UK Centre for Ecology & Hydrology

Assessing impacts of atmospheric eutrophication and acidification in the Republic of Ireland (2018)

A report to the Environmental Protection Agency to inform data submission under the Convention on Long-Range Transboundary Air Pollution

Bill Bealey[1], David B. Kelleghan[2], Thomas Cummins[3], Ed C. Rowe[4], Tom Curran[2], Massimo Vieno[1], Sam Tomlinson[5], Ed Carnell[1], Kasia Sawicka[4], Cristina Martin Hernandez[1]

[1]UK Centre for Ecology & Hydrology, Bush Estate, Penicuik, Midlothian EH26 0QB, UK
[2]UCD School of Biosystems and Food Engineering. Agriculture and Food Science Centre, University College Dublin, Belfield, Dublin 4, Ireland
[3]UCD School of Agriculture and Food Science, Agriculture and Food Science Centre, University College Dublin, Belfield, Dublin 4, Ireland
4UK Centre for Ecology & Hydrology. Environment Centre Wales, Deiniol Road, Bangor, Gwynedd LL57 2UW, UK
[5]UK Centre for Ecology & Hydrology, Lancaster Environment Centre, Library Avenue, Bailrigg, Lancaster, LA1 4AP, UK

UK Centre for Ecology & Hydrology

UCD DUBLIN University College Dublin Ireland's Global University

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UKCEH reference	07640
UKCEH contact details	Bill Bealey UK Centre for Ecology & Hydrology, Bush Estate, Penicuik, Midlothian, EH26 0QB, UK t: +44 (0)131 4458529 e: bib@ceh.ac.uk
Authors	Bill Bealey, David B. Kelleghan, Thomas Cummins, Ed C. Rowe, Tom Curran, Massimo Vieno, Sam Tomlinson, Ed Carnell, Kasia Sawicka, Cristina Martin Hernandez
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1. Executive Summary

Atmospheric pollution in relation to acidification and eutrophication arise from both reactive nitrogen and sulphur which are important drivers for biodiversity loss globally. Impacts from acidification are decreasing across Europe - in 2010 the area impacted from acidification had decreased to 7% from 43% in 1980. However, at the same time, despite decreasing from 84% in 1990 to 63% in 2010, a large portion of Europe is still being impacted by eutrophication from atmospheric nitrogen deposition (distinct from nitrogen inputs in land run-off). Such eutrophication is due to deposition of reactive nitrogen, principally ammonia, ammonium and nitrogen oxides. With decreasing emissions of sulphur alongside nitrogen dioxide, it is likely that less aerosol ammonium is being formed which can result in higher local concentrations of atmospheric ammonia, and associated increase in its local deposition. Impacts from both acidification and eutrophication occur when a critical load is exceeded thereon; this refers to an amount of pollutant which will cause a negative effect based on evidence. The UN-ECE Convention on Long-Range Transboundary Air Pollution (CLRTAP) requires signatory parties to submit data on critical loads to the International Cooperative Programme on Modelling and Mapping of Critical Levels and Loads and Air Pollution Effects, Risks and Trends (ICP-M&M). Maps and data on critical loads, levels and exceedances are also important for local, regional and national planning.

This report describes the estimation of air pollution pressure for the Republic of Ireland, in terms of the deposition and concentration of specific pollutants (sulphur and forms of nitrogen), and the calculation of critical load values for particular habitats. Together, these datasets allow assessment of the amount and spatial patterns of critical load and critical level exceedances. This report presents modelled deposition (and concentrations) of air pollutants relevant to critical load exceedance. A state-of-the-art model EMEP4IE operated by UKCEH has been used to model both concentration and deposition rates using the EPAs most recent emission model MapÉire as its primary input. These model outputs were validated using monitoring data where available and trends in deposition rates across Ireland inferred. Ecosystem receptor maps were generated to which suitable critical loads for nutrient nitrogen and acidity were applied. This utilised a review of datasets that have become available since the last ICP-M&M call for data, including Ireland's National Park and Wildlife Service's (NPWS) Habitat Asset Register. A national Critical Load for Acidity map for both mineral and peat soils was also developed using best available data. The primary function for these models being their submission under CLRTAP to ICP-M&M, to allow for international assessment of critical load exceedances.

