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Critical Loads and Soil-Vegetation Modelling

Authors: Julian Aherne, Kayla Wilkins and Hazel Cathcart

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Rialtas na hÉireann
Government of Ireland

ENVIRONMENTAL PROTECTION AGENCY

The Environmental Protection Agency (EPA) is responsible for protecting and improving the environment as a valuable asset for the people of Ireland. We are committed to protecting people and the environment from the harmful effects of radiation and pollution.

The work of the EPA can be divided into three main areas:

Regulation: *We implement effective regulation and environmental compliance systems to deliver good environmental outcomes and target those who don't comply.*

Knowledge: *We provide high quality, targeted and timely environmental data, information and assessment to inform decision making at all levels.*

Advocacy: *We work with others to advocate for a clean, productive and well protected environment and for sustainable environmental behaviour.*

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- large scale industrial activities (*e.g. pharmaceutical, cement manufacturing, power plants)*;
- intensive agriculture *(e.g. pigs, poultry)*;
- the contained use and controlled release of Genetically Modified Organisms *(GMOs)*;
- sources of ionising radiation *(e.g. x-ray and radiotherapy equipment, industrial sources)*;
- large petrol storage facilities;
- waste water discharges;
- dumping at sea activities.

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- Enforcing Regulations such as Waste Electrical and Electronic Equipment (WEEE), Restriction of Hazardous Substances (RoHS) and substances that deplete the ozone layer.
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- Monitoring and reporting on Bathing Water Quality.

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- Monitoring air quality and implementing the EU Clean Air for Europe (CAFÉ) Directive.
- Independent reporting to inform decision making by national and local government *(e.g. periodic reporting on the State of Ireland's Environment and Indicator Reports)*.

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- Funding environmental research to identify pressures, inform policy and provide solutions in the areas of climate, water and sustainability.

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- Assessing the impact of proposed plans and programmes on the Irish environment *(e.g. major development plans)*.

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- Monitoring radiation levels, assessing exposure of people in Ireland to ionising radiation.
- Assisting in developing national plans for emergencies arising from nuclear accidents.
- Monitoring developments abroad relating to nuclear installations and radiological safety.
- Providing, or overseeing the provision of, specialist radiation protection services.

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- Office of Environmental Sustainability
- Office of Environmental Enforcement
- Office of Evidence and Assessment
- Office of Radiation Protection and Environmental Monitoring
- Office of Communications and Corporate Services

The EPA is assisted by an Advisory Committee of twelve members who meet regularly to discuss issues of concern and provide advice to the Board.

EPA RESEARCH PROGRAMME 2014–2020

Critical Loads and Soil-Vegetation Modelling

(2012-CCRP-MS.7)

EPA Research Report

Prepared for the Environmental Protection Agency

by

Trent University

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Cover image: Emily Olmstead, Trent University, collecting the moss species *Hylocomium splendens* and *Pleurozium schreberi* in Connemara, Galway, during the 2015 ICP Vegetation Moss Biomonitoring Survey. Photograph credits: Kayla Wilkins, May 2015.

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Executive Summary

It is well established that anthropogenic air pollution can have negative impacts on the natural environment, through both direct effects on vegetation and indirect effects on the acid and nutrient status of soils and waters. The Convention on Long-range Transboundary Air Pollution (CLRTAP; also called the Air Convention) under the United Nations Economic Commission for Europe (UNECE) was the first international legally binding instrument to deal with the problems of air pollution on a broad regional scale. The Convention established six International Cooperative Programmes (ICPs) on Forests, Waters, Materials, Vegetation, Integrated Monitoring and Modelling and Mapping to identify the most endangered areas, ecosystems and other receptors by considering the damage that has been caused to terrestrial and aquatic ecosystems and materials. The work of the ICPs has underpinned scientific research on the impacts of air pollution during the last three decades.

This report presents results from the research project “Critical Loads and Soil-Vegetation Modelling” funded by the Environmental Protection Agency. The principal objectives of this project were to update critical loads of acidity and eutrophication for terrestrial and aquatic ecosystems in Ireland, to evaluate the potential impacts of nitrogen deposition on plant species diversity and to expand national participation in the ICPs. The project specifically responded to “calls for data” under the CLRTAP. This report describes the critical load database submitted to ICP Modelling and Mapping in response to the 2015–2017 call for data, the response to ICP Vegetation under the 2015 Moss Biomonitoring Survey, and the submission of water chemistry data to ICP Waters.

The research outputs directly support international policies under the UNECE Air Convention and the European Union Clean Air Policy Package:

- Under the revised Gothenburg Protocol, much of the country is predicted to achieve non-exceedance of critical loads of acidity by 2030. In contrast, exceedance of critical loads of eutrophication is not predicted to change by 2030, owing to national increases in reduced nitrogen deposition.
- Biodiversity-related critical loads for nitrogen (determined using the PROPS-CLF model for eight habitats) suggest that Irish habitats are more sensitive to nitrogen deposition than the recommended empirical critical load ranges for European habitats.
- Moss biomonitoring indicates that trace element deposition is low over Ireland and has decreased substantially during the last two decades. Nitrogen content in moss was correlated with modelled total nitrogen deposition and showed an east-to-west decreasing gradient.
- During the last three decades, there has been a significant increase in surface water pH in response to reductions in “acidic” atmospheric deposition, as observed at the three long-term ICP Waters lakes (Glendalough, Lough Maumwee and Lough Veagh).
- Community-level change points were identified along a nitrogen deposition gradient for 12 habitats; these change points suggest that empirical critical loads of nitrogen for Irish habitats are lower than the recommended ranges.

National critical load data have made an important contribution to the abatement of long-range transboundary air pollution; however, critical loads have been virtually ignored under national policy assessments. Therefore, it is recommended that (1) there should be a wider adoption of critical loads in national policy assessments [e.g. Article 6.3 of the Habitats Directive (92/43/EEC), ecosystem monitoring under the new National Emission Ceilings Directive (2016/2284/EU)]; (2) there should be continued development of biodiversity critical loads; (3) statistical modelling procedures should be used to set empirical critical loads of nutrient nitrogen that are specific to Irish habitats; (4) the national participation in the well-established network of ICPs should be formalised and strengthened; (5) there should be national participation in the 2020 Moss Biomonitoring Survey under ICP Vegetation; and (6) the national critical load database should continue to be revised in response to scientific and technical updates.

1 Introduction

1.1 The Effects of Air Pollution on Natural Ecosystems

It is well established that anthropogenic air pollution can have negative impacts on the natural environment, through both direct effects on vegetation and indirect effects on the acid and nutrient status of soils and waters (EEA, 2014; WGE, 2014). This report focuses on the effects of sulphur (S) and nitrogen (N), persistent organic pollutants (POPs), mercury (Hg) and trace element emissions on natural ecosystems. These pollutants can travel several hundred or even thousands of kilometres in the atmosphere before deposition occurs and potential damage to the environment is caused. Given this, efforts to reduce the extent of possible environmental damage must be underpinned by national and international legislation aimed at controlling emissions. The Convention on Long-range Transboundary Air Pollution (CLRTAP) under the United Nations Economic Commission for Europe (UNECE) was the first international legally binding instrument to deal with the problems of air pollution on a broad regional scale. It was signed in 1979, laying down the general principles of international co-operation through an institutional framework that brings together research and policy (see Figure 1.1). Early in the discussions on the Convention, it was recognised that a good understanding of the harmful effects of air pollution was a prerequisite for reaching an agreement on effective pollution control.

1.2 International Cooperative Programmes

The Working Group on Effects (WGE) was established under the Convention to develop the necessary international co-operation on the research and monitoring of pollutant effects [1]. The WGE provides information on the degree and geographical extent of the impacts of major air pollutants on the environment. Its six International Cooperative Programmes (ICPs), on Forests, Waters, Materials, Vegetation, Integrated Monitoring and Modelling and Mapping (Figure 1.1), identify the most endangered areas, ecosystems and other receptors by considering the damage that has been caused to terrestrial and aquatic ecosystems and materials. An important part of this work is long-term monitoring. The work is underpinned by scientific research on dose–response relationships, critical loads and levels, and damage evaluation.

The ICP on Modelling and Mapping of Critical Levels and Loads and Air Pollution Effects, Risks and Trends (ICP Modelling and Mapping) is tasked with the determination of receptor-specific critical loads for indirect effects of the (long-term) deposition of various air pollutants, the mapping of pollutant depositions that exceed critical thresholds, and the establishment of appropriate methods as a basis for assessing potential damage. A critical load is defined as "a quantitative estimate of exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge" (Nilsson and Grennfelt, 1988). The critical loads approach is used under the CLRTAP and the European Union (EU) National Emission Ceilings Directive (NECD, 2001/81/EC) to quantify the impacts of acidifying and eutrophying air pollutant deposition on ecosystems and to guide policies on reducing the environmental impacts of transboundary air pollutants, such as S and N. Ireland has actively participated in ICP Mapping and Modelling since 1991.

The ICP on Effects of Air Pollution on Natural Vegetation and Crops (ICP Vegetation) focuses on quantifying the risks posed by ozone pollution and the atmospheric deposition of heavy metals, N and POPs to vegetation. Every 5 years, a survey is conducted on the concentration of heavy metals and the N concentration in naturally growing mosses, to assess the spatial variation of and temporal trends in atmospheric deposition to vegetation at a high spatial resolution. Ireland did not participate in the ICP Vegetation Moss Biomonitoring Survey prior to 2015.

1 See www.unece.org/environmental-policy/conventions/envlrtapwelcome/convention-bodies/working-group-on-effects.html (accessed 18 February 2020).

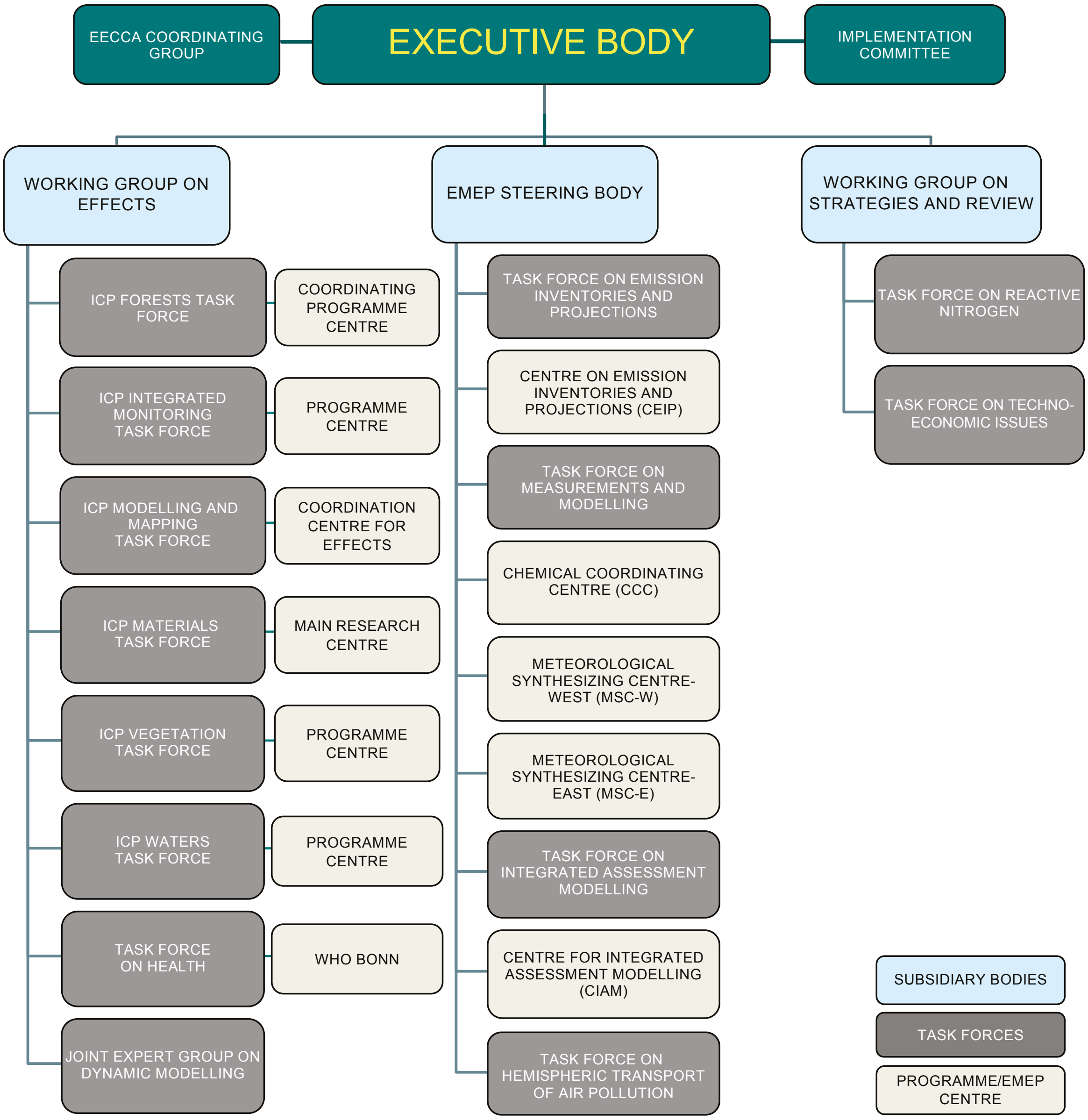

Figure 1.1. Organisational framework of the CLRTAP. The Executive Body is the governing body of the Convention. The Working Group on Strategies and Review is the principal negotiating body for the Convention. The Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe (EMEP) provides scientific support in the areas of atmospheric monitoring and modelling; emission inventories and emission projections; and integrated assessment. The WGE provides information on the degree and geographical extent of the impacts of major air pollutants on human health and the environment. Its six ICPs and the Task Force on Health identify the most endangered areas, ecosystems and other receptors by considering the damage that has been caused to human health, terrestrial and aquatic ecosystems, and materials. Source: www.unece.org/env/lrtap/welcome.html (accessed 18 February 2020).

The ICP on Assessment and Monitoring of the Effects of Air Pollution on Rivers and Lakes (ICP Waters) co-ordinates a network of surface water monitoring sites across Europe – the data obtained provide information on dose–response relationships and long-term trends in water quality in response to emission reductions. Since the mid-1980s, Ireland has participated in ICP Waters.

1.3 Study Objectives and Policy Context

The principal objectives of this project were to update critical loads of acidity and eutrophication for terrestrial and aquatic ecosystems in Ireland, to evaluate the potential impacts of N deposition on plant species diversity, and to expand national participation under the ICPs. The project built on existing national databases (see Aherne and Farrell, 2000; Aherne *et al.*, 2014, 2017), incorporating new methodologies and datasets when appropriate. The project specifically responded to "calls for data" under the CLRTAP. This report describes the critical load database submitted to ICP Modelling and Mapping in response to the 2015–2017 call for data, the response to ICP Vegetation under the 2015 Moss Biomonitoring Survey and the submission of water chemistry data to ICP Waters. In addition, the project contributed to the broader development and application of national critical loads, e.g. the discussion of the relevance of N deposition to the Habitats Directive – 92/43/EEC – with the National Parks & Wildlife Service (NPWS). The project outputs have been published in peer-reviewed journals, presented at international conferences (see Appendix 1) and submitted to ICP Modelling and Mapping, ICP Vegetation and ICP Waters in response to data calls, and the associated databases have been submitted to the Secure Archive For Environmental Research,[2] managed by the Environmental Protection Agency (EPA).

The specific project objectives were to:

- update national critical loads of acidity and eutrophication for terrestrial and aquatic ecosystems, including the first submission of biodiversity-related critical loads for Irish habitats to ICP Modelling and Mapping;
- establish national engagement with ICP Vegetation through participation in the 2015 Moss Biomonitoring Survey;
- revive national participation in ICP Waters, respond to annual calls for water chemistry data and fill data gaps in the ICP Waters database since the 1999 hiatus;
- evaluate the effects of N deposition on plant species diversity in Annex I habitats through statistical change point analysis.

These project outputs directly supported national obligations under the CLRTAP and the EU NECD. Nonetheless, there is significant scope for a wider adoption of critical loads to support national and European policy. The long-standing well-established network of ICPs provides an obvious framework for national monitoring activities and a mechanism to build national research capacity supported by international co-operation.

2 Available at http://erc.epa.ie/safer (accessed 18 February 2020).

2 International Cooperative Programme Modelling and Mapping

2.1 National Participation in ICP Modelling and Mapping

Ireland has previously responded to more than 10 calls for data on critical loads from the Coordination Centre for Effects (CCE) of ICP Modelling and Mapping under the CLRTAP, beginning in 1991; updates were submitted for the periods 1996–1999, 2001, 2003, 2005, 2010 and 2012. The last response, which was to the 2011–2012 call for data, was a substantial update to the critical load database, with major revisions made to the receptor ecosystems map, nutrient removal and the addition of aquatic critical loads (Aherne *et al.*, 2017).

