House,
Richview, Clonskeagh
Rd., Dublin 14.

Cite as follows: Kelly-
Quinn, M., Feeley, H.
and Bradley, C. 2020
Status of freshwater
invertebrate biodiversity
in Ireland's rivers – time
to take stock. *Biology
and Environment:
Proceedings of the
Royal Irish Academy*
2020. DOI: 10.3318/
BIOE.2020.09

Received 23 January 2020.
Accepted 24 April 2020.
Published 31 August 2020.

and regulate temperature, while higher rainfall and increased flood events can lead to the release of pollutants and increase instream and channel physical disturbance and damage. Some 23 of the 31 core ecological processes underpinning freshwater ecosystem functioning and ecosystem services provision have already been affected by climate change (Scheffers *et al.* 2016). As noted by Staudt *et al.* (2013) ecosystems already under stress are likely to be more rapidly and severely impacted by climate change; this, together with the uncertainty relating to the nature of changes due to multiple stressor interactions, further confounds and complicates efforts to mitigate the impacts.

Ireland, like most parts of Europe, has yet to meet the objectives of the EU Water Framework Directive (WFD). In 2019 the Environmental Protection Agency reported that in the most recent national assessment (covering period 2013–18) 47.2% of surface water bodies are in unsatisfactory moderate, poor, or bad ecological status (O’Boyle *et al.* 2019). This represents a net decline of 4.4% (117) of surface water bodies monitored since the 2010–15 assessment period. The number of river water bodies at poor and bad status has increased while further losses of unpolluted high-status river water bodies was noted (see O’Boyle *et al.* 2019 for more details) which highlights serious threats to Irish freshwater biodiversity. As noted by O’Boyle *et al.* (2019) these high-status sites are important reservoirs of Irish aquatic biodiversity. Nutrients and fine sediment are the key stressors (O’Boyle *et al.* 2019, Davis *et al.* 2018) but there is also evidence of pesticide and herbicide impacts in some areas, although limited assessments of biocide impact on invertebrate biodiversity have been carried out in Ireland. Many of these pressures have been identified as impacting protected habitats and species (NPWS 2019a, 2019b).

Ecological status assessment for the WFD is based on indicator taxa that are often not identified to species level and therefore does not necessarily provide sufficient detailed information on the state of freshwater biodiversity in Ireland’s rivers and lakes (e.g. O’Connor 2016). A good body of information exists on the diversity, distribution and status of Ireland’s fish fauna. Less attention has been focused on the state of invertebrate diversity even though they support key ecosystem processes such as nutrient cycling. Given the continuing pollution and other pressures such as physical habitat degradation and invasive species in Irish freshwaters as well as the growing concern about biodiversity loss, it is now timely to take stock of the information base on freshwater invertebrate biodiversity in Ireland and identify where future investigations should be focussed to improve knowledge to a level that can better inform conservation efforts.

This paper:

1. Interrogates available macroinvertebrate datasets and published results to answer a number of questions; a) What is the state of knowledge of freshwater invertebrate biodiversity in Ireland’s rivers?; b) What is known in terms of their threat status? and c) What is the impact of pollution on macroinvertebrate biodiversity in Irish rivers?
2. Investigates the potential use of surrogates to monitor biodiversity of macroinvertebrates in Irish rivers. It was hypothesised that species richness of the Ephemeroptera, Plecoptera and Trichoptera—either singularly or combined—would be significantly correlated with total taxon richness.
3. Uses the results from objectives 1 and 2 as well as other sources of information to discuss emerging threats to macroinvertebrate biodiversity, key knowledge gaps and options for monitoring invertebrate biodiversity.

METHODS

THE STATE OF KNOWLEDGE OF FRESHWATER INVERTEBRATE BIODIVERSITY IN IRELAND’S RIVERS

Tables of the numbers of species in key invertebrate groups in lotic and lentic freshwaters were compiled using information from peer-reviewed published papers and reports. Sources used to compile these numbers are available in Feeley *et al.* (2017), but notable sources include Ashe *et al.* (1998), Byrne *et al.* (2009), Ferriss *et al.* (2009) and O’Connor and Nelson (2012). Additional sources were also consulted to update several groups including the Trichoptera (e.g. O’Connor 2019; O’Connor and O’Connor 2019) and the Chironomidae (Murray 2018, 2019a,b; Murray and Ashe 2017; Murray and Langton 2018; Murray *et al.* 2018). Similarly, the number of ephemeropteran species has increased with the addition of *Baetis atlanticus* (Soldán and Godunko 2006) to the Irish list (Feeley and Macadam 2020), while data from a recent review of the Coleoptera are included (Foster *et al.* 2020). Experts on some groups (see acknowledgements and Table 2) were consulted to supplement the available published information. An evaluation of the level of information available on species distribution was undertaken.

WHAT DO WE KNOW IN TERMS OF THEIR THREAT STATUS?

Counts of threatened species were extracted from the International Union for the Conservation of Nature and Natural Resources (IUCN) Regional

Red Lists for Irish aquatic species; these included Mollusca (gastropods and bivalves) (Byrne *et al.* 2009), Coleoptera (water beetles) (Foster *et al.* 2009), Odonata (damselfly and dragonflies) (Nelson *et al.* 2011), Ephemeroptera (mayflies) (Kelly-Quinn and Regan 2012) and Plecoptera (stoneflies) (Feeley *et al.* 2020a). This information was tabulated to highlight and summarise the threat status of the assessed invertebrates and to make comparisons with vertebrate species found in freshwaters that were assessed using IUCN Regional Red List criteria and methods, namely amphibians and freshwater fish (King *et al.* 2011) and the otter (Marnell *et al.* 2019).

IMPACT OF POLLUTION ON MACROINVERTEBRATE BIODIVERSITY IN IRISH RIVERS.

Analysis was carried out on macroinvertebrate data from two sources to provide an insight into the impact of anthropogenic pressures on macroinvertebrate

biodiversity in rivers. The data were all collected from the range of riverine mesohabitats (riffle, run, glide, shallow pools and included marginal areas) at each site and therefore captured the best representation of the macroinvertebrate fauna present.

The first dataset held largely species-level macroinvertebrate data collected as part of the AGRIBASELINE Project (see McMahon *et al.* 2012) between spring 2007 and spring 2009 from thirty small, second and third order streams and rivers draining grass-based agricultural lands in three separate geographical regions, in the north-west (counties Sligo and Leitrim), midlands (counties Offaly and Laois) and south (county Cork) of Ireland (Figure 1). These data were used in this paper to assess changes in macroinvertebrate biodiversity across an agricultural intensity gradient. Agricultural land covers over 65% of the land area of Ireland and the associated activities have been identified as the main cause of ecological decline in Irish freshwaters due largely to elevated nutrient

Fig. 1—Location of AGRIBASELINE Project sampling sites: the north-west (black circles), midlands (black squares) and south (black triangles) of Ireland.

inputs (O'Boyle *et al.* 2019). These three regions were chosen to represent predominately extensive non-dairy agriculture in the north-west, hereafter referred to as low intensity agriculture, medium agricultural intensity in the midlands comprising mixed non-dairy and dairy farming, and intensive dairy agriculture in the south, hereafter referred to as high intensity agriculture. These regional categories of agricultural land-use intensity were based on the census atlas of agriculture in Ireland at the time (Lafferty *et al.* 1999) and have been applied in agricultural studies in Ireland previously (McMahon *et al.* 2012). The catchment areas in each region were below 150m in elevation and had a minimum of 70% agricultural land cover. Information on site and regional characteristics is provided in McMahon *et al.* (2012). All study streams drained limestone, shale or sandstone and predominately mineral soils (Table 1). Instream habitats were dominated by short riffle-run sequences, interspersed with shallow pools (approx. 20–30cm deep) and were generally dominated by cobbles with some coarse gravel and sand, typical of small streams in Ireland (Feeley *et al.* 2012a).