This project generated a range of models, many of which were used within this project to update our understanding of atmospheric impacts across Ireland. While this report focuses on exceedance of critical loads for nutrient nitrogen, and acidification; it also reviews potential effects from atmospheric ammonia. Remaining models are available to be incorporated into future projects. All modelled outputs are listed below;

- Empirical critical loads nutrient nitrogen on on receptor ecosystems
- Steady State Mass Balance critical loads for nutrient nitrogen on managed broadleaf woodlands
- Steady State Mass Balance critical loads for nutrient nitrogen on managed conifer woodlands
- Steady State Mass Balance critical loads for acidity for mineral soils
- Steady State Mass Balance critical loads for acidity for peat soils
- Mean annual ammonia concentrations
- Mean annual dry deposition of ammonia
- Mean annual wet deposition of ammonia
- Mean annual concentrations of nitrogen dioxide
- Mean annual concentrations of sulphur dioxide
- Mean annual dry deposition of nitrogen dioxide
- Mean annual wet deposition of nitrogen dioxide
- Mean annual total nitrogen deposition
- Mean annual dry deposition of sulphur dioxide
- Mean annual wet deposition of sulphur dioxide
- Mean annual ozone concentrations
- Mean annual nitric acid concentrations
- Mean annual PM fine concentrations

- Mean annual PM2.5 fine concentrations
- Mean annual sulphate concentrations
- Mean annual total nitrate concentrations

Emission maps generated highlight that ammonia emissions are strongly linked with agricultural areas, where emissions of nitrogen oxides follow roads and urban areas; with sulphur dioxide also associated with urban areas, principally paired with industrial sites. Source apportioned atmospheric ammonia concentration and reactive nitrogen deposition models were used to assess nutrient nitrogen critical load exceedances across both critical load maps produced and the Natura 2000 network. Ammonia concentration modelling highlighted, that on average critical levels for atmospheric ammonia were highest in Monaghan, Cavan and Meath and lowest in Kerry, Donegal and Mayo. A number of counties including Laois, Kildare, Cork and Donegal had a number of hotspot areas with high concentrations likely from sources such as intensive agriculture. On average all counties exceed the lower critical level for lichen and moss species of 1 µg m^{-3}, with the lowest average concentration in Co. Mayo (1.1 µg m^{-3}) and the highest in Co. Monaghan (3.9 µg m^{-3}) Spatial heterogeneity within counties is important, and many include areas which fall below this threshold, similarly many areas within the counties have much higher concentrations. When assessed across the Natura 2000 network, 81% of Special Areas of Conservation and 78% of Special Protection Areas exceed the critical level for sensitive species (1µg m^{-3}).

This work highlighted that 36% of the area of selected habitats (bogs, heaths, seminatural grasslands, marshes, fens, sand dunes, woodlands & forests) exceeds its critical load for nitrogen deposition. This report goes on to highlight the number of Special Areas of Conservation (SAC) with critical loads exceeded for nitrogen deposition. A total of 439 SAC sites are designated across Ireland with 408 of those having an Annex I habitat – the other 31 sites had only Annex II species listed. 327 sites had at least one habitat sensitive to nitrogen deposition and of those 128 had part of its site exceeding the critical load for the most sensitive feature. For some sites there were occasionally more than one habitat with the minimum critical load at a site. 39% of the number of SACs with sensitive habitats (i.e., qualifying features) exceeded their critical loads, which is 29% of the entire SAC network. This report goes on to summarise nitrogen deposition across the Natura 2000 network (Both SACs and Special Protection Areas), without detailing exceedance of site-specific thresholds.

Future assessments required under CLRTAP need to consider the updated data available for submission, most notably the 2020 census for agriculture and newly developed EPA and Tailte Éireann landcover map. These data will both improve the estimation of pollutant emissions/concentrations/deposition and the resolution at which critical loads can be mapped. This work will continue to link with the National Ecosystem Monitoring Network (NEMN), which aims to monitor these pollutants and their effects across Irish ecosystems, as required under the National Emission reduction Commitments Directive (2016/2284/EU). Such monitoring will support verification of future models, through atmospheric monitoring conducted on NEMN Level 2[1] and NEMN Level 2 core[2] sites. Additionally, current and future models can be applied to examine data collected across the proposed NEMN Level 1[3] network of sites where ecological assessments are performed and moss and soil samples are taken for tissue nitrogen and soil chemistry, respectively.

[1] NEMN sites focused on monitoring atmospheric ammonia concentrations.

[2] NEMN sites focused on monitoring atmospheric deposition of reactive nitrogen.

[3] NEMN sites focused on monitoring ecological indicators.

2. Introduction

Atmospheric pollution is an important driver for impacts to natural and seminatural ecosystems. Such impacts typically arise either from direct exposure in the atmosphere, or through the acidification and eutrophication of both freshwater and terrestrial habitats. Where nitrogen deposition is recognised internationally as the third most important driver for biodiversity loss (following climate and land use change), impacts arising from sulphur pollution are likely decreasing coupled with decreased emissions. Reactive nitrogen, such as ammonia, ammonium or nitrogen oxides are the principal concern for nitrogen deposition and subsequent eutrophication and acidification impacts on ecosystems. In Ireland, with continually increasing ammonia emissions, and likely reduction of aerosol formation (due to decreasing sulphur and nitrogen oxide emissions), the eutrophying and acidifying effects of nitrogen deposition and direct effects from ammonia exposure needs to be central to all biodiversity and agricultural plans going forward.