Under the current project, Ireland participated in the 2015–2017 call for data,[3] which represented a minor update to the critical loads database since the 2011–2012 submission. In response to the call, a database was produced containing critical loads for S and N on the new 0.10° × 0.05° longitude–latitude grid, with the addition of critical loads of eutrophication ($CL_{eut}N$) and protection status for receptor ecosystems (see section 2.2). The 2015–2017 call for data also requested N and S critical load functions for biodiversity, i.e. thresholds of acid and N deposition below which the loss of specific plant species does not occur according to present knowledge (see section 2.3).

2.2 Acidity and Eutrophication Critical Loads

Critical loads of acidity and eutrophication were calculated following well-established methods described in the ICP mapping manual (CLRTAP, 2014)[4] and by de Vries *et al.* (2015). The acidifying impact of S and N deposition defines a critical load function (CLF) incorporating the most important biogeochemical processes that affect long-term soil acidification (see Appendix 2). The function is defined by three quantities: the maximum critical load of S ($CL_{max}S$), the minimum critical load of N ($CL_{min}N$) and the maximum critical load of N ($CL_{max}N$). The determination of these three quantities, and the 5th percentile for each mapping grid, is described in detail in the mapping manual (CLRTAP, 2014). To determine critical loads, a receptor ecosystems map of semi-natural habitats classified according to the European Nature Information System (EUNIS) (pan-European) was employed (described in detail by Aherne *et al.*, 2017). Habitats from the receptor map were updated with protection status, identifying Nature Reserves, Natural Heritage Areas (NHAs), Special Areas of Conservation (SACs) and Special Protection Areas (SPAs).

Exceedance of critical loads, i.e. when atmospheric deposition of S and N is in excess of the ecosystem critical load, is used as an indicator of the long-term harmful effects of air pollution on natural ecosystems. Total deposition of S and oxidised and reduced N was taken from the multi-layer Eulerian EMEP/MSC-W[5] model (Simpson *et al.*, 2012). Atmospheric deposition of S declined substantially between 1995 and 2015 and is projected to decline further by 2030 (estimated under the revised Gothenburg Protocol, GP2030), with all of the country receiving $< 300\,mg\,m^{-2}\,a^{-1}$ (compared with $> 800\,mg\,m^{-2}\,a^{-1}$ during 1995; Figure 2.1). A strong declining trend is also shown for oxidised N (NO_x); however, reduced N (NH_y) has been predicted to increase in the north and the south-east parts of the country by 2030 (see Figure 2.1), probably because of growth and changes in the agricultural industry. Note that NH_y represents a larger proportion of total N deposition than NO_x in Ireland.

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3 Details of the 2015–2017 call for data and the database template are available at www.umweltbundesamt.de/en/call-for-data?parent=69334 (accessed 18 February 2020).

4 The mapping manual is available at www.umweltbundesamt.de/en/manual-for-modelling-mapping-critical-loads-levels?parent=68093 (accessed 18 February 2020).

5 European Monitoring and Evaluation Programme/Meteorological Synthesising Centre-West.

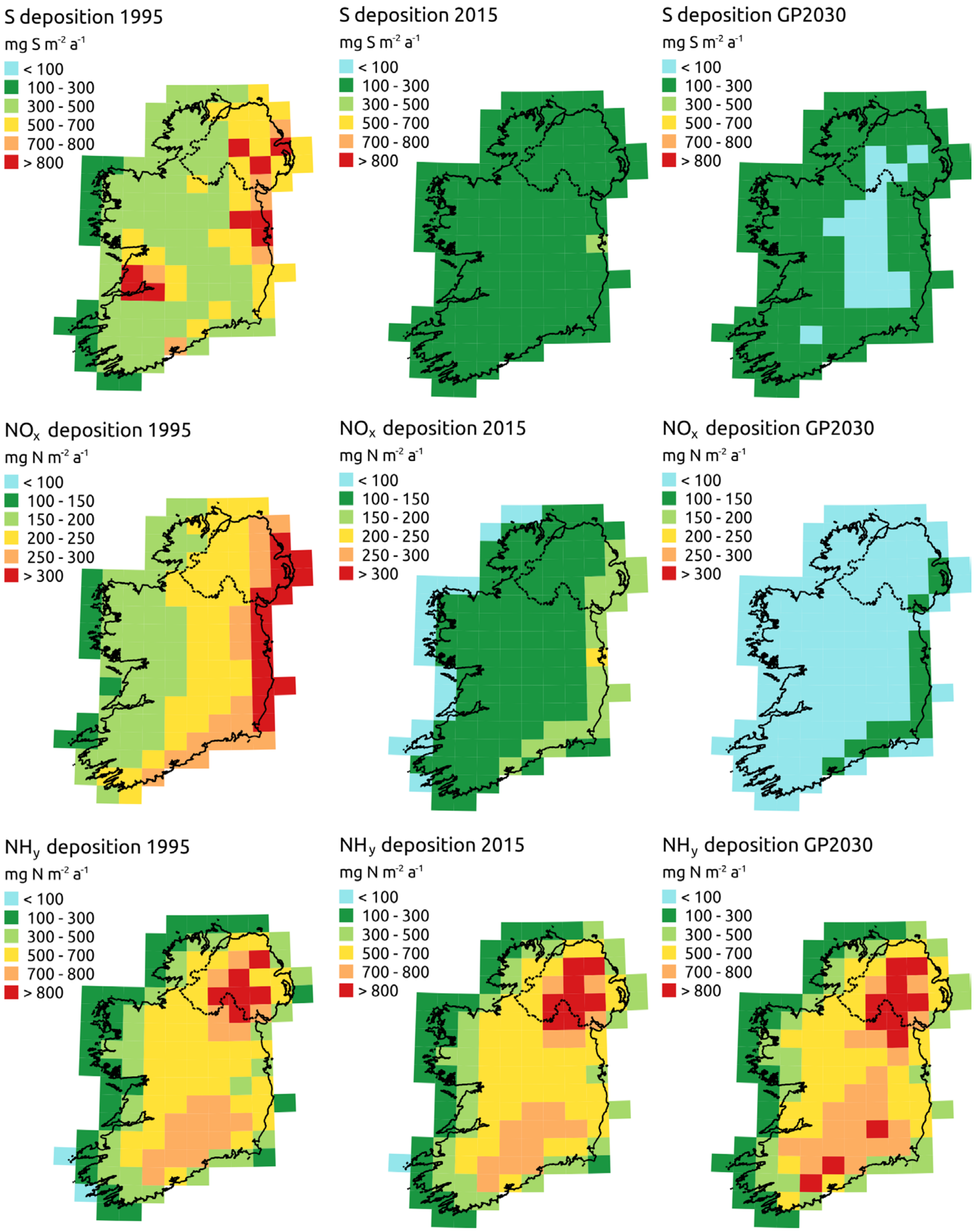

Figure 2.1. Modelled total S, NO_x and NH_y deposition to average land cover in 1995, 2015 and 2030 under GP2030 from the EMEP/MSC-W chemical transport model shown on the 0.50° × 0.25° longitude–latitude grid.

Exceedances of critical loads of acidity and eutrophication were assessed based on average accumulated exceedance (AAE; for methods see CLRTAP, 2014) for 1995, 2015 and 2030. Widespread acidity exceedance was estimated in almost every region in 1995 (see Figure 2.2 for $CL_{max}S$ and Figure 2.3 for exceedance), with many areas receiving deposition > 800 eq ha^{-1} a^{-1} in excess of its critical loads. A large decline in exceeded areas and in the magnitude of acidity exceedance was seen by 2015, and further improvements are predicted by 2030 (projected under GP2030), with much of the country

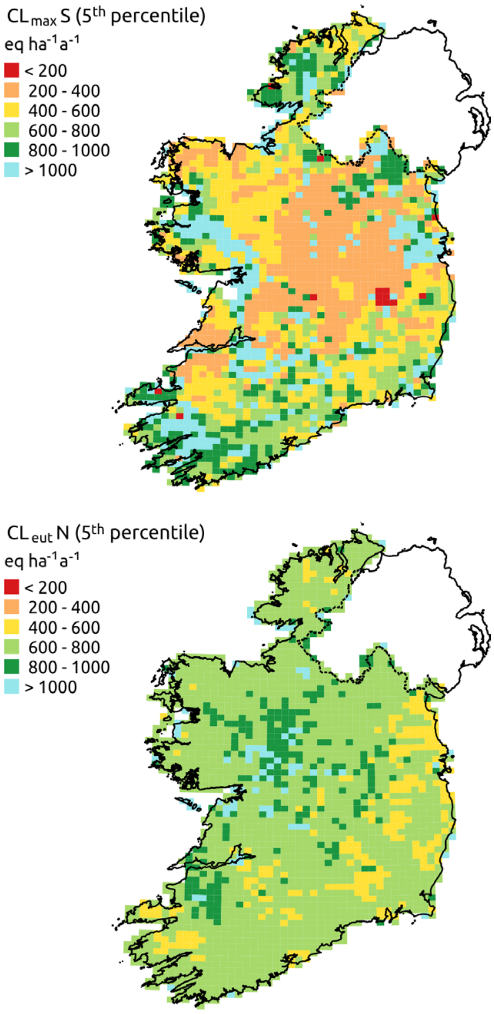

Figure 2.2. Fifth percentile of CL_{max}S and CL_{eut}N shown on the 0.10° × 0.05° longitude–latitude grid.

achieving non-exceedance by 2030 (Figure 2.3; Table 2.1). In 1995, many regions experienced eutrophication exceedances above 800 eq $ha^{-1} a^{-1}$, particularly in the area around Dublin (Figure 2.3; Table 2.1) and to a lesser extent the agricultural areas of the interior south-east. The magnitude of exceedance for most of the country dropped to below 200 eq $ha^{-1} a^{-1}$ by 2015 but is not predicted to change appreciably by 2030, with most of the country still in exceedance (Figure 2.3).

2.3 Critical Loads for Biodiversity

The 2015–2017 call for data encouraged countries to submit critical loads for biodiversity, i.e. thresholds of acid and N deposition below which the loss of specific plant species does not occur according to present knowledge (Hettelingh *et al.*, 2017). This was the first time that the call for data included a biodiversity component; Ireland was one of seven countries to respond to the call. The PROPS-CLF model (Reinds *et al.*, 2014), used to assess the probability of plant species occurrence as a function of abiotic environmental factors, was used to estimate biodiversity critical loads for nitrogen (CLN_{max}) and sulphur (CLS_{max}). The model was applied to ~420 plant relevé plots representing eight EUNIS habitats (Table 2.2). The CLRTAP operates under the EUNIS habitat classification system; however, national interests often require an Annex I habitat specification (see Appendix 3 for a crosswalk between EUNIS and Annex I habitat classes). Relevé carbon (C) and N soil data and species abundance data were obtained from the NPWS from field surveys conducted between 2007 and 2013. The PROPS-CLF model outputs a Habitat Suitability Index (HSI) for selected plant species; plant species selected were based on habitat-specific positive indicator species provided by the NPWS. The critical loads for biodiversity were determined at a normalised HSI of 0.667.

The HSI ranged from 0.119 (EUNIS code E2.2) to 0.912 (E3.51), with a median of 0.492 (Figure 2.4). Habitat-averaged CLN_{max} was higher for grassland habitats than for heath or peatland habitats (Table 2.2). In general, CLN_{max} values were broadly consistent with current recommended empirical critical load ranges (Figures 2.4 and 2.5; Bobbink and Hettelingh, 2011); heathland (F4.11, F4.2, F2), dry calcareous grassland (E1.26) and mesic grassland (E2.2) habitat averages were below the recommended critical load range, and the remaining habitats were within the recommended range. The results of the PROPS-CLF analysis were submitted in response to the CCE 2015–2017 call for data.

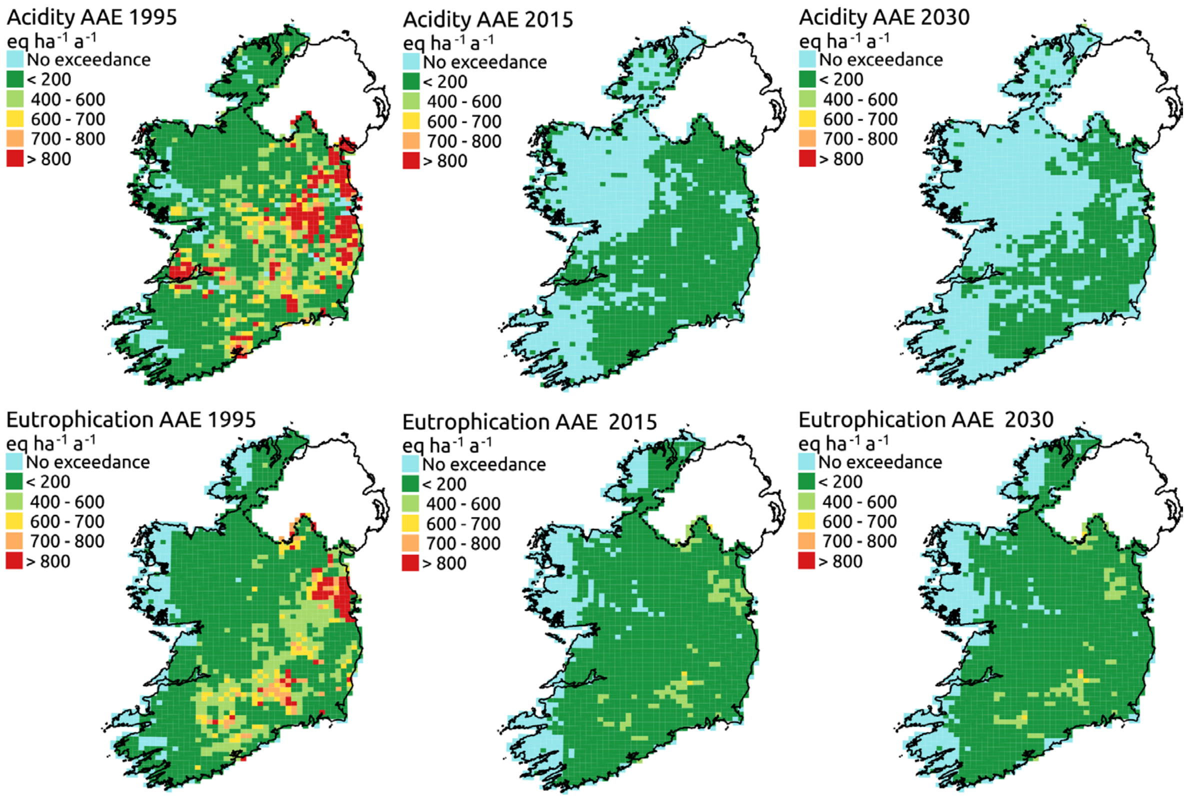

Figure 2.3. AAE of critical loads of acidity (top) and eutrophication (bottom) under modelled total S and N deposition during 1995, 2015 and 2030 under GP2030. The figure indicates areas where critical loads (2017 data submission; see Figure 2.2) are exceeded (units: eq ha^{-1} a^{-1}) on the 0.10° × 0.05° longitude–latitude grid (see Figure 2.1).

Table 2.1. Statistical summaries for the 5th percentile of $CL_{max}S$ and $CL_{eut}N$, and exceedances in 1995, 2015 and 2030 (for deposition see Figure 2.1) for terrestrial ecosystems (terrestrial and aquatic ecosystems for $CL_{max}S$)

Parameter	Year	$CL_{max}S$	$CL_{eut}N$
Ecosystem area (km^2)		13,519.2	17,974.6
Average critical load (eq ha^{-1} a^{-1})[a]		748.0	691.6
Average accumulated exceedance (eq ha^{-1} a^{-1})[b]	1995	248.1	127.5
	2015	12.4	54.2
	2030	5.8	57.7
Exceeded ecosystem area (km^2)	1995	807.7	630.5
	2015	738.8	582.9
	2030	615.6	582.8
Exceeded ecosystem area (percentage of mapped area)	1995	43.1	39.9
	2015	8.7	27.8
	2030	4.6	27.2

[a]Average of the 5th percentile of critical loads from every grid cell (weighted by ecosystem area).
[b]Exceedance refers to the average accumulated exceedance of critical loads of acidity and not exceedance with respect to S only.

Table 2.2. Average soil C and N content (%), average CLN_{max} (kg N ha^{-1} a^{-1}) and average maximum HSI by EUNIS class (habitat description, corresponding Annex I code and the number of relevés in each class are also given)

EUNIS code[a]	EUNIS habitat description	Annex I code	*n*	C (%)	N (%)	CLN_{max}[b]	Max. HSI
F4.11	Northern wet heath	4010	12	41.1	2.3	5.3	0.60
F4.2	Dry heaths	4030	18	33.4	1.6	7.4	0.65
F2	Arctic, alpine and subalpine scrub habitats	4060	8	42.4	1.8	4.5	0.77
E1.26	Sub-Atlantic semi-dry calcareous grasslands	6210	66	9.1	0.8	14.2	0.40
E1.7	Non-Mediterranean dry acidic grasslands	6230	63	10.3	0.8	14.9	0.69
E3.51	Moist and wet oligotrophic grasslands	6410	206	10.6	0.8	18.8	0.49
E2.2	Low- and medium-altitude hay meadows	6510	30	8.8	0.8	12.3	0.39
D1	Raised and blanket bogs[c]	7130	8	47.2	2.2	5.2	0.66

[a]PROPS-CLF was also applied to oak woodland relevés (G1.8) but the results were not meaningful.
[b]CLN_{max} was estimated using PROPS-CLF at a normalised HIS of 0.667 (see Figure 2.5).
[c]Data for blanket bog habitat only (Annex I 7130).

