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Nitrogen–Sulfur Critical Loads: Assessment of the Impacts of Air Pollution on Habitats

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.*

Our Responsibilities

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We regulate the following activities so that they do not endanger human health or harm the environment:

- waste facilities *(e.g. landfills, incinerators, waste transfer stations)*;
- 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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- Monitoring and reporting on Bathing Water Quality.

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- Monitoring air quality and implementing the EU Clean Air for Europe (CAFÉ) Directive.
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- 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 2021–2030

Nitrogen–Sulfur Critical Loads: Assessment of the Impacts of Air Pollution on Habitats

(2016-CCRP-MS.43)

EPA Research Report

Prepared for the Environmental Protection Agency

by

Trent University

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Front cover image: Kayla Wilkins.

DISCLAIMER

This report is based on research carried out/data from 31 March 2017 to 28 February 2021. More recent data may have become available since the research was completed.

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

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Executive Summary

It is well established that anthropogenic air pollution can have negative impacts on the natural environment, both in terms of direct effects on vegetation and indirectly through effects on the acid and nutrient status of soils and waters. The Convention on Long-range Transboundary Air Pollution (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. Scientific research under the Air Convention has shown that elevated atmospheric nitrogen deposition can result in changes to the plant communities of natural and semi-natural ecosystems, resulting in decreases in plant biodiversity.

Here we report results from the Environmental Protection Agency-funded research project 2016-CCRP-MS.43 "Nitrogen–sulfur critical loads: assessment of the impacts of air pollution on habitats". The principal objective of this project was to apply gradient modelling techniques to revise and refine empirical critical loads of nutrient nitrogen specific to Annex I habitats. Further, to improve our understanding of nitrogen deposition, we modelled deposition velocities for gaseous and particulate nitrogen species to provide a comprehensive assessment of observation-based total nitrogen deposition. The research outputs directly support international policies under the UNECE Air Convention, EU Clean Air Policy Package and Habitats Directive:

- We estimated that nitrogen deposition at Valentia Observatory during 2006–2015 was 8.3 kg N ha^{-1} y^{-1}, with a maximum deposition of 19.3 kg N ha^{-1} y^{-1} during 2009. Dry deposition made up 40% of total deposition, which was dominated by reduced species (56%), that is, wet ammonium, dry particulate ammonium and dry gaseous ammonia.
- We observed a statistically significant increase in the dry deposition of gaseous and particulate nitrogen at Valentia Observatory during 2006–2015.
- We revised and refined empirical critical loads of nutrient nitrogen for 17 Annex I habitats using gradient studies. Our analysis suggests that habitats within the Atlantic biogeographic region have critical loads at the low end or lower than existing recommended ranges for European habitats.
- Our analysis suggests that plant species in blanket bogs and heathlands are the most sensitive to total nitrogen deposition; we recommend an empirical critical load of 5 kg N ha^{-1} y^{-1}.
- Our preliminary estimates of exceedance suggest that more than 9000 km^2 of habitat receives nitrogen deposition in excess of their critical load, with more than 400 km^2 exceeded by more than 5 kg N ha^{-1} y^{-1}.

National critical load data have made an important contribution to the abatement of long-range transboundary air pollution. Therefore, we recommended that (1) there should be a wider adoption of critical loads into national policy assessments (e.g. Article 6.3 of the Habitats Directive); (2) national participation in the network of International Cooperative Programmes (ICPs) under the Air Convention should be strengthened through the obligatory National Emissions Ceiling Directive (NECD) ecosystem monitoring; (3) there should be continued development of biodiversity critical loads as recommended under the UNECE Air Convention; (4) gradient modelling techniques should be used to refine empirical critical loads of nutrient nitrogen specific to Irish habitats; and (5) the observed increasing trend in the dry deposition of gaseous and particulate nitrogen should be further investigated.

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. Since 1990, there have been significant reductions in emissions of sulfur dioxide, nitrogen oxides, non-methane volatile organic compounds and particulate matter across Europe. However, less progress has been made with atmospheric emissions of reduced nitrogen, that is, gaseous ammonia, primarily from agricultural sources. It is well established that elevated atmospheric nitrogen deposition can result in changes to the plant communities of natural and semi-natural ecosystems by shifting competitive interactions (e.g. through eutrophication) or by limiting the suitability of a habitat for some species (e.g. through acidification). Quantitative measurements of these changes include changes in species composition, increases in biomass, and decreases in biodiversity (Bobbink *et al*., 2010; de Vries *et al*., 2015).

1.2 Study Objectives and Policy Context

The principal objective of this project was to use gradient modelling techniques to revise and refine empirical critical loads of nutrient nitrogen specific to Annex I habitats. Further, to improve our understanding of nitrogen deposition, we modelled deposition velocities for gaseous and particulate nitrogen species to provide a comprehensive assessment of observation-based total nitrogen deposition. The project built upon existing critical load and habitat assessments (Aherne and Farrell, 2000; Aherne *et al*., 2014, 2017, 2020), incorporating new methodologies and datasets where appropriate. The outputs have directly contributed to the broader development and application of national critical loads, for example to support the National Parks & Wildlife Service (NPWS) in reporting under Article 17 of the European Union (EU) Habitats Directive (92/43/EEC). Project outputs have been presented at international workshops (see Appendix 1), submitted to data calls from International Cooperative Programmes (ICPs) under the Air Convention (see Appendix 1), and the associated databases have been submitted to the Environmental Protection Agency (EPA).

The specific project objectives were to:

- apply a deposition velocity model to assess the magnitude and trend of long-term atmospheric dry deposition of gases and particles and wet deposition of sulfur and nitrogen pollutants at Valentia Observatory during 2006–2015 (Chapter 2);
- apply gradient modelling techniques to revise and refine empirical critical loads of nutrient nitrogen specific to Annex I habitats (Chapter 3).

The project outputs directly support national obligations under the United Nations Economic Commission for Europe (UNECE) Air Convention, the EU National Emissions Ceiling Directive (NECD) and the EU Habitats Directive.

2 Modelling the Atmospheric Deposition of Gases and Particles

Dry deposition refers to the transfer of atmospheric gases and particles to the Earth's surface. Along with wet deposition, it is an important component in determining the total deposition of an atmospheric pollutant to an ecosystem. Wet deposition is readily measured through precipitation collection (e.g. Aherne *et al*., 2014); dry deposition is more challenging owing to the complexity of the processes involved, which depend on land cover and climatic conditions (Wesely and Hicks, 2000; Pryor *et al*., 2008; CLRTAP, 2014). One key variable in determining dry deposition is the deposition velocity (V_d), that is, the rate of gas or particle transfer from the atmosphere.

Determining V_d for a particular land cover is complicated by the heterogeneity of terrestrial ecosystems. Different plant species and foliage types have been found to have different particle capture efficiencies (Beckett *et al*., 2000; Freer-Smith *et al*., 2005). Numerous models have been developed to estimate V_d; however, their output can differ greatly (Ruijrok *et al*., 1995; Hicks *et al*., 2016; Saylor *et al*., 2019), and a small change in V_d can result in a large difference in dry deposition (Saylor *et al*., 2019). This can have important implications for setting ecological thresholds or critical loads (see, for example, Wilkins and Aherne, 2015; Wilkins *et al*., 2016; Hettelingh *et al*., 2017; Aherne *et al*., 2020). Nonetheless, dry deposition models play a central role in assessing the impact of atmospheric pollutant deposition to sensitive habitats, for example in support of the UNECE Air Convention (Gothenburg Protocol) or under Article 17 reporting of the EU Habitats Directive (92/43/EEC).

Numerous studies have estimated dry deposition using literature-based V_d (e.g. Staelens *et al*., 2012; Henry and Aherne, 2014); these are generalised values assigned to each land cover (e.g. coniferous forest, grassland or water). However, literature-based V_d may not be transferable between regions and they fail to capture the spatial or temporal differences in meteorology.

The objective of this study was to assess the temporal and spatial variability of V_d for atmospheric pollutants at synoptic weather stations and, along with measured air concentrations and wet deposition, to assess the temporal changes in total deposition of nitrogen and sulfur at Valentia Observatory. We employed the widely used big-leaf model developed by Zhang *et al*. (2001; revised 2003), which requires hourly meteorology, to determine V_d for 31 different gaseous species and three particulate matter (PM) size classes ($<2.5\,\mu m$, $2.5–10\,\mu m$, $>10\,\mu m$). We modelled V_d to 12 different land covers during two year-long periods (1999–2000 and 2013–2014) associated with short-term ammonia monitoring networks and for a 10-year period (2006–2015) at Valentia Observatory, which monitors air and precipitation chemistry under the UNECE Air Convention.

2.1 Big-leaf Model Input Parameters

The big-leaf model was selected because of its performance against observed data and its widespread use (Zhang *et al*., 2009; de Vos and Zhang, 2012). The model requires nine meteorological inputs, primarily hourly observations from meteorological stations (Table 2.1). Twenty-three synoptic weather stations (https://www.met.ie) offered complete (or nearly complete) meteorological data for the 2013–2014 period, and a subset of 10 sites for the 1999–2000 period (Figure 2.1). We estimated V_d at each station for 12 land cover types to evaluate the influence of land cover under equivalent meteorological conditions.

Hourly grass temperature was used to represent surface temperature. Where grass temperature was unavailable, an offset pattern was used by applying the average relative distance from air temperature (by date and time), based on the sites with both air and grass temperature measurements. Hourly windspeed was measured at a height of 10 m above ground and reported in knots (converted to $m\,s^{-1}$). Hourly relative humidity was reported as a percentage and converted to fraction. Sea level surface pressure (hPa) was converted to atmospheric surface pressure (mbar) using site elevation. Precipitation (mm) and air temperature (K) were directly used in the model.

Table 2.1. Hourly meteorological input parameters required by the big-leaf deposition velocity model and their sources

Variable	Unit	Source
Temperature at Z2[a]	K	Met Éireann
Surface temperature[b]	K	Met Éireann (or estimated)
Windspeed at Z2	$m\,s^{-1}$	Met Éireann
Relative humidity	fraction	Met Éireann
Solar irradiance	$W\,m^{-2}$	Met Éireann (estimated)
Precipitation	mm	Met Éireann
Surface pressure	mbar	Met Éireann
Cloud cover	fraction	Met Éireann (or NCAR RDA satellite estimate)
Snow depth	mm	Set to 0

[a]Z2 refers to measurement height of the observation (10 m above ground).

[b]Grass temperature was used to represent surface temperature.

NCAR RDA, National Centre for Atmospheric Research, Research Data Archive.

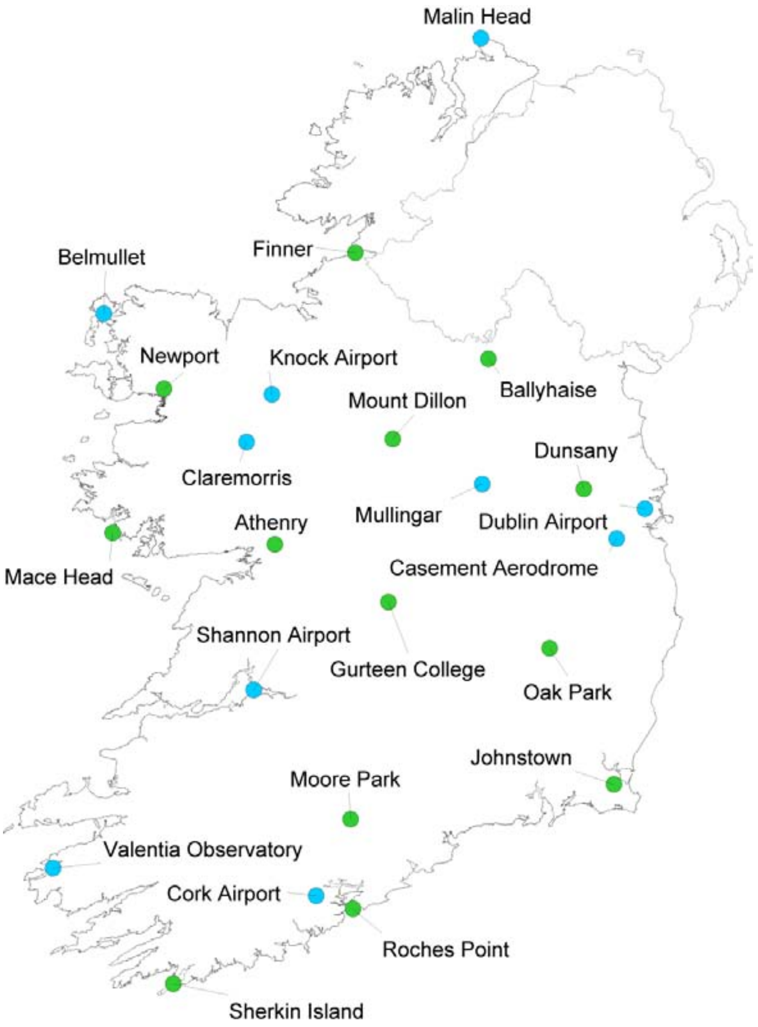

Figure 2.1. Location of synoptic weather stations (https://www.met.ie) with meteorological data required by the big-leaf deposition velocity model (Zhang *et al.*, 2003); the blue-filled circles indicate stations with data for 1999–2000 and 2013–2014 (*n* = 10) and green-filled circles indicate stations with data for 2013–2014 only (*n* = 13).