Thresholds have been set to quantify impacts to ecosystems based on the amount of pollutant they are either exposed to or receive; these are termed critical loads and critical levels. A critical load is a threshold which defines the sensitivity of a habitat to deposition of reactive nitrogen from the atmosphere. For example, bogs have a critical load of 5 – 10 kg N ha^{-1} $year^{-1}$; and are hence impacted when nitrogen deposition exceeds these thresholds. A nutrient nitrogen Critical Load is a measure of how sensitive a habitat is to atmospheric nitrogen deposition. If a habitat receives more nitrogen than its critical load, it will be negatively impacted. Similarly, limits have been set on the concentrations of many pollutants which cause an impact; these are termed critical levels. The critical levels for atmospheric ammonia are set at 1 µg m^{-3} for lichens and moss species (i.e. relevant to bog, heath, oak woodlands, etc) and 3 µg m^{-3} for all other higher plants and associated habitats. Where atmospheric ammonia is a substantial contributor to reactive nitrogen deposition, both concentration and deposition require separate thresholds to ensure identification of potential impacts. When either a critical level or a critical load is exceeded, it is likely the habitat is being negatively impacted.

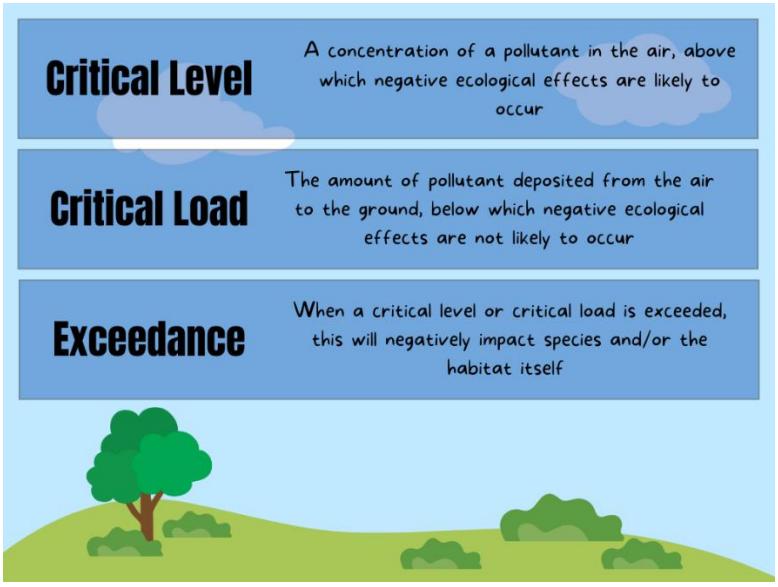

Figure 1. Definition of critical levels, loads and exceedances relative to atmospheric ammonia and nitrogen deposition.

The UN-ECE Convention on Long-Range Transboundary Air Pollution (CLRTAP) requires signatory parties to submit data on critical loads to the International Cooperative Programme on Modelling and Mapping of Critical Levels and Loads and Air Pollution Effects, Risks and Trends (ICP-M&M). The EPA funded this project in 2020 to compile and submit this data on behalf of the EPA. The focus of this call for data was on critical loads for two types of atmospheric pollution: critical loads for acidity and critical loads for nutrient nitrogen. Nitrogen is an acidifying pollutant which needs to be considered as a component of Critical Loads of Acidity. The effects of nitrogen as a nutrient element are distinct from its role as an acidifier, and is also harmful to ecosystems and biodiversity.

The primary source of mapped land use data was the Habitats Assets Register for Ireland, compiled by the National Parks and Wildlife Service (NPWS) in 2017 based on a combination of 46 habitat datasets including

the CORINE Land Cover (CLC) from 2016. The datasets available were reviewed and any refinements to ancillary data sets to deliver improved mapping were considered e.g. EPA-Teagasc Soils and Subsoils dataset; forest cover datasets; species occurrence datasets to refine habitat classes; precipitation as a potential modifier for critical loads. EPA funded research has supported the development of empirical critical loads of nutrient nitrogen for Europe using Irish data (Aherne et al., 2021). Aherne et al., 2021 utilised National Parks and Wildlife Service surveys to quantify the effect nitrogen deposition is having on vegetation communities across Ireland, clarifying the specific thresholds for impacts on Irish habitats from nitrogen deposition. These values are used by EPA for Integrated Pollution Control (IPC)/Industrial Emissions (IED) licensing when reviewing contributions of ammonia from intensive pig and poultry farms to sensitive habitats within Natura 2000 sites. They are also used to apply critical loads to habitats nationally within this report. Empirical critical loads across Europe have hence been updated, and this updated document should be considered for future European submissions (Bobbink et al., 2022).