To confirm that the sites represented a nutrient gradient, water samples were collected in autumn 2007 to determine the concentrations of nitrate ($\text{NO}_3\text{-N}$) and soluble reactive phosphorus (SRP) instream. All samples were collected during prolonged base flow conditions. Details of analysis procedures are the same as those outlined in Feeley *et al.* (2013). A clear gradient in nitrate was evident with the mean NO_3 recorded increasing from 0.35mg N/L (± 0.17 standard error (SE)) to 3.13 (± 0.02 SE) mg N/L to 5.04 (± 0.47 SE) mg N/L at sites in low, medium and high intensity agriculture catchments, respectively (Figure 2a). The pattern was not so distinct for soluble reactive phosphorus (SRP) but the high agriculture intensity sites (0.04 $\mu\text{g/L}$ ± 0.011 SE) recorded the highest mean SRP concentration while concentrations were similar at both low (0.03 $\mu\text{g/L}$ ± 0.009 SE) and medium (0.03 $\mu\text{g/L}$ ± 0.001 SE) agriculture intensity catchments (Figure 2b). It is recognised that there will be natural among-site variations in the three regions, as well as variation in the nature of inputs, including multiple stressors, from agriculture and other catchment uses.

The macroinvertebrates were sampled across the three regions in spring 2007 (April) and in autumn 2007 (September and October), autumn 2008 and spring 2009 during extended periods of low flow. Six 1-minute multi-habitat kick samples were taken using a standard Freshwater Biological Association (FBA) pond net (230x225mm frame, mesh 0.9mm), with all mesohabitats present sampled in proportion to their relative representation in a 50m stretch of river. Samples were preserved using 70% industrial methylated

spirits. In the laboratory, each sample was sorted after being washed through a 500 μm sieve. The Ephemeroptera, Plecoptera, Trichoptera, Coleoptera, Odonata, Hemiptera, Gastropoda and Crustacea were identified to species level, with Diptera identified to genus or sub-family (Simuliidae and Chironomidae) level using standard Freshwater Biology Association identification keys. All other taxa were identified to the lowest taxonomic unit feasible. Regional site data recorded for each season are presented as mean and standard error, while difference in overall (all seasons combined) mean regional taxon richness were tested using one-way ANOVA in PRIMER 6.1.12 and PERMANOVA+ (Clarke and Gorley 2006; Anderson *et al.* 2008). Similarities in regional community composition and structure were visualised (uncommon species included) with non-metric multidimensional scaling (nMDS) based on Bray-Curtis similarities of $\log(X+1)$ transformed data in PRIMER 6 + PERMANOVA+ 1.0.2 (Clarke and Gorley 2006; Anderson *et al.* 2008).

The second dataset was used to highlight examples of the effects of new and emerging threats such as pesticides to freshwater biodiversity. It comprised unpublished data from sites on two rivers: the Glennagannon (Site A) and Glen rivers (Site B) in Co. Donegal. Both rivers were suspected of being polluted by the insecticide cypermethrin, which is used to treat sheep and new forest (including re-afforested) plantations for pests. Macroinvertebrates were collected by the EPA using multi-habitat kick sampling (see Feeley *et al.* 2020b for more details) in summer or early autumn between 1993 and 2019 (Site A) and between 1997 and 2018 (Sites B). Taxa were identified generally to family-level for Diptera, non-elmid Coleoptera and Trichoptera; genus-level for most Ephemeroptera, Plecoptera and Gammariidae and species-level for *Baetis rhodani/atlanticus*, Elmidae and Gastropoda (Feeley *et al.* 2020b). Where taxonomic resolution differed across sampling years the highest level common across the years was used to normalise the data. A suspected toxic event or events, as a result of pesticide use and/or disposal within the catchment above the sampling point, was believed to have occurred at unspecified dates between 2010 and 2016 at both locations. Changes in taxon richness and categorical relative abundance were analysed over this period as a measure of toxic effects on instream biodiversity.

THE POTENTIAL USE OF SURROGATES TO ASSESS OVERALL BIODIVERSITY OF MACROINVERTEBRATES IN IRISH RIVERS

In the context of future monitoring options, the final analysis investigated the use of surrogates to assess overall biodiversity of macroinvertebrates in

Table 1—AGRIBASELINE Project sites sampled in spring and autumn 2007, agricultural intensity, location, RIVTYPE category and selected physical characteristics.

<i>Agricultural intensity</i>	<i>Site names</i>	<i>Latitude</i>	<i>Longitude</i>	<i>RIVTYPE</i>	<i>Elevation</i>	<i>Slope category</i>	<i>Order</i>	<i>Geology</i>	<i>Soil</i>
Low	Aleen River	54.159702	-8.4556177	31	33	0.005	2	Limestone/shale	Mineral
	River at Lackagh	54.144399	-8.4584646	31	40	0.005	3	Limestone/shale	Mineral
	Owenbeg River	54.265749	-8.9573589	32	56	0.005-0.02	2	Limestone/shale	Mineral
	River near Corbally	53.937415	8.0574103	31	43	0.005	3	Limestone/shale	Mineral
	River near Foxborough	53.940978	-8.0047059	32	45	0.005-0.02	2	Limestone/shale	Mineral
	River near Fargrim	53.935990	-7.9827470	31	39	0.005	2	Limestone/shale	Mineral PD
	Castlerogy stream	54.062967	-7.8308089	31	50	0.005	2	Limestone/shale	Mineral PDPT
	River near Fohera	54.058882	-7.7976381	31	58	0.005	3	Limestone/shale	Mineral PDPT
	River near Knockaghy	53.900633	-7.5080576	11	75	0.005	3	Sandstone/shale	Mineral PD
	Trib. of Garty Lough	53.929392	-7.5654390	11	67	0.005	3	Sandstone/shale	Mineral SW
Medium	River at Cloonbonny	53.384158	-7.9088426	32	44	0.005-0.02	2	Limestone	Mineral PDPT
	Trib. of Little Brosna River	53.079918	-7.8877723	32	65	0.005-0.02	2	Limestone	Mineral SW
	Trib. of River Brosna 1	53.313102	-7.7102662	31	45	0.005	2	Limestone	Mineral SW
	Trib. of River Brosna 2	53.286361	-7.7264627	31	40	0.005	2	Limestone	Cut
	River near Farifield	53.324599	-7.4184534	31	80	0.005	2	Limestone	Cut
	Silver River	53.305727	-7.4931083	31	55	0.005	2	Limestone	Mineral
	Toberfin River	53.250952	-7.4029407	31	50	0.005	2	Limestone	Cut
	Hw of River Boyne 1	53.346391	-7.0135337	31	76	0.005	2	Limestone	Mineral DW
	Hw of River Boyne 2	53.358015	-7.0934648	31	65	0.005	3	Limestone	Mineral DW
	Garr River	53.403044	-7.0403435	31	70	0.005	2	Limestone	Mineral
High	Farahy River	52.228276	-8.4169708	32	67	0.005-0.02	3	Limestone	Mineral PD
	Funshion River	52.253632	-8.4088755	31	65	0.005	2	Limestone	Mineral DW
	Allow River	52.207392	-8.9031814	31	100	0.005	2	Sandstone/shale	Mineral
	Trib. of River Allow	52.214467	-8.8828685	31	110	0.005	2	Sandstone/shale	Mineral PD
	Knoppoge River	52.054607	-8.2539815	12	40	0.005-0.02	3	Sandstone	Mineral DW
	Marinahone River	52.068767	-8.1661464	12	40	0.005-0.02	2	Sandstone	Mineral DW
	Black Brook River	51.973839	-8.4279943	12	45	0.005-0.02	3	Sandstone	Mineral SW
	Bulterstown River	51.964595	-8.3471206	22	65	0.005-0.02	3	Sandstone	Mineral SW
	Trib. of Womanagh River	51.940064	-7.9812399	22	20	0.005-0.02	2	Sandstone	Mineral PD
	Tourig River	51.974850	-7.9529034	22	30	0.005-0.02	3	Limestone	Mineral DW