Hourly solar irradiance ($W m^{-2}$) was estimated using the “fCompl” function in the “solaR” R package (Perpiñán, 2012), which requires daily global radiation (converted from $J cm^{-2}$ to $Wh m^{-2}$) and daily average temperature. Where daily global radiation was unavailable, it was estimated from daily sunshine duration using the “ap” function in the “sirad” R package (Bojanowski, 2016). The function requires the Ångström–Prescott coefficients for the study location; we used $A=0.21$ and $B=0.67$ based on McEntee (1980) and following Goodale *et al.* (1998). Alternatively, daily solar irradiance was estimated from daily maximum and minimum temperature using the “mh” function in the “sirad” R package. Hourly solar irradiance at Dublin Airport was estimated using each of these three approaches. The results of the sunshine duration method and minimum and maximum daily temperature method were both strongly correlated with the results of method that used daily global radiation ($r=0.98$ and 0.94, respectively).

Cloud fraction was reported in octas (divided by 8 to get a 0−1 fraction). Where cloud fraction was unavailable, National Centre for Atmospheric Research, Research Data Archive (NCAR RDA) satellite estimates of cloud fraction (reported in per cent) were used (Saha *et al*., 2010 and 2011 for 1999−2000 and 2013−2014, respectively). The snow depth was set to 0 mm year-round, as snow is generally rare in Ireland and does not usually accumulate.

2.2 Spatial and Temporal Variation in Deposition Velocity

At each station, V_d for 31 gaseous species and three PM size classes was estimated, but data analysis was primarily limited to nitrogen and sulfur species. Spatial variation in V_d was evaluated using relative standard deviation (RSD) between stations for each land cover category. Temporal variation in seasonal and monthly V_d was evaluated for selected land covers. The significant difference in V_d for sulfur dioxide (SO_2) and ammonia (NH_3) between 1999–2000 and 2013–2014 was tested using a Mann–Whitney *U*-test for selected land covers.

Average annual V_d in 2013−2014 (across sites) ranged from 0.036 $cm s^{-1}$ [nitrogen dioxide (NO_2) over water and inland lakes] to 3.73 $cm s^{-1}$ [nitric acid (HNO_3) over evergreen needleleaf trees], with an overall average V_d of 0.87 $cm s^{-1}$ (Table 2.2). The land cover with the lowest V_d was water (average across sites and atmospheric pollutants), followed by crops, short grass and forbs, long grass, deciduous shrubs, swamp, evergreen broadleaf shrubs, urban, deciduous broadleaf trees, transitional forest, mixed wood forest and evergreen needleleaf trees. The atmospheric pollutant with the highest average annual V_d (averaged across all sites and land cover classes) was HNO_3 (2.36 $cm s^{-1}$), followed by NH_3 (0.87 $cm s^{-1}$) and SO_2 (0.87 $cm s^{-1}$). The spatial variation in annual average V_d across stations was approximately 20%, slightly lower for NO_2 (16%) and higher for particulate matter with a diameter generally less than 2.5 µm ($PM_{2.5}$, 27%) across all land covers (Table 2.2 and Figure 2.2). Notably, $PM_{2.5}$ was consistently variable across all land covers.

In general, for all atmospheric pollutants, the highest seasonal V_d primarily occurred during winter, except for NO_2 (Table 2.3). Across land cover categories, the highest seasonal V_d also primarily occurred during winter, except for crops and predominantly deciduous broadleaf trees and deciduous shrubs, which had summer maximums (Table 2.3). Although V_d varied throughout the year (Figure 2.3 and Table A2.1a,b), the seasonal patterns were not the same for all land covers. For example, the V_d for deciduous broadleaf trees decreased at a greater rate through the winter months, presumably due to loss of leaves.

At five stations (Belmullet, Claremorris, Knock Airport, Malin Head and Mullingar), there was a significant difference ($\alpha=0.01$ Mann–Whitney *U*-test) between the two periods (1999–2000 and 2013–2014) in the V_d of NH_3 and SO_2 to the four selected land cover types (evergreen needleleaf trees, deciduous broadleaf trees, short grass and forbs, and urban). In general, V_d was higher during 1999–2000, except at Claremorris. There was no significant difference in V_d of NH_3 or SO_2 to the four land covers modelled at Valentia Observatory. At four stations (Casement Aerodrome, Cork Airport, Dublin Airport and Shannon Airport) there were significant differences in V_d for NH_3 and SO_2 to some of the four land covers (see Table A2.2). Where significant differences occurred, 5 out of the 10 stations had higher average V_d during 1999–2000, and 3 out of the 10 had higher average V_d during 2013–2014 (see Table A2.2).

Table 2.2. Average annual V_d (cm s^{-1}) by land cover for selected gaseous species and PM size classes across 23 meteorological stations during 2013–2014. The RSD represents the spatial variation between the stations ($n = 23$) for each land cover and across land cover

Land cover code	Land cover type	Dry V_d (cm s^{-1})						RSD (%)					
		SO_2	NO_2	HNO_3	NH_3	$PM_{2.5}$	PM_{10}	SO_2	NO_2	HNO_3	NH_3	$PM_{2.5}$	PM_{10}
C	Crops	0.571	0.372	1.495	0.642	0.183	0.281	19.8	14.8	26.0	18.3	25.8	18.4
DBT	Deciduous broadleaf trees	0.821	0.422	2.984	0.907	0.300	0.514	20.5	17.4	20.5	19.3	25.7	34.2
DS	Deciduous shrubs	0.613	0.356	1.871	0.685	0.201	0.255	22.2	17.5	24.8	20.7	25.8	14.4
EBS	Evergreen broadleaf shrubs	0.789	0.382	2.365	0.882	0.240	0.344	21.9	18.3	22.4	20.5	26.1	25.8
ENT	Evergreen needleleaf trees	1.170	0.647	3.734	1.270	0.348	1.692	16.8	19.2	14.7	16.0	25.9	35.5
LG	Long grass	0.617	0.383	1.577	0.693	0.166	0.283	22.2	15.4	25.2	20.6	26.1	20.4
MWF	Mixed wood forest	1.043	0.619	3.442	1.168	0.317	0.733	19.0	18.4	16.8	17.6	25.8	35.0
S	Swamp	0.933	0.387	2.079	1.040	0.227	0.227	24.2	14.0	22.5	22.8	26.1	6.9
SGF	Short grass and forbs	0.575	0.321	1.591	0.617	0.188	0.255	24.6	18.5	25.2	23.6	26.1	14.8
TF	Transitional forest	1.039	0.612	3.442	1.159	0.317	0.733	19.0	18.6	16.8	17.7	25.8	35.0
U	Urban	0.691	0.260	3.061	0.729	0.363	0.298	17.4	14.7	20.0	16.9	25.9	13.4
W	Water	0.583	0.036	0.646	0.618	0.114	0.222	31.7	4.2	34.4	31.6	32.9	13.0
AVE	Average	0.787	0.400	2.357	0.867	0.247	0.486	21.6	15.9	22.4	20.4	26.5	22.3
MED	Median	0.740	0.382	2.222	0.805	0.233	0.290	21.2	17.5	22.5	19.9	25.9	19.4
RSD%	RSD (%)	27.1	42.5	41.1	27.5	32.5	86.8						

PM_{10}, particulate matter with a diameter generally < 10 µm.

2.3 Total Nitrogen and Sulfur Deposition at Valentia Observatory

Total (wet plus dry) nitrogen and sulfur deposition was estimated at a daily resolution during a 10-year period (1 January 2006 to 31 December 2015) for Valentia Observatory. Hourly V_d values were averaged by day and combined with daily observations of gaseous nitrogen dioxide (NO_2), nitric acid (HNO_3), ammonia (NH_3), sulfur dioxide (SO_2), particulate nitrate (pNO_3^-), ammonium (pNH_4^+), sulfate (pSO_4^{2-}) and wet precipitation chemistry. Short grass and forbs (SGF) was selected as the land cover based on site observation. Daily total deposition of nitrogen (TN) and sulfur (TS) was calculated as follows:

$$\begin{aligned} TN = & \text{ wet } (NO_3^- + NH_4^+) + ([gNO_2] \cdot V_{d\text{–}NO_2} \\ & + [pNO_3^-] \cdot V_{d\text{–}PM_{2.5}} + [gHNO_3] \cdot V_{d\text{–}HNO_3} \\ & + [gNH_3] \cdot V_{d\text{–}NH_3} + [pNH_4^+] \cdot V_{d\text{–}\,PM_{2.5}}) \end{aligned} \qquad (2.1)$$

$$\begin{aligned} TS = & \text{ wet } SO_4^{2-} + ([gSO_2] \cdot V_{d\text{–}SO2} \\ & + [pxSO_4^{2-}] \cdot V_{d\text{–}PM_{2.5}} + [pssSO_4^{2-}] \cdot V_{d\text{–}PM_{10}}) \end{aligned} \qquad (2.2)$$

$$\begin{aligned} TxS = & \text{ wet } xSO_4^{2-} + ([gSO_2] \cdot V_{d\text{–}SO_2} \\ & + [pxSO_4^{2-}] \cdot V_{d\text{–}PM_{2.5}}) \end{aligned} \qquad (2.3)$$

where g refers to gaseous species, p refers to particulate species, PM refers to particulate matter size class (with a diameter < 2.5 or < 10.0 µm), “x” refers to anthropogenic (or excess) sulfur and “ss” refers to sea salt sulfate, i.e. $[pSO_4^{2-}] - [pxSO_4^{2-}]$.

The average annual total sulfur deposition at Valentia Observatory during the 10-year modelling period was 15.0 kg S ha^{-1}, ranging from 6.8 kg S ha^{-1} (2012) to 42.1 kg S ha^{-1} (2008). The majority of total sulfur deposition was sea salt sulfate. The annual average anthropogenic sulfur deposition was 2.4 kg S ha^{-1}, ranging from 1.3 kg S ha^{-1} (2012) to 4.5 kg S ha^{-1} (2009), and was dominated (81%) by wet sulfate (SO_4^{2-}) deposition (Figure 2.4).

Average annual total nitrogen deposition was 8.3 kg N ha^{-1} during the period 2006–2015, ranging from 4.7 kg N ha^{-1} (2011) to 19.3 kg N ha^{-1} (2009). Like anthropogenic sulfur deposition, the highest

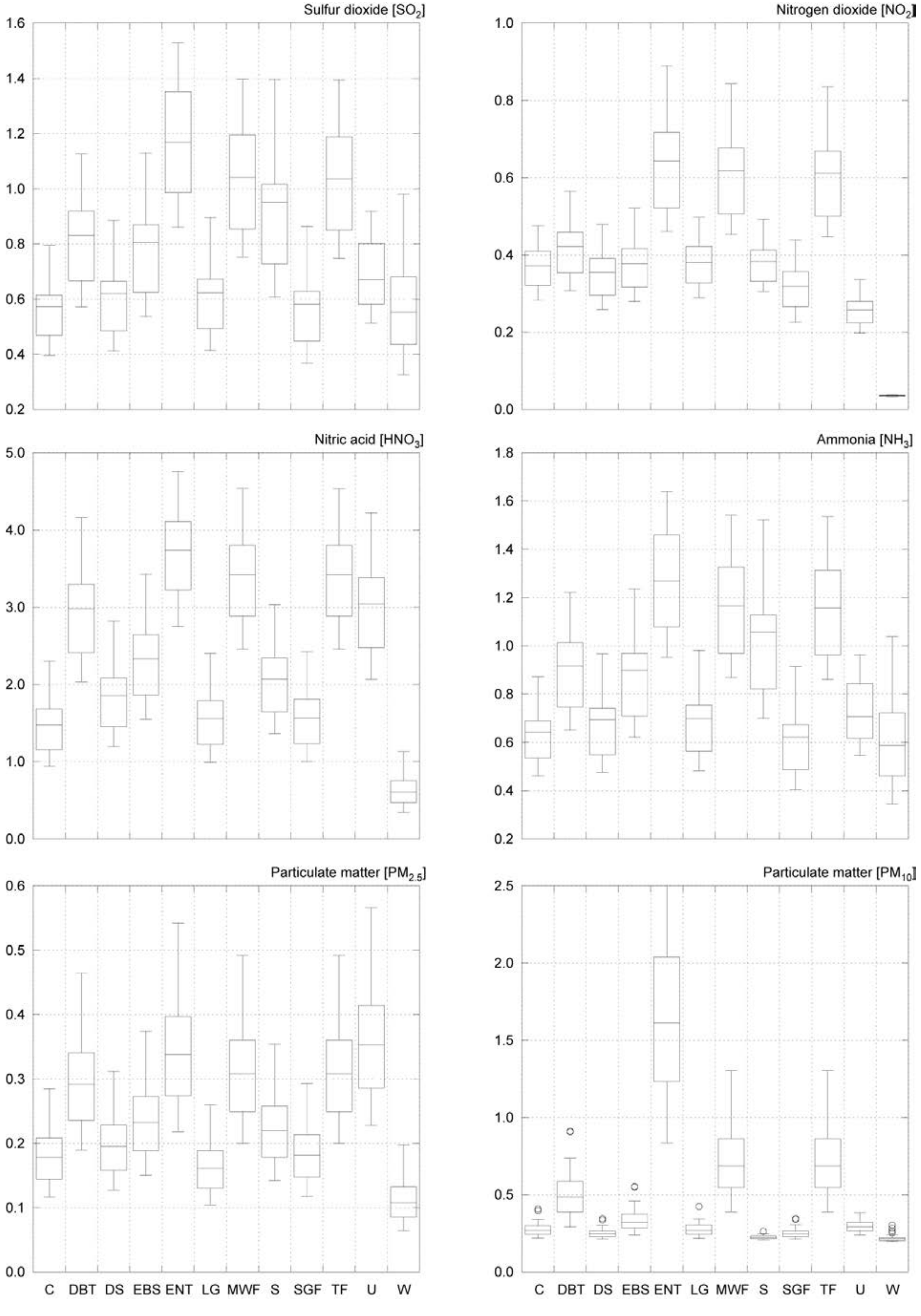

Figure 2.2. Average monthly V_d (cm s^{-1}) by land cover for selected gaseous species and PM size classes across 23 meteorological stations during 2013–2014. See Table 2.2 for definitions of the land cover abbreviations.