The critical load is an important concept when assessing the risks to ecosystems from air pollution, and 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 & Grennfelt). It thus represents a threshold level of pollution deposition from the atmosphere, above which harm is likely. Maps and data on critical loads and exceedances are also useful for local, regional and national planning. Similarly, a critical level is defined as a threshold concentration of an air pollutant. ICP-M&M focuses on three types of air pollution:

a) the deposition of acidifying pollutants i.e. sulphur (S) and nitrogen (N) in both reduced (NH_y) and oxidised (NO_x) forms.
b) the deposition of eutrophying pollutants i.e. nitrogen in both reduced and oxidised forms.
c) The concentration of gaseous ammonia (NH_3).

Air pollution pressure has been re-estimated using a widely used atmospheric model, EMEP-WRF. The EMEP-WRF model is an atmospheric-chemistry transport model (ACTM) based on the EMEP MSc-W model (https://github.com/metno/emep-ctm), using the Weather Research Forecast (WRF – www.wrf-model.org) model as the meteorological driver. The EMEP-WRF UK, also named EMEP4UK, represents atmospheric composition in high detail, with a capability to simulate hourly air pollution interactions over decadal scales at high horizontal resolution, and the effects of photochemistry. An output for the whole EMEP-WRF Irish domain (named EMEP4IE) at 1x1 km^2 grid resolution was produced using the best available emission data (MapEIre), with hourly averaged output for chemistry (EMEP4IE) and hourly for meteorology (WRF). This has allowed the amount and composition of pollutant deposition to be assessed for the Republic of Ireland, including nitrogen and sulphur deposition (including habitat specific depositions), and concentrations of ammonia and also particulate matter (PM_{10}) for human receptor assessment in SCAIL-Agriculture (Simple Calculation of Atmospheric Impact Limits-Agriculture).

Where the focus of the UN-ECE CLRTAP and the previous National Emission Ceilings Directive (2001/81/EC) was on limiting national emissions, this approach was revised in the updated National Emission reduction Commitments Directive (2016/2284/EU). It is now required in addition to reducing national emissions, to monitor and report air pollution impacts on sensitive ecosystems within each Member State. Ireland's response to this requirement is the implementation of the National Ecosystem Monitoring Network, operated by the EPA. This network will monitor both the air pollutants themselves and their effects.

3. Developing Nutrient Nitrogen Critical Load Maps for Sensitive Ecosystems

The deposition rates for acidity and nutrient-N that result in impacts should be seen as critical loads depend on the properties of the receptor ecosystem. Sensitivity is determined by the ecosystem's capacity to absorb or re-export the pollutant, and on the resilience of components such as individual species or ecosystem functions. In this section we review briefly how critical load values are assigned and recommend methods for assigning these values for Ireland. The recommended methods have been applied to generate maps of critical load values for Ireland, which were used in the response to the Coordination Centre for Effects Call for Data in April 2021.

The main basis for assigning critical loads for Nutrient-nitrogen (Nutrient-N) for semi-natural habitats was the empirical critical loads (CLempN) agreed in UNECE expert workshops (Berne 2002 Achermann & Bobbink 2003; and Nordwijkerhout 2010 Bobbink & van Hettelingh 2011). These were set based on EUNIS (EUropean Nature Information System) habitat classes, in most cases with a suggested range of values. Revisions to the recommended CLempN values were applied to all habitats based on Aherne et al 2021. The recommended values were based on two approaches to assessing the influence of N deposition on plant species diversity within Annex I habitats: a gradient approach (threshold indicator species analysis) and an approach using the Probability of Occurrence of Plant Species (PROPS) species-niche model. We assessed which point on the given range of CLempN values is most appropriate to apply for each habitat, taking into account the uncertainty attached to each range, and potential modifiers such as annual precipitation.

The preparation of critical load maps has three main components: (A) mapping and distribution of habitats sensitive to the nitrogen and acidity (the receptor ecosystems); (B) determination of the critical load values or functions to be assigned to those habitats; (C) developing grid-based maps used to develop site-relevant critical loads. The primary source of mapped land use data was the Habitats Assets Register for Ireland, compiled by the National Parks and Wildlife Service (NPWS) in 2017 based on a combination of 46 habitat datasets including the CORINE Land Cover (CLC) from 2016. The datasets available were reviewed and any refinements to ancillary data sets to deliver improved mapping were considered e.g., EPA-Teagasc Soils and Subsoils dataset; forest cover datasets; species occurrence datasets to refine habitat classes; precipitation as a potential modifier for critical loads. The Habitat Asset Register has already assigned Level 1 EUNIS categories for Irish habitats. The process of sorting and aggregating these habitats went through a series of stages and how these were assigned are described within this report.