Hw = headwaters, Trib. = tributary, PD = deep poorly drained, PDPT = poorly drained with peaty topsoil, SW = shallow well drained, cut = raised bog (cutaway/cutover), DW = deep well-drained.

Fig. 2—The mean ($\pm$ standard error) nitrate ($\text{NO}_3\text{-N}$) and soluble reactive phosphorus (SRP) concentrations recorded across low, medium and high agricultural intensity sites over the study period during the AGRIBASELINE Project.

Irish rivers. Surrogate taxa have been used previously to address problems assessing biodiversity and conservation measures (e.g. Ormerod *et al.* 2010; Guareschi *et al.* 2012). Four spatially and temporally extensive river macroinvertebrate datasets (AGRIBASELINE project as outlined above, the Biodiversity Project (Bradley 2001; Bradley *et al.* 2002), the RIVTYPE project (Kelly-Quinn *et al.* 2005) and Callanan *et al.* (2008) on headwater streams) were compiled to investigate whether the richness of selected macroinvertebrate groups correlated with the remaining macroinvertebrate richness. The four datasets were derived from samples collected at 582 river sites across Ireland, covering spring, summer and autumn seasons and all had species-level taxonomic resolution for Plecoptera, Ephemeroptera, Trichoptera, Coleoptera, Gammaridae, Hirudinea and Gastropoda. All other taxa were brought to the lowest feasible resolution, usually genus.

To test for potential surrogates of biodiversity, groups with the most accurate available taxonomic information, namely the Plecoptera, Ephemeroptera, Trichoptera and Coleoptera, as well as the combined Ephemeroptera, Plecoptera, Trichoptera (EPT) metric and combined Ephemeroptera, Trichoptera (ET) metric were used. Other groups were not examined owing to the lack of spatial occurrence (e.g. lack of snails and gammarids in soft waters). Using the approach of Guareschi *et al.* (2012) the taxon richness values of these different groups (e.g. Ephemeroptera, Plecoptera, etc.) were correlated against the remaining richness (RR) using Spearman correlation (as data were not normally distributed) in Statistica 7 software. For example, to test if Ephemeroptera richness could predict and estimate overall community richness, the number of Ephemeroptera species recorded was correlated with the total number of taxa recorded less the Ephemeroptera.

RESULTS

THE STATE OF KNOWLEDGE OF
FRESHWATER INVERTEBRATE
BIODIVERSITY IN IRELAND'S RIVERS

Estimated numbers of species in the various invertebrate groups in freshwater habitats and separately for rivers where information is available, together with an evaluation of the level of information available on the distribution of species are provided in Table 2. The microinvertebrates, mostly <1mm in size, are, apart from the Rotifera and the planktonic crustaceans, represented by relatively few species and check lists for several orders have been updated since 2000. In contrast, records for the species-rich Rotifera date back to the 1980s. The macroinvertebrates are represented by just over 2500 known species. Some of the macroscopic Crustacea and a number of the insect groups (e.g. Ephemeroptera, Plecoptera, Trichoptera, Coleoptera, Odonata, Heteroptera and Chironomidae) are well studied but even these have yielded new species in recent years. Among the most species rich of the well recorded groups are the Chironomidae with 324 of the known species that occur in Ireland's freshwaters found in rivers. The Chironomidae represent almost 50% of the known Irish freshwater dipteran species. Apart from the Chironomidae most other Diptera are poorly recorded with most taxa left at family- or subfamily-level. The proportion of species in the various groups that occur in rivers varies from 100% (Ephemeroptera) to 10% (e.g. Heteroptera), and there are several groups where only a conservative estimate can be provided, e.g. Crustacea.

While checklists can be generated for most groups, significant gaps exist in terms of species distribution (Table 2). Nevertheless, detailed and comprehensive distributional data have been compiled (and periodically updated) for several aquatic groups (e.g. Ephemeroptera, Chironomidae, Coleoptera, Hemiptera, Odonata, Plecoptera and Trichoptera), which are available through the National Biodiversity Data Centre at <https://maps.biodiversityireland.ie/Dataset/>.

WHAT DO WE KNOW IN TERMS OF THEIR
THREAT STATUS?

The threat status of the five invertebrate groups that have been assessed are summarised in Table 3. For comparison the status of the assessed fish, amphibians and the otter are included. Sixteen of the species assessed, including 10 aquatic insects, five snails and the eel, are critically endangered in Ireland. Eleven species, (eight water beetles, one stonefly and two snails) or 2.3% of the invertebrate species examined are considered now extinct in Ireland (Table 3). The red list of non-marine molluscs includes terrestrial species but many of these favour moist habitats. Of

the 150 species assessed one third were considered vulnerable or endangered, half of which are aquatic including *Margaritifera margaritifera* and *Margaritifera durrovensis* Philips, 1928. In contrast, no vertebrate species have been lost in recent decades (Table 3).

IMPACT OF POLLUTION
ON MACROINVERTEBRATE
BIODIVERSITY IN IRISH RIVERS

From the analysis on the AGRIBASELINE project data (the influence of agricultural intensification on the biodiversity of streams and rivers) little variation in species richness at site-level across the four sampling periods was detected (Figure 3a). However, when the total regional diversity (in terms of total species recorded) for the study period was examined, species richness was seen to decline with increasing agricultural intensity (Figure 3b) (and associated nutrient/organic pollution—see Figure 2). While a downward trend in richness was observed with increasing intensity only the high agricultural intensity region had a richness (107.0 ± 1.8 SE) significantly different ($F_{2,57} = 4.477, P = 0.01$) from low (120.5 ± 5.8) and medium (113.7 ± 3.2 SE) agricultural intensity regions (Figure 3b).

Similarly, when the variation in species composition (richness and abundance) was examined, it was evident that the streams draining high agricultural intensity have more similar composition, with low variation in stream-level communities despite having more geochemically varied geology (Figure 4). In contrast the communities in low and medium intensity agricultural catchments varied across sites and seasons, supporting the results shown in Figure 4. Most of the taxa missing from the higher agricultural intensity catchments are known pollution-sensitive species or rare and less common species of Ephemeroptera (e.g. *Centropilum luteolum* Müller, 1776, *Paraleptophlebia cincta* (Retzius, 1783), *Ephemera danica* Müller, 1764), Coleoptera (various) and Trichoptera (e.g. *Chaetopteryx villosa* (Fabricius, 1798), *Limnephilus lunatus* Curtis, 1834, *L. marmoratus* Curtis, 1834), amongst others.