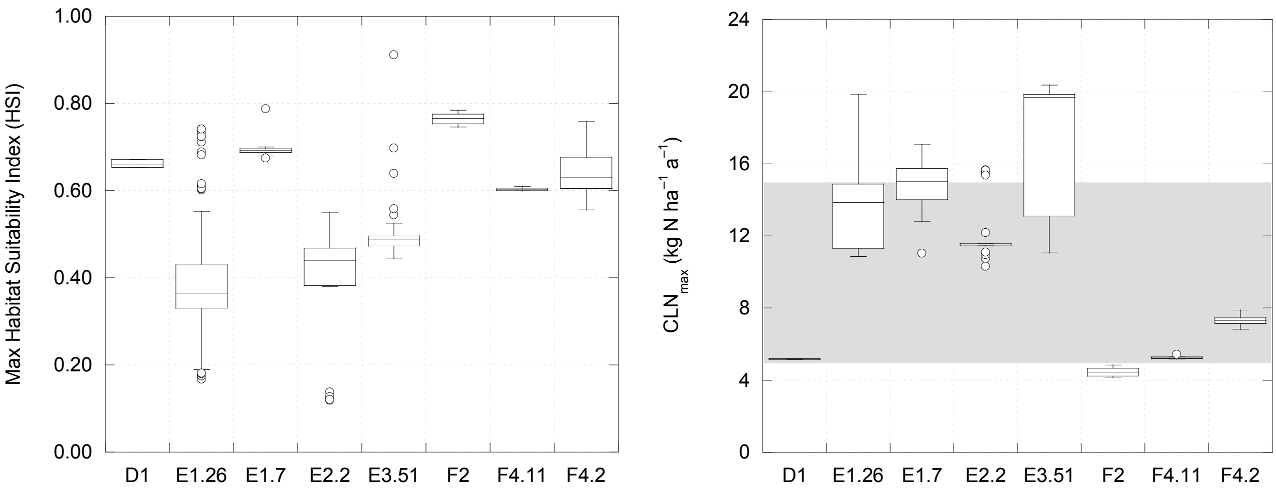

Figure 2.4. Box plots showing the HSI and CLN_{max} (kg N ha^{-1} a^{-1}) for each EUNIS habitat class (see Table 2.2). The grey band represents the range of 5–15 kg N ha^{-1} a^{-1}.

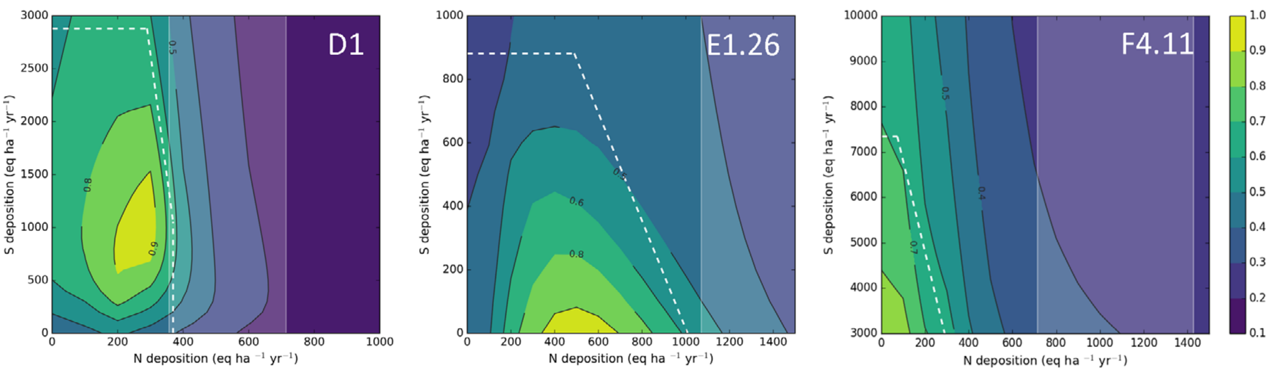

Figure 2.5. Average HSI isoline plots for three EUNIS habitats (D1, E1.26 and F4.11). The white dashed line indicates the average N–S critical load function; the number of vegetation plots (relevés) for each habitat ranged from 8 (D1) to 66 (E1.26). The vertical shading indicates the recommended range for the empirical critical load of nutrient N ($CL_{emp}N$). The plots represent the average of multiple isoline relevé plots for each individual habitat (see Table 2.2).

3 International Cooperative Programme Vegetation

3.1 National Participation in ICP Vegetation

Ireland has had limited participation in the ICP Vegetation programme,[6] which focuses on the impacts of tropospheric ozone on vegetation and the atmospheric deposition of heavy metals, N and POPs to vegetation. Since 1990, ICP Vegetation has co-ordinated the European Moss Biomonitoring Survey, which is conducted every 5 years to assess the atmospheric deposition of pollutants. Under the current project, Ireland participated in the 2015 European Moss Biomonitoring Survey and made its first data submission in response to the 2015 call for data.

During the period May–August 2015,[7] more than 170 sites were surveyed for two moss species, *Hylocomium splendens* and *Pleurozium schreberi*,[8] following survey protocols described in the ICP Vegetation moss monitoring manual (ICP Vegetation, 2010). To ensure national coverage, sampling sites were selected from a 25 km × 25 km sub-grid of the national grid. Moss tissue was collected at 130 sites (Figure 3.1); *H. splendens* was found most frequently (n = 113), followed by *P. schreberi* (n = 17), with both species sampled at 12 sites. Unwashed samples were stored in paper bags and air dried prior to analysis. Moss tissue from all sites was analysed for heavy metal concentrations (including total Hg) and N content, and a subset of sites was analysed for radionuclides (n = 24) and POPs (n = 9). Tissue concentration data for more than 30 elements at 130 sites were submitted to ICP Vegetation along with the analysis of moss reference material.

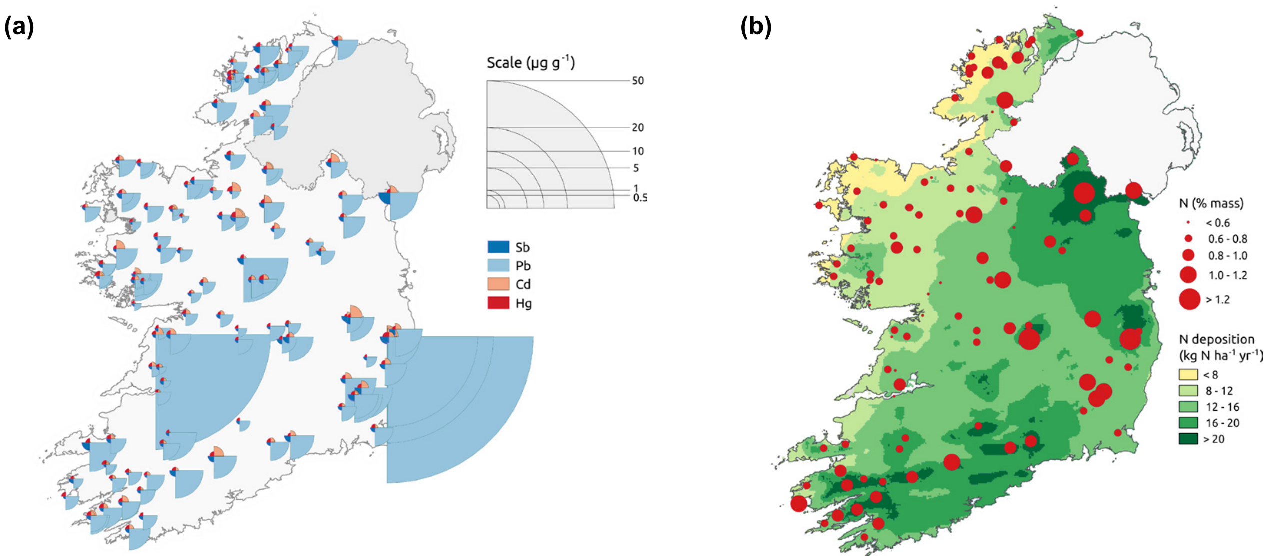

Figure 3.1. Moss tissue (*H. splendens*) sampling locations (n = 113) in the 2015 ICP Vegetation Moss Biomonitoring Survey. (a) Tissue concentrations (µg g^{-1}) of antimony (Sb), lead (Pb), cadmium (Cd) and Hg; (b) N content (% mass) in moss tissue overlaid on total N deposition (kg N ha^{-1} a^{-1}) for grasslands (Henry and Aherne, 2014).

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6 See https://icpvegetation.ceh.ac.uk (accessed 18 February 2020).

7 Two field campaigns: 27 May–5 June and 28 July–5 August 2015.

8 ICP Vegetation recommends surveying only pleurocarpous mosses; two pleurocarpous moss species are favoured: *Hylocomium splendens* and *Pleurozium schreberi*.

3.2 Heavy Metals and Nitrogen

Heavy metal concentrations were determined using a triple-quad inductively coupled plasma mass spectrometer (ICP-MS) following acid digestion (Mars 6 microwave digester). Total Hg was determined using a direct analyser (Milestone DMA-80). The concentration of N (and C and S; %) was determined using an Elementar vario MACRO CNS analyser, following pulverisation using a hand mill. Spatial variation (autocorrelation[9]) for heavy metals was explored using Moran's *I*-test (Moran, 1950).

Concentrations of cadmium (Cd), antimony (Sb), lead (Pb) and Hg (Figure 3.1; for other metals see Table 3.1) were low compared with those in other European countries participating in the 2010–2011 Moss Biomonitoring Survey (Harmens *et al.*, 2013). The location of Ireland on the western periphery of Europe, and the prevailing winds from the Atlantic, mean that it receives relatively "clean air" compared with continental European countries. A spatial trend was observed in the tissue concentrations of Pb (Moran's $I = 0.45$, $p < 0.05$), suggesting point sources of emissions within the country (Figure 3.1). In general, moss tissue had a lower average N content than all

Table 3.1. Summary of heavy metal and nutrient concentrations ($n = 113$) and radionuclide activity ($n = 23$) in moss tissue sampled during 2015 under the ICP Vegetation Moss Biomonitoring Survey

Element	*n*	Minimum	Maximum	Mean	Median	90th percentile
Al (μg g^{-1})	113	22.36	815.36	132.55	100.94	219.43
V (μg g^{-1})	113	0.14	2.01	0.56	0.50	0.98
Cr (μg g^{-1})	95	0.02	2.65	0.38	0.23	0.83
Mn (μg g^{-1})	113	6.30	797.46	187.33	150.19	363.78
Fe (μg g^{-1})	113	41.96	798.87	146.27	107.50	229.47
Co (μg g^{-1})	113	0.02	2.23	0.11	0.07	0.19
Ni (μg g^{-1})	54	0.05	7.42	1.15	0.53	2.74
Cu (μg g^{-1})	113	1.34	47.71	4.39	3.27	5.92
Zn (μg g^{-1})	113	4.86	167.16	30.10	22.21	59.04
As (μg g^{-1})	110	0.00	0.97	0.12	0.09	0.20
Se (μg g^{-1})	113	0.11	1.20	0.44	0.38	0.77
Sr (μg g^{-1})	113	4.73	81.29	18.56	16.39	29.59
Mo (μg g^{-1})	111	0.01	5.51	0.39	0.21	0.86
Ag (μg g^{-1})	91	0.00	0.25	0.05	0.05	0.09
Cd (μg g^{-1})	92	0.00	0.43	0.08	0.05	0.18
Sb (μg g^{-1})	112	0.01	0.44	0.07	0.05	0.13
Ba (μg g^{-1})	113	1.63	178.29	14.16	9.90	22.54
Tl (μg g^{-1})	101	0.00	0.24	0.02	0.01	0.04
Pb (μg g^{-1})	113	0.14	65.78	2.39	0.72	2.33
Hg (μg g^{-1})	113	0.01	0.07	0.04	0.03	0.05
%N	113	0.54	1.33	0.79	0.75	1.04
%S	113	0.13	0.24	0.17	0.16	0.21
^{210}Pb (Bq kg^{-1})	23	225.51	968.04	550.38	511.93	868.78
^{137}Cs (Bq kg^{-1})	16	3.06	41.38	14.05	10.41	23.94
^{7}Be (Bq kg^{-1})	8	283.10	604.35	420.68	376.19	601.30
^{40}K (Bq kg^{-1})	17	57.17	155.42	94.09	85.07	120.27

Be, beryllium.

9 Spatial autocorrelation describes the presence of systematic variation in a variable, i.e. the tendency for sites that are close to one another to have similar values of the variable.

other European countries in the 2010–2011 Moss Biomonitoring Survey (Harmens *et al.*, 2013) except Finland (average = 0.77%, n = 426). Nitrogen content in moss (average = 0.80%, n = 113; Table 3.1) was correlated with modelled total N deposition (Henry and Aherne, 2014; Figure 3.1) and showed a weak significant linear relationship ($R^2 = 0.18$, $p < 0.05$).

3.3 Persistent Organic Pollutants

Moss (*H. splendens*) tissue from three 50 m × 50 m sampling plots at each of the three ICP Waters catchments (Glendalough, Lough Maumwee and Lough Veagh; see Chapter 4) was analysed for POPs, including polycyclic aromatic hydrocarbons (PAHs[10]). Tissue samples were freeze-dried and extracted using accelerated solvent extraction, following EPA method 3534a. The extracts were rotary-evaporated, cleaned by gel permeation chromatography and sent to the Great Lakes Institute for Environmental Research (GLIER),[11] University of Windsor, ON, Canada, for analysis.

Many of the POPs and PAHs analysed were below the detection levels (Appendix 4). Only two brominated diphenyl ethers (BDEs) were observed in moss tissue across the three catchments, BDE-47 and BDE-99, which are the dominant congeners of commercial pentaBDE. Although pentaBDE production has been phased out in Europe and North America, it was predominantly produced in North America and, as such, its presence may indicate long-range transport. Polychlorinated biphenyls (PCBs) observed in moss tissue across the three catchments were dominated by congeners below 99, which are lighter and more likely to undergo long-range transport. PCBs have been banned for decades but are still present in the atmosphere (Pozo *et al.*, 2009). Organochlorine pesticides (OCPs) in moss tissue were dominated by chlorobenzenes [i.e. 1,2,4,5-tetrachlorobenzene (TCB), 1,2,3,4-TCB, pentachlorobenzene (QCB), hexachlorobenzene (HCB)] and dichlorodiphenyldichloroethylene (DDE), a breakdown product of dichlorodiphenyltrichloroethane (DDT). The concentrations of PAHs observed in moss tissue across the three catchments were notably higher than the concentrations of other POPs (Table 3.2). Observed PAHs were dominated by phenanthrene and naphthalene, which are low molecular weight (lighter) PAHs (i.e. two or three benzene rings). Moss tissue from Glendalough had the greatest concentration of PAHs, whereas the concentrations of BDEs and PCBs were highest at Lough Veagh (Table 3.2).

3.4 Radionuclides

A subset of the mosses collected for the ICP Vegetation Moss Biomonitoring Survey was analysed for radionuclides (n = 24; Figure 3.2) by the EPA's Office of Radiological Protection Ireland (Table 3.1). Naturally occurring Pb-210 (^{210}Pb) activity was

Table 3.2. Average (n = 3) total Hg, monomethylmercury, PAHs, BDEs, OCPs and PCBs detected in moss (from triplicate plots) at three ICP Waters catchments (see Figure 4.1)

Parameter	Units	Glendalough	Lough Maumwee	Lough Veagh
THg	$\mu g\ g^{-1}$	0.05	0.01	0.02
MMHg	$\mu g\ g^{-1}$	0.010	0.006	0.008
MMHg:THg	%	22.1	40.5	36.3
PAHs	$\mu g\ kg^{-1}$	36.114	11.145	22.094
BDEs	$\mu g\ kg^{-1}$	0.381	0.195	0.538
OCPs	$\mu g\ kg^{-1}$	0.155	0.779	0.563
PCBs	$\mu g\ kg^{-1}$	0.270	0.224	0.665

MMHg, monomethylmercury; THg, total Hg.

10 PAHs are not always anthropogenic in source, as they are produced from a variety of combustion processes; nonetheless, they are persistent in nature and many have similar qualities to POPs, e.g. they travel great distances in the atmosphere and can bind to organic matter.