Table 2.3. Average seasonal (winter, spring, summer and autumn) V_d (cm s^{-1}) by land cover for selected gaseous species and particulate matter size classes across 23 meteorological stations during 2013–2014. The shading indicates the season with the highest deposition velocity for each land cover. See Table 2.2 for definitions of the land cover abbreviations

Species	Season	C	DBT	DS	EBS	ENT	LG	MWF	S	SGF	TF	U	W
SO_2	Winter	0.587	0.735	0.680	1.038	1.526	0.690	1.271	1.193	0.744	1.263	0.807	0.773
	Spring	0.522	0.791	0.590	0.751	1.122	0.516	1.045	0.912	0.550	1.035	0.619	0.566
	Summer	0.708	1.008	0.652	0.692	0.983	0.662	0.998	0.828	0.513	1.003	0.663	0.494
	Autumn	0.470	0.749	0.533	0.684	1.061	0.602	0.866	0.810	0.497	0.860	0.678	0.506
NO_2	Winter	0.307	0.333	0.333	0.380	0.782	0.344	0.630	0.363	0.353	0.619	0.226	0.037
	Spring	0.345	0.417	0.365	0.397	0.647	0.330	0.661	0.418	0.321	0.647	0.243	0.036
	Summer	0.531	0.568	0.418	0.423	0.585	0.482	0.676	0.429	0.328	0.681	0.311	0.035
	Autumn	0.301	0.368	0.309	0.327	0.580	0.375	0.512	0.338	0.283	0.504	0.259	0.035
HNO_3	Winter	1.551	2.840	1.966	2.896	4.230	1.736	3.820	2.515	1.974	3.819	3.491	0.880
	Spring	1.429	2.955	1.824	2.329	3.717	1.300	3.498	2.059	1.566	3.497	2.929	0.622
	Summer	1.779	3.389	2.050	2.120	3.508	1.651	3.409	1.891	1.431	3.412	2.915	0.536
	Autumn	1.224	2.754	1.650	2.132	3.496	1.623	3.051	1.863	1.406	3.050	2.923	0.554
NH_3	Winter	0.604	0.752	0.712	1.094	1.605	0.719	1.345	1.267	0.772	1.329	0.823	0.818
	Spring	0.579	0.879	0.669	0.857	1.239	0.566	1.198	1.037	0.595	1.180	0.650	0.601
	Summer	0.873	1.180	0.773	0.828	1.099	0.805	1.177	0.967	0.576	1.186	0.729	0.525
	Autumn	0.511	0.815	0.587	0.756	1.145	0.681	0.961	0.896	0.530	0.950	0.715	0.536
$PM_{2.5}$	Winter	0.213	0.338	0.229	0.307	0.447	0.197	0.384	0.290	0.241	0.384	0.467	0.157
	Spring	0.176	0.288	0.195	0.233	0.337	0.144	0.317	0.220	0.182	0.317	0.352	0.109
	Summer	0.188	0.308	0.202	0.208	0.301	0.159	0.298	0.197	0.163	0.298	0.314	0.093
	Autumn	0.159	0.267	0.179	0.213	0.311	0.164	0.271	0.202	0.167	0.271	0.324	0.100
PM_{10}	Winter	0.272	0.497	0.258	0.449	2.334	0.280	0.945	0.245	0.301	0.945	0.340	0.261
	Spring	0.254	0.453	0.245	0.327	1.641	0.227	0.733	0.225	0.247	0.733	0.295	0.212
	Summer	0.339	0.671	0.276	0.292	1.368	0.309	0.664	0.219	0.233	0.664	0.276	0.204
	Autumn	0.257	0.435	0.241	0.311	1.447	0.316	0.596	0.221	0.241	0.596	0.281	0.212

total deposition was observed during 2009 owing to elevated wet deposition. Further, average annual wet deposition again accounted for the majority of total nitrogen deposition, but dry deposition made up 40% of total nitrogen deposition (Figure 2.4). Reduced nitrogen species [wet ammonium (NH_4^+), NH_3 and pNH_4^+] contributed slightly more (56%) to the annual total nitrogen deposition than oxidised species [wet nitrate (NO_3^-), NO_2, HNO_3 and pNO_3^-]. Particulate deposition was the smallest contributor to total deposition (5%); however, a significant increasing temporal trend ($p < 0.05$, Mann–Kendall test) was observed in both dry deposition of particulate ($Z = 2.86$) and gaseous ($Z = 2.33$) nitrogen species during 2006–2015.

Wet deposition made up the majority of total nitrogen deposition at Valentia Observatory, followed by gaseous and then particulate deposition. Gaseous nitrogen included NO_2 and NH_3, which are predominantly from anthropogenic sources, particularly road transport and agriculture, respectively. Grouping nitrogen deposition by oxidised and reduced species reveals that reduced species made up the majority of total nitrogen deposition, consistent with other European countries (EMEP, 2018).

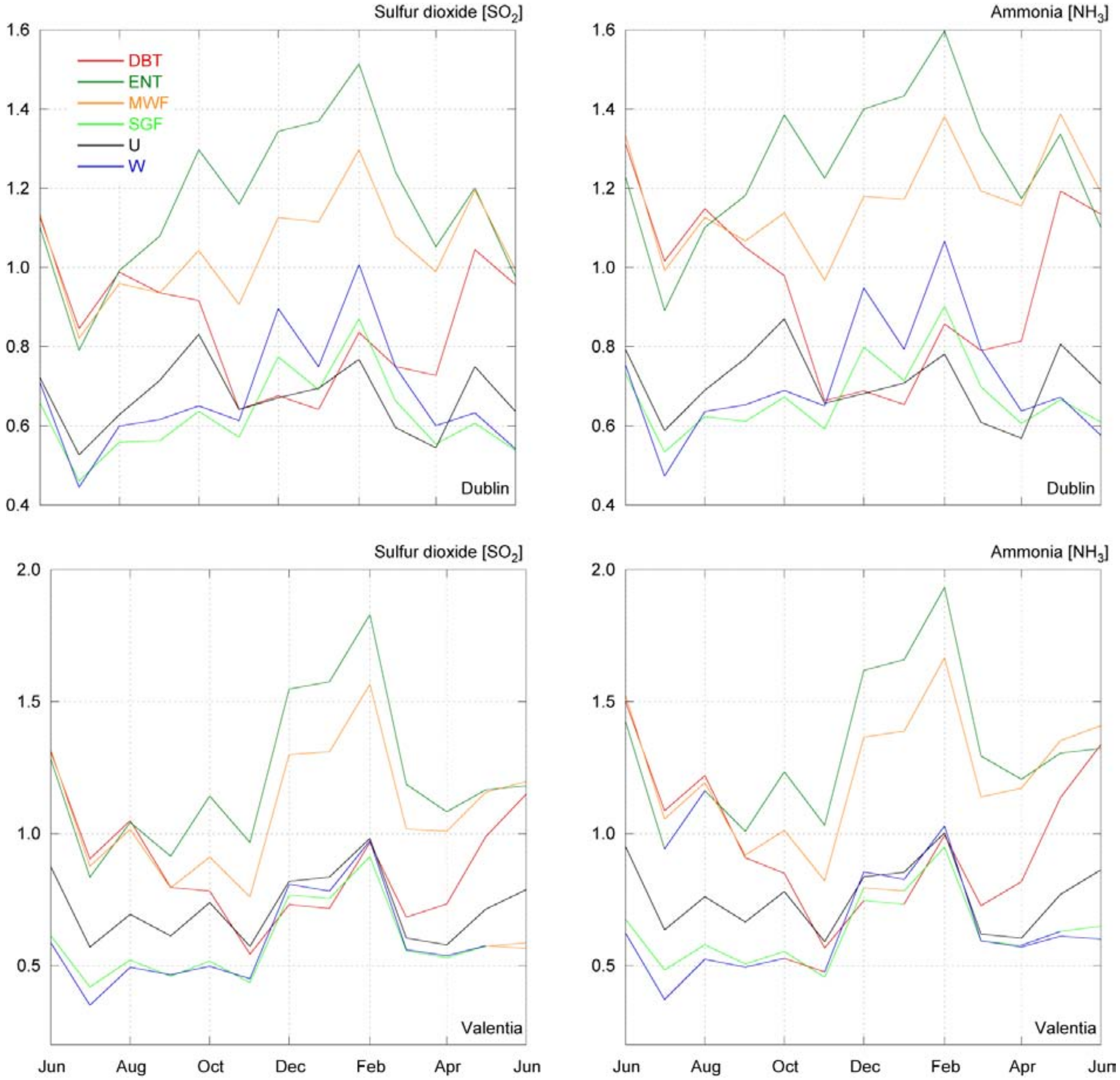

Figure 2.3. Average monthly V_d (cm s^{-1}) for sulfur dioxide (SO_2) and ammonia (NH_3) to six land cover types at Dublin Airport (top) and Valentia Observatory (bottom) during 2013–2014. DBT, deciduous broadleaf trees; ENT, evergreen needleleaf trees; MWF, mixed wood forest; SGF, short grass and forbs; U, urban; W, water.

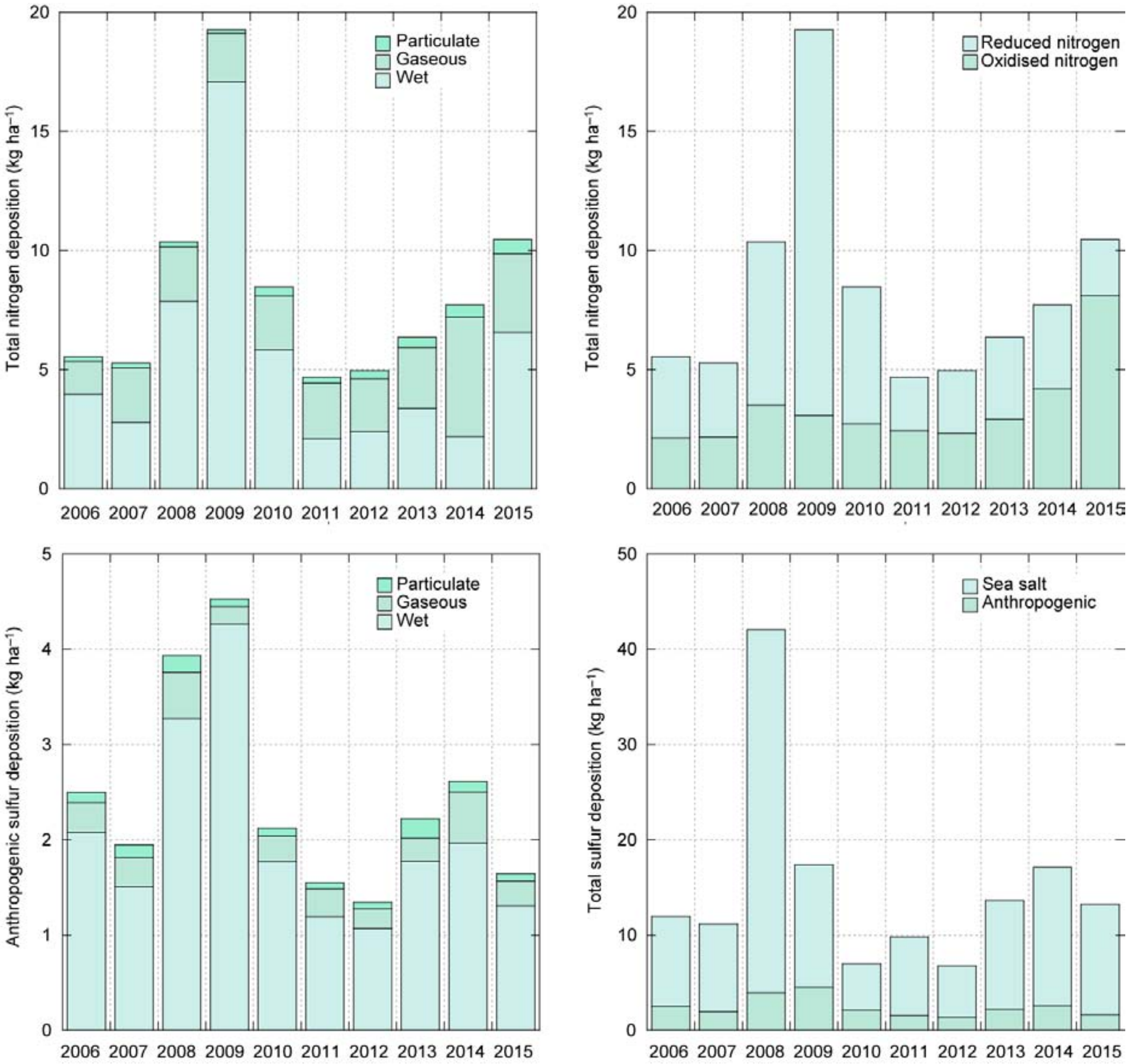

Figure 2.4. Total nitrogen and sulfur deposition at Valentia Observatory from 2006 to 2015. Top left: total nitrogen deposition grouped by wet [nitrate (NO_3^-) and ammonium (NH_4^+)], gaseous [nitrogen dioxide (NO_2), nitric acid (HNO_3) and ammonia (NH_3)] and particulate (NO_3^- and NH_4^+) species. Top right: total nitrogen deposition grouped by oxidised [wet nitrate (NO_3^-), gaseous nitrogen dioxide (NO_2) and nitric acid (HNO_3) and particulate NO_3^-] and reduced [wet ammonium (NH_4^+), gaseous ammonia (NH_3) and particulate NH_4^+] species. Bottom left: total anthropogenic sulfur deposition grouped by wet non-marine sulfate (SO_4^{2-}), gaseous sulfur dioxide (SO_2) and particulate non-marine SO_4^{2-} species. Bottom right: total sulfur deposition grouped by anthropogenic (non-marine) and sea salt (marine) species.