The threat of emerging pollutants—including pesticides—can be stark, and their use can result in a drastic loss of taxa (Figure 5). At Site A the suspected pesticide release almost halved the macroinvertebrate richness from on average 18 taxa from a two-minute kick sample to only 10 taxa after three-minutes kick sampling (Figure 5). The taxa absent in 2013 and 2016 were predominantly insect taxa. Only a few insect taxa known to have multiple or continuous generations remained, namely *Baetis rhodani/atlanticus*, Chironomidae, Simuliidae, and *Limnius volckmari* (Panzer, 1793) and Hydraenidae beetles were recorded in 2016. Samples were dominated in terms of abundances by non-insect invertebrates such as water mites Hydrachnidia, *Potamopyrgus antipodarum* (Gray, 1843) snails, worms and gammarids.

Table 2—The estimated biodiversity of invertebrate life in Irish freshwaters.

Group	Subphylum	Class/subclass	Order/Family	Estimated no. of taxa/ species – all freshwaters	Estimated no. of taxa/ species in rivers	Distribution information
Rotifera	-	Eurotatoria	Bdelloidea Ploima Flosculariaceae Collothecaceae Ctenostomatida Plumatellida Spongillidae Various ¹ Limnomedusae Chaetonotida Chordodidae Gordiidae Various ¹ Lumbriculidae Naididae ² Lumbricidae Enchytraeidae Other Oligochaeta Rhynchobdellida Arhynchobdellida Various ¹ Various ¹ Araneidae Hydrachnellae Anostraca Diplostraca Decapoda	72 195 29 10 1 8 5 35 1 3 2 1 26 4 46 1 19 3 8 7 33 22 2 120 1 72 2	unknown unknown unknown unknown unknown unknown 5 unknown 0 unknown unknown 1 12 ^{CE} 4 25 1 ? 1	* * * * * * ** * * * * * * ** ** ** * * * * * * * * *
Bryozoa	-	Gymnolaemata Phylactolaemata				
Porifera	-	Demospongiae				
Tardigrada	-	Eutardigrada				
Cnidaria	-	Hydrozoa				
Gastrotricha	-	Gordioida				
Nematomorpha	-					
Platyhelminthes	-	Turbellaria				
Annelida	-	Oligochaeta ^a				
Mollusca	-	Hirudinea Gastropoda Bivalvia Arachnida				
Arthropoda	Chelicerata Crustacea ^b	Branchiopoda Malacostraca				

Table 2—(Continued)

Group	Subphylum	Class/subclass	Order/Family	Estimated no. of taxa/ species – all freshwaters	Estimated no. of taxa/ species in rivers	Distribution information
			Isopoda	5	5	★★
			Amphipoda	13 ^{CE}	13 ^{CE}	★★
	Branchiura		Arguloida	1	1	★
	Copepoda		Calanoida	7	0 ^{CE}	★
			Cyclopoida	36	20 ^{CE}	★
			Siphonostomatoida	3	3 ^{CE}	★
			Harpacticoida	26	20 ^{CE}	★
	Ostracoda		Podocopida	61	50 ^{CE}	★
	Insecta		Coleoptera ^e	244	61 ³	★★★
Hexapoda			Collembola	17	unknown	★
			Chironomidae ^d	542	324	★★★
			Other Diptera	558 ^{CE}	unknown	★
			Ephemeroptera	34	34	★★★
			Hemiptera (Heteroptera) ^e	59	6	★★
			Hymenoptera	17	?	★
			Lepidoptera	5	?	★
			Megaloptera	2	2	★
			Neuroptera	4	4	★
			Odonata ^e	27 ^R	6	★★★
			Plecoptera	19	18	★★★
			Trichoptera ^f	156	105	★★★

Modified from Feeley *et al.* (2017) but see also method section for other references. ¹too many orders to list. ²included species formerly in the Tubificidae;

³ included species found occasionally in rivers, seepages and springs, ^R resident (non-migratory) species only; ^{CE} conservative estimate, number of riverine species consulted with personal communications; ^a Pascal Sweeney, ^b Julian Reynolds, ^c Gareth Foster, ^d Declan Murray, ^e Brian Nelson (note Saldidae and Aepophilidae not included), ^f Jim O'Connor. ★ - poor information with isolated records, ★★ - moderate level of information giving some indication of the species distributions, ★★★ good level of information, maps generated for some (see <https://maps.biodiversityireland.ie/Dataset/>). Note the information in this table may be incomplete due to the difficulty locating up-to-date data. Where information was available on habitat estuaries and brackish water species were excluded, but this cannot be guaranteed. Some groups (e.g. microscopic Crustacea) include hyporheic and groundwater species. Extant species/taxa included only.

Table 3—A comparison of assessments of threat status of select groups of invertebrate and vertebrate fauna in Irish freshwaters.

Common name(s)	Scientific name/ grouping	No. of species assessed	Conservation status						
			LC	NT	VU	EN	CR	RE	DD
Beetles (water only) ¹	Coleoptera	244	148	24	22	11	8	8	23
Mayflies ²	Ephemeroptera	33	24	2	3	2	1	-	1
Dragonflies & Damselflies ³	Odonata	24	19	1	2	2	-	-	-
Stoneflies ⁴	Plecoptera	20	17	-	1	-	1	1	-
Non-marine snails ⁵	Mollusca	150*	97	6	26	14	5	2	-
Total n (%)		471	305 (64.8)	33 (7.0)	54 (11.5)	29 (6.2)	15 (3.2)	11 (2.3)	24 (5.1)
Freshwater vertebrates									
Lamprey ⁶	Petromyzonidae	3	1	-	2	-	-	-	-
Salmon, Trout & Char ⁶	Salmonidae	3	2	1	-	-	-	-	-
Eels ⁶	<i>Anguilla anguilla</i>	1	-	-	-	-	1	-	-
Stickleback ⁶	Gasterosteidae	2	2	-	-	-	-	-	-
Frog & Natterjack toad ⁶	Anura	2	1	-	-	1	-	-	-
Smooth Newt ⁶	Caudata	1	-	-	-	-	-	-	-
Otter ⁷	<i>Lutra lutra</i>	1	1	-	-	-	-	-	-
Total n (%)		13	7 (53.8)	1 (7.7)	2 (15.4)	1 (7.7)	1 (7.7)	0 (0)	0 (0)

See methods section for references. The following are IUCN threat categories and the assessments followed IUCN regional red list methods LC = least concern, NT = near threatened, VU = Vulnerable, EN = endangered, CR = critically endangered, RE = regionally endangered, DD = data deficient. 1 – Foster *et al.* (2009); 2 – Kelly-Quinn and Regan (2012); 3 – Nelson *et al.* (2011); 4 – Feeley *et al.* (2020); 5 – Byrne *et al.* (2009); 6 – King *et al.* (2011); 7 – Marnell *et al.* (2019). ★ included terrestrial species.

Fig. 3—a) Mean stream-level species-level richness of aquatic macroinvertebrates in relation to agricultural intensity over four sampling seasons (in 2007 and 2008), b) the mean regional species-level richness of the same streams in relation to agricultural intensity (Y axis begins at 100 for clarity, low and medium > high intensity, $P = 0.01$). Aut = autumn and Spr = spring. A description of agricultural bands used is available in the methods section.