3.1. Introduction to types of Critical Load

Essentially, there are two approaches to assigning critical loads – mass-balance, and empirical. The mass-balance approach is sometimes called "steady-state mass balance" (SSMB), although all types of critical load are set to avoid harmful effects in the long term, i.e., once the system has reached a steady state. Mass-balance critical load values are assigned on the basis that the ecosystem will withstand an influx of pollutant if this is balanced by exports (including safe rates of storage within ecosystem pools such as soil organic matter). In the case of acidity, there may also be counterbalancing inflows of basic cations, such as calcium from mineral weathering. Empirical critical loads are assigned on the basis of observations from experiments in which pollutant loads were increased, or from surveys across a pollution gradient, as the maximum deposition rate at which significant harmful effects are not observed.

The focus of the Coordination Centre for Effects call for data is on critical loads for two types of atmospheric pollution: Critical Loads for Acidity (CLA) and Critical Loads for Nutrient-N (CLnutN). Nitrogen is an acidifying pollutant (irrespective of whether it is deposited in its reduced or oxidised form) which needs to be considered as a component of CLA. The effects of nitrogen as a nutrient element are distinct from acidification and can also be very harmful to ecosystems and biodiversity. Only mass-balance approaches

are used to assign critical load for acidity values. Values for CLnutN are often assigned using empirical data[4] (CLnutN) but may also be defined using a mass-balance approach (Figure 2).

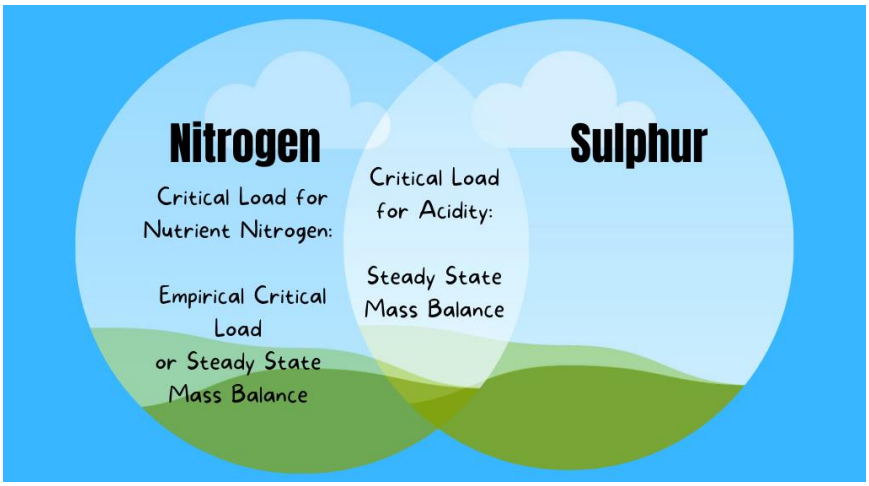

Figure 2. Critical Load concepts. Nitrogen and sulphur both contribute to acidity Critical Load for Acidity load (CLA) which is always determined using a Steady State Mass Balance approach (SSMB). The Critical Load Nutrient-N critical load (CLnutN) may be determined using mass balance or using empirical data (CLempN).

Assigning a critical load value requires, as a minimum, knowing the habitat (Figure 3). If a mass-balance approach is taken, information about soil type, fertilisation, and other management practices should also be taken into account. For the Coordination Centre for Effects Call for Data, a single CLnutN and a single critical load for acidity value need to be assigned per 0.1° x 0.05° grid cell (11.1 x 5.55 km), for each habitat in that grid cell. This requires a single value per cell for the underlying data. Methods for assigning site-relevant critical loads are described below.