3 Empirical Critical Loads of Nutrient Nitrogen

It is well established that elevated atmospheric nitrogen deposition can affect the plant communities of natural and semi-natural ecosystems by shifting competitive interactions (e.g. through eutrophication) or by limiting habitat suitability (e.g. through acidification). Impacts include changes in species composition, increases in biomass and decreases in biodiversity (Bobbink *et al*., 2010).

One approach that can inform regulations to protect natural and semi-natural habitats from the harmful effects of elevated atmospheric nitrogen deposition is the assessment of habitat-specific critical loads[1] (CLRTAP, 2014). Empirical critical loads of nutrient nitrogen ($CL_{emp}N$) have been recommended for a number of habitats based on experimental nitrogen additions (Bobbink and Hettelingh, 2011). The $CL_{emp}N$ for a given habitat is generally presented as a range, which allows for variability within a habitat across its spatial extent and also accounts for methodological uncertainty.

During the last decade, gradient approaches[2] have been used to assess the influence of nitrogen deposition on plant species diversity (e.g. Aherne *et al*., 2017, 2020); these studies can potentially be used to revise and refine the recommended $CL_{emp}N$ with respect to habitats in the Atlantic region. National interest in air pollution effects on semi-natural habitats is driven, at least in part, by the requirement of EU Member States to maintain habitats of conservation importance in a “favourable state” under the Habitats Directive (92/43/EEC).

In this study, we used two gradient approaches to assess the influence of nitrogen deposition on plant species diversity in Annex I habitats. Our objective was to revise the recommended $CL_{emp}N$ to support the assessment of habitat conservation status under Article 17 of the Habitats Directive. The approach considered positive indicator species for each habitat, an important criterion for assessing habitat quality (Rowe *et al*., 2016).

3.1 Plant Species in Annex I Habitats

Vegetation survey data (species abundances) were obtained from the NPWS for 17 habitats or habitat groups (Table 3.1). Relevé data were obtained from several surveys and grouped by Annex I classification. In addition, soil data (i.e. nitrogen and carbon content) were available for a subset of the relevés (Table 3.1). The relevés were further refined to better represent uniform vegetation communities for each habitat; for example, only relevés at an altitude greater than 150 m were included in habitat 7130, (upland) blanket bog, and, similarly, only relevés on acid parent material were included in habitat 6230, (non-calcareous) species-rich *Nardus* upland grassland (see Table 3.1). However, no refinements were applied to habitat 5130 (which is composed of five vegetation communities) owing to the limited number of relevés (per vegetation community). The dominant vegetation community for habitat 5130 was dry siliceous heath and raised bog (*Calluna vulgaris*–*Erica cinerea*); therefore, all subsequent analyses assumed all relevés were from this community. The number of relevés per habitat ranged from 32 to 1804, and the number of plant species per habitat ranged from 15 to 275; species appearing fewer than three times in the dataset were excluded (Table 3.1). 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. In general, the assessment of conservation status includes a presence–absence checklist of positive indicator species for each habitat, with the identification (presence) of a specific number

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[1] A critical load is defined as “a quantitative estimate of an 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).

[2] All plant species occur in a limited range, and within their range they tend to be most abundant around their particular environmental optimum. The composition of plant communities thus changes along environmental gradients. In the current study we assessed plant species abundance along a gradient in atmospheric nitrogen deposition. There are a number of data analysis techniques that assist the interpretation of community composition in terms of species’ responses to environmental gradients (Ter Braak and Prentice, 1988).

Table 3.1. Annex I habitats (code and description), number of relevés per habitat, number of species per habitat, data sources and number of relevés per habitat with soil data

Annex I code	Description	Number per habitat: Relevé	Species	Relevés with soil data	Source
1xxx	Salt marshes (1310, 1330, 1410)	1804	65		SMMP
21xx	Sand dunes (2110, 2120, 2130, 2170, 2190, 21A0)	102	92		SDMP
4010	Northern Atlantic wet heaths with *Erica tetralix*	231	131	55	NSUH
4030	European dry heaths	164	123	56	NSUH
4060	Alpine and boreal heaths	97	89	48	NSUH
5130	*Juniperus communis* formations on heaths or calcareous grasslands	181	142		NJS[a]
6210	Semi-natural dry grasslands and scrubland facies on calcareous substrates (*Festuco–Brometalia*)	507	275	68	ISGS
6230	Species-rich *Nardus* grasslands, on silicious substrates in mountain areas (and submountain areas in continental Europe)	108[b]	156	63	ISGS
6410	Molinia meadows on calcareous, peaty or clayey-silt-laden soils (*Molinion caeruleae*)	366	182	200	ISGS
6430	Hydrophilous tall herb fringe communities of plains and of the montane to alpine levels	77[c]	172	22	ISGS (50) NSUH (27)
6510	Lowland hay meadows (*Alopecurus pratensis*, *Sanguisorba officinalis*)	125	105	30	ISGS
7110	Active raised bogs	389	15		RBS[d]
7130	Active blanket bogs	247[e]	115	50	NSUH
7230	Alkaline fens	32	96		
8220	Siliceous rocky slopes with chasmophytic vegetation	54	125		NSUH
8240	Limestone pavements	166	112		LPS
91A0	Old sessile oak woods with *Ilex* and *Blechnum* in the British Isles	319	206		NSNW

[a] **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: bryophytes were not recorded in this survey.**

[b] **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).**

[c] **There are two distinct vegetation communities for habitat 6430 in Ireland, lowland and upland; both were included but only the results for the latter are reported here.**

[d] **Only indicator species were recorded in the raised bog survey.**

[e] **Includes only relevés at elevation > 150 m.**

ISGS, Irish Semi-natural Grassland Survey; LPS, Limestone Pavement Survey; NJS, National Juniper Survey; NSNW, National Survey of Native Woodlands; NSUH, National Survey of Upland Habitats; RBS, Raised Bogs Survey; SDMP, Sand Dune Monitoring Project; SMMP, Salt Marsh Monitoring Project.

Source: National Parks & Wildlife Service (https://www.npws.ie).

of species as one criterion for good status. For this reason, the current study focused on changes in positive indicator species.

3.2 Probability of Plant Species

The PROPS (Probability of Plant Species) model estimates the probability of occurrence of plant species as a function of nitrogen deposition, soil chemistry and climate (Reinds *et al*., 2015; Slootweg *et al*., 2015; Wamelink *et al*., 2020). The model consists of species-specific statistical response functions fitted to presence-absence data using a logistic regression technique (e.g. Ter Braak and Looman 1986). In PROPS, the effect of nitrogen on species occurrence probability was modelled using nitrogen deposition and soil carbon to nitrogen ratio (C/N) as short-term and long-term explanatory variables, respectively. Two databases were used to parameterise and validate the PROPS model: plant species occurrence for 16,000 relevés, mainly in the Netherlands, Austria, Ireland, Denmark and the UK, with associated soil measurements, and a second database with plant species occurrence in approximately 800,000 relevés in Europe (Reinds *et al*., 2015; Slootweg *et al*., 2015).

The habitat suitability index (HSI) is used as an indicator or measure of plant diversity from PROPS; it is similar to the Habitat Quality Index (Rowe *et al*., 2009), and the "biodiversity score" from Van Dobben and Wamelink (2009; see also Van Dobben *et al*., 2015). The HSI is defined as the arithmetic mean of the "normalised" probabilities of occurrence of the species of interest. For a given vegetation unit or habitat, the normalised probabilities of all desired species (i.e. positive indicator species) are computed, and the HSI is determined. A nitrogen−sulfur critical load function (CLF) can be estimated by selecting a predefined fraction of the optimal HSI, here set to 80% of the optimum[3] following Slootweg *et al*. (2015) to determine the minimum and maximum critical load of nitrogen and sulfur for a set of plants representative of a given habitat. We applied the PROPS with critical load function (PROPS-CLF) to 592 plant relevé plots with soil data representing nine Annex I habitats (Tables 3.1 and A3.1 and Figure 3.1) and were predominantly interested in the maximum nitrogen critical load (CLN_{max}) output to inform the refinement of $CL_{emp}N$; the average of site-specific CLN_{max} was used to represent the CLN_{max} for a habitat.

3.3 Threshold Indicator Taxa Analysis

The TITAN (Threshold Indicator Taxa Analysis) model detects changes in taxa distributions (e.g. plant species abundance) along an environmental gradient (e.g. nitrogen deposition); the location along the gradient where the greatest change occurs is called the "change point" (Baker and King, 2010). Evidence for community thresholds are suggested by a convergence (or synchrony) of individual taxa change points along the environmental gradient.[4] TITAN produces two change points (see Figure A3.1): one represents the species that significantly decrease in abundance along the environmental gradient (z−) and the other represents the species that significantly increase along the environmental gradient (z+).

Here, we expand and revise the work of Wilkins *et al*. (2016) by increasing the number of habitats and improving estimates of total nitrogen deposition using modelled dry deposition velocities (see Chapter 2 and Figure A3.2). Plant species abundance was assessed relative to total atmospheric nitrogen deposition; both the z− community change point and the number of positive indicator species for a given habitat that were decreasing in abundance were used in the revision of $CL_{emp}N$. Approximately 5000 relevés were assessed (Table 3.1 and Figure 3.1); however, not all results were used in the $CL_{emp}N$ revision; for example, for some habitats, positive indicator species did not decrease in abundance.

3.4 Empirical Critical Load of Nutrient Nitrogen for Annex I Habitats

We used three strands of information to refine empirical critical loads for Annex I habitats in the Atlantic biogeographic region: (1) existing recommended $CL_{emp}N$ ranges (Bobbink and Hettelingh, 2011), (2) z– community change points from TITAN, weighted towards change points showing a decrease in positive indicator species[5] and (3) the average habitat CLN_{max} from PROPS-CLF (see Figure A3.3); the last two thresholds were based only on changes in plant species diversity. Recommended $CL_{emp}N$ values are available for a number of European Nature

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[3] Although somewhat arbitrary, 80% of optimum HSI follows initial applications under the Air Convention. It is worth noting that the most widely used acidity chemical criterion for terrestrial ecosystems is the critical base cation to aluminium ratio (BC/Al_{crit}) with a selected limit of 1. The limit was derived from experimental data for Norway spruce, which showed a 20% growth reduction at $BC/Al_{crit} = 1$ under laboratory conditions.

[4] A community threshold may not be the point along a nitrogen deposition gradient where "significant harmful effects" occur but rather it is the point where there is a statistically significant shift in community composition.

[5] As previously noted, a community change point may not be the point along a nitrogen deposition gradient where "significant harmful effects" occur but rather it is the point where there is a statistically significant shift (decrease) in community composition. In the current study we gave weight to that point only if it included positive indicator species.