Numbers of taxa had returned to expected values in 2019. The data from Site B, showed a greater and more sustained decline in taxon richness and total abundances (Figure 5), reflecting loss of pollution-sensitive taxa such as the Ephemeroptera and Trichoptera.

THE POTENTIAL USE OF SURROGATES TO ASSESS OVERALL BIODIVERSITY OF MACROINVERTEBRATES IN IRISH RIVERS

Trichoptera family richness was the best surrogate of total richness in this study for the river datasets used (Figure 6c), showing the strongest

Fig. 4—nMDS showing the similarity in macroinvertebrate community composition and structure between sites sampled across the three different agricultural intensities. The closer the sites the more similar is their macroinvertebrate community. Aut = autumn, Spr = spring. Low, Medium and High = agricultural intensity in the draining catchment.

correlation with remaining richness (RR). The ET metric (Figure 6f) and ephemeropteran richness (Figure 6a) were similar in performance, both having good relationships with RR and therefore, could be considered as surrogates. The Coleoptera performed next best, followed by the EPT metric (Figure 6e). The poorest relationship was with plecopteran richness which had no significant correlation with RR (Figure 6b).

DISCUSSION

This paper used the best available information to address the questions posed in relation to numbers of macroinvertebrate species in Irish rivers, their threat status and impacts of anthropogenic pressures. Although the paucity of species-level data was an issue, it also highlighted the significant gaps that exist for some taxa. First, this paper examined the state of knowledge of the macroinvertebrates of Irish rivers both in terms of species counts and their distribution. Ireland is often considered to have a depauperate freshwater invertebrate fauna compared with Britain and mainland Europe (McCarthy 1986; Murray and O'Connor 1992). Despite this, a complete inventory of freshwater invertebrate species in rivers does not exist and this is also true of other freshwater habitats (e.g. lakes). Based on the available checklists there are approximately 2500 known invertebrate species in Ireland's freshwaters (including

lentic waters), which, depending on the taxonomic group, represents between 60% and 80% of the species that occur in Britain. Exactly how many species occur in rivers is difficult to determine given the uncertainties around species counts for some groups and the lack of reference to the type of waterbody in some of the species record's literature.

The recent additions of new species of Trichoptera (e.g. O'Connor and O'Connor 2019) and Ephemeroptera (Feeley and Macadam 2020) to the Irish species lists of two well-studied groups, together with the incomplete species checklists for most of the Diptera (with the exception of the Chironomidae), highlight how much work needs to be done before we have a full inventory of the freshwater invertebrate fauna and can determine the numbers of species that occur in the different habitat types. Furthermore, information on species distribution is lacking for several groups and the fact that most species are not ubiquitous (Bradley 2001) challenges efforts to adequately capture their distribution across the country. For example, based on an analysis of macroinvertebrates in 50 reference river sites by Kelly-Quinn *et al.* (2005), almost half of the macroinvertebrate species occurred at less than 5% of sites. Furthermore, taxon richness at an unpolluted site can be highly variable. Bradley (2001) noted the total number of taxa (from all samples and all seasons) recorded at any one site over the study period ranged from 32 to 123. The mean values based on three replicates in a given sample ranged from 16 to 69 taxa. In the RIVTYPE project (Kelly-Quinn

Fig. 5—Long-term trend in taxonomic richness and categorical abundances associated with suspected pesticide pollution in the Glennagannon River (Site A) and Glen River (Site B) in Co. Donegal (EPA data).

et al. 2005), a total of 278 macroinvertebrate taxa representing 94 families, was recorded across the 50 sites between October 2002 and October 2003. However, the combined total taxon richness at a site for the three seasons ranged from 52 to 109 taxa.

The paucity of information on species distribution, together with the high spatial and temporal variability limits the ability to determine the habitat requirements of some species, apart from those occurring in riffles, and without this information it is difficult to target effective conservation programmes to protect species diversity and key ecosystem processes. However, deciding where to target resources also requires a knowledge of what is rare or unusual and what locations support the greatest range of

species. The latter are particularly important refugia from which river reaches recovering from the effects of pollution can be potentially repopulated (Feeley and Kelly-Quinn 2012).

While the threats to relatively few groups have been assessed they nevertheless highlight some concerns. With the exception of the Mollusca, which includes some terrestrial species, between two (Ephemeroptera and Plecoptera) and 27 species (Coleoptera) are threatened with extinction or are already regionally extinct. It should be noted that three of these assessments were carried out over eight years ago using records that were in many cases over 10 years old, and the current status of many of these species is largely unknown. Lack of data with

Fig. 6—Relationship between proposed richness surrogates and the remaining richness (RR), i.e. overall richness minus that of the examined group or metric. r = Spearman correlation.

adequate spatial and temporal coverage curtails what and when assessments can be carried out. Consideration should be given to how best to capitalise on existing monitoring and research to capture the data for status assessment.

Despite the variability in taxon richness and species composition at the unpolluted sites analysed, and the level of identification used in the various studies, and considering the varied geology, the impact of anthropogenic pressures is still clearly detectable. As in many other countries, freshwaters in Ireland are impacted by several anthropogenic pressures delivering multiple stressor ‘cocktails’ and physical habitat alterations. For example, the River Basin Management Plan (2018–21) characterisation assessment highlighted the fact that over 48% of ‘at

risk’ waterbodies in Ireland are impacted by more than one significant pressure; agriculture is one of those key pressures (O’Boyle *et al.* 2019). The analysis undertaken in this paper has highlighted that regional diversity is reduced in streams draining intensive agriculture, and even more so when temporal turnover and variation in community composition and structure are considered. This is mainly due to loss of the pollution-sensitive species but also of less common species resulting homogenisation of communities (e.g. loss of rare taxa). This may in part be the result of reduced habitat heterogeneity (e.g. due to siltation and other hydromorphological impacts such as channel drainage) in association with the occurrence of unsuitable hydrochemical conditions. Homogenisation is considered an important

aspect of the modern biodiversity crisis (Olden and Rooney 2006). Impacts on biodiversity are likely to be more severe in response to toxic chemicals such as biocides, with impact on richness as well as overall community abundance as illustrated in this paper—albeit with limited data—and this result is supported in the literature (e.g. Berenzen *et al.* 2005). While species richness, in isolation as a measurement of impact on biodiversity, can be helpful and informative, it can mask changes at different temporal scales (Larson *et al.* 2018). Spatial and temporal measurements such as assessments of abundance data, seasonal and regional turnover, as well as changes to community composition and structure, as used in this study, should be considered in biodiversity assessments ensuring that subtle or slower changes (e.g. loss of rare species and regional homogenisation) in biodiversity are detected.