11 See www1.uwindsor.ca/glier (accessed 18 February 2020).

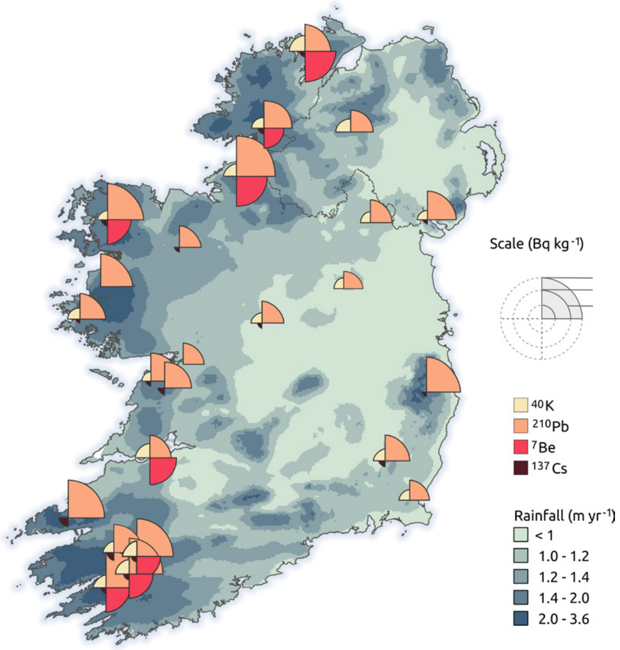

Figure 3.2. Location of sites (n = 24) where moss tissue was collected for radionuclide analysis. Segments represent ^{210}Pb, ^{137}Cs, ^{7}Be (beryllium) and ^{40}K (potassium) concentrations; visibly absent segments represent values below laboratory detection limits. Green shading depicts long-term annual average rainfall.

observed in every sample (average: 550.4 Bq kg^{-1}) and was correlated with average annual rainfall, as well as selenium and strontium concentrations, suggesting that deposition dominated by Atlantic air masses was the primary source. While only ^{210}Pb was found to be significantly correlated with rainfall, spatial clustering also suggested marine air mass sources of caesium-137 (^{137}Cs). Increased ^{137}Cs deposition was recorded in Ireland after the Fukushima nuclear incident in 2011 (EPA, 2015). While it can be assumed that the majority of the radionuclide deposition from the Fukushima accident to Ireland occurred shortly after the incident, the green tissue in moss is generally assumed to represent an average of 2–3 years' deposition.

3.5 Changes in Heavy Metals Deposition between 1995 and 2015

The Fly-Ash and Metals in Europe (FLAME) project (Rose *et al.*, 1998) measured heavy metal concentrations in moss tissues at > 35 locations in Ireland during the period 1994–1996. Under the current study, 25 of the FLAME sites were resampled to investigate temporal trends in metal concentrations. In both studies, *H. splendens* and *P. shreberi* were sampled where present; heavy metal concentrations were averaged by site if both species were sampled (and analysed). Censored values were present for some metals in the 2015 Moss Biomonitoring Survey because of method detection limits; censored values were imputed using the log ratio data augmentation (lrDA) method implemented in the zCompositions package for R (Palarea-Albaladejo and Martin-Fernandez, 2015). A statistically significant decline in median concentrations was observed for almost all heavy metals (Table 3.3 and Figure 3.3).

Table 3.3. Median heavy metal concentration (µg g^{-1}) in moss tissue from lake catchments (n = 25) sampled under the 1994–1996 FLAME project and the 2015 ICP Vegetation Moss Biomonitoring Survey

Element	1995 median	2015 median	Change (%)[a]
Al	516.0	90.4	–82.5
V	2.60	0.48	–81.5
Cr	2.70	0.26	–90.5
Fe	585.0	122.0	–79.1
Co	0.36	0.08	–78.9
Ni	0.69	0.00	–99.4
Cu	5.56	3.52	–36.7
Cd	0.44	0.05	–88.9
Pb	4.30	0.61	–85.7

[a]The change (% decrease) in heavy metal concentrations between surveys is estimated as the percentage difference from 1995.

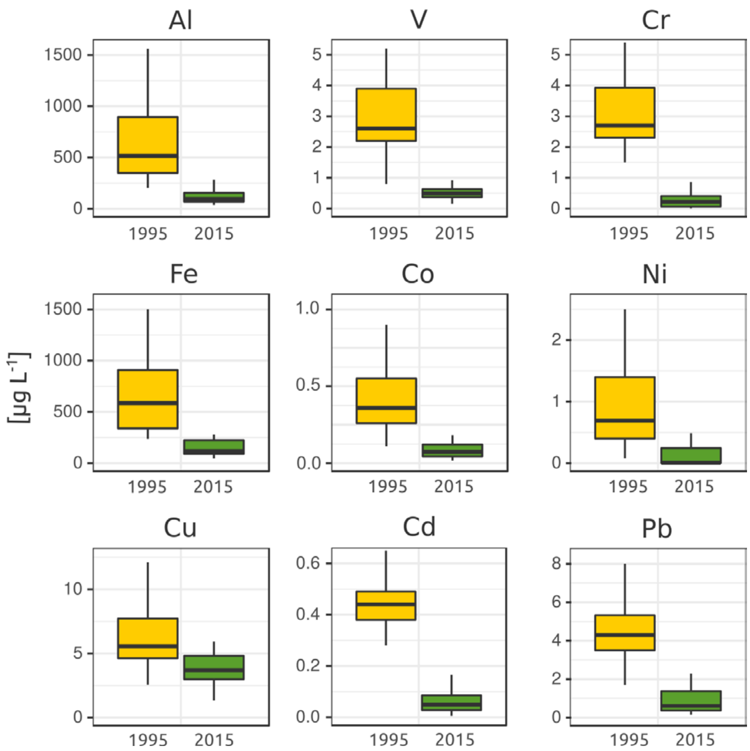

Figure 3.3. Box-plot comparison of heavy metal concentrations (µg g^{-1}) in moss tissue at 25 lake catchments during the 1994–1996 FLAME project (yellow) with concentrations from the 2015 ICP Vegetation Moss Biomonitoring Survey (green).

4 International Cooperative Programme Waters

4.1 National Participation in ICP Waters

Ireland's participation in ICP Waters began during the mid-1980s. The main objective of the programme is to assess the degree to which atmospheric pollution has affected surface waters, particularly with regard to issues such as acidification, heavy metals and POPs. Furthermore, the programme evaluates long-term trends and variations in aquatic chemistry through an international network of surface water monitoring sites. Three lakes, Lough Maumwee, Lough Veagh and Glendalough (Figure 4.1), and their inflow streams ($n = 9$), were originally selected in 1983 as part of a national acid-sensitive lake water survey (Bowman, 1986, 1991). Given this, these lakes have the longest continuous observed water chemistry record (since 1984) for acid-sensitive surface waters in Ireland (Bowman, 1986). The three lakes and their inflows have been included in ICP Waters since 1984 (1988 for Lough Veagh and its inflows). In general, the lakes and inflows were sampled on a bi-annual basis (winter – typically November or December – and late spring – May or June) during the period 1984–2009 (1988–2009 for Lough Veagh), with greater frequency during the periods 1984–1985 and 1987–1989. Since 2007, the three lakes have been sampled at least six times a year under the Water Framework Directive (WFD) – 2000/60/EC; however, monitoring of the inflows ceased prior to 2010.

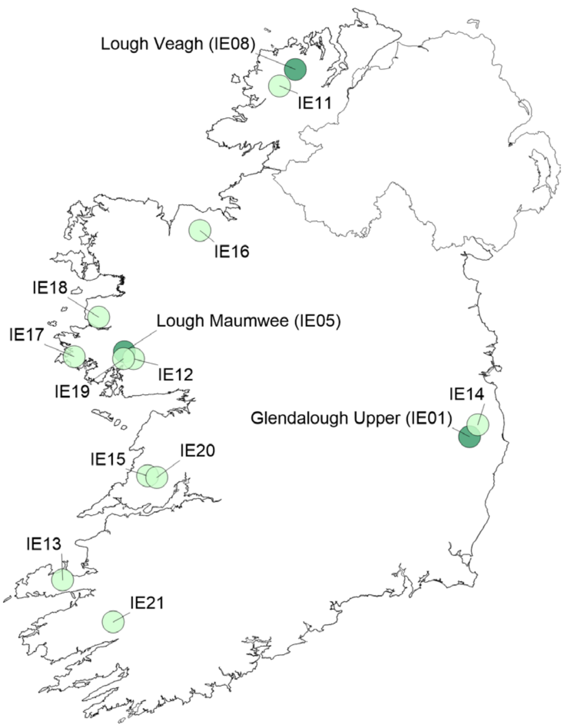

Figure 4.1. Location of lakes in the ICP Waters programme (*n* = 14); three lakes have participated in ICP Waters since 1984 (Glendalough, Lough Maumwee and Lough Veagh). The other lakes became part of the ICP Waters programme during 2013, with 2007 being the first data submission year (see Tables 4.1 and 4.2).

Despite the early participation in ICP Waters, national data submissions (of water chemistry) to ICP Waters ceased after 1999. The current project responded to two calls for data and re-established national data submissions to ICP Waters. In addition, the original three ICP Waters sites (Lough Maumwee, Lough Veagh and Glendalough) were selected for a focused catchment-based study on POPs and Hg, to build research capacity at Irish ICP Waters sites.

4.2 Response to Calls for Data

During 2013, the ICP Waters call for data focused on long-term data, to support the assessment of trends. In response to this call, all available data for the three lakes and their inflows between 1984 and 2013 were submitted to ICP Waters. The data record spanning three decades demonstrates the response of surface waters to reductions in "acidic" atmospheric deposition (Figure 4.2). The long-term trends in water chemistry are further discussed by Garmo *et al.* (2015). The submission was composed of ~1000 records of major ion chemistry (up to 30 parameters) for the three lakes during the 30-year period (1984–2013).

During 2013, following discussions with ICP Waters and the EPA, a revised lake network was included in the ICP Waters programme. The revised network replaced the inflows (unmonitored since 2009) with new sites (monitored under the WFD), providing greater spatial coverage and bringing the total

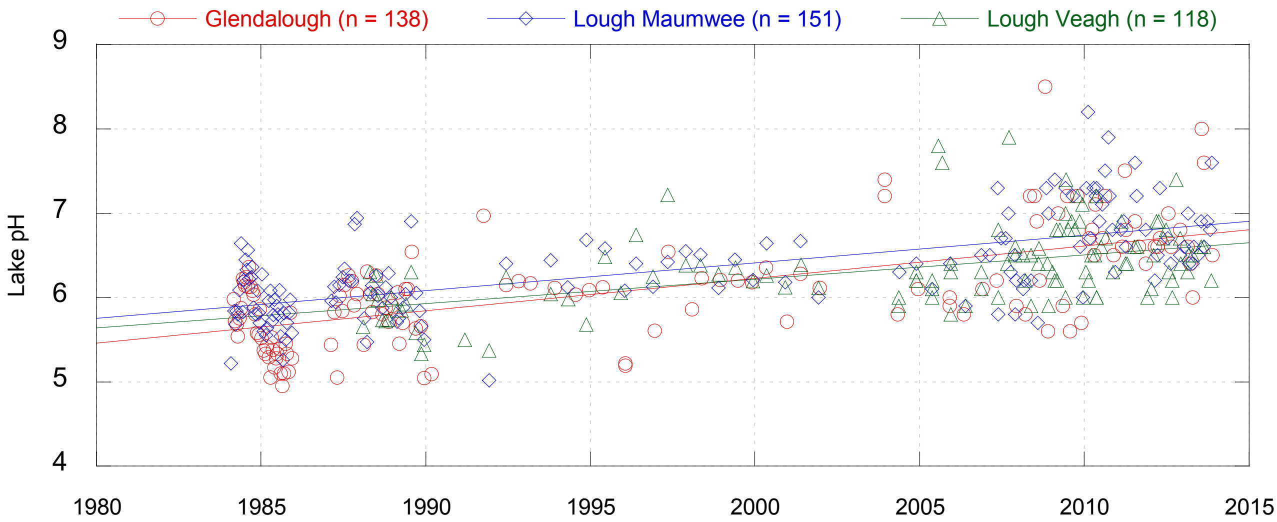

Figure 4.2. Lake pH between 1984 and 2014 (more than three decades) at Glendalough, Lough Maumwee and Lough Veagh (see Figure 4.1 for locations). Data were submitted to ICP Waters in response to the 2013 call for data. The best-fit linear regression line indicates a significant increase in surface water pH at each lake.

Table 4.1. Lake ID, lake name, lake area and co-ordinates for sites that submit water chemistry data to the ICP Waters programme (*n* = 14)[a]

Lake ID	Lake name	County	Area (ha)	Latitude (decimal degrees)	Longitude (decimal degrees)
IE01	Glendalough Upper	Wicklow	166.7	53.00521	–6.35722
IE05	Lough Maumwee	Galway	27.5	53.47738	–9.54100
IE08	Lough Veagh	Donegal	106.7	55.04752	–7.95363
IE11	Barra	Donegal	62.3	54.95574	–8.10400
IE12	Bofin	Galway	92.1	53.43770	–9.45429
IE13	Cam	Kerry	7.9	52.20597	–10.05228
IE14	Dan	Wicklow	102.4	53.06933	–6.27918
IE15	Doo	Clare	153.9	52.79277	–9.30487
IE16	Easky	Sligo	118.7	54.15336	–8.85182
IE17	Fadda	Galway	46.9	53.44326	–10.00595
IE18	Glencullin	Mayo	34.1	53.66339	–9.78657
IE19	Nahasleam	Galway	28.0	53.43684	–9.54759
IE20	Naminna	Clare	20.2	52.78408	–9.22064
IE21	Upper	Kerry	34.9	51.98090	–9.58815

[a]See Figure 4.1 for lake location and Table 4.2 for summary data.

number of lakes to 14 (Figure 4.1 and Table 4.1). Under the 2017 call for data, water chemistry data for the 14 lakes between 2007 and 2016 (10 years) were submitted to ICP Waters (Table 4.2). The data submission included 36,756 water quality observations; however, 11,200 were reported as being below the detection limit. Nonetheless, this still equated to approximately five observations a year for the 36 variables during the 10-year period for the 14 lakes. Only two lakes had a median pH below 6.0 (Table 4.2). Although these lakes are monitored under the WFD, their inclusion in ICP Waters provides greater analysis and assessment, harmonised methods, quality control and an assessment of long-term changes in the context of other data contributions (www.icp-waters.no).

Table 4.2. Median chemistry data for lakes in ICP Waters between 2007 and 2016 (10 years)[a]

Code	Lake name (county number)	pH	Alk. (μeq L^{-1})	Cond. (μS cm^{-1})	SO_4^{2-} (mg L^{-1})	xSO_4^{2-} (mg L^{-1})	Cl^- (mg L^{-1})	Ca^{2+} (mg L^{-1})	Mg^{2+} (mg L^{-1})	Na^+ (mg L^{-1})	K^+ (mg L^{-1})	Al (μg L^{-1})	Fe (μg L^{-1})	Mn (μg L^{-1})	DIN (μg N L^{-1})	TP (μg P L^{-1})	O_2 (mg O_2 L^{-1})	DOC (mg C L^{-1})	Colour (mg Pt L^{-1})
IE01	Glendalough WW (55)	6.6	79.9	33	3.0	2.3	5.1	1.4	0.7	3.3	0.20	116	160	38.0	220	10	10.8	4.0	40
IE05	Maumwee G (91)	6.6	92.9	59	2.4	0.8	13.0	1.3	0.9	7.0	0.36	34	40	5.6	56	10	10.9	6.6	30
IE08	Veagh DL (175)	6.4	77.9	64	2.3	0.9	15.0	1.1	1.0	8.0	0.37	77	70	4.0	119	14	11.1	6.1	54
IE11	Barra DL (74)	6.3	159.9	53	2.4	1.0	12.5	1.0	0.9	6.9	0.37	79	81	8.0	120	11	11.0	7.1	54
IE12	Bofin G (56)	6.8	159.9	77	2.4	0.7	17.0	2.5	1.2	9.4	0.39	34	205	13.0	47	11	11.0	8.0	55
IE13	Cam KY (201)	5.0	40.0	60	2.2	0.5	13.5	0.7	1.0	7.8	0.50	57	119	12.0	180	18	10.5	5.5	55
IE14	Dan WW (154)	5.3	58.0	37	1.8	1.2	6.5	1.1	0.6	4.0	0.28	170	242	51.0	129	14	10.1	11.1	127
IE15	Doo CE (131)	6.7	175.4	91	3.4	1.4	19.8	4.0	2.0	11.0	0.87	95	410	40.5	173	13	10.5	8.5	92
IE16	Easky SO (79)	6.7	135.9	50	1.7	0.6	11.0	1.2	0.8	6.0	0.32	46	135	9.7	13	10	11.0	7.9	60
IE17	Fadda G (55)	6.1	54.0	129	3.8	0.8	32.1	1.2	1.9	17.0	0.61	25	39	7.4	261	<DL	10.9	6.0	37
IE18	Glencullin MO (74)	7.0	124.9	51	2.0	0.8	11.0	1.0	1.1	6.0	0.37	21	47	9.7	230	10	11.2	4.2	24
IE19	Nahasleam G (55)	6.6	145.9	79	2.7	0.8	18.0	2.3	1.1	9.9	0.40	30	98	14.0	28	10	10.8	7.0	59
IE20	Naminna CE (47)	6.6	96.9	84	5.0	3.4	17.4	3.6	1.3	10.0	1.00	61	161	19.5	221	9	10.5	6.1	59
IE21	Upper KY (654)	6.4	119.9	50	1.4	0.2	10.0	1.6	0.9	5.9	0.30	39	53	18.0	130	14	10.3	4.3	28
Median		6.6	108.4	59	2.4	0.8	13.3	1.3	1.0	7.4	0.37	51	109	12.5	130	11	10.9	6.4	54

Note that many of the individual chemical observations were below the limits of detection. The median values across all lakes are also provided. The full dataset was submitted to ICP Waters during 2017 in response to its "call for data".