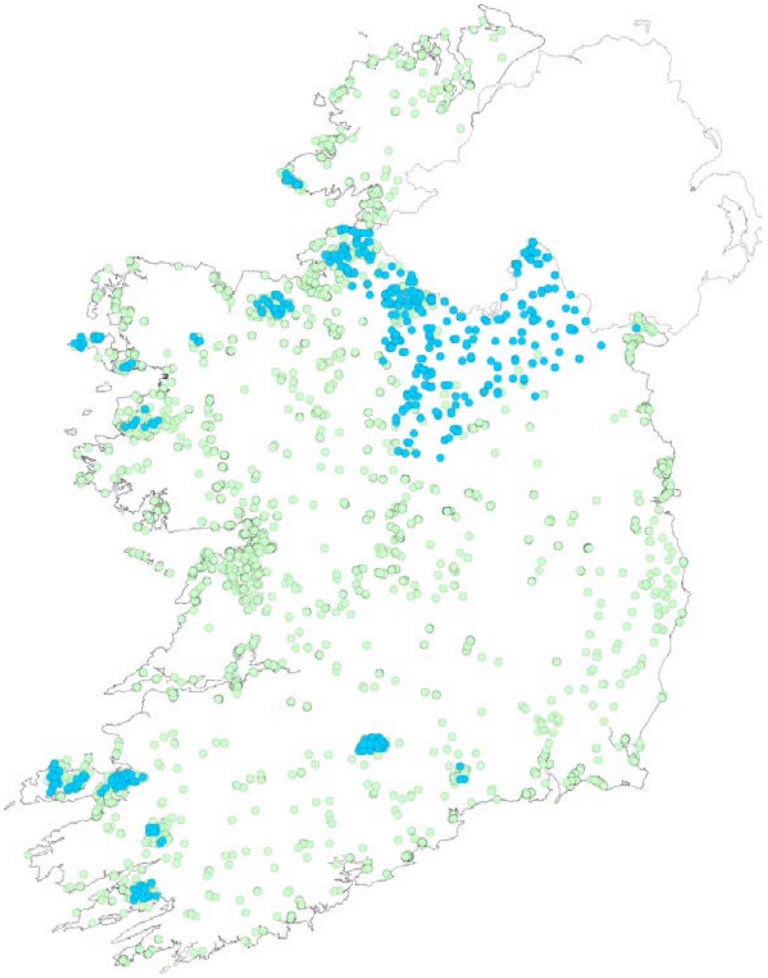

Figure 3.1. Location of plant relevé plots used in PROPS-CLF (blue-filled circles; *n* = 592) and TITAN (green-filled circles; *n* = 4969).

Information System (EUNIS) habitats (Bobbink and Hettelingh, 2011); for most habitats, there is a direct correspondence between the EUNIS and the Annex I classification systems. In this study, we were interested in the influence of nitrogen deposition on Annex I habitats and, therefore, we used the correspondence between EUNIS and Annex I to assign an existing $CL_{emp}N$ range to Annex I habitats (Table 3.2); existing $CL_{emp}N$ values were unavailable for four habitats (5130, 6430, 8220 and 8240).

CLN_{max} (PROPS-CLF) and the z– community change point (TITAN) were compared with the existing recommended $CL_{emp}N$ ranges for each habitat. The thresholds were used to revise the existing $CL_{emp}N$ range and, where possible, to suggest a single critical load within the range that would best protect the vegetation communities and biodiversity of Annex I habitats in the Atlantic biogeographic region. We refined the existing $CL_{emp}N$ by narrowing the span of the range to 5 kg or shifting the range (generally lower) based on the gradient studies. Like the methodology of the European-wide critical load system, we used ranges to represent uncertainty or variability in the $CL_{emp}N$ threshold.

Thresholds from both gradient studies were not available across all habitats; both CLN_{max} and z– community change point (with positive indicator species) were available for seven habitats (4010, 4060, 6210, 6410, 6430, 6510 and 7130), and z– only was available for eight habitats (1xxx, 21xx, 5130, 7110, 7230, 8220, 8240 and 91A0). We gave greater weighting to CLN_{max}, as PROPS-CLF is supported by a much larger database of observations[6] than the TITAN

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[6] Although PROPS-CLF is supported by a large database of observations (relevés) these data do not cover all habitats (across the full extent of the N gradient). In the current study, PROPS did not provide sensible results for habitat 91A0.

Table 3.2. Empirical critical loads of nutrient nitrogen ($CL_{emp}N$) for Annex I habitats in the Atlantic biogeographic region based on z– community change points and CLN_{max} thresholds from TITAN and PROPS-CLF (kg N ha^{-1} y^{-1}). The underline on the revised $CL_{emp}N$ range indicates the exact $CL_{emp}N$ within the recommend range; otherwise, the midpoint is recommended

Annex I code	EUNIS[a] code 2007	$CL_{emp}N$[b] ICP M&M	No. z– (No. PI)	No. z+ (No. PI)	z– CP	z+ CP	CLN_{max}	$CL_{emp}N$ ABR
1xxx[c]	A2.5x	20–30	15 (11)	8 (9)	7.8	7.5	–	5–10
21xx[d]	B1.x [N]	10–20	7 (6)	0 (0)	6.2	10.3[e]	–	5–10
4010	F4.11 [S]	10–20	11 (4)	6 (5)	4.7	6.4	4.5	5–10
4030	F4.2 [S]	10–20	17 (0)	5 (0)	5.6	7.6	6.1	5–10
4060	F2.2 [S]	5–15	15 (5)	6 (1)	5.6	5.6	2.9	5–10
5130[f]	F3.16 [S]	–	19 (16)	23 (11)	6.2	6.6	–	5–10
6210	E1.26 (E1.2) [R]	15–25	68 (7|10)[g]	33 (3|8)	6.5	8.6	12.1	5–15
6230	E1.7 (E1.71) [R]	10–15	18 (0|0)	11 (0|5)	5.1	5.5	4.5	5–15
6410	E3.51 [R]	15–25	26 (1|8)	19 (0|3)	6.8	6.7	14.8	5–15
6430	E5.5 [R]	–	20 (2)	10 (5)	5.6	8.6	12.4	5–15
6510	E2.2 [R]	20–30	8 (0|1)	11 (0|1)	6.4	10.4	11.3	5–15
7110[h]	D1.11 [Q]	5–10	4 (3)	5 (2)	6.7	10.2	–	5–10
7130	D1.22 [Q]	5–10	15 (8)	12 (6)	6.1	8.3	4.7	5–10
7230	D4.1 [Q]	15–30	5 (2)	2 (1)	5.5	6.1	–	5–10
8220	H3.1	–	2 (1)	0 (0)	5.4	6.9[e]	–	5–10
8240	H3.511	–	15 (8)	8 (4)	5.8	6.1	–	5–10
91A0	G1.83 [T]	10–15	62 (17)	8 (0)	8.1	10.1	–	10–15

[a] Parentheses indicate alternative crosswalk correspondence between Annex I and EUNIS and square brackets indicate the EUNIS 2020 code letter.

[b] Bobbink and Hettelingh (2011) as adopted by ICP M&M.

[c] Salt marshes (1310, 1330, 1410).

[d] Sand dunes (2110, 2120, 2130, 2170, 2190, 21A0).

[e] No significant community change points; z– CP set to average of species with z– change points.

[f] *Juniperus communis* formations, similar results for acidic and calcareous vegetation groups; *Juniperus communis* was one of the species that showed a decrease (z–) in abundance; bryophytes were not recorded in the survey.

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

[h] Species abundance included only 15 indicator species.

–, not determined; ABR, Atlantic biogeographic region; CP, change point; ICP, International Cooperative Programme on Modelling and Mapping; PI, positive indicator.

analysis, which was based entirely on the species abundances observed at the study sites. In general, the thresholds from PROPS or TITAN were within (or close to) the existing recommended $CL_{emp}N$ ranges for about 40% of the habitats.

The following rules were established to determine how the CLN_{max} and z– thresholds were used to revise and refine the existing $CL_{emp}N$ for a given habitat. The z− community change points were considered in the process only if positive indicator species were significantly decreasing in abundance:

- If CLN_{max} and z– thresholds were similar (4010, 4060 and 7130), then $CL_{emp}N$ was set to a 5 kg range that generally encompassed both thresholds. The revised $CL_{emp}N$ was typically at the low end or lower than the existing range.
- If CLN_{max} and z– thresholds were divergent (6210, 6410, 6430 and 6510), then $CL_{emp}N$ was set to a 10 kg range that encompassed both thresholds. In general, thresholds were below (z–) or within (CLN_{max}) the existing $CL_{emp}N$ range.
- If only CLN_{max} was available (4030 and 6230), then the threshold was used to refine or shift the

existing $CL_{emp}N$ range; for example, for habitat 4030 the existing range of 10–20 kg N ha^{-1} y^{-1} was shifted to 5–10 kg N ha^{-1} y^{-1}, with 7.5 kg N ha^{-1} y^{-1} recommended within that range. These habitats also had z– thresholds that were generally consistent with the CLN_{max} thresholds (within ≈0.5 kg N ha^{-1} y^{-1}), but they were ignored in the revision process, as positive indicator species did not decrease in abundance.

- If only z– was available, then the threshold was used to generally indicate the location of $CL_{emp}N$ within the existing range (7110 and 91A0), to revise to a new (lower) range (1xxx, 21xx and 7230) or to propose a range for habitats without existing $CL_{emp}N$ (5130, 8220 and 8240).

The average habitat CLN_{max} from PROPS-CLF ranged from 2.9 kg N ha^{-1} y^{-1} (for 4060) to 14.8 kg N ha^{-1} y^{-1} (for 6410) across the nine habitats (Table 3.2). The CLN_{max} was below the existing recommended critical load range for six habitats; the remaining three habitats had CLN_{max} thresholds close to the lower end of the existing $CL_{emp}N$ range (within 0.5 kg N ha^{-1} y^{-1}). Decreasing (z–) community change points were determined by TITAN for all 17 habitats and ranged from 4.7 to 8.1 kg N ha^{-1} y^{-1} (mean 6.1 kg N ha^{-1} y^{-1}; Table 3.2). Two habitats (4030 and 6230) were excluded because their z– community change point did not include positive indicator species. Where thresholds were available from both gradient approaches, in general they were in relative agreement with the existing recommended $CL_{emp}N$ range, that is, both gradients were generally below or within the $CL_{emp}N$ range.

The PROPS-CLF and TITAN thresholds were not expected to consistently agree, as they are based on different statistical approaches. Further, the TITAN change point analysis was based on all plant species within a habitat, whereas PROPS-CLF was based only on positive indicator species, which may have contributed to discrepancies between change points and CLN_{max} thresholds. However, divergence thresholds (> 5 kg N ha^{-1} y^{-1} differences) were observed only for grassland habitats (6210, 6410, 6439 and 6510), with z– community change points < CLN_{max}. Nonetheless, both approaches do infer an ecological threshold for a given habitat to atmospheric nitrogen deposition, and consistent results more strongly supported the revision of the $CL_{emp}N$ to a narrow range for habitats in the Atlantic biogeographic region.

Where both CLN_{max} (PROPS-CLF) and z– community change point (TITAN) thresholds were available for a given habitat, some trends did emerge. For heathland habitats (4010 and 4060) and blanket bogs (7130), the thresholds converged towards a single $CL_{emp}N$, that is, 5 kg N ha^{-1} y^{-1} both at the low end or lower than the existing recommended range for those habitats (Table 3.2). In habitats where CLN_{max} and z− thresholds were divergent (6210, 6410, 6430 and 6510), the $CL_{emp}N$ was revised to a 10 kg range that encompassed both thresholds. The width of the range represents uncertainty or variability in the threshold (i.e. the $CL_{emp}N$ range for 6230 probably represents acid to neutral grasslands), consistent with the original methodology of the $CL_{emp}N$ recommendations; however, in the current study, where possible the span of the range was reduced and sometimes shifted based on the gradient results.

Seven habitats (1xxx, 21xx, 5130, 7110, 7230, 8220 and 8240) did not have the soil C/N data required by PROPS-CLF. In general, under TITAN the majority of species showing significant decreases in abundance for these seven habitats were positive indicator species, and more positive indicator species were decreasing than increasing across the observed nitrogen deposition gradient. For salt marshes (1xxx), 11 of the 15 species with a z− change point were positive indicator species, and the z− community change point was well below the existing recommended $CL_{emp}N$ range. Although soil C/N data were available for oak woodlands (91A0), PROPS-CLF did not produce a CLN_{max} threshold, suggesting that there may not be enough background data in PROPS on Atlantic oak woodlands. In contrast, a large number of positive indicator species ($n = 7$) significantly decreased in abundance across the available nitrogen deposition gradient, and so the revised $CL_{emp}N$ was set to the low end of the existing recommended $CL_{emp}N$ range.