Looking to the future, climate change is set to exert further pressure and complicate efforts to assess the impact of other stressors or determine the cause of biodiversity change. Overall, few species-level datasets are available in Ireland that can accurately quantify the impact of climate change on aquatic invertebrate biodiversity (e.g. Woodward *et al.* 2015). While increases in stream temperature can lead to changes in species distribution (e.g. Scheffers *et al.* 2016), with range expansion or contraction for some, it can also provide opportunities for newly arrived species to fill vacant niches within the island's relatively depauperate fauna or at the very least pose a threat through competition or other interactions. It is possible through riparian vegetation management to mitigate to some extent potential temperature increases (e.g. Ryan and Kelly-Quinn 2016); however, more significant for Ireland is the potential impact of extreme flooding on invertebrate biodiversity in rivers as illustrated by Feeley *et al.* (2012b) who have reported significant declines both in taxon richness and density caused by an extreme twelve-hour flooding event. Similar results have been reported from the Araglin River in Co. Cork by Twomey and Giller (1991) and more recently by Woodward *et al.* (2015), with recovery of many species and groups taking years or even decades, especially in the non-insect groups, owing to a lack of adult flight to aid recovery. Changes to precipitation patterns may also bring more severe and prolonged drought which can also exacerbate the impact of pollution. For example, O'Boyle *et al.* (2019) noted that the low-flow conditions in summer 2018 may have contributed to a rise in fish kills. The impact on macroinvertebrates is less well known but reductions in oxygen owing to higher instream temperatures will likely exacerbate any pre-existing pressures on invertebrate communities. Similarly, contrasting extreme events that occur close to one another in time (e.g. a drought following a major

hydrological storm event) and those at abnormal times of year (e.g. major flood events in summer) will magnify the negative effects on invertebrate biodiversity (Woodward *et al.* 2015).

So where do we go from here? Clearly the impact of pollution and habitat degradation as well as restoration measures need to be addressed and various initiatives are in train to address the problem. Mitigating the effects of climate change such as extreme flooding is more challenging and is the subject of ongoing research. In the interim we need to consider how best to protect our aquatic invertebrate species complement. A multi-pronged approach will be necessary. One priority is the identification of species 'hotspots' for special protection, many of which may be outside protected areas. These are critical as sources of species for the ecological recovery of sites impacted by pollution and other pressures. Some such areas have been identified by Feeley and Kelly-Quinn (2012) in the Slieve Bloom Mountains in the midlands of Ireland and the Killarney region in the south west. These areas may not necessarily contain large numbers of species but may contain species that are not commonly found elsewhere. Further areas need to be identified and prioritised for protection in the next River Basin Management Plan. Small water bodies should be targeted for identification of hotspots as they can also support a high proportion of a catchment's biodiversity due to their inherent habitat heterogeneity (Biggs *et al.* 2017). This task could potentially be aligned with the future work on the 'Blue Dot' Catchments Programme (River Basin Management Plan 2018–2021). However, these initiatives need to be linked to targets and actions in the current and further iterations of Ireland's National Biodiversity Action Plan.

Protecting freshwater macroinvertebrate biodiversity clearly requires a strategy to address knowledge gaps on the island's species complement, their distribution, ecological requirements and community composition (at species level) as well as how best to track biodiversity change. Quantifying temporal trends in abundances and diversity, and initiating long-term studies are among the priorities highlighted by 72 authors in a paper formulating a roadmap for insect conservation and recovery (Harvey *et al.* 2020). Apart from the need for dedicated funding for biodiversity studies, there is a serious lack of taxonomic expertise and trained taxonomists in most of the groups we have examined in this paper. Many of the experts are retired and some are continuing to record on a voluntary basis. Indeed, in many cases expertise is limited to one or two individuals. It is not possible to generate comprehensive inventories of species with the current expertise given the time requirements, spatial spread and inadequate funding. It would also require training and ongoing support of a new

generation of taxon experts through dedicated and resourced training and education programmes (e.g. third-level institutes or workshops by bodies such as the National Biodiversity Data Centre). At the same time, we need to improve the current knowledge base. The analysis of surrogate groups highlighted the potential use of the Trichoptera and Ephemeroptera as surrogates of macroinvertebrate diversity at a study site. No examination of biodiversity will be perfect given deficiencies in species identification, habitat coverage, seasonal coverage, etc., and redundancies in data usage, collection and continuity. Nevertheless, this study offers some insight into achieving a potential approach for tracking biodiversity change in riverine communities but does require further testing.

Recent developments in DNA metabarcoding could help identify biodiversity patterns and a wider range of species across the tree of life by using DNA sequences instead of morphology (e.g. Deiner *et al.* 2016; Pawlowski *et al.* 2018). It could also be used to identify the aforementioned biodiversity hotspots or areas with rare or specialist species. In fact, the hidden biodiversity on genetic level in Ireland's freshwaters (e.g. cryptic species) has yet to be addressed and will likely lead to many additional new species. For example, *Baetis atlanticus* has always been present in rivers in Ireland but it took parallel genetics and morphological investigations to highlight differences with *B. rhodani* (Pictet, 1843) and its consequent discovery in Ireland (Feeley and Macadam 2020). Furthermore, the assessment of the variation in genetic diversity within invertebrate populations will potentially highlight their resilience to future threats such as climate change. Wheeler (2020) acknowledged that molecular data will be important in building inventories but suggests that taxonomy and comparative morphology should play a leading role. What is clear is that the molecular and traditional morphology-based approaches should not be seen as competitors but rather as two complementary approaches that are needed to address the substantial knowledge gaps that urgently need to be addressed.

This paper was largely focused on macroinvertebrates diversity in rivers. This is just one of the many freshwater habitats on the island. A review of the macroinvertebrate diversity in other freshwater habitats is recommended to provide a more comprehensive picture of the status of freshwater invertebrates and where conservation action is needed.

Stemming the loss of freshwater biodiversity cannot be left to just the regulatory authorities and conservation bodies; it requires a wider engagement of policy makers and citizens, which can only be achieved through communication and recognition of the pivotal role biodiversity plays in the delivery of a range of goods and benefits that are central to our well-being.

ACKNOWLEDGEMENTS

Thanks to the following for data collection: Amel Maki (AGRIBASELINE Project) and Bryan Kennedy, Martin McGarrigle and Patricia McCreesh (EPA). We are also grateful to experts who provided information on the counts of species in rivers; Julian Reynolds (Crustacea), Pascal Sweeney (Oligochaeta), Declan Murray (Chironomidae), Jim O'Connor (Trichoptera), Garth Foster (Coleoptera), Brian Nelson (Heteroptera and Odonata), Evelyn Moorkens and Roy Anderson (Mollusca). Thanks to Mary Gurrie, Shane O'Boyle, Julian Reynolds and two anonymous reviewers for their suggestions and constructive comments.

REFERENCES

- Abell, R. 2002 Conservation biology for the biodiversity crisis: A freshwater follow-up. *Conservation Biology* **16**, 1435–37.
- Anderson, M.J., Gorley, R.N. and Clarke, K.R. 2008 *PERMANOVA for PRIMER: Guide to software and statistical methods*. Plymouth. PRIMER-E Ltd.
- Ashe, P., O'Connor, J.P. and Murray, D.A. 1998 A checklist of Irish aquatic insects. *Occasional Publication of the Irish Biogeographical Society* **3**, 1–80.
- Berenzen, N., Kumke, T., Schulz, H.K. and Schulz, R. 2005 Macroinvertebrate community structure in agricultural streams: impact of runoff-related pesticide contamination. *Ecotoxicology and Environmental Safety* **60**, 37–46.
- Biggs, J., Kelly-Quinn, M. and von Fumatti, S. 2017 The importance of small waterbodies for biodiversity and ecosystem services: implications for policy makers. *Hydrobiologia* **793**, 3–39.
- Bradley, C. 2001 *The Macroinvertebrate Communities of Reference River Sites in Ireland*. Ph.D. Thesis, National University of Ireland.
- Bradley, C.M., Kelly-Quinn, M., Tierney, D., Murray, D.A. and Ashe, P.J. 2002 Preliminary analysis of the longitudinal patterns occurring in macroinvertebrate assemblages in river catchments in Ireland. *Verhandlungen des Internationalen Verein Limnologie* **28**, 1–5.
- Byrne, A., Moorkens, E.A., Anderson, R., Killeen, I.J. and Regan, E.C. 2009 *Ireland Red List No. 2 – Non-Marine Molluscs*. Dublin. National Parks and Wildlife Service, Department of the Environment, Heritage and Local Government.
- Callanan, M., Baars, J.-R. and Kelly-Quinn, M. 2008 Critical influence of seasonal sampling on the ecological quality assessment of small headwater streams. *Hydrobiologia* **610**, 245–55.
- Cham, S., Nelson, B., Parr, A., Prentice, S., Smallshire, D. and Taylor, P. (eds) 2014 *Atlas of Dragonflies in Britain and Ireland*. Telford: Field Studies Council.
- Clarke, K.R. and Gorley, R.N. 2006 *PRIMER v6: User Manual/Tutorial*. PRIMER-E Ltd, Plymouth, UK.
- Davis, S., Ó hUallacháin, D., Mellander, P.-E., Kelly, A.-M., Matthaei, C.D., Piggott, J.J. and Kelly-Quinn, M.