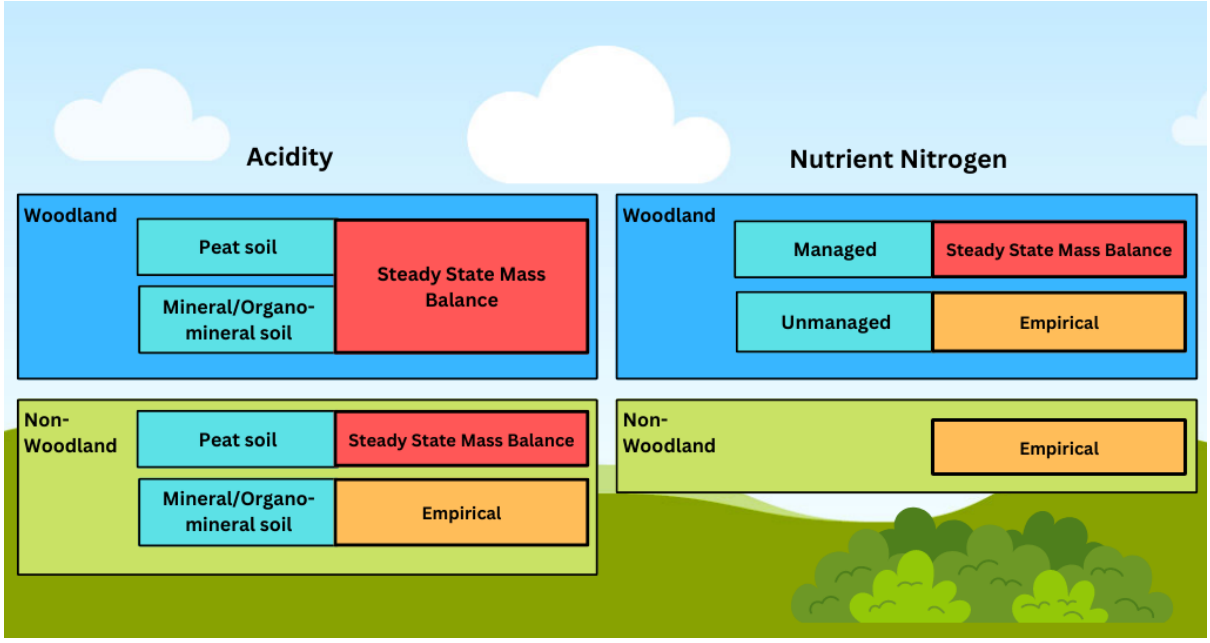

Figure 3. Critical load approaches for Ireland showing approach taken by habitat type.

3.2.Review existing land-use / habitat maps and ancillary data for Ireland

To define critical loads to habitats an underlying map of habitats across Ireland is required, as different habitats have different critical loads depending on their sensitivity. Selected habitats were obtained from National Parks and Wildlife Service (NPWS) Habitats Asset Register in 2017 based on a combination of 46

[4] Empirical data refers to data derived from research.

habitat datasets including the CORINE Land Cover (CLC) from 2016 (Figure 4). The process involved the sorting and aggregation of habitats into broader habitat classes for determining critical loads. To assist the process other datasets were used including the Irish Soil Information System map[5], bedrock data[6] and the Survey of Native Woodlands[7]. Where "mosaic" habitats occurred (principally upland habitats), the habitat type based on CORINE landcover was applied. Use of the EUNIS (EUropean Nature Information System) habitat classification enables a consistent approach in different countries. The ICP M&M Coordination Centre for Effects (CCE) has adopted EUNIS as the basis for its critical load assessments. For Ireland the Habitat Assets Register and ancillary maps identified were used to derive a final set of habitat classes to be used for assigning critical loads. The final habitat map was projected to a resolution of 0.1^{o} x 0.05 ^{o} grid cells required by the Coordination Centre for Effects for EU mapping. This approach is detailed in Appendix 1.

3.3.Assigning Critical Loads for Nutrient Nitrogen, $CL_{nut}N$

The main basis for assigning critical loads for nutrient-nitrogen for selected semi-natural habitats was the empirical critical loads ($CL_{emp}N$) agreed in UNECE expert workshops (Berne 2002 Achermann & Bobbink 2003; and Nordwijkerhout 2010 Bobbink & van Hettelingh 2011). These were set on the basis of EUNIS classes, in most cases with a suggested range of values. Revisions to the recommended $CL_{emp}N$ values were applied to all habitats based on Aherne et al 2021. The recommended values were based on two approaches to assessing the influence of nitrogen deposition on plant species diversity within Annex I habitats: a gradient approach (threshold indicator species analysis) and an approach using the PROPS species-niche model.

The $CL_{emp}N$ values assigned to selected habitat classes are shown in Table 1 with the final mapping value in the 'Assigned' column. Revised values from Aherne et al. (2021) were used for the majority of the critical load values. For habitats where Aherne et al. (2021) did not provide a value, the mid-point of the suggested empirical critical loads for nutrient nitrogen (Nordwijkerhout, 2010) range was used.

Table 1: Empirical critical loads for nutrient nitrogen assigned to habitat classes. CLempN are given for i) current UNECE Nordwijkerhout workshop 2010 ranges, ii) a revised Aherne 2021 mapping value, and iii) the final Assigned values used in this project. Where a value from Aherne is not given a mid-point is used from the 2010 range. Areas of each habitat are also given, in km2 and as % of the land area of the Republic of Ireland.