3.5 Exceedance of Empirical Critical Loads for Nutrient Nitrogen

The revised $CL_{emp}N$ (Table 3.2) support obliged reporting on habitat status under Article 17 of the Habitats Directive by providing biodiversity-based $CL_{emp}N$ for the determination of exceedance. $CL_{emp}N$ is a simple measure of the sensitivity of Annex I

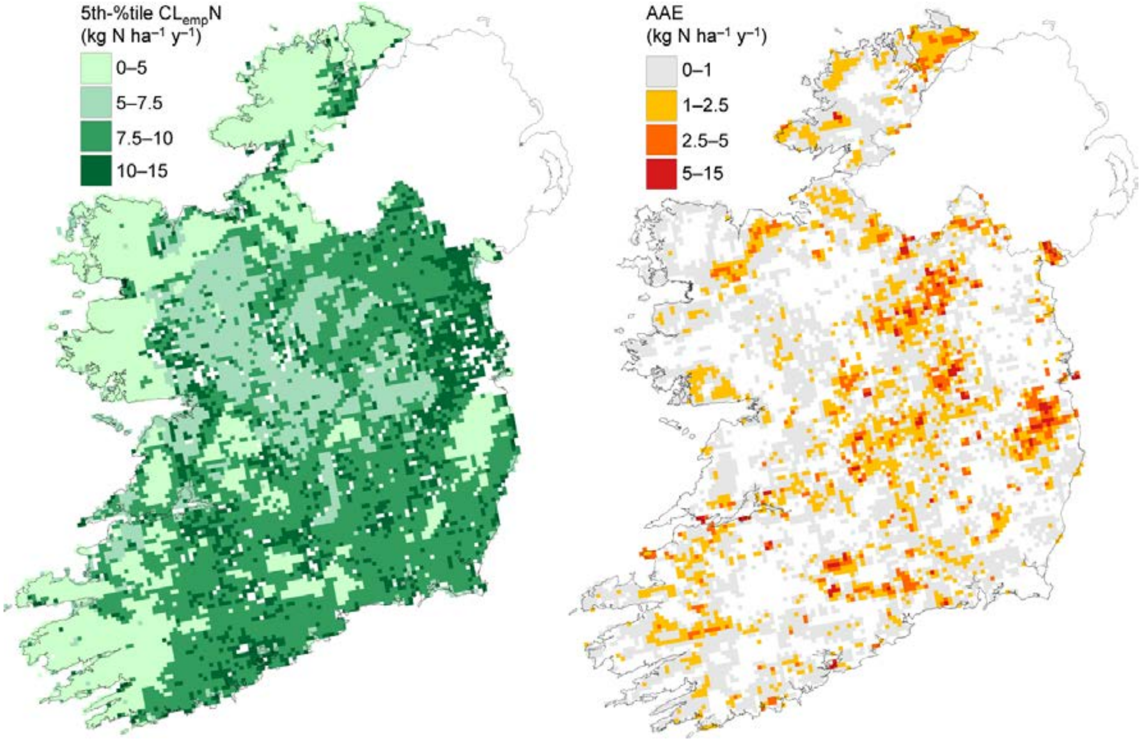

Figure 3.2. The 5th percentile of $CL_{emp}N$ set to protect habitat biodiversity (left) and average accumulated exceedance (AAE) of $CL_{emp}N$ under observation-based total nitrogen deposition (right). Critical load and exceedance were mapped on the 2.5 km² MÉRA grid.

habitats to atmospheric nitrogen deposition, whereas exceedance indicates the risk and areal extent of biodiversity loss from eutrophication. Although the mapping of critical load and determination of exceedance were beyond the scope of this report, a preliminary assessment was carried out to evaluate the potential risk of eutrophication. The $CL_{emp}N$ values for Annex I habitats (Table 3.2) were mapped to land cover categories from CORINE (Coordination of Information on the Environment) (EEA, 2018) and "receptor ecosystem" habitats from Aherne *et al*. (2017); the 5th percentile $CL_{emp}N$ for mapped habitats was presented on the Met Éireann Reanalysis (MÉRA) grid (2.5 km²). Total nitrogen deposition obtained from Aherne *et al*. (2017) and Henry and Aherne (2014) was mapped onto the MÉRA grid, and NH_3 dry deposition was updated using modelled V_d (Chapter 2; see also Figure A3.2).

The 5th percentile $CL_{emp}N$ ranged from 5 to 15 kg N ha^{-1} y^{-1} with an average of 8.6 kg N ha^{-1} y^{-1} across the mapped ecosystem area (19,122 km²; Figure 3.2). Nitrogen deposition exceeded $CL_{emp}N$ in more than 9000 km² of mapped habitat (48% of mapped area); however, the average accumulated exceedance (AAE) across the mapped area was less than 1 kg N ha^{-1} y^{-1}. Areal exceedance was dominated by a large number of habitats with low-magnitude exceedance, that is, the habitat area with exceedance >1 kg N ha^{-1} y^{-1} was 5333 km² (28% of the mapped area) and habitat area with exceedance >5 kg N ha^{-1} y^{-1} dropped to 410 km² (2% of the mapped area).

4 Conclusions

The principal objective of this project was to develop the use of gradient modelling techniques (PROPS-CLF and TITAN) to revise and refine $CL_{emp}N$ specific to Annex I habitats. Further, to improve our understanding of nitrogen deposition, we modelled deposition velocities V_d for gaseous and particulate nitrogen species to provide a comprehensive assessment of observation-based total nitrogen deposition. Project outputs have been used to support reporting under Article 17 of the EU Habitats Directive and the UNECE Air Convention. Following from this, we conclude the following.

- This is the first national study to provide a comprehensive assessment of long-term trends in total nitrogen deposition. However, the analysis was limited to Valentia Observatory, which is the only station with the required atmospheric chemistry data. We estimated that the annual average total (wet and dry) nitrogen deposition at Valentia Observatory during 2006–2015 was 8.3 kg N ha^{-1} y^{-1}, with a maximum deposition of 19.3 kg N ha^{-1} during 2009. Dry deposition made up 40% of total nitrogen deposition, compared with 19% for total anthropogenic sulfur deposition. Total nitrogen deposition was dominated by reduced species (56%), that is, wet ammonium, dry particulate ammonium and dry gaseous ammonia.
- Despite significant reductions in pollutant emissions across Europe during the past decade, we observed a statistically significant increase in the dry deposition of gaseous and particulate nitrogen at Valentia Observatory during 2006–2015.
- We revised and refined $CL_{emp}N$ for 17 Annex I habitats using gradient studies. This is the first study to use multiple gradient techniques to establish biodiversity-based empirical critical loads of nutrient nitrogen. Our analysis suggests that habitats within the Atlantic biogeographic region have critical loads at the low end or lower than existing recommended ranges for European habitats.
- Our analysis suggests that plant species in blanket bog (7130) and heathland (4010 and 4060) habitats are the most sensitive to total nitrogen deposition; we recommend a biodiversity-based $CL_{emp}N$ of 5 kg N ha^{-1} y^{-1}.
- Our preliminary estimates of exceedance suggest that more than 9000 km^2 of habitat receive nitrogen deposition in excess of biodiversity-based $CL_{emp}N$, with nitrogen deposition exceeding $CL_{emp}N$ by more than 5 kg N ha^{-1} y^{-1} on more than 400 km^2.

5 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, partially owing to 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 from this, we recommend:

- There should be wider adoption and integration of critical loads into national and international policy assessments. For example, critical loads should be used to inform (a) obliged NECD ecosystem monitoring, (b) reporting under Articles 6 and 17 of the Habitats Directive and (c) licensing under the Industrial Emissions Directive (e.g. for large-scale agricultural installations).
- National participation in the well-established network of ICPs should be formalised and strengthened. This long-standing network provides an obvious framework for national monitoring activities, such as the obliged NECD ecosystem monitoring. The network readily facilitates international co-operation, as evidenced by participation in ICP Waters. We recommended that the ICP and *European Monitoring and Evaluation Programme* (EMEP) monitoring sites become focal points to build national research capacity.
- Nitrogen impacts are considered a serious threat to biodiversity; as such, there should be continued development of biodiversity critical loads. It is certain that critical loads will continue to play an important role in European air policy strategies, especially with respect to the impacts of nitrogen deposition on plant species diversity.
- There needs to be greater understanding of the effects of nitrogen deposition to Irish habitats. Gradient modelling techniques can be used to revise and refine empirical critical loads of nutrient nitrogen specific to Irish habitats. Our analysis suggests widespread exceedance of critical loads for nutrient nitrogen. However, the analysis was limited by the lack of a national land cover (habitat) map and national maps of atmospheric nitrogen deposition.
- There is a long history of transboundary air pollutant monitoring in Ireland, as exemplified by the establishment of the precipitation chemistry network by Met Éireann during the 1950s. However, there have been few national assessments of atmospheric deposition, and there is currently only one monitoring station where total nitrogen deposition can be comprehensively assessed: Valentia Observatory. We observed an increasing trend in the dry deposition of gaseous and particulate atmospheric nitrogen at Valentia Observatory during 2006–2015; this trend requires further investigation.

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Abbreviations

AAE	Average accumulated exceedance
$CL_{emp}N$	Empirical critical load of nutrient nitrogen
CLF	Critical load function
CLN_{max}	Maximum biodiversity-related critical load of nitrogen
CORINE	Coordination of Information on the Environment
EPA	Environmental Protection Agency
EU	European Union
EUNIS	European Nature Information System
HSI	Habitat suitability index
ICP	International Cooperative Programme
MÉRA	Met Éireann Reanalysis
NECD	National Emissions Ceiling Directive
NPWS	National Parks & Wildlife Service
PM	Particulate matter
$PM_{2.5}$	Particulate matter with a diameter generally $<2.5\,\mu m$
PROPS	Probability of Plant Species
PROPS-CLF	Probability of Plant Species with critical load function
RSD	Relative standard deviation
TITAN	Threshold Indicator Taxa Analysis
UNECE	United Nations Economic Commission for Europe

Appendix 1 Project Outputs

A1.1 Peer-reviewed Publications

Olmstead, E. and Aherne, J., 2019. Are tissue concentrations of *Hylocomium splendens* a good predictor of nitrogen deposition? *Atmospheric Pollution Research* 10(1): 80–87.

Roblin, B. and Aherne, J., 2020. Moss as a biomonitor for the atmospheric deposition of anthropogenic microfibres. *Science of the Total Environment* 715: 136973.

Roblin, B., Ryan, M., Vreugdenhil, A. and Aherne, J., 2020. Ambient atmospheric deposition of anthropogenic microfibres and microplastics on the western periphery of Europe (Ireland). *Environmental Science & Technology* 54(18): 11100–11108.

Nelson, S.A.M. and Aherne, J., 2020. Decadal changes in trace metal concentrations in upland headwater lakes. *Bulletin of Environmental Contamination and Toxicology* 105: 679–684.

A1.2 Technical Reports

Aherne, J., 2017. Data call: ICP Waters. Water chemistry data for 14 lakes covering the period 2007–2016. Submission: 20 September 2017 (data).

Aherne, J., 2018. Regional acidification assessment call: ICP Waters. Water chemistry data for the 49 ‘acid’ lakes under the WFD monitoring programme for the period 2010–2017. Submission: 6 February 2018 (data).

Aherne, J., 2018. Data call: ICP Waters. Water chemistry data for 14 lakes covering the period 2016–2017. Submission: 23 November 2018 (data).

Wilkins, K., Cathcart, H. and Aherne, J., 2018. High spatio-temporal resolution dry deposition velocity mapping using the MÉRA dataset. MÉRA Workshop Proceedings. Met Éireann 2018.

Austnes, K., Aherne, J., Arle, J. *et al*., 2018. *Regional Assessment of the Current Extent of Acidification of Surface Waters in Europe and North America. ICP Waters Report 135/2018*. Norwegian Institute for Water Research, Oslo.

Aherne, J., Wilkins, K. and Cathcart, H., 2019. NPWS: Empirical critical loads of nutrient nitrogen for Annex I habitats and total nitrogen deposition. Supporting data for Article 17 reporting under Habitats Directive. Submission: 1 April 2019 (data).

Aherne, J., 2019. Lake samples: EPA. Sampling of upland Water Framework Directive lakes for EPA. Sample submission: 20 May 2019 (water samples).

Frontasyeva M., Harmens H., Uzhinskiy A., Chaligava, O. and participants of the moss survey, 2020. *Mosses As Biomonitors of Air Pollution: 2015/2016 Survey on Heavy Metals, Nitrogen and POPs in Europe and Beyond*. Report of the ICP Vegetation Moss Survey Coordination Centre, Joint Institute for Nuclear Research, Dubna, Russian Federation, 136 pp.

Aherne, J., Wilkins, K. and Cathcart, H., Hanley, O. and McEntagart, J., 2020. Country Report: Ireland. In Frontasyeva M., Harmens, H. *et al*. (eds), *Mosses As Biomonitors of Air Pollution: 2015/2016 Survey on Heavy Metals, Nitrogen and POPs in Europe and Beyond.* Report of the ICP Vegetation Moss Survey Coordination Centre, Joint Institute for Nuclear Research, Dubna, Russian Federation, 136 pp. ISBN 978-5-9530-0508-1.

Aherne, J., 2020. Call for Data on Critical Loads: ICP M&M. Review of Empirical Critical Loads and Steady-State Critical Loads 2019–2021. Submission: 20 April 2020 (report).

A1.3 Conferences and Workshops

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

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

Moldan, F. and Aherne, J., 2017. Ecosystem effects of sulphur and nitrogen deposition in the future. 50 Years of Acid Rain Research and Control, The Royal Swedish Academy of Forestry and Agriculture, Stockholm, Sweden, 6–7 November 2017 (oral presentation).

Cathcart, H., Wilkins, K. and Aherne, J., 2018. High spatio-temporal resolution maps of atmospheric dry deposition velocities using the MÉRA dataset. MÉRA Workshop, Met Eireann, Dublin, Ireland, 17 May 2018 (oral presentation).

Roblin, B. and Aherne, J., 2018. Atmospheric deposition of microplastics into remote lake catchments. Microplastics2018, Ascona, Switzerland, 28–31 October 2018 (oral presentation).