[a]The summary includes lake identifiers (ICP Waters lake ID, lake name, county abbreviation and maximum number of observations) and median observations for 18 chemical parameters.

Alk., alkalinity; Cond., conductivity; DIN, dissolved inorganic N; DOC, dissolved organic C; Pt, platinum; TP, total phosphorus; x, excess or non-sea salt.

4.3 Mercury and Persistent Organic Pollutants in Irish Lake Catchments

To build research capacity at the ICP Waters sites, the three long-term (since 1984) acid-sensitive lakes under the programme (Lough Veagh, Lough Maumwee and Glendalough; Figure 4.1) were selected for focused pollution studies. All three lakes are located in coastal rural areas isolated from point sources of pollution (Bowman, 1986). Water, lake sediment, soil and vegetation were sampled at each lake catchment and analysed for Hg and POPs. Note that the vegetation results are reported under ICP Vegetation (see Chapter 3).

Elevated Hg is of concern owing to its toxicity in the environment and its potential to enter the food chain. Hg may be emitted naturally through volcanic activity or biomass burning, but anthropogenic contributions through fossil fuel burning and other activities have resulted in increased global levels of Hg in ecosystems (Pirrone *et al.*, 2010). Monomethylmercury (MMHg) is a highly toxic form of Hg that results from the methylation of Hg (generally in aquatic ecosystems) and which can bioaccumulate and biomagnify up the food chain to fish and human consumption. Samples were tested for both total Hg and MMHg to quantify their presence in the three lake catchments.

Surface water samples were collected at three locations at each lake ($n = 9$) and analysed for total Hg using a Tekran model 2600 cold vapour atomic fluorescence spectrometer (CVAFS) mercury analysis system, following US EPA method 1631; and for MMHg using a Tekran model 2700 CVAFS mercury analysis system following US EPA method 1630. Sediment was dredged from three locations in each lake, and soil was additionally sampled at three locations in each catchment as composites from 0–10-cm cores collected from four corners and the midpoint of a 20 m × 20 m plot. Three samples of *H. splendens* moss were collected in proximity to the soil sampling plots and the composite samples were cleaned of debris (i.e. grass) by hand and stored in 1-L amber glass jars. Samples were air-dried at room temperature within 6 hours of collection. Sediment, soil and moss samples were analysed for total Hg in triplicate using a Tekran model 2600 CVAFS mercury analysis system and for MMHg in triplicate using a Tekran model 2700 CVAFS mercury analysis system. For further details on the method used see McFarland (2016).

Total Hg and MMHg were detected in all samples except for surface waters in the case of MMHg (Table 4.3); Scott (2012) found similar levels of total Hg and MMHg in five headwater lake catchments in Ireland. The concentrations of Hg varied between catchments; the highest concentrations in sediment were observed at Glendalough, whereas the highest concentrations in soil were observed in Lough Veagh (Table 4.3).

POPs are volatile at low temperatures and tend to travel long distances in the atmosphere. They are typically readily incorporated into organisms owing to their lipophilic nature, and there is evidence of POP biomagnification along the food chain (discussed in Jones and De Voogt, 1999; Blais, 2005). Many POPs are known as carcinogens or endocrine disruptors or cause other adverse health effects, such as reproductive and immune dysfunction (reviewed in Colborn *et al.*, 1993; El-Shahawi *et al.*, 2010). POPs are banned or heavily restricted in many countries through the establishment of the Stockholm Convention, which came into effect in 2004. Ireland signed the treaty in 2010 (Stockholm Convention, 2012).

This study examined concentrations in soil, sediment and vegetation of total PCBs, BDEs, OCPs and PAHs, in an effort to contribute POPs background data for Ireland at Glendalough, Lough Maumwee and Lough Veagh (Table 4.3). For details on the method, see McFarland (2016). Note that the vegetation results are reported under ICP Vegetation (see Chapter 3).

POPs were observed in all catchments; the concentrations in sediment and soil were dominated by PAHs, followed by PCBs, OCPs and BDEs (Table 4.3). The highest concentrations of PAHs were observed at Lough Veagh, followed by Glendalough. In contrast, the highest concentrations of PCBs and OCPs were observed in sediment at Glendalough and in soil at Lough Veagh (Table 4.3).

Table 4.3. Average concentrations from replicate samples (*n* = 3) of THg, MMHg, PAHs, BDEs, OCPs and PCBs in water (THg only), sediment and soil from three ICP Waters lake catchments: Glendalough, Lough Maumwee and Lough Veagh (see Figure 4.1)

	Units	Glendalough	Lough Maumwee	Lough Veagh
Water				
THg [2015]	$ng\,L^{-1}$	4.67	4.18	3.79
THg [2016]	$ng\,L^{-1}$	3.33	3.68	4.48
Sediment				
THg	$ng\,g^{-1}$	24.90	8.86	9.14
MMHg	$ng\,g^{-1}$	1.25	0.58	0.45
PAHs	$ng\,g^{-1}$	504.59	473.30	1230.63
BDEs	$ng\,g^{-1}$	0.92	0.24	1.31
OCPs	$ng\,g^{-1}$	4.47	0.75	2.74
PCBs	$ng\,g^{-1}$	4.07	1.76	2.89
Soil				
THg	$ng\,g^{-1}$	143.23	138.75	173.47
MMHg	$ng\,g^{-1}$	0.35	0.54	2.65
PAHs	$ng\,g^{-1}$	184.01	78.71	204.08
BDEs	$ng\,g^{-1}$	0.28	1.07	0.46
OCPs	$ng\,g^{-1}$	0.94	0.78	5.76
PCBs	$ng\,g^{-1}$	1.73	1.37	3.45

THg, total Hg.

5 Impacts of Atmospheric Nitrogen Deposition

5.1 Plant Species Diversity

During the last century, the burning of fossil fuels and the extensive application of agricultural fertilisers has led to a dramatic increase in plant-available N globally (Galloway *et al.*, 2008). Airborne gases and particles from these sources are eventually removed from the atmosphere through wet and dry deposition; elevated N deposition can result in changes to the plant communities of the receptor ecosystem (reviewed in Bobbink *et al.*, 2010). There is growing evidence that elevated N deposition is a major driver of biodiversity loss in natural and semi-natural ecosystems; Sala *et al.* (2000) list N deposition as one of the top 10 drivers of biodiversity loss globally, ranked closely behind climate change and land use change.

The overall objective of this study was to evaluate the potential impacts of N deposition on plant species diversity in semi-natural habitats in Ireland. This builds on the earlier work of Aherne *et al.* (2017), who found that a decrease in plant species richness was associated with increasing atmospheric N deposition in both acid and neutral calcareous semi-natural grasslands. In the current study, the relationship between N deposition and plant communities was explored for a number of semi-natural Annex I habitats using Threshold Indicator Taxa Analysis (TITAN; Baker and King, 2010), which is a statistical technique used to infer where along a (N deposition) gradient the greatest plant community change occurs. For further details see Wilkins and Aherne (2016) and Wilkins *et al.* (2016). Understanding how elevated N deposition affects natural and semi-natural ecosystems can support the development of empirical critical loads of nutrient N ($CL_{emp}N$) under the CLRTAP and the NECD, reporting under Article 17 of the EU Habitats Directive and EPA licensing to protect sensitive habitats.

5.2 Vegetation Change Points within Annex I Habitats

To assess the influence of elevated atmospheric N deposition to natural and semi-natural vegetation communities in Ireland, TITAN was applied to 22 Annex I habitats (Table 5.1). The objective was to identify community-level change points and then use the inferred community thresholds for atmospheric N deposition to inform $CL_{emp}N$. Vegetation survey data (species abundances) were obtained from the Irish NPWS; relevés were grouped by the Annex I designation, assigned during the surveys. Long-term (1991–2010) total N deposition maps were obtained from Henry and Aherne (2014) on a 5 km × 5 km grid, but the ammonia (NH_3) dry deposition component was adjusted for different habitat types using habitat-specific deposition velocities (Table 5.1), and vegetation-specific dry deposition for oxidised N was obtained from the EMEP model (www.emep.int). The deposition velocities used followed de Kluizenaar and Farrell (2000) and were consistent with Staelens *et al.* (2012).

Community-level change points were identified for 12 habitats, with seven habitats showing a decrease in the number of positive indicator species[12] (Table 5.2 and Figure 5.1). In three habitats (4060, 7130, 8210), the change point was within the recommended critical load range, while in eight habitats the change points were below the recommended critical load range. For eight habitats, more than 10% of the total recorded species significantly decreased in abundance along the N deposition gradient (habitats 4030, 4060, 5130, 6210, 6410, 6510, 7130, 91A0); for oak woodlands (91A0) 31% of species significantly decreased in abundance. Change points could not be determined for 10 habitats, potentially owing to their small sample

12 The NPWS also provided a list of positive and negative indicator species for each Annex I habitat; for grassland habitats, the list of species was further delineated into high-quality and general indicator species.

size (all except 7110 had <65 relevés; see Table 5.1) or the narrow observed range of total N deposition in the study area. Increasing the sample size and sampling range for those habitats may help to clarify whether or not these habitats are sensitive to elevated atmospheric N.

Table 5.1. Annex I habitats (code and description), number of relevés per habitat, number of species per habitat,[a] data sources and NH_3 dry deposition velocities

Annex I code	Description	Relevés	Species	Source	NH_3 V_{dep} (cm s^{-1})
4010	Northern Atlantic wet heaths with *Erica tetralix*	231	131	NSUH	1.5
4030	European dry heaths	164	123	NSUH	1.5
4060	Alpine and boreal heaths	97	89	NSUH	1.5
5130[b]	*Juniperus communis* formations on heaths or calcareous grasslands	191	142	NJS	1.5
6150	Siliceous alpine and boreal grasslands	34	52	NSUH	1.0
6210	Semi-natural dry grasslands and scrubland facies on calcareous substrates (*Festuco–Brometalia*)	507	275	ISGS	1.0
6230[c]	Species-rich *Nardus* grasslands on silicious substrates in mountain areas (and sub-mountain areas in continental Europe)	108	156	ISGS	1.0
6410	*Molinia* meadows on calcareous, peaty or clayey-silt-laden soils (*Molinion caeruleae*)	366	182	ISGS	1.0
6430[d]	Hydrophilous tall herb fringe communities of plains and of the montane to alpine levels	77	68	ISGS (50) NSUH (27)	1.0
6510	Lowland hay meadows (*Alopecurus pratensis*, *Sanguisorba officinalis*)	125	105	ISGS	1.0
7110[e]	Active raised bogs	111	15	RBS	1.0
7130[f]	Active blanket bogs	247	120	NSUH	1.0
7140	Transition mires and quaking bogs	23	45	NSUH	1.0
7150	Depressions on peat substrates of the *Rhynchosporion*	30	42	NSUH	1.0
7230	Alkaline fens	32	96	NSUH	1.0
8110	Siliceous scree of the montane to snow levels (*Androsacetalia alpinae* and *Galeopsietalia ladani*)	64	90	NSUH	1.0
8120	Calcareous and calcshist screes of the montane to alpine levels (*Thlaspietea rotundifolii*)	12	29	NSUH	1.0
8210	Calcareous rocky slopes with chasmophytic vegetation	37	92	NSUH	1.0
8220	Siliceous rocky slopes with chasmophytic vegetation	54	125	NSUH	1.0
91A0	Old sessile oak woods with *Ilex* and *Blechnum* in the British Isles	319	206	NSNW	2.0
91D0	Bog woodland	35	84	NSNW	2.0
91E0	Alluvial forests with *Alnus glutinosa* and *Fraxinus excelsior* (*Alno-Padion*, *Alnion incanae*, *Salicion albae*)	177	270	NSNW	2.0

Source: NPWS (www.npws.ie).

[a]Rare species, i.e. those appearing fewer than three times in the dataset, were excluded.

[b]Habitat 5130 is composed of five vegetation communities (Cooper *et al.*, 2012): group 1 (*n*=36 relevés), wet grassland, heath or bog (*Carex flacca–Succisa pratensis*); group 2 (*n*=29), exposed calcareous rock (*Teucrium scorodonia–Geranium sanguineum*); group 3 (*n*=31), dry calcareous heath and grassland (*Lotus corniculatus–Trifolium pratensis*); group 4 (*n*=58), dry siliceous heath and raised bog (*Calluna vulgaris–Erica cinerea*); and group 5 (*n*=37), dry calcareous or neutral grassland including coastal dunes (*Galium verum–Pilosella officinarum*). Note that bryophytes were not recorded in this survey.

[c]Calcareous and non-calcareous vegetation communities of habitat 6230 have been identified in Ireland; the current study includes only relevés on acid parent material (base-poor type).

[d]There are two distinct vegetation communities for habitat 6430 in Ireland, lowland (<150 m, *n*=50) and upland (>150 m, *n*=27); TITAN was applied to both lowland and combined lowland and upland communities.

[e]Only indicator species were recorded in the Raised Bog Survey.

[f]Includes only relevés at elevation >150 m.

ISGS, Irish Semi-natural Grassland Survey; NJS, National Juniper Survey; NSNW, National Survey of Native Woodlands; NSUH, National Survey of Upland Habitats; RBS, Raised Bog Survey; V_{dep}, deposition velocity.

Table 5.2. TITAN analysis for Annex I habitats, number of individual taxa for which a significant decrease/increase in abundance (#z−/#z+ taxa) was identified across the N deposition gradient (number of positive indicator – #PI – species for each habitat with a significant decrease/increase in abundance), significant community-level change point for decreasing/increasing taxa across the N deposition gradient (sum z–/+ change point in kg N ha^{-1} a^{-1}), the sum z−/+ 95th percentile, the recommended range for $CL_{emp}N$ (source: Bobbink and Hettelingh, 2011) and the corresponding EUNIS habitat class (or assumed analogue where recommend critical load ranges do not exist)

Annex I Code	#z– taxa (#PI)	#z+ taxa (#PI)	sum z– change point	sum z– 95th	sum z+ change point	sum z+ 95th	Critical load (kg N ha^{-1} a^{-1})	EUNIS code
4010	12 (8)	8 (2)	4.9	6.9	9.1	10.1	10–20	F4.11
4030	19 (0)	6 (1)	4.1	5.7	12.0	16.4	10–20	F4.2
4060	20 (9)	5 (1)	5.5	5.9	7.6	8.7	5–15	F2
5130	26 (12)	22 (0)	4.8	6.1	6.5	10.2	(10–20)	(F4.2)
6210	67 (7|9)[a]	38 (4|9)	8.3	8.3	8.5	8.7	15–25	E1.26
6230	15 (0|1)	14 (0|2)	3.9	7.3	6.5	6.6	10–15	E1.7
6410	22 (2|4)	24 (2|5)	6.3	6.8	11.9	13.6	15–25	E3.51
6510	11 (0|1)	13 (1|2)	7.5	7.6	8.7	11.9	20–30	E2.2
7130	22 (15)	7 (0)	4.9	7.8	13.7	14.3	5–10	D1
8210	5 (1)	3 (0)	5.7	5.9	6.1	7.9	(5–10)	(E4.2)
91A0	65 (18)	10 (1)	8.8	9.4	15.2	15.4	10–15	G1.8
91E0[b]	20 (2)	8 (1)	15.3	15.9	17.7	18.7	–	–

[a]Number of high-quality indicator species | and high-quality plus general indicator species with a significant change in abundance.

[b]Given the potential input of N from surface waters, it may not be appropriate to assign a change point based on atmospheric N deposition to alluvial forest habitats; furthermore, there is no recommended empirical critical load range for this habitat.