Habitat (EUNIS Codes) in Republic of Ireland	**Area of habitat** (km^2) (% of land mass)	**Empirical Nitrogen (N) Class Name** (Nordwijkerhout 2010)	**Empirical critical loads for nutrient nitrogen Range 2010**	**Empirical critical loads for nutrient nitrogen Aherne 2021**	**Assigned Empirical critical loads for nutrient nitrogen***
			Kg N ha^{-1} yr^{-1}		
Bogs (D1)	7091 (10.1)	Raised and blanket bogs	5-10	5	5
Dry Acid grassland (E1.7)	462 (0.7)	Non-Mediterranean dry acidic and neutral closed grasslands	10-15	5	5
Wet Acid grassland (E3.52)	173 (0.2)	Heath (Juncus) meadows and humid (Nardus stricta) swards	10-20	10	10
Dry Calcareous grassland (E1.26)	382 (0.5)	Sub-Atlantic semi-dry calcareous grasslands	15-25	-	20
Dry heath (F4.2)	318 (0.5)	Dry heaths	10-20	7.5	7.5
Wet heath (F4.11)	950 (1.4)	Northern wet heath: *Calluna*-dominated wet heath (upland moorland)	10-20	5	5
Marsh and fen (D2)	81 (0.1)	Valley mires, poor fens and transition mires	10-15	7.5	7.5

[5] https://data.gov.ie/dataset/irish-soil-information-system-national-soils-map

[6] https://www.gsi.ie/en-ie/programmes-and-projects/geological-mapping/Pages/Data-and-Maps.aspx

[7] https://www.npws.ie/maps-and-data/habitat-and-species-data

Moss and lichen-dominated mountain ridges > 300m (E4.2)	221 (0.3)	Moss- and lichen dominated mountain summits	5-10	-	7.5
Oligotrophic and Mesotrophic Water bodies (C1)	245 (0.3)	Permanent oligotrophic lakes, ponds and pools (including soft-water lakes)	3-10	-	6.5
Salt Marsh (A2.5)	41 (0.1)	Pioneer, low-mid, mid-upper saltmarshes	20-30	7.5	7.5
Sand Dunes (B1.4)	121 (0.2)	Coastal stable dune grasslands	8-15	7.5	7.5
Unmanaged Broadleaf Woodland (G1.8)	1735 (2.5)	Broadleaved deciduous woodland	10-20	10	10
Managed Broadleaf Woodland (G1)	921 (1.3)				SSMB
Managed Coniferous woodland (G3.1)	4142 (5.9)				SSMB

**Where vegetation change points are not available the midpoint of the 2010 $CL_{emp}N$ range was used.*

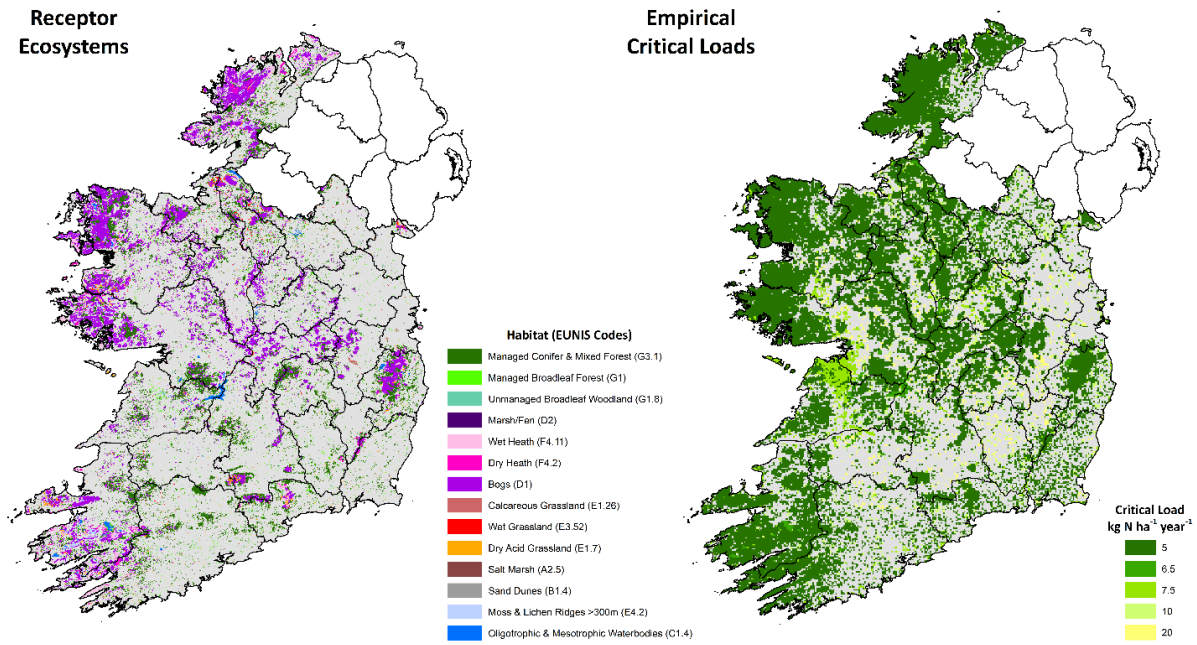

Figure 4. Left: Seminatural receptor ecosystems based on NPWS Habitats Assets Register. Middle: Empirical critical loads for semi-natural receptor ecosystems

4. Developing Nutrient Nitrogen Critical Load Maps for Managed Woodland

The Steady State Mass Balance (SSMB) method is the most commonly used model for the calculation of acidity and nutrient nitrogen critical loads for managed woodland ecosystems. This model is based on balancing the N and acidic inputs and outputs from the ecosystem, to derive a critical load which ensures that a critical chemical limit (related to effects on the ecosystem) is not exceeded.