- 2018 Multiple-stressor effects of sediment, phosphorus and nitrogen on stream macroinvertebrate communities. *Science of the Total Environment*, **637–638**, 577–87.
- Deiner, K., Fronhofer, E.A., Mächler, E., Walser, J.-C. and Altermatt, F. 2016 Environmental DNA reveals that rivers are conveyor belts of biodiversity information. *Nature Communications* **7**, 12544.
- Dudgeon *et al.* 2006 Freshwater biodiversity: importance, threats. *Biological Reviews* **81**, 163–82.
- Dudgeon, D. 2014 Threats to Freshwater Biodiversity in a Changing World. In B. Freedman (ed.) *Global environmental change*. Switzerland. Springer.
- Dudgeon, D. 2019 Multiple threats imperil freshwater biodiversity in the Anthropocene. *Current Biology* **29**, R960–67.
- Feeley, H.B. and Kelly-Quinn, M. 2012 An evaluation of local and regional diversity of benthic macroinvertebrate communities in two small regions of Ireland and their potential as localised refugia for certain taxonomic group. *Biology and Environment Proceedings of the Royal Irish Academy* **112**, 1–12.
- Feeley, H.B., Woods, M., Baars, J.-R. and Kelly-Quinn, M. 2012a Refining a kick sampling strategy for the bioassessment of benthic macroinvertebrates in headwater streams. *Hydrobiologia* **683**, 53–68.
- Feeley, H.B., Davies, S., Bruen, M., Blacklocke, S. and Kelly-Quinn, M. 2012b The impact of a catastrophic storm event on benthic macroinvertebrate communities in upland headwater streams and potential implications for ecological diversity and assessment of ecological status. *Journal of Limnology* **71**, 309–18.
- Feeley, H.B., Bruen, M., Blacklocke, S. and Kelly-Quinn, M. 2013 A regional examination of episodic acidification response to reduced acidic deposition and the influence of plantation forests in Irish headwater streams. *Science of the Total Environment* **443**, 173–83.
- Feeley, H.B., Baars, J.-R. and Kelly-Quinn, M. 2016 *The Stonefly (Plecoptera) of Ireland: Distributions, Life Histories and Ecology*. Waterford. National Biodiversity Data Centre.
- Feeley H.B., Bruen, M., Bullock, C., Christie, M., Kelly, F. and Kelly-Quinn, M. 2017 *Irish Freshwater Resources and Assessment of Ecosystem Services Provision*. Report Number 207. Wexford. Environmental Protection Agency.
- Feeley, H.B. and Macadam, C.R. 2020 *Baetis atlanticus* (Soldán and Godunko) (Ephemeroptera: Baetidae): a mayfly new to Ireland. *Irish Naturalists' Journal* **37**, 58–59.
- Feeley, H.B., Baars, J.-R., Kelly-Quinn, M. and Nelson, B. 2020a *Ireland Red List No. 13: Stoneflies (Plecoptera)*. Dublin. National Parks and Wildlife Service, Department of Culture, Heritage and the Gaeltacht.
- Feeley, H.B., Bradley, C., Free, G., Kennedy, B., Little, R., McDonnell, N., Plant, C., Trodd, W., Wynne, C. and O' Boyle, S. 2020b A national macroinvertebrate dataset collected for the biomonitoring of Ireland's river network, 2007–2018. *Scientific Data* **7**, 280.
- Ferriss, S.E., Smith, K.G. and Inskipp, T.P. 2009 *Irish Biodiversity: A Taxonomic Inventory of Fauna*. Irish Wildlife Manuals, No. 38. Dublin. National Parks and Wildlife Service, Department of Environment, Heritage and Local Government. Available online: <http://www.npws.ie/sites/default/files/publications/pdf/IWM38.pdf> (accessed 27 march 2020)
- Foster, G.N., Nelson, B.H. and O'Connor, Á. 2009 *Ireland Red List No. 1 – Water beetles*. Dublin. National Parks and Wildlife Service, Department of Environment, Heritage and Local Government.
- Foster, G.N., Bilton, D.T., Hammond, M. and Nelson, B.H., 2020. *Atlas of Water Beetles of Britain and Ireland – Smaller Families of Polyphaga*. Wallingford. Biological Records Centre, UK
- Guareschi *et al.* 2012 Aquatic macroinvertebrate biodiversity: patterns and surrogates in mountainous Spanish national parks. *Aquatic Conservation - Marine and Freshwater Ecosystems* **22**, 598–615.
- Harvey, J.A., Heinen, R. and Armbretch, I. 2020 International scientists formulate a roadmap for insect conservation and recovery. <https://doi.org/10.1038/s41559-019-1079-8>
- IPBES 2019 Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Díaz *et al.* (eds.). Bonn, Germany. IPBES secretariat.
- Kelly-Quinn, M. and Bracken, J.J. 2000 The distribution of the Ephemeroptera in Ireland. *Occasional Publication of the Irish Biogeographical Society* **5**, 223pp.
- Kelly-Quinn *et al.* 2005 *Water Framework Directive – Characterisation of Reference Conditions and Testing of Typology of Rivers (2002- W-LS-7)*. Final Report for the Environmental Protection Agency, Wexford, Ireland, 1–49.
- Kelly-Quinn, M. and Regan, E.C. 2012 *Ireland Red List No. 7: Mayflies (Ephemeroptera)*. Dublin. National Parks and Wildlife Service, Department of Arts, Heritage and the Gaeltacht.
- King *et al.* 2011 *Ireland Red List No. 5: Amphibians, Reptiles and Freshwater Fish*. Dublin. National Parks and Wildlife Service, Department of Arts, Heritage and the Gaeltacht, Dublin.
- Lafferty, S., Commings, P. and Walsh, J.A. 1999 *Irish Agriculture in Transition: A Census Atlas of Agriculture in the Republic of Ireland*. Dublin. Teagasc.
- Larson, S., Chase, J.M., Durance, I. and Ormerod, S.J. 2018 Lifting the veil: richness measurements fail to detect systematic biodiversity change over three decades. *Ecology* **99**, 1316–26.
- Marnell, F., Looney, D. and Lawton, C. 2019 *Ireland Red List No. 12: Terrestrial Mammals*. Dublin. National Parks and Wildlife Service, Department of the Culture, Heritage and the Gaeltacht.
- Markovic, D., Carrizo, S.F., Karcher, O., Walz, A. and David, J.N.W. 2017 Vulnerability of European freshwater catchments to climate change. *Global Change Biology* **23**(9), 3567–80.
- McCarthy, T.K. 1986 Biogeographical aspects of Ireland's invertebrate fauna. *Occasional Publication of the Irish Biogeographical Society* **5**, 67–81.
- McMahon *et al.* 2012 Different bioindicators measured at different spatial scales vary in their response to agricultural intensity. *Ecological Indicators* **18**, 676–83.
- Murphy, C. and Charlton, R. 2008 Climate Change and Water Resources. In *Climate Change – Refining the Impacts for Ireland (2001-CD-C3-M1)*. EPA STRIVE Programme 2007–2013 (177). Wexford. Environmental Protection Agency.