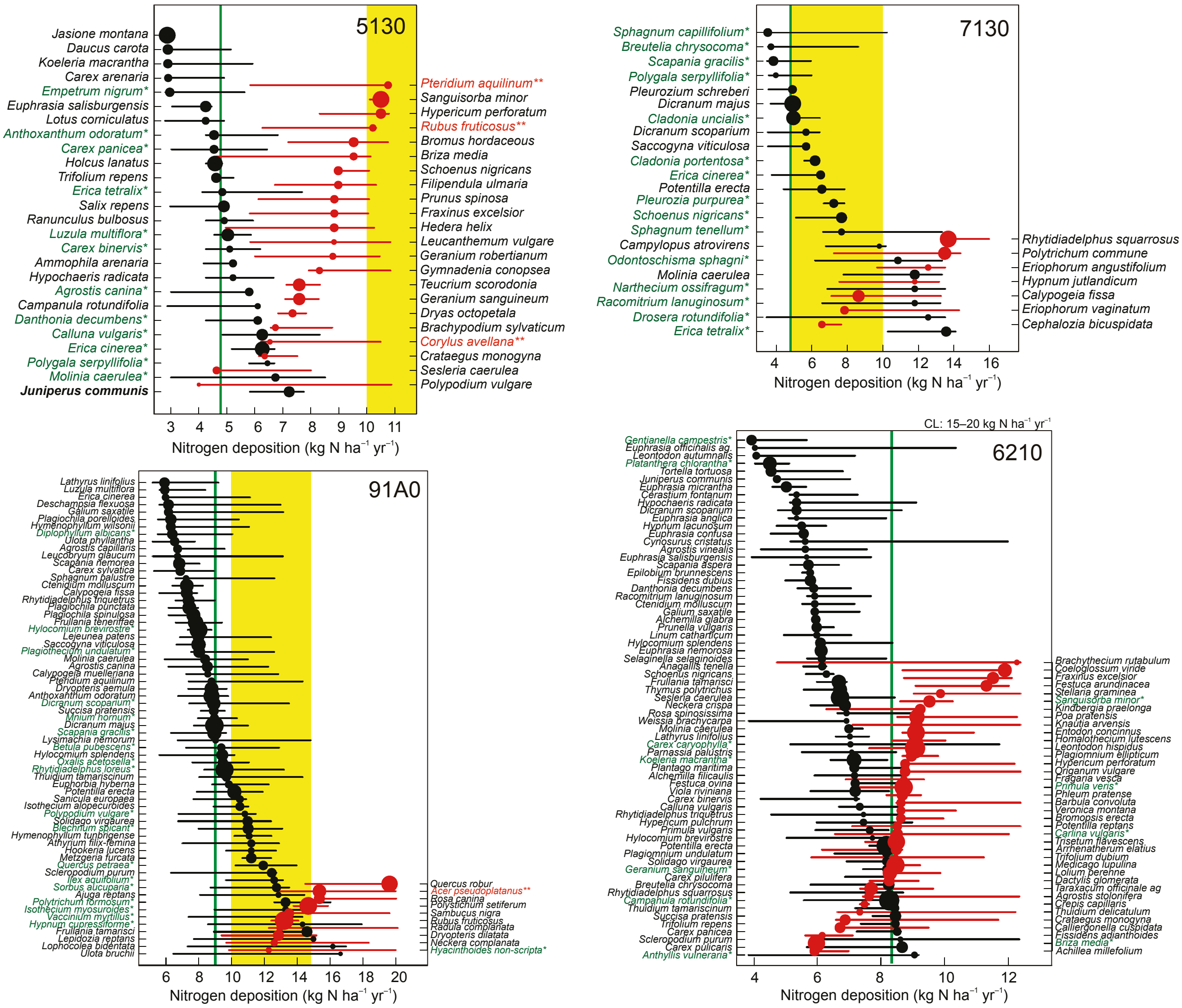

Figure 5.1. Individual taxa sum z– (black dots) and sum z+ (red dots) change points for Annex I habitats 5130, 6210, 7130 and 91A0 (see Table 5.1 for habitat descriptions). The green vertical line indicates the community-level change point and the yellow shading indicates the current recommended critical load range (see Table 5.2). Dot sizes represent the reliability of the estimates (larger dot size = greater reliability) and horizontal lines represent uncertainty (longer lines = greater uncertainty). Positive indicator species for each habitat are identified by an asterisk (and coloured green); indicator species decreased (z– axis) and increased (z+ axis) in abundance under N deposition. Note that, for habitat 5130, indicators species are shown only for the vegetation community (see Table 5.1) dry siliceous heath and raised bog (*Calluna vulgaris–Erica cinerea*). Furthermore, only high-quality indicators are shown for habitat 6210 (see Table 5.2). Negative indicators species are identified by two asterisks (and coloured red). See Wilkins *et al.* (2016) for plots of other habitats.

6 Conclusions

The principal objectives of this project were to determine the critical load of acidity and $CL_{eut}N$ (and biodiversity) for terrestrial and aquatic ecosystems, to strengthen national participation in the CLRTAP and to evaluate the potential impacts of N deposition on plant species diversity. The project responded to the 2015–2017 call for data from ICP Modelling and Mapping, participated in the 2015 Moss Biomonitoring Survey under ICP Vegetation and responded to two calls for data from ICP Waters. In addition, the project evaluated the influence of N deposition on 22 Annex I habitats. The project outputs have been used to support the GP2030 and the EU Clean Air Policy Package.

- Under GP2030 depositions, much of the country is predicted to achieve non-exceedance of critical loads of acidity by 2030. In contrast, exceedance of $CL_{eut}N$ is not predicted to change by 2030, owing to national increases in reduced N deposition.
- Biodiversity critical loads of N (determined using the PROPS-CLF model for eight habitats) were broadly consistent with current recommended empirical critical load ranges, although heathland, dry calcareous grassland and mesic grassland habitat averages were below the recommend range.
- Moss biomonitoring indicates that trace element deposition is low over Ireland and has substantially decreased during the last two decades. The concentration of POPs in moss was dominated by lighter congeners that have a greater tendency to undergo long-range transport, such as commercial pentabromodiphenyl ether, which was predominantly produced in North America.
- N content in moss was correlated with modelled total N deposition and showed an east-to-west decreasing gradient.
- During the last three decades, there has been a significant increase in surface water pH in response to reductions in “acidic” atmospheric deposition, as observed at the three long-term ICP Waters lakes that have been monitored since 1984 (Glendalough, Lough Maumwee and Lough Veagh).
- POPs were observed at the three long-term ICP Waters catchments (Glendalough, Lough Maumwee and Lough Veagh); the concentrations in sediment and soil were dominated by PAHs, followed by PCBs, OCPs and BDEs.
- Community-level change points were identified along a N deposition gradient for 12 habitats, with seven habitats showing a decrease in the number of positive indicator species under increasing N deposition. The change points were below the recommended critical load range for 8 of the 12 habitats.

7 Recommendations

National critical load data have made an important contribution to the development of effects-based international polices on the abatement of long-range transboundary air pollution. Nonetheless, critical loads have been virtually ignored under national policy assessments, partly because of the lack of a national strategy on air pollution and perhaps a lack of awareness on the use of critical loads on a European scale. Following on from this, there are several concrete recommendations:

- There should be wider adoption and integration of critical loads into national and international policy assessments, e.g. critical loads should be used to inform (a) the requirement for NECD ecosystem monitoring, (b) reporting under Articles 6 and 17 of the Habitats Directive and (c) licensing under the Industrial Emissions Directive – 2010/75/EU.
- N impacts are considered a serious threat to biodiversity; as a result, there should be continued development of biodiversity critical loads. To support future calls for data under ICP Modelling and Mapping, the determination of biodiversity critical loads should be expanded to include more habitat types, supported by the development of plant relevé–soil chemistry databases.
- There needs to be greater understanding of the effects of N deposition to semi-natural habitats in Ireland. Statistical modelling procedures, such as TITAN, should be used to inform (establish) $CL_{emp}N$ specific to Irish habitats. There are clear synergies between the Habitat Directive (92/43/EEC) and the Clean Air Directive (2008/50/EC), specifically with respect to Natura 2000 sites.
- National participation in the well-established network of ICPs should be formalised and strengthened. The long-standing network provides an obvious framework for national monitoring activities, such as the requirement for NECD ecosystem monitoring. The network readily facilitates international co-operation, as evidenced by participation in ICP Waters. It is recommended that the ICP and EMEP monitoring sites become focal points to build national research capacity.
- There should be national participation in the 2020 Moss Biomonitoring Survey under ICP Vegetation. The 2015 survey provided new information on the spatial deposition of trace elements, POPs, radionuclides and N.
- The national critical load database should continue to be revised in response to scientific and technical updates, and in response to calls for data from the CLRTAP. Critical loads will continue to play an important role in European air policy strategies, especially with respect to the impacts of N deposition on plant species diversity.

References

Aherne, J. and Farrell, E.P. (eds), 2000. *Determination and Mapping of Critical Loads for Sulphur and Nitrogen and Critical Levels for Ozone in Ireland*. Environmental Protection Agency, Johnstown Castle, Ireland.

Aherne, J., Burton, A., Scott, H., Whitfield, C. and Wolniewicz, M., 2014. *Influence of Transboundary Air Pollution on Acid-sensitive Ecosystems*. CCRP Report Series No. 31. Environmental Protection Agency, Johnstown Castle, Ireland.

Aherne, J., Henry, J. and Wolniewicz, M., 2017. *Development of Critical Loads for Ireland: Simulating Impacts on Systems (SIOS).* Environmental Protection Agency, Johnstown Castle, Ireland.

Baker, M.E. and King, R.S., 2010. A new method for detecting and interpreting biodiversity and ecological community thresholds. *Methods in Ecology and Evolution* 1(1): 25–37.

Blais, J.M., 2005. Biogeochemistry of persistent bioaccumulative toxicants: processes affecting the transport of contaminants to remote areas. *Canadian Journal of Fisheries and Aquatic Sciences*, 62(1): 236–243.

Bobbink, R. and Hettelingh, J.P., 2011. *Review and Revision of Empirical Critical Loads and Dose–Response Relationships: Proceedings of an Expert Workshop, Noordwijkerhout, 23–25 June 2010*. National Institute for Public Health and the Environment, Bilthoven, the Netherlands.

Bobbink, R., Hicks, K., Galloway, J., Spranger, T., Alkemade, R., Ashmore, M., Bustamante, M., Cinderby, S., Davidson, E., Dentener, F., Emmett, B., Erisman, J.W., Fenn, M., Gilliam, F. Nordin, A., Pardo, L. and De Vries, W., 2010. Global assessment of nitrogen deposition effects on terrestrial plant diversity: a synthesis. *Ecological Applications* 20(1): 30–59.

Bowman, J., 1986. *Precipitation Characteristics and the Chemistry and Biology of Poorly Buffered Irish Lakes: A Western European Baseline for "Acid Rain" Impact Assessment*. An Foras Forbartha, Dublin.

Bowman, J., 1991. *Acid-sensitive Surface Waters in Ireland*. Environment Research Unit, Dublin.

CLRTAP (Convention on Long-Range Transboundary Air Pollution), 2014. Mapping critical loads for ecosystems. In *Manual on Methodologies and Criteria for Modelling and Mapping Critical Loads and Levels*. Umwelbundesamt, Berlin. Available online: https://www.umweltbundesamt.de/en/manual-for-modelling-mapping-critical-loads-levels?parent=68093 (accessed 18 February 2020).

Colborn, T., vom Saal, F.S. and Soto, A.M., 1993. Developmental effects of endocrine-disrupting chemicals in wildlife and humans. *Environmental Health Perspectives* 101(5): 378.

Cooper, F., Stone, R.E., McEvoy, P. Wilkins, T. and Reid, N., 2012. *The Conservation Status of Juniper Formations in Ireland*. Irish Wildlife Manuals, No. 63, National Parks & Wildlife Service. Department of Environment, Heritage and Local Government, Dublin.

de Kluizenaar, Y. and Farrell, E.P., 2000. *Ammonia Monitoring in Ireland: A Full Year of Ammonia Monitoring, Set-up and Results*. Environmental Protection Agency, Johnstown Castle, Ireland.

de Vries, W., Hettelingh, J.-P. and Posch, M. (eds), 2015. *Critical Loads and Dynamic Risk Assessments: Nitrogen, Acidity and Metals in Terrestrial and Aquatic Ecosystems.* Environmental Pollution Series Vol. 25. Springer Netherlands, Dordrecht, the Netherlands.

EEA (European Environment Agency), 2014. *Effects of Air Pollution on European Ecosystems: Past and Future Exposure of European Freshwater and Terrestrial Habitats to Acidifying and Eutrophying Air Pollutants*. EEA Technical Report No. 11. EEA, Copenhagen.

El-Shahawi, M.S., Hamza, A., Bashammakh, A.S. *et al.*, 2010. An overview on the accumulation, distribution, transformations, toxicity and analytical methods for the monitoring of persistent organic pollutants. *Talanta* 80(5): 1587–1597.

EPA (Environmental Protection Agency), 2015. *Radioactivity: Monitoring of the Irish Environment 2012–2013*. EPA, Johnstown Castle, Ireland.

Fossitt, J.A., 2000. *A Guide to Habitats in Ireland*. Heritage Council/Chomhairle Oidhreachta, Kilkenny, Ireland.

Galloway, J.N., Townsend, A.R., Erisman, J.W., Bekunda, M., Cai, Z., Freney, J.R., Martinelli, L.A., Seitzinger, S.P. and Sutton, M.A., 2008. Transformation of the nitrogen cycle: recent trends, questions, and potential solutions. *Science* 320: 889–892.

Garmo, Ø.A., de Wit, H., Høgåsen, T., Lund, E., Wright, R.F., Aherne, J., Arle, J., Colombo, L., Fölster, J., Hruška, J., Indriksone, I., Jeffries, D., Krám, P., Monteith, D.T., Paterson, A., Rogora, M., Rzychon, D., Steingruber, S., Stoddard, J.L., Talkop, R., Ulanczyk, R.P. and Vuorenmaa, J., 2015. Trends in water chemistry. In Garmo, Ø.A., de Wit H. and Fjellheim, A. (eds), *Chemical and Biological Recovery in Acid-Sensitive Waters: Trends and Prognosis*. NIVA-rapport 6847; ICP Waters-rapport 119/2015. Norsk institutt for vannforskning, Oslo.

Harmens, H., Norris, D., Mills, G. and the participants of the Moss Survey, 2013. *Heavy Metals and Nitrogen in Mosses: Spatial Patterns in 2010/2011 and Long-term Temporal Trends in Europe*. ICP Vegetation Programme Coordination Centre, Centre for Ecology and Hydrology, Bangor, Gwynedd, UK.

Henry, J. and Aherne, J., 2014. Nitrogen deposition and exceedance of critical loads for nutrient nitrogen in Irish grasslands. *Science of the Total Environment* 470–471: 216–223. https://doi.org/10.1016/j.scitotenv.2013.09.047

Hettelingh, J.-P., Posch, M. and Slootweg J. (eds), 2017. *European Critical Loads: Database, Biodiversity and Ecosystems at Risk. CCE Final Report 2017*. RIVM Report 2017–0155. National Institute for Public Health and the Environment, Bilthoven, the Netherlands.

ICP Vegetation (International Cooperative Programme on Effects of Air Pollution on Natural Vegetation and Crops), 2010. *Heavy Metals in European Mosses: 2010 Survey, Monitoring Manual*. Harmens, H. (ed.). ICP Vegetation Coordination Centre, Bangor, Gwynedd, UK. Available online: https://icpvegetation.ceh.ac.uk/get-involved/manuals (accessed 18 February 2020).

Jones, K.C. and De Voogt, P., 1999. Persistent organic pollutants (POPs): state of the science. *Environmental Pollution* 100(1–3): 209–221.

McFarland, V., 2016. Mercury and persistent organic pollutants in remote acid sensitive Irish lake catchments. MSc Thesis. Trent University, Peterborough, ON, Canada.

Moran, P.A.P., 1950. Notes on continuous stochastic phenomena. *Biometrika* 37(1): 17–23.

Nilsson, J. and Grennfelt, P., 1988. *Critical Loads for Sulphur and Nitrogen*. *Miljörapport 1988*. Nordic Council of Ministers, Copenhagen.

Palarea-Albaladejo, J. and Martin-Fernandez, J.A., 2015. zCompositions – R package for multivariate imputation of left-censored data under a compositional approach. *Chemometrics Intelligent Laboratory Systems* 143: 85–96.

Pirrone, N., Cinnirella, S., Feng, X., Finkelman, R.B., Friedli, H.R., Leaner, J., Mason, R., Mukherjee, A.B., Stracher, G.B., Streets, D.G. and Telmer, K., 2010. Global mercury emissions to the atmosphere from anthropogenic and natural sources. *Atmospheric Chemistry and Physics* 10(13): 5951–5964.

Pozo, K., Harner, T., Lee, S.C., Wania, F., Muir, D.C.G. and Jones, K.C., 2009. Seasonally resolved concentrations of persistent organic pollutants in the global atmosphere from the first year of the GAPS study. *Environmental Science and Technology* 43(3): 796–803.

Reinds, G.J., Mol-Dijkstra, J., Bonten, L., Wamelink, W., de Vries, W. and Posch, M., 2014. VSD+PROPS: recent developments. In: Slootweg, J., Posch, M. and Hettelingh, J.-P. (eds), *Modelling and Mapping the Impacts of Atmospheric Deposition on Plant Species Diversity in Europe: CCE Status Report 2014*. RIVM Report 2014–0075. National Institute for Public Health and the Environment, Bilthoven, the Netherlands, pp. 47–53.

Rose, N.L., Alliksaar, T., Bowman, J.J., Boyle, J., Coles, B., Harlock, S., Juggins, S., Punning, J.M., St. Clair-Gribble, K., Vukic, J. and Watt, J., 1998. The FLAME research project: introduction and methods. *Water, Air, and Soil Pollution* 106(3–4): 205–218.