Roblin, B. and Aherne, J., 2018. The use of moss (*Hylocomium splendens*) as a biomonitor for microplastics. Microplastics2018, Ascona, Switzerland, 28–31 October 2018 (poster presentation).

Posch, M. and Aherne, J., 2018. Past, present and future of critical loads ‒ European perspective. 40 Years of Monitoring Atmospheric Deposition: Historical Legacy and Looking Ahead to the Future, NADP Scientific Symposium, Albany, United States, 5–9 November 2018 (oral presentation).

Nelson, S., Aherne, J. and Hintelmann, H., 2018. A decadal increase in mercury in upland Irish lakes. NADP Scientific Symposium, Albany, NY, 5–9 November 2018 (oral presentation).

Roblin, B. and Aherne, J., 2018. Atmospheric deposition of microfibers. NADP Scientific Symposium, Albany, NY, 5–9 November 2018 (oral presentation).

Aherne, J., 2019. Critical loads, nitrogen deposition, and SCAIL. SCAIL Agriculture, Hibernian Hotel, Main Street, Mallow, Ireland, 13 February 2019 (oral presentation).

Aherne, J. and Roblin, B., 2019. 32nd ICP Vegetation Task Force meeting, Valahia University of Targoviste, Romania, 18–21 February 2019 (oral presentation).

Aherne, J., 2019. Reinvent the wheel? Ecosystem Monitoring under the NEC Directive, New Forest Estate, Tyrrellspass, Westmeath, Ireland, 21 May 2019 (oral presentation).

Aherne, J., Roblin, B. and Nelson, S., 2019. Atmospheric transport of microplastics to lake catchments. 35th ICP Waters Task Force Meeting jointly with ICP IM, Helsinki, Finland 4–6 June 2019 (oral presentation).

Aherne, J., Wilkins, K. and Cathcart, H., 2020. Irish contribution to the review of empirical critical loads for nitrogen. 36th Task Force Meeting and 27th CCE Workshop, Microsoft Teams, 21–23 April 2020 (oral presentation).

Aherne, J., 2020. Atmospheric transport of pollutants to lake catchments. 32nd ICP Waters Task Force Meeting, Microsoft Teams, 11–12 May 2020 (oral presentation).

Aherne, J., Wilkins, K., Cathcart, H. and Bleasdale, A., 2020. Gradient studies and statistical methods in 16 Irish habitats – How we have used gradient studies to estimate empirical critical loads. Review and Revision of Empirical Critical Loads for Nitrogen, German Environment Agency (Umweltbundesamt), Dessau (online), Germany, 15–16 June 2020 (oral presentation).

Appendix 2 Modelling the Atmospheric Deposition of Gases and Particles

Table A2.1a. Average monthly V_d (cm s^{-1}) by land cover for selected gaseous species across 23 meteorological stations during 2013–2014. The shading indicates the month with the highest (grey) and lowest (green) V_d for each land cover. See Table 2.2 for definition of land cover abbreviations

Species	Month	C	DBT	DS	EBS	ENT	LG	MWF	S	SGF	TF	U	W
SO_2	1	0.534	0.639	0.597	0.942	1.434	0.601	1.174	1.061	0.661	1.167	0.762	0.667
	2	0.636	0.864	0.780	1.145	1.661	0.737	1.402	1.321	0.819	1.390	0.874	0.854
	3	0.484	0.694	0.585	0.786	1.193	0.535	1.027	0.950	0.575	1.013	0.598	0.609
	4	0.484	0.712	0.542	0.701	1.040	0.493	0.980	0.866	0.522	0.972	0.551	0.541
	5	0.598	0.968	0.644	0.766	1.134	0.520	1.129	0.919	0.552	1.122	0.709	0.548
	6	0.730	1.116	0.730	0.779	1.109	0.594	1.140	0.938	0.571	1.139	0.748	0.561
	7	0.630	0.869	0.555	0.586	0.810	0.595	0.842	0.685	0.437	0.856	0.554	0.395
	8	0.763	1.041	0.670	0.711	1.030	0.798	1.013	0.860	0.530	1.014	0.688	0.526
	9	0.599	0.894	0.585	0.688	1.032	0.699	0.894	0.830	0.507	0.891	0.704	0.519
	10	0.446	0.832	0.590	0.768	1.204	0.644	0.963	0.891	0.549	0.957	0.785	0.544
	11	0.364	0.520	0.423	0.595	0.947	0.464	0.741	0.710	0.436	0.733	0.544	0.454
	12	0.589	0.702	0.664	1.028	1.481	0.732	1.238	1.197	0.753	1.232	0.784	0.799
NO_2	1	0.283	0.298	0.296	0.340	0.717	0.308	0.573	0.330	0.319	0.563	0.212	0.036
	2	0.326	0.367	0.375	0.423	0.855	0.365	0.696	0.407	0.381	0.679	0.237	0.037
	3	0.291	0.341	0.338	0.368	0.668	0.317	0.608	0.384	0.313	0.590	0.207	0.036
	4	0.331	0.396	0.351	0.397	0.616	0.330	0.647	0.419	0.319	0.636	0.226	0.035
	5	0.413	0.514	0.406	0.427	0.657	0.343	0.727	0.451	0.332	0.717	0.295	0.036
	6	0.532	0.619	0.466	0.460	0.661	0.407	0.765	0.476	0.353	0.762	0.338	0.036
	7	0.503	0.510	0.364	0.384	0.485	0.460	0.584	0.376	0.297	0.600	0.274	0.034
	8	0.558	0.577	0.426	0.424	0.609	0.579	0.679	0.435	0.334	0.681	0.320	0.036
	9	0.410	0.466	0.358	0.373	0.596	0.474	0.574	0.387	0.306	0.569	0.302	0.035
	10	0.269	0.384	0.329	0.353	0.640	0.389	0.546	0.364	0.306	0.538	0.282	0.036
	11	0.225	0.254	0.241	0.256	0.504	0.263	0.415	0.264	0.237	0.404	0.195	0.034
	12	0.312	0.332	0.328	0.378	0.774	0.361	0.623	0.352	0.358	0.615	0.231	0.037
HNO_3	1	1.355	2.449	1.698	2.623	3.932	1.464	3.520	2.258	1.750	3.519	3.189	0.751
	2	1.708	3.260	2.245	3.117	4.470	1.823	4.066	2.722	2.152	4.064	3.740	0.976
	3	1.336	2.780	1.814	2.452	3.813	1.368	3.472	2.145	1.642	3.470	2.905	0.676
	4	1.346	2.762	1.687	2.206	3.613	1.245	3.392	1.976	1.497	3.391	2.747	0.591
	5	1.606	3.325	1.972	2.330	3.727	1.288	3.630	2.058	1.557	3.630	3.134	0.600
	6	1.857	3.630	2.227	2.355	3.770	1.495	3.711	2.095	1.595	3.712	3.206	0.614
	7	1.531	2.972	1.798	1.784	3.058	1.453	2.982	1.604	1.206	2.987	2.442	0.423
	8	1.949	3.566	2.124	2.221	3.695	2.005	3.536	1.975	1.492	3.537	3.099	0.571
	9	1.608	3.186	1.853	2.173	3.579	1.847	3.199	1.918	1.447	3.200	3.068	0.569
	10	1.130	3.003	1.796	2.308	3.732	1.713	3.243	2.001	1.516	3.242	3.255	0.595
	11	0.934	2.074	1.301	1.915	3.178	1.309	2.711	1.671	1.256	2.709	2.447	0.499
	12	1.591	2.810	1.955	2.949	4.288	1.922	3.875	2.566	2.018	3.874	3.542	0.912

Table A2.1b. Average monthly V_d (cm s^{-1}) by land cover for selected gaseous species and particulate matter size classes across 23 meteorological stations during 2013–2014. The shading indicates the month with the highest (grey) and lowest (green) V_d for each land cover. See Table 2.2 for definition of land cover abbreviations

Species	Month	C	DBT	DS	EBS	ENT	LG	MWF	S	SGF	TF	U	W
NH_3	1	0.551	0.653	0.623	0.991	1.509	0.625	1.240	1.126	0.685	1.226	0.778	0.705
	2	0.656	0.889	0.824	1.214	1.759	0.770	1.495	1.414	0.851	1.472	0.893	0.904
	3	0.506	0.734	0.641	0.864	1.295	0.572	1.141	1.051	0.608	1.114	0.612	0.645
	4	0.538	0.795	0.618	0.814	1.157	0.547	1.140	0.997	0.571	1.124	0.575	0.575
	5	0.694	1.109	0.749	0.893	1.265	0.579	1.314	1.062	0.607	1.300	0.763	0.582
	6	0.885	1.299	0.865	0.925	1.242	0.686	1.340	1.094	0.637	1.339	0.821	0.596
	7	0.802	1.034	0.665	0.720	0.909	0.746	1.005	0.810	0.503	1.030	0.614	0.420
	8	0.932	1.206	0.788	0.841	1.146	0.984	1.185	0.997	0.590	1.188	0.753	0.558
	9	0.694	1.006	0.665	0.787	1.131	0.830	1.022	0.941	0.553	1.015	0.759	0.551
	10	0.463	0.896	0.645	0.844	1.296	0.719	1.061	0.982	0.584	1.050	0.825	0.576
	11	0.376	0.541	0.451	0.637	1.009	0.495	0.799	0.766	0.454	0.784	0.560	0.481
	12	0.606	0.716	0.690	1.076	1.548	0.762	1.298	1.262	0.779	1.287	0.799	0.845
$PM_{2.5}$	1	0.188	0.297	0.199	0.271	0.395	0.169	0.340	0.256	0.213	0.340	0.413	0.136
	2	0.231	0.371	0.256	0.333	0.485	0.207	0.417	0.315	0.261	0.417	0.506	0.173
	3	0.176	0.287	0.200	0.248	0.360	0.154	0.322	0.234	0.194	0.322	0.376	0.119
	4	0.169	0.274	0.187	0.224	0.326	0.139	0.308	0.212	0.175	0.308	0.340	0.103
	5	0.182	0.302	0.200	0.226	0.327	0.140	0.320	0.213	0.176	0.320	0.341	0.104
	6	0.201	0.338	0.220	0.231	0.333	0.155	0.333	0.218	0.180	0.333	0.348	0.105
	7	0.160	0.264	0.176	0.176	0.253	0.137	0.253	0.166	0.137	0.253	0.264	0.074
	8	0.203	0.322	0.210	0.218	0.316	0.184	0.307	0.206	0.170	0.307	0.330	0.099
	9	0.184	0.295	0.193	0.217	0.315	0.178	0.283	0.205	0.169	0.283	0.329	0.101
	10	0.157	0.280	0.190	0.227	0.332	0.173	0.285	0.215	0.178	0.285	0.347	0.107
	11	0.135	0.225	0.152	0.196	0.285	0.142	0.245	0.185	0.153	0.245	0.298	0.092
	12	0.219	0.346	0.232	0.316	0.460	0.214	0.396	0.299	0.248	0.396	0.481	0.163
PM_{10}	1	0.255	0.430	0.241	0.399	2.003	0.249	0.815	0.236	0.279	0.815	0.318	0.242
	2	0.283	0.553	0.275	0.484	2.598	0.276	1.046	0.252	0.316	1.046	0.358	0.271
	3	0.247	0.426	0.245	0.356	1.803	0.235	0.759	0.229	0.259	0.759	0.305	0.220
	4	0.244	0.400	0.237	0.311	1.565	0.222	0.700	0.222	0.241	0.700	0.290	0.206
	5	0.271	0.534	0.254	0.316	1.555	0.223	0.739	0.223	0.242	0.739	0.289	0.209
	6	0.329	0.748	0.290	0.317	1.599	0.243	0.777	0.224	0.243	0.777	0.292	0.207
	7	0.295	0.566	0.259	0.260	1.045	0.268	0.533	0.212	0.220	0.533	0.254	0.199
	8	0.393	0.700	0.279	0.299	1.460	0.416	0.682	0.220	0.236	0.682	0.283	0.204
	9	0.319	0.540	0.257	0.312	1.448	0.388	0.619	0.222	0.241	0.619	0.282	0.211
	10	0.229	0.424	0.241	0.319	1.580	0.300	0.621	0.224	0.244	0.621	0.291	0.210
	11	0.224	0.342	0.225	0.304	1.314	0.260	0.549	0.219	0.238	0.549	0.272	0.213
	12	0.278	0.507	0.258	0.464	2.401	0.314	0.974	0.248	0.309	0.974	0.345	0.270

Table A2.2. Comparison of significant differences (Mann–Whitney *U*-test, α = 0.01) in V_d between two time periods, 1999–2000 (T1) and 2013–2014 (T2) for four land cover types for SO_2 and NH_3. Where a significant difference occurred, the time period with the greater V_d is listed

	ENT		DBT		SGF		U	
Station	SO_2	NH_3	SO_2	NH_3	SO_2	NH_3	SO_2	NH_3
Belmullet	T1	T1	T1	T1	T1	T1	T1	T1
Casement Aerodrome	NSD	NSD	NSD	NSD	T1	T1	NSD	NSD
Claremorris	T2	T2	T2	T2	T2	T2	T2	T2
Cork Airport	T2	T2	T2	T2	NSD	NSD	T2	T2
Dublin Airport	NSD	NSD	NSD	NSD	T2	T2	NSD	NSD
Knock Airport	T1	T1	T1	T1	T1	T1	T1	T1
Malin Head	T1	T1	T1	T1	T1	T1	T1	T1
Mullingar	T1	T1	T1	T1	T1	T1	T1	T1
Shannon Airport	T2	T2	T2	T2	NSD	NSD	T2	T2
Valentia Observatory	NSD	NSD	NSD	NSD	NSD	NSD	NSD	NSD

DBT, deciduous broadleaf trees; ENT, evergreen needleleaf trees; NSD, no significant difference; SGF, short grass and forbs; U, urban.