4.1. Nutrient-N Critical Loads for managed woodland

$CL_{emp}N$ values are not available for managed woodlands and a SSMB approach is applied for (productive) woodlands to ensure the protection of the long-term ecosystem function (e.g. soils, trees, and linked aquatic

ecosystems). The SSMB approach calculates the long-term inputs and outputs of nitrogen from the system. The critical load corresponds to the load when the system is at a steady state. Excess nitrogen input is likely to lead to exceedance of a critical rate of nitrogen leaching.

$$\boldsymbol{CLnut(N)} = \boldsymbol{N_i} + \boldsymbol{N_u} + (\boldsymbol{N_{le(acc)}} / (\mathbf{1} - \boldsymbol{f_{de}})) \qquad (1)$$

where:

Ni = acceptable annual level of nitrogen immobilisation in soil organic matter (including forest floor)
Nu = net removal of nitrogen in vegetation and harvested animals
fde = the denitrification fraction
Nle(acc) = acceptable level of total annual nitrogen leaching (NO_3^- + NH_4^+ + organic N) from the rooting zone

4.2.Nitrogen Immobilisation (N_i)

A maximal acceptable value for a sustainable long-term net Nitrogen immobilisation was used in the 2012 data submission by Aherne (2017), with values of 3 kg N ha^{-1} yr^{-1} for Histosols[8] and Podzols[9], and 1 kg N ha^{-1} yr^{-1} for all other soils. In comparison the Mapping Manual ranges are lower, (CLRTAP 2017, section V.3.1.3.1), with values between 0.2–0.8 kg N ha^{-1} yr^{-1}. For consistency with the most recent data submission, the values by Aherne et al. (2017) were used (Table 2).

Table 2. Nitrogen immobilisation values set for two soil types – 3 kg N ha^{-1} yr^{-1} set for Histols and Podzols (including peats and peaty gleys) and 1 kg N ha^{-1} yr^{-1} for all other soils.

Class	Nitrogen Immobilisation kg N ha^{-1} yr^{-1}	Irish Soil Information System terms
Histosols & Podzols	3	Peats, Podzols
All other soils	1	All other soils, including Urban
Not categorised	Undefined	Water body, Rock, Island

4.3.Nitrogen Uptake (N_u)

Nitrogen uptake for managed broadleaf woodland was estimated using a typical yield class, wood density and nitrogen stem concentration. Based on Aherne 2017 values for broadleaf woodlands were set to an annual growth rate of 6 m^3 timber ha^{-1} $year^{-1}$; a wood density of 550 kg m^{-3}; and nitrogen content of 0.13 molc kg^{-1}.

$$\boldsymbol{N_u} = \mathbf{YC} \times \text{fÏ} \times \boldsymbol{C_N} \qquad (2)$$

where :
Nu= nitrogen uptake (kg N ha^{-1} yr^{-1})
YC is yield class or annual growth rate (m^3 timber ha^{-1} $year^{-1}$)
fÏ is the density of stem wood (kg m^{-3})
C_N is the content of nitrogen in stems (molc kg^{-1})

Nutrient uptake by conifer forests was based on calculations from the ForSite project (Johnson et al. 2016) where uptake was assumed to be represented by the nitrogen in above-ground biomass at the point of whole-tree harvesting. The unit has a time component of one year, achieved by dividing forest-harvest amounts by the time between establishment and felling. Harvests are above ground whole-tree clearfells with removal off site of all stem, branch, and foliar biomass, with no returns (e.g. ash or char).

4.4. Denitrification (f_{de})

This denitrification-proportion (a better term than "denitrification fraction") represents the nitrogen that is removed by denitrification processes, and thus does not contribute to acidification. Denitrification is a microbial process where nitrogen compounds (e.g. nitrate) are released back into the atmosphere as gases of nitrous oxide (N_2O) or/and di-nitrogen (N_2). The denitrification fraction (f_{de}) is determined by soil texture and drainage status and were categorised, using mapped soil-association units and according to their principal soil series, into values assigned to classes as defined in Table A2.3 of Aherne et al., 2017, and shown in Table 3 below.

[8] soil consisting primarily of organic materials

[9] podzols are the typical soils of coniferous or boreal forests

Table 3. Denitrification expressed as a proportion of Nitrogen deposition for different soil classes.

Class	Proportion of Nitrogen deposition denitrified	Irish Soil Information System terms	World Reference Base for Soil Resources (WRB)
Peats	0.8	Peats	Histosols
Peaty Gleys	