Sala, O.E., Chapin, F.S., Armesto, J.J., Berlow, E., Bloomfield, J., Dirzo, R., Huber-Sanwald, E., Huenneke, L.F., Jackson, R.B., Kinzig, A., Leemans, R., Lodge, D.M., Mooney, H.A., Oesterheld, M., LeRoy Poff, N., Skyes, M.T., Walker, B.H., Walker, M. and Wall, D.H., 2000. Global biodiversity scenarios for the year 2100. *Science* 287(5459): 1770–1774.

Scott, H., 2012. Long-range atmospheric transport and fate of persistent organic pollutants and mercury in Irish headwater lake catchments. MSc Thesis. Trent University, Peterborough, ON, Canada.

Simpson, D., Benedictow, A., Berge, H., Bergström, R., Emberson, L.D., Fagerli, H., Flechard, C.R., Hayman, G.D., Gauss, M., Jonson, J.E., Jenkin, M.E., Nyíri, A., Richter, C., Semeena, V.S., Tsyro, S., Tuovinen, J.P., Valdebenito, Á. and Wind, P., 2012. The EMEP MSC-W chemical transport model: technical description. *Atmospheric Chemistry and Physics* 12: 7825–7865.

Staelens, J., Wuyts, K., Adriaenssens, S., Van Avermaet, P., Buysse, H., Van den Bril, B., Roekens, E., Ottoy, J.P., Verheyen, K., Thas, O. and Deschepper, E., 2012. Trends in atmospheric nitrogen and sulphur deposition in northern Belgium. *Atmospheric Environment* 49: 186–196.

Stockholm Convention, 2012. *Protecting Human Health and the Environment from Persistent Organic Pollutants*. Stockholm Convention, Geneva. Available online: chm.pops.int (accessed 18 February 2020).

WGE (Working Group on Effects), 2014. *Impacts of Air Pollution on Ecosystems, Human Health and Materials under Different Gothenburg Protocol Scenarios*. WGE, United Nations Economic Commission for Europe, New York, NY.

Wilkins, K. and Aherne, J., 2016. Vegetation community change in Atlantic oak woodlands along a nitrogen deposition gradient. *Environmental Pollution* 216: 115–124.

Wilkins, K., Aherne, J. and Bleasdale, A., 2016. Vegetation community change points suggest that critical loads of nutrient nitrogen may be too high. *Atmospheric Environment* 146: 324–331.

Abbreviations

AAE	Average accumulated exceedance
BDE	Brominated diphenyl ether
C	Carbon
CCE	Coordination Centre for Effects
Cd	Cadmium
$CL_{emp}N$	Empirical critical load of nutrient nitrogen
$CL_{eut}N$	Critical load of eutrophication
CLF	Critical load function
$CL_{max}N$	Maximum critical load of nitrogen (acidity)
$CL_{min}N$	Minimum critical load of nitrogen (acidity)
CLN_{max}	Maximum biodiversity-related critical load of nitrogen
$CL_{nut}N$	Critical load of nutrient nitrogen
CLRTAP	Convention on Long-range Transboundary Air Pollution
CLS_{max}	Maximum critical load of sulphur
Cs	Caesium
CVAFS	Cold vapour atomic fluorescence spectrometer
DDE	Dichlorodiphenyldichloroethylene
DDT	Dichlorodiphenyltrichloroethane
EMEP	European Monitoring and Evaluation Programme
EPA	Environmental Protection Agency
EUNIS	European Nature Information System
FLAME	Fly-Ash and Metals in Europe
GP2030	Revised Gothenburg Protocol
HCB	Hexachlorobenzene
Hg	Mercury
HSI	Habitat Suitability Index
ICP	International Cooperative Programme
MMHg	Monomethylmercury
N	Nitrogen
NECD	National Emission Ceilings Directive
NH_3	Ammonia
NH_y	Reduced nitrogen
NO_x	Oxidised nitrogen
NPWS	National Parks & Wildlife Service
OCP	Organochlorine pesticide
PAH	Polyaromatic hydrocarbon
Pb	Lead
PCB	Polychlorinated biphenyl
POP	Persistent organic pollutant
PROPS-CLF	Probability of plant species (with critical load function)
QCB	Pentachlorobenzene
S	Sulphur
Sb	Antimony
TCB	Tetrachlorobenzene
TITAN	Threshold Indicator Taxa Analysis

UNECE	United Nations Economic Commission for Europe
WFD	Water Framework Directive
WGE	Working Group on Effects

Appendix 1 Project Outputs

A1.1 Peer-reviewed Publications

Burns, D.A., Aherne, J, Gay, D.A. and Lehmann, C.M.B., 2016. Acid rain and its environmental effects: recent scientific advances. *Atmospheric Environment* 146: 1–4.

Cathcart, H. and Wilkins, K., 2015. Hunting high and low for *Hylocomium* in Ireland. *Field Bryology* 114: 33–36.

Curtis, C.J., Posch, M., Aherne, J., Fölster, J., Forsius, M., Larssen, T. and Moldan, F., 2015. Assessment of critical loads of acidity and their exceedances for European lakes. In de Vries, W., Hettelingh, J.-P. and Posch, M. (eds), *Critical Loads for Nitrogen, Acidity and Metals for Terrestrial and Aquatic Ecosystems*, Chapter 17. Environmental Pollution, Vol. 25. Springer, Dordrecht, the Netherlands.

Reinds, G.J., Posch, M., Aherne, J. and Forsius, M., 2015. Assessment of critical loads of sulphur and nitrogen and their exceedances for terrestrial ecosystems in the northern hemisphere. In de Vries, W., Hettelingh, J.-P. and Posch, M. (eds), *Critical Loads for Nitrogen, Acidity and Metals for Terrestrial and Aquatic Ecosystems*, Chapter 15. Environmental Pollution, Vol. 25. Springer, Dordrecht, the Netherlands.

Wilkins, K. and Aherne, J., 2015. Interspecies comparison of nitrogen content and heavy metal concentrations in *Isothecium myosuroides* and *Thuidium tamariscinum* mosses in Irish Atlantic oak woodlands. *Annals of Botany* 5: 71–78.

Wilkins, K. and Aherne, J., 2016. Vegetation community change in Atlantic oak woodlands along a nitrogen deposition gradient. *Environmental Pollution* 216: 115–124.

Wilkins, K., Aherne, J. and Bleasdale, A., 2016. Vegetation community change points suggest that critical loads of nutrient nitrogen may be too high. *Atmospheric Environment* 146: 324–331.

A1.2 Technical Reports

Aherne, J., Cathcart, H., Wilkins, K., McEntagart, J., Dodd, D. and Bleasdale, A., 2017. Ireland: National Focal Centre report. In Hettelingh, J.-P., Posch, M. and Slootweg, J. (eds), *European Critical Loads: Database, Biodiversity and Ecosystems at Risk. CCE Final Report 2017*. RIVM Report 2017-0155. National Institute for Public Health and the Environment, Bilthoven, the Netherlands.

ICP Vegetation, 2015. *Air Pollution and Vegetation: 2014/2015*. ICP Vegetation Annual Report. Centre for Ecology and Hydrology, Bangor, Gwynedd, UK. Available online: icpvegetation.ceh.ac.uk/publications/annual (accessed 18 February 2020).

ICP Vegetation, 2016. *Air Pollution and Vegetation: 2015/2016*. ICP Vegetation Annual Report. Centre for Ecology and Hydrology, Bangor, Gwynedd, UK. Available online: icpvegetation.ceh.ac.uk/publications/annual (accessed 18 February 2020).

Garmo, Ø.A., *et al.*, 2015. Trends in water chemistry. In Garmo, Ø.A., de Wit, H. and Fjellheim, A. (eds), *Chemical and Biological Recovery in Acid-Sensitive Waters: Trends and Prognosis*. NIVA-rapport 6847; ICP Waters-rapport 119/2015. Norsk institutt for vannforskning, Oslo, Norway.

A1.3 Conferences and Workshops

Aherne, J., 2015. Critical loads – and ecosystem impacts of air pollutants. Clean Air Conference, Wood Quay Venue, Dublin, 28 September 2015 (oral presentation).

Aherne, J., 2015. Transboundary air pollution – ecosystem health and critical loads. EPA Air Quality Research Seminar, Pearse Street, Dublin, 18 March 2015 (oral presentation).

Aherne, J., 2016. Atmospheric deposition, acidification and its role in dissolved organic carbon. Irish Natural Organic Matter 2016, Galway, Ireland, 16 June 2016 (oral presentation).

Aherne, J., 2017. Critical loads of nitrogen deposition to protect biodiversity in Irish habitats. National Parks & Wildlife Service, Ely Place, Dublin, 11 May 2017 (oral presentation).

Aherne, J., Bleasdale, A., Dodd, D. and Lanigan, G.J., 2013. An overview of the N ‘issue’ in Ireland. Nitrogen Deposition and the Nature Directives, Joint Nature Conservation Committee *(JNCC)*, Peterborough, UK, 2–4 December 2013 (oral presentation).

Aherne, J., Johnson, J, Farrell, T. and Bowman, J., 2014. Acidification and recovery: observations from EMEP and ICP sites in Ireland. Paper presented at the 22nd ICP-IM Task Force Meeting, Westport, Ireland, 7–9 May 2014 (oral presentation).

Aherne, J., Henry, J., Wolniewicz, M., Cummins, T., Posch, M. and Dodd, D., 2015. Exceedance of critical loads of acidity and eutrophication. Clean Air Conference, Wood Quay Venue, Dublin, 28 September 2015 (poster presentation).

Aherne, J., Cathcart, H., Cowden, P., Olmstead, E. and Wilkins, K. 2017. Moss biomonitoring in Ireland: 2015 survey. ICP Vegetation, 30th Task Force Meeting Poznan, Poland, 14–17 February 2017 (oral presentation).

Henry, J. and Aherne, J.,2013. Potential impacts of nitrogen deposition on plant diversity and soil chemistry in acid and neutral-calcareous Irish grasslands. 23rd CCE Workshop and 29th Task Force Meeting of the ICP M&M, Copenhagen, Denmark, 8–11 April 2013 (poster presentation).

Henry, J. and Aherne, J., 2013. Potential impacts of nitrogen deposition on plant diversity and soil chemistry in acid and neutral-calcareous Irish grasslands. Nitrogen Deposition and the Nature Directives, Joint Nature Conservation Committee (JNCC*)*, Peterborough, UK, 2–4 December 2013 (poster presentation).

Olmstead, E. and Aherne, J. 2015. Has heavy metal deposition in background regions responded to two decades of emissions regulations? 9th International Conference on Acid Deposition, Rochester, New York, USA, 19–23 October 2015 (poster presentation).

Wilkins, K. and Aherne, J., 2013. Influence of nitrogen deposition on species diversity in Irish oak woodlands. *Nitrogen Deposition and the Nature Directives, Joint Nature Conservation Committee (JNCC)*, Peterborough, UK, 2–4 December 2013 (poster presentation).

Wilkins, K. and Aherne, J., 2014. Setting critical loads of nutrient nitrogen for Irish oak woodlands. 24th CCE Workshop and 30th ICP M&M Task Force Meeting, Rome, Italy, 7–10 April 2014 (poster presentation).

Wilkins, K. and Aherne, J., 2015. Heavy metal and nitrogen concentration in mosses in Irish Atlantic oak woodland. 28th ICP Vegetation Workshop, Rome, Italy, 3–5 February 2015 (poster presentation).

Wilkins, K. and Aherne, J., 2015. Vegetation community change points in Irish Annex I habitats along a nitrogen deposition gradient. 25th CCE Workshop and 31st ICP M&M Task Force Meeting, Zagreb, Croatia, 20–23 April 2015 (poster presentation).

Wilkins, K. and Aherne, J., 2015. Vegetation community change points suggest that critical loads for nutrient nitrogen are too high. 9th International Conference on Acid Deposition, Rochester, New York, USA, 19–23 October 2015 (poster presentation).

Wilkins, K. and Aherne, J., 2016. Vegetation community change points suggest that critical loads for nutrient nitrogen are too high. 26th CCE Workshop and 32nd ICP M&M Task Force Meeting, Dessau, Germany, 19–22 April 2016 (poster presentation).

Wilkins, K., Cathcart, H. and Aherne, J., 2017. Biodiversity critical loads for Irish habitats: preliminary results. 33rd ICP M&M Task Force Meeting, Wallingford, UK, 4–6 April 2017 (oral presentation).

A1.4 Research Dissertations

McFarland, V., 2016. Mercury and persistent organic pollutants in remote acid sensitive Irish lake catchments. MSc Thesis. Trent University, Peterborough, ON, Canada.

Olmstead, E., 2016. *Hylocomium splendens* as a biomonitor of atmospheric nitrogen. BSc Undergraduate Thesis. Trent University, Peterborough, ON, Canada.

Wilkins K, 2014. Influence of nitrogen deposition on the vegetation community of Irish oak woodlands. MSc Thesis. Trent University, Peterborough, ON, Canada.

Appendix 2 Modelling and Mapping Critical Loads

Anthropogenic emissions of S and NO_x result in acidic deposition that can potentially acidify soils and impact vegetation. In addition, N is an essential plant nutrient that is limited in many ecosystems. Elevated N deposition can cause eutrophication, leading to changes in plant community composition and the leaching of N into the environment.

Critical loads are widely used to evaluate the potential risks of both acidification and eutrophication; a critical load represents the maximum amount of S and N deposition that does not cause harmful effects to natural ecosystems. When deposition of S and N exceeds the critical load, there is a risk of damage.

The acidifying impact of S and N deposition defines a CLF incorporating the most important biogeochemical processes that affect long-term soil acidification (CLRTAP, 2014). The function is defined by three quantities (see Figure A2.1): $CL_{max}S$, $CL_{min}N$ and $CL_{max}N$.

The eutrophying impact of N deposition can be derived from a balance of long-term sources and sinks of N ($CL_{nut}N$) or can be based on habitat-specific empirical observations of plant diversity change under N deposition ($CL_{emp}N$). $CL_{eut}N$ is the minimum of $CL_{nut}N$ and $CL_{emp}N$. Critical load data are typically reported in units of eq (equivalents) $ha^{-1}\,a^{-1}$.

At the national level, critical loads are determined for numerous ecosystems at multiple locations (from 100 to > 1000 locations) and typically summarised (and mapped) on the EMEP grid scale (see Figure 2.2). All ecosystems in an EMEP grid cell are protected if deposition stays below the minimum of all of the critical load values. However, to discard outliers, account for uncertainties in the critical load calculations and ensure that a sufficient percentage of ecosystems are protected, critical loads are set at the 5th percentile of all critical loads in an EMEP grid (protecting 95% of the ecosystem area in a grid cell).

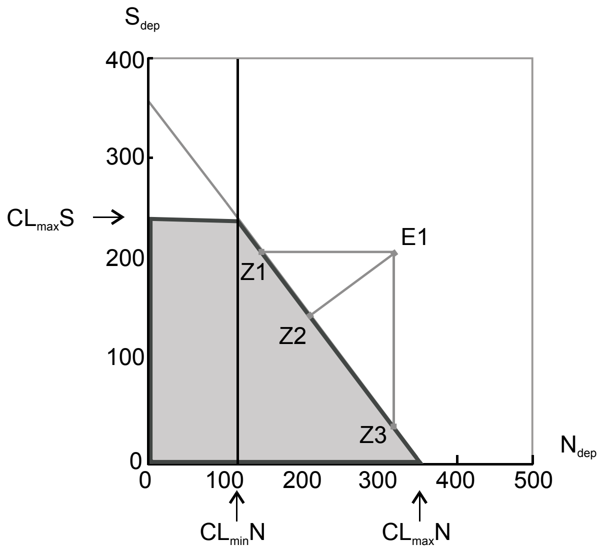

Figure A2.1. Relationship between N and S (acidic) deposition and the critical load of S and N acidity, the CLF. Deposition pairs (N_{dep}, S_{dep}) lying on the function, shown as a thick line, or below in the grey shaded area do not exceed the critical load. The point E1 denotes acidic deposition of N and S in excess of the critical load function. Reducing N_{dep}, point Z1 is reached and, therefore, non-exceedance, without reducing S_{dep}; alternatively, non-exceedance can be reached by reducing S_{dep} only (Z3); finally, with a smaller reduction of both S_{dep} and N_{dep}, non-exceedance can also be reached (Z2). Source: CLRTAP (2014).