- Murray, D.A. 2018 Further distribution records of Chironomidae (Insecta: Diptera) in Ireland from past collections. *Bulletin of the Irish Biogeographical Society* **42**, 58–74.
- Murray, D.A. 2019a Records and checklist of Chironomidae (Insecta: Diptera) in County Louth and an updated summary of species distribution in Ireland. *Bulletin of the Irish Biogeographical Society* **43**, 42–56.
- Murray, D.A. 2019b New county and hydrometric area records of Chironomidae (Insecta: Diptera) in Ireland from recent and past collections. *Bulletin of the Irish Biogeographical Society* **43**, 19–27.
- Murray, D.A. and Ashe, P.J. 2017 Additional distribution records of Chironomidae (Insecta: Diptera) in Ireland from recent and past collections. *Bulletin of the Irish Biogeographical Society* **41**, 112–14.
- Murray, D.A. and Langton, P.H. 2018 Doubt and certainty in records of *Micropsectra recurvata* Goetghebuer (Insecta: Diptera: Chironomidae) in Ireland. *Bulletin of the Irish Biogeographical Society* **42**, 155–58.
- Murray, D.A. and O'Connor, J.P. 1992 Observations on the distribution of some chironomids (Diptera) and caddisflies (Trichoptera) in the Killarney area, Ireland. *Aquatic Ecology* **24**, 393–96.
- Murray, D.A., O'Connor, J.P. and Ashe, P.J. 2018 Chironomidae (Diptera) of Ireland – a review, checklist and their distribution in Europe. *Occasional Publication of the Irish Biogeographical Society* Number 12. Published by the Irish Biogeographical Society in association with University College Dublin and the Environmental Protection Agency. 404pp.
- Nelson, B. and Thompson, R. 2004 *The Natural History of Ireland's Dragonflies*. Belfast. Ulster Museum.
- Nelson, B., Ronayne, C. and Thompson, R. 2011 *Ireland Red List No. 6: Damselflies and Dragonflies (Odonata)*. Dublin. National Parks and Wildlife Service, Department of the Environment, Heritage and Local Government.
- NPWS 2019a The Status of EU Protected Habitats and Species in Ireland. D. Lynn and F. O'Neill (eds) Volume 3: Species Assessments. Unpublished NPWS report.
- NPWS 2019b The Status of EU Protected Habitats and Species in Ireland. D. Lynn and F. O'Neill (eds) Volume 2: Habitat Assessments. Unpublished NPWS report.
- O'Boyle et al. 2019 *Water Quality in Ireland 2013–2018*. Wexford. Environmental Protection Agency.
- O'Connor, Á. 2016 Incorporating nature conservation objectives and measures into the Water Framework Directive. *Biology and Environment: Proceedings of the Royal Irish Academy* **116**, 329–37.
- O'Connor, J.P. 2015 A catalogue and atlas of the caddisflies (Trichoptera) of Ireland. *Occasional Publication of the Irish Biogeographical Society*, Number 11, 646pp.
- O'Connor, J.P. 2019 *Hydroptila vectis* Curtis, 1834 new to Ireland and the first Irish adult of *Tricholeiochiton fagesii* (Guinard, 1879) (Trichoptera: Hydroptilidae). *Entomologist's Monthly Magazine* **155**, 163–67.
- O'Connor, J.P. and O'Connor, M.A. 2019 *Hydroptila lotensis* Mosely, 1930, new to Ireland and a second Irish record of *Hydroptila vectis* Curtis, 1834, (Trichoptera: Hydroptilidae). *Entomologist's Monthly Magazine* **155**, 229–34.
- O'Connor, J.P. and Nelson, B., 2012 *An Annotated Checklist of the Irish Hemiptera and Small Orders*. Dublin. The Irish Biogeographical Society.
- Olden, J.D. and Rooney, T.P. 2006 On defining and quantifying biotic homogenization. *Global Ecology and Biogeography* **15**, 113–20.
- Ormerod, S.J., Durance, I., Terrier, A. and Swanson, A.M. 2010 Priority Wetland Invertebrates as Conservation Surrogates. *Conservation Biology* **24**, 573–82.
- Pawlowski et al. 2018 The future of biotic indices in the ecogenomic era: Integrating (e)DNA metabarcoding in biological assessment of aquatic ecosystems. *Science of the Total Environment* **637–638**, 1295–310.
- Reid et al. 2019 Emerging threats and persistent conservation challenges for freshwater biodiversity. *Biological Reviews* **94**, 840–73.
- Riley, W.D., Potter, E.C.E., Biggs, J., Collins, A.L., Jarvie, H.P., Kelly-Quinn, M., Siriwardena, G.M. 2018 Small Water Bodies in Great Britain and Ireland: Ecosystem function, human-generated degradation, options for restorative action. *Science of the Total Environment* **645**, 1598–616.
- River Basin Management Plan (2018–2021) Department of Housing, Planning and Local Government. https://www.housing.gov.ie/sites/default/files/publications/files/rbmp_report_english_web_version_final_0.pdf Accessed 13.1.20
- Ryan, D. and Kelly-Quinn, M. 2016 Riparian vegetation management for water temperature regulation: implications for the production of macroinvertebrate prey of salmonids. *Fisheries Management and Ecology* **23**, 519–30.
- Sánchez-Bayo, F. and Wyckhuys, K.A.G. 2019 Worldwide decline of the entomofauna: A review of its drivers. *Biological Conservation* **232**, 8–27.
- Scheffers et al. 2016 The broad footprint of climate change from genes to biomes to people. *Science* **354**, aaf7671.
- Staudt et al. 2013 The added complications of climate change: understanding and managing biodiversity and ecosystems. *Frontiers in Ecology and Environment* **11**(9), 494–501.
- Strayer, D.L. and Dudgeon, D. 2010 Freshwater biodiversity conservation: Recent progress and future challenges. *Journal of the North American Benthological Society* **29**, 344–58.
- Twomey, H. and Giller, P.S. 1991 The effects of catastrophic flooding on the benthos and fish of a tributary of the river Araglin, Co. Cork. In M.W. Steer (ed.) *Irish rivers: Biology and management*. Dublin. Royal Irish Academy.
- Woodward, G., Bonada, N., Feeley, H.B. and Giller, P.S. 2015 Resilience of a stream community to extreme climatic events and long-term recovery from a catastrophic flood. *Freshwater Biology* **60**, 2497–510.
- Wheeler, Q. 2020 A taxonomic renaissance in three acts. *Megataxa* **001**(1), 004–008.
- WWF 2018 *Living Planet Report 2018: Aiming Higher* (Eds M. Grooten and R.E. A. Almond). WWF International, Gland, Switzerland.