Appendix 3 Empirical Critical Loads of Nutrient Nitrogen

Table A3.1. The PROPS-CLF model inputs and data sources for the application to Annex I habitats (*n* = 592 relevés) in the Atlantic biogeographic region (see Table 3.1)

Description	Unit	Source
C:N of soil compartment	$g\,g^{-1}$	Determined on pulverised soils using a carbon/nitrogen/sulfur analyser (samples obtained from NPWS surveys)
Annual precipitation	$m\,y^{-1}$	Long-term (1981–2010) mean annual precipitation obtained from Met Éireann
Annual average soil temperature	°C	Aherne *et al.* (2017)
Percolation at the bottom of the rooting zone	$m\,y^{-1}$	Aherne *et al.* (2017)
Exponent a (> 0) in [Al] = gibbsite equilibrium constant $KAl_{ox}.[H]^{a}$	–	Constant: 3
Log_{10} gibbsite equilibrium constant KAl_{ox}	$mol\,L^{-1}$	Aherne *et al.* (2017)
CO_2 pressure in soil solution	–	Constant: 10
Net input of base cations	$eq\,m^{-2}$	Aherne *et al.* (2017)
Net sink of nitrogen	$eq\,m^{-2}$	Constant: 0.01067
Denitrification fraction	–	Aherne *et al.* (2017)
Total concentration of organic acids	$mol\,m^{-3}$	Constant: 0

Al, aluminium; eq, equivalents.

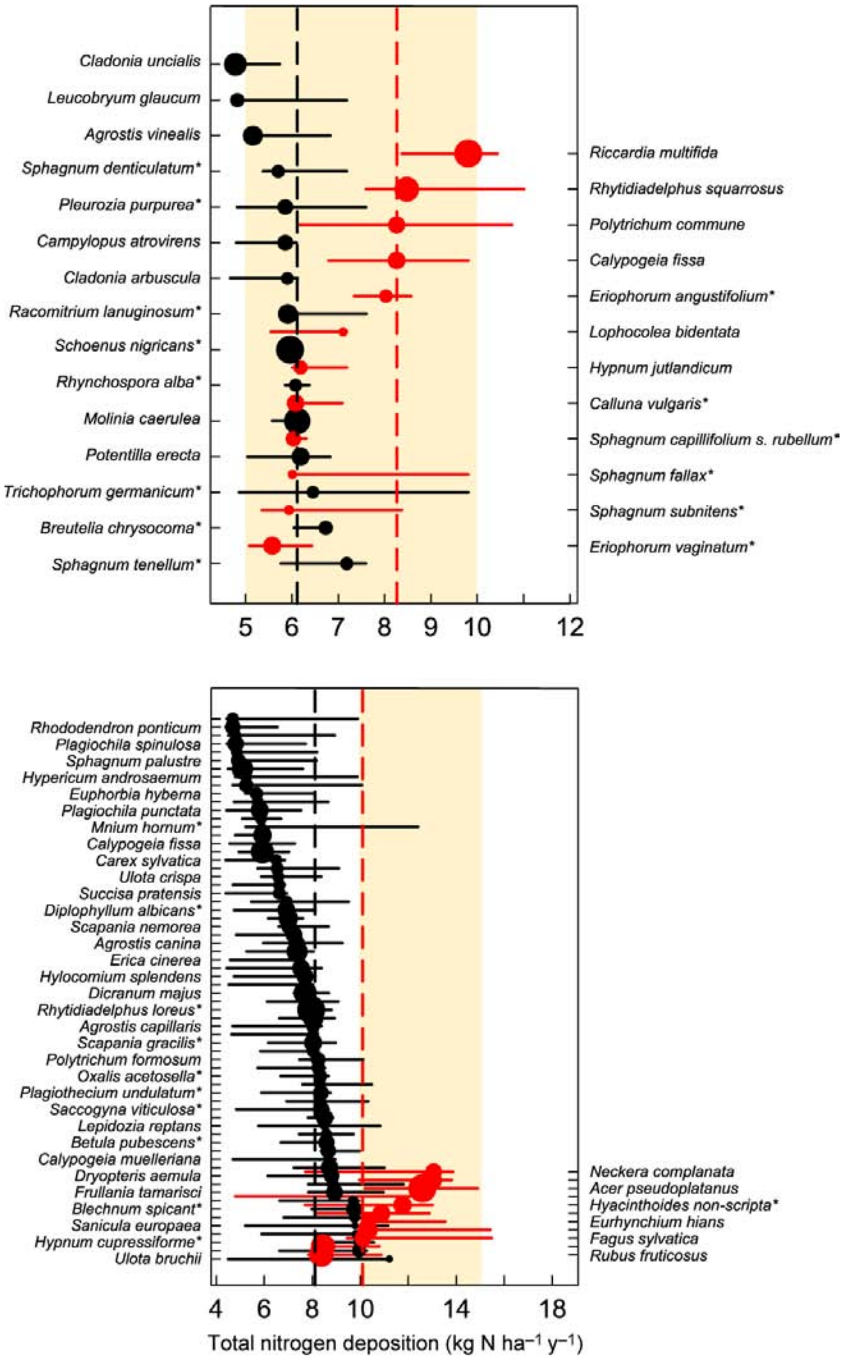

Figure A3.1. Individual species change points for species significantly changing in abundance across the nitrogen deposition gradient in two Annex I habitats [7130: blanket bogs (top) and 91A0: old sessile oak woods with *Ilex* and *Blechnum* (bottom)]. Dashed vertical lines show the community-level change points for decreasing (black) and increasing (red) species. The positive indicator species for each habitat are denoted by an asterisk. The yellow shaded area represents the range of the $CL_{emp}N$ (Bobbink and Hettelingh, 2011).

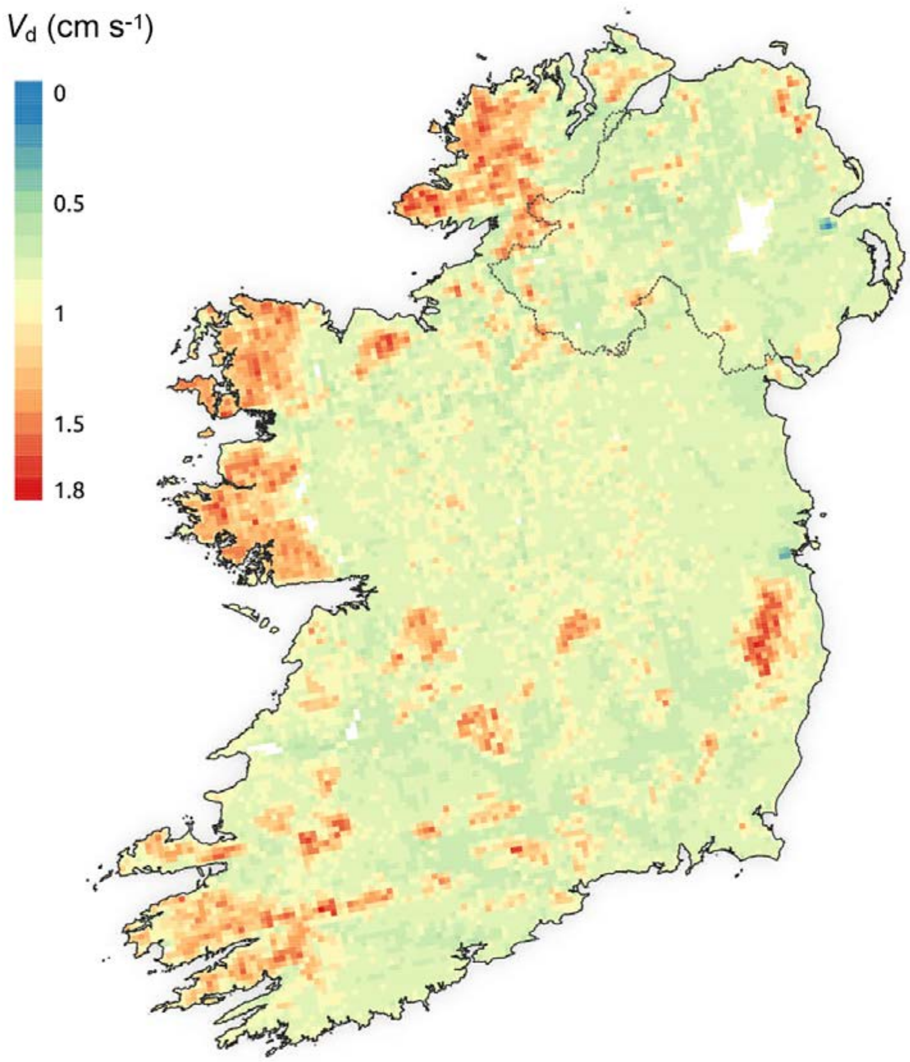

Figure A3.2. Average annual ammonia (NH_3) dry deposition velocity estimated using the big-leaf model (Zhang *et al.*, 2003) with Met Éireann Reanalysis (MÉRA) meteorological data for 2013–2014 and CORINE 2018 land cover. The MÉRA project provides downscaled 2.5 km^2 resolution meteorological data at 3-hourly timesteps (Gleeson *et al.*, 2017). Land cover proportions within each 2.5 km^2 grid were extracted from CORINE (EEA, 2018).

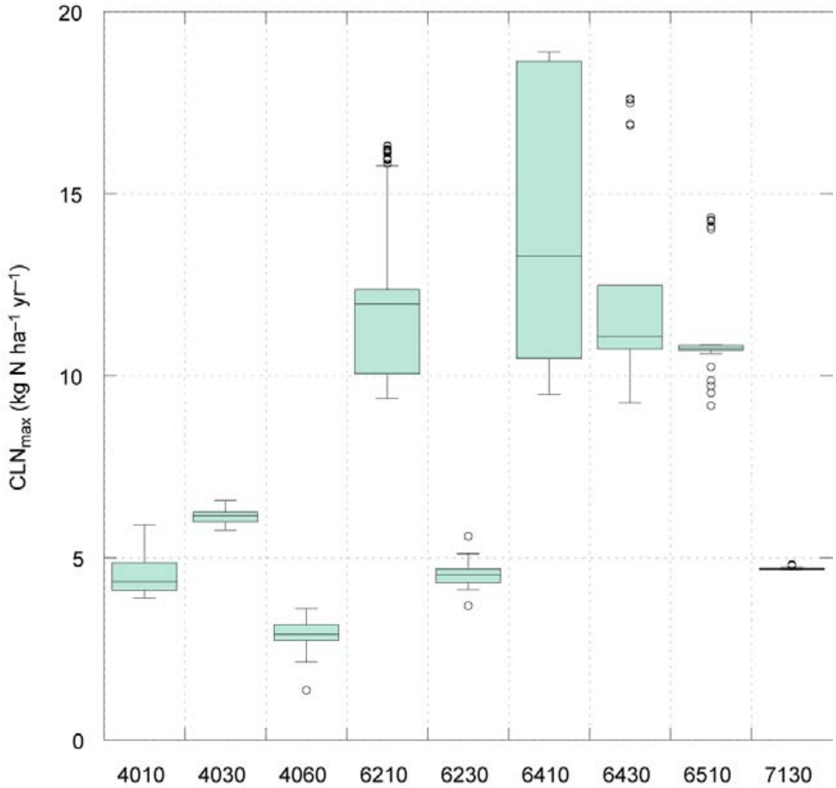

Figure A3.3. Boxplots of the CLN$_{max}$ from PROPS-CLF for nine Annex I habitats (see Table 3.1). Lower and upper box edges represent the first and third quartiles, the horizontal line within the box represents the median, whiskers extend to the largest (or smallest) value that is no further than 1.5 times the distance between the first and third quartiles, and the dots represent data points that are beyond the whiskers.

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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Nitrogen–Sulfur Critical Loads: Assessment of the Impacts of Air Pollution on Habitats

Authors: Julian Aherne, Kayla Wilkins and Hazel Cathcart

The Convention on Long-range Transboundary Air Pollution (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 Air 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 hundreds 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 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 the UNECE's Air Convention. In addition, critical loads are widely used by European Union (EU) 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

We developed empirical critical loads of nutrient nitrogen specific to Annex I habitats. Our analysis suggests that plant species in blanket bogs and heathlands are the most sensitive to total nitrogen deposition; we recommend an empirical critical load of 5 kg N ha–1 y–1. In addition, we modelled the deposition velocities for gaseous and particulate nitrogen species to provide a comprehensive assessment of observation-based total nitrogen deposition. We observed a statistically significant increase in the dry deposition of gaseous and particulate nitrogen at Valentia Observatory during 2006–2015. 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 required ecosystem monitoring under the EU National Emissions Ceiling Directive.

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