Appendix 3 Habitat Crosswalk

Table A3.1. Habitat crosswalk showing linkages between Annex I, Fossitt and EUNIS habitat codes[a]

Annex code	Fossitt code	EUNIS code	$CL_{emp}N$ range
1130	CW2	(A2.5x)	(20–30)
1140	LS4	((A2.5))	((20–30))
1150	CW1	(A2.5x)	(20–30)
1220	CB1	–	–
1230	CS1/CS2/CS3	–	–
1310	CM1	A2.53/A2.54/A2.55	20–30
1320	CM1	A2.53/A2.54/A2.55	20–30
1330	CM1/CM2	A2.53/A2.54/A2.55	20–30
1410	CM2	(A2.5x)	(20–30)
1420	CM1	(A2.5x)	(20–30)
2110	CD1	B1.3	10–20
2120	CD2	B1.3	10–20
2130	CD3	B1.4	8–15
2140	CD3	(B1.5)	(10–20)
2150	CD3	B1.5	10–20
2160	CD4	–	–
2170	CD3/CD5	((B1.8))	((10–20))
2190	CD5	B1.8	10–20
21A0	CD6	((B1.4))	((8–15))
2270	–	G3.7	3–15
2330	–	E1.94/E1.95	8–15
3110	FL2	C1.1	3–10
3130	FL2	C1.1	3–10
3140	FL3	(C1.16)	(10–20)
3150	FL4	–	–
3160	FL1	C1.4	3–10
3180	FL6	–	–
3260	FW1/FW2	–	–
3270	FW1/FW2	–	–
4010	HH3	F4.11	10–20
4030	HH1/HH2	F4.2	10–20
4060	HH4	F2	5–15
4080	–	F2	5–15
5130	GS1/HH1/HH2/WS1	–	–
6130	GS1/GS3	–	–
6150	–	E4.3	5–10
6170	–	E4.4	5–10
6210	GS1	E1.26	15–25
6220	–	E1.3	15–25
6230	GS3	E1.7	10–15
6270	–	E1.7	10–15
6410	GS4	E3.51	15–25
6430	FS2/GM1	(E4.3)	(5–10)

Table A3.1. Continued

Annex code	Fossitt code	EUNIS code	$CL_{emp}N$ range
6510	GS2	E2.2	20–30
6520	–	E2.3	10–20
7110	PB1	D1	5–10
7120	PB1	(D1)	(5–10)
7130	PB2/PB3	D1	5–10
7140	PF3	D2	10–15
7150	PB1/PB2/PB3/PB	–	–
7210	PF1	(D4.1)	(15–30)
7220	FP1	(D4.2)	(15–25)
7230	PF1	D4.1	15–30
7240	–	D4.2	15–25
8110	ER3	((E4.3/E4.2))	((5–10))
8120	ER4	((E4.4/E4.2))	((5–10))
8210	ER2	((E4.4/E4.2))	((5–10))
8220	ER1	((E4.3/E4.2))	((5–10))
8310	EU1	–	–
9010	–	G3.A/G3.B	5–10
9020	–	G1.A	15–20
9050	–	G3.A	5–10
9110	–	G1.6	10–20
9120	–	G1.6	10–20
9130	–	G1.6	10–20
9140	–	G1.6	10–20
9150	–	G1.6	10–20
9160	–	G1.A	15–20
9170	–	G1.A	15–20
9180	–	G1.A	15–20
9190	–	G1.8	10–15
91A0	WN1	G1.8	10–15
91C0	–	G3.4	5–15
91D0	WN7	–	–
91E0	WN4	–	–
91J0	WN3	–	–
9330	–	G2.1	10–20
9340	–	G2.1	10–20
9410	–	G3.1	10–15
9530	–	G3.5	15

Where possible, equivalent habitats were taken from Fossitt (2000) and Bobbink and Hettelingh (2011). Otherwise, "comparable" habitats are given in single brackets (), or "best guess" habitats are given in double brackets (()). The recommended CLempN range is also given (in kg N ha^{-1} a^{-1}).

Appendix 4 Persistent Organic Pollutants

Table A4.1. Percentage of samples below the detection limit in the analysis of PAHs, OCPs, BDEs and PCBs

POPs	Soil (%)	Moss (%)	Sediment (%)
PAHs			
Naphthalene	0.0	11.1	0.0
Acenaphthylene	0.0	11.1	0.0
Acenaphthene	0.0	11.1	0.0
Fluorene	0.0	11.1	0.0
Phenanthrene	0.0	0.0	0.0
Anthracene	66.7	33.3	33.3
Fluoranthene	0.0	0.0	0.0
Pyrene	0.0	44.4	11.1
Benzo(a)anthracene	0.0	77.8	11.1
Chrysene/triphenylene	0.0	22.2	0.0
Benzo(b)fluoranthene	0.0	66.7	11.1
Benzo(k)fluoranthene	0.0	0.0	0.0
Benzo(a)pyrene	66.7	77.8	66.7
Indeno(1,2,3-cd)pyrene	33.3	77.8	22.2
Dibenzo(a,h)anthracene	22.2	77.8	22.2
Benzo(g,h,i)perylene	66.7	77.8	66.7
OCPs			
1,2,4,5-TCB	0.0	44.4	33.3
1,2,3,4-TCB	0.0	66.7	0.0
QCB	0.0	55.6	44.4
HCB	0.0	11.1	0.0
Alpha-benzene hexachloride	77.8	100.0	88.9
Beta-benzene hexachloride	88.9	100.0	100.0
Gamma-benzene hexachloride	100.0	100.0	88.9
Octachlorostyrene	100.0	100.0	100.0
Heptachlor epoxide	66.7	100.0	100.0
Oxychlordane	44.4	44.4	100.0
trans-Chlordane	100.0	100.0	100.0
cis-Chlordane	100.0	100.0	100.0
trans-Nonachlor	22.2	100.0	66.7
p,p'-DDE	0.0	55.6	11.1
Dieldrin	11.1	100.0	100.0
p,p'-DDD	44.4	100.0	33.3
cis-Nonachlor	77.8	100.0	55.6
p,p'-DDT	44.4	100.0	88.9
Mirex	100.0	100.0	44.4
BDEs			
BDE-17	100.0	100.0	88.9
BDE-28	88.9	100.0	77.8
BDE-49	100.0	100.0	100.0
BDE-47	33.3	22.2	22.2
BDE-100	88.9	100.0	66.7

Table A4.1. Continued

POPs	Soil (%)	Moss (%)	Sediment (%)
BDE-99	33.3	77.8	11.1
BDE-85	100.0	100.0	100.0
BDE-154	77.8	100.0	55.6
BDE-153	100.0	100.0	88.9
BDE-183	100.0	100.0	100.0
BDE-207	100.0	100.0	100.0
BDE-206	100.0	100.0	100.0
BDE-209	100.0	100.0	100.0
PCBs			
PCB-17	100.0	100.0	100.0
PCB-18	100.0	100.0	100.0
PCB-31/28	22.2	33.3	11.1
PCB-33	55.6	66.7	33.3
PCB-44	88.9	100.0	55.6
PCB-49	66.7	100.0	22.2
PCB-52	0.0	22.2	0.0
PCB-70	66.7	88.9	33.3
PCB-74	11.1	100.0	22.2
PCB-87	77.8	100.0	22.2
PCB-95	11.1	100.0	33.3
PCB-99	11.1	100.0	33.3
PCB-101	0.0	66.7	0.0
PCB-105	33.3	100.0	33.3
PCB-110	0.0	77.8	0.0
PCB-118	0.0	100.0	33.3
PCB-128	44.4	100.0	33.3
PCB-138	0.0	66.7	0.0
PCB-149	0.0	100.0	22.2
PCB-151	33.3	100.0	33.3
PCB-153/132	0.0	44.4	0.0
PCB-156	77.8	100.0	77.8
PCB-158	88.9	100.0	33.3
PCB-170	44.4	88.9	33.3
PCB-171	77.8	100.0	55.6
PCB-177	22.2	100.0	55.6
PCB-180	0.0	88.9	22.2
PCB-183	66.7	100.0	33.3
PCB-187	11.1	100.0	22.2
PCB-191	100.0	100.0	100.0
PCB-194	11.1	100.0	44.4
PCB-195	100.0	100.0	88.9
PCB-199	11.1	100.0	33.3
PCB-205	77.8	100.0	88.9
PCB-206	22.2	100.0	22.2
PCB-208	88.9	100.0	88.9
PCB-209	77.8	100.0	33.3

[a]There are nine samples per medium (soil, moss and sediment) based on triplicate samples per lake catchment (Glendalough, Lough Maumwee and Lough Veagh).

AN GHNÍOMHAIREACHT UM CHAOMHNÚ COMHSHAOIL
Tá an Ghníomhaireacht um Chaomhnú Comhshaoil (GCC) freagrach as an gcomhshaol a chaomhnú agus a fheabhsú mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ó éifeachtaí díobhálacha na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialú: *Déanaimid córais éifeachtacha rialaithe agus comhlíonta comhshaoil a chur i bhfeidhm chun torthaí maithe comhshaoil a sholáthar agus chun díriú orthu siúd nach gcloíonn leis na córais sin.*

Eolas: *Soláthraímid sonraí, faisnéis agus measúnú comhshaoil atá ar ardchaighdeán, spriocdhírithe agus tráthúil chun bonn eolais a chur faoin gcinnteoireacht ar gach leibhéal.*

Tacaíocht: *Bímid ag saothrú i gcomhar le grúpaí eile chun tacú le comhshaol atá glan, táirgiúil agus cosanta go maith, agus le hiompar a chuirfidh le comhshaol inbhuanaithe.*

Ár bhFreagrachtaí

Ceadúnú
Déanaimid na gníomhaíochtaí seo a leanas a rialú ionas nach ndéanann siad dochar do shláinte an phobail ná don chomhshaol:
- saoráidí dramhaíola *(m.sh. láithreáin líonta talún, loisceoirí, stáisiúin aistrithe dramhaíola)*;
- gníomhaíochtaí tionsclaíocha ar scála mór *(m.sh. déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta)*;
- an diantalmhaíocht *(m.sh. muca, éanlaith)*;
- úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe *(OGM)*;
- foinsí radaíochta ianúcháin *(m.sh. trealamh x-gha agus radaiteiripe, foinsí tionsclaíocha)*;
- áiseanna móra stórála peitril;
- scardadh dramhuisce;
- gníomhaíochtaí dumpála ar farraige.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil
- Clár náisiúnta iniúchtaí agus cigireachtaí a dhéanamh gach bliain ar shaoráidí a bhfuil ceadúnas ón nGníomhaireacht acu.
- Maoirseacht a dhéanamh ar fhreagrachtaí cosanta comhshaoil na n-údarás áitiúil.
- Caighdeán an uisce óil, arna sholáthar ag soláthraithe uisce phoiblí, a mhaoirsiú.
- Obair le húdaráis áitiúla agus le gníomhaireachtaí eile chun dul i ngleic le coireanna comhshaoil trí chomhordú a dhéanamh ar líonra forfheidhmiúcháin náisiúnta, trí dhíriú ar chiontóirí, agus trí mhaoirsiú a dhéanamh ar leasúchán.
- Cur i bhfeidhm rialachán ar nós na Rialachán um Dhramhthrealamh Leictreach agus Leictreonach (DTLL), um Shrian ar Shubstaintí Guaiseacha agus na Rialachán um rialú ar shubstaintí a ídíonn an ciseal ózóin.
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Uisce
- Monatóireacht agus tuairisciú a dhéanamh ar cháilíocht aibhneacha, lochanna, uiscí idirchriosacha agus cósta na hÉireann, agus screamhuiscí; leibhéil uisce agus sruthanna aibhneacha a thomhas.
- Comhordú náisiúnta agus maoirsiú a dhéanamh ar an gCreat-Treoir Uisce.
- Monatóireacht agus tuairisciú a dhéanamh ar Cháilíocht an Uisce Snámha.

Monatóireacht, Anailís agus Tuairisciú ar an gComhshaol
- Monatóireacht a dhéanamh ar cháilíocht an aeir agus Treoir an AE maidir le hAer Glan don Eoraip (CAFÉ) a chur chun feidhme.
- Tuairisciú neamhspleách le cabhrú le cinnteoireacht an rialtais náisiúnta agus na n-údarás áitiúil *(m.sh. tuairisciú tréimhsiúil ar staid Chomhshaol na hÉireann agus Tuarascálacha ar Tháscairí)*.

Rialú Astaíochtaí na nGás Ceaptha Teasa in Éirinn
- Fardail agus réamh-mheastacháin na hÉireann maidir le gáis cheaptha teasa a ullmhú.
- An Treoir maidir le Trádáil Astaíochtaí a chur chun feidhme i gcomhair breis agus 100 de na táirgeoirí dé-ocsaíde carbóin is mó in Éirinn.

Taighde agus Forbairt Comhshaoil
- Taighde comhshaoil a chistiú chun brúnna a shainaithint, bonn eolais a chur faoi bheartais, agus réitigh a sholáthar i réimsí na haeráide, an uisce agus na hinbhuanaitheachta.

Measúnacht Straitéiseach Timpeallachta
- Measúnacht a dhéanamh ar thionchar pleananna agus clár beartaithe ar an gcomhshaol in Éirinn *(m.sh. mórphleananna forbartha)*.

Cosaint Raideolaíoch
- Monatóireacht a dhéanamh ar leibhéil radaíochta, measúnacht a dhéanamh ar nochtadh mhuintir na hÉireann don radaíocht ianúcháin.
- 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 cosanta ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Faisnéis Inrochtana agus Oideachas
- Comhairle agus treoir a chur ar fáil d'earnáil na tionsclaíochta agus don phobal maidir le hábhair a bhaineann le caomhnú an chomhshaoil agus leis an gcosaint raideolaíoch.
- Faisnéis thráthúil ar an gcomhshaol ar a bhfuil fáil éasca a chur ar fáil chun rannpháirtíocht an phobail a spreagadh sa chinnteoireacht i ndáil leis an gcomhshaol *(m.sh. Timpeall an Tí, léarscáileanna radóin)*.
- Comhairle a chur ar fáil don Rialtas maidir le hábhair a bhaineann leis an tsábháilteacht raideolaíoch agus le cúrsaí práinnfhreagartha.
- Plean Náisiúnta Bainistíochta Dramhaíola Guaisí a fhorbairt chun dramhaíl ghuaiseach a chosc agus a bhainistiú.

Múscailt Feasachta agus Athrú Iompraíochta
- Feasacht chomhshaoil níos fearr a ghiniúint agus dul i bhfeidhm ar athrú iompraíochta dearfach trí thacú le gnóthais, le pobail agus le teaghlaigh a bheith níos éifeachtúla ar acmhainní.
- Tástáil le haghaidh radóin a chur chun cinn i dtithe agus in ionaid oibre, agus gníomhartha leasúcháin a spreagadh nuair is gá.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil
Tá an ghníomhaíocht á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóirí. Déantar an obair ar fud cúig cinn d'Oifigí:
- An Oifig um Inmharthanacht Comhshaoil
- An Oifig Forfheidhmithe i leith cúrsaí Comhshaoil
- An Oifig um Fianaise is Measúnú
- Oifig um Chosaint Radaíochta agus Monatóireachta Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag comhaltaí air agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

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Critical Loads and Soil-Vegetation Modelling

Climate - Water - Sustainability
Identifying pressures • Informing policy • Developing solutions

Authors: Julian Aherne, Kayla Wilkins and Hazel Cathcart

The Air Convention under the United Nations Economic Commission for Europe (UNECE) was the first international legally binding instrument to deal with the problems of air pollution on a broad regional scale. The Convention established six International Cooperative Programmes (ICPs) on Forests, Waters, Materials, Vegetation, Integrated Monitoring, and Modelling and Mapping to identify the most endangered areas, ecosystems and other receptors by considering the damage that has been caused to terrestrial and aquatic ecosystems and materials.

Identifying Pressures

Air pollution can have unacceptable impacts on the natural environment. Pollutants, such as sulfur and nitrogen oxides, can travel several hundred or even thousands of kilometres before damage, for example acidification and eutrophication, occurs. Initial efforts to reduce the extent of environmental damage led to national and international legislation aimed at controlling emissions of long-range transboundary air pollution. The work of the Air Convention has underpinned scientific research on the impacts of air pollution during the last three decades. Emphasis on a cost-effective abatement strategy, based on scientific criteria, led to the development of the critical loads concept. In simple terms, this concept indicates how much pollutant deposition an ecosystem can tolerate without undergoing unacceptable long-term damage.

Informing Policy

Critical loads are widely used as a tool for assessing the sensitivity of terrestrial and aquatic habitats; exceedance, whereby atmospheric pollutant deposition is greater than the habitat critical load, is used as an indicator of unacceptable effects. The critical loads approach underpins emissions reduction policies under UNECE's Air Convention. In addition, critical loads are widely used by European Union Member States to assess the impacts of national policies on the level of exceedance, evaluate the permitting and licensing of emissions from industrial and agricultural facilities, and support Appropriate Assessments under Article 6.3 of the Habitats Directive (92/43/EEC).

Developing Solutions

This report describes the determination of critical loads of acidity and eutrophication for terrestrial and aquatic ecosystems in Ireland. In addition, the project evaluated the potential impacts of nitrogen deposition on plant species diversity and expanded national participation in the ICPs. The project specifically responded to "calls for data" under the Air Convention. The report describes the critical load database submitted to ICP Modelling and Mapping in response to the 2015–2017 call for data, the response to ICP Vegetation under the 2015 Moss Biomonitoring Survey, and the submission of water chemistry data to ICP Waters. National critical load data have made an important contribution to the abatement of long-range transboundary air pollution; however, critical loads have been virtually ignored under national policy assessments. It is recommended that national participation in the well-established network of ICPs should be formalised and strengthened. The long-standing network provides an obvious framework for national monitoring activities, such as the requirement for ecosystem monitoring under the EU National Emission Ceilings Directive (2016/2284/EU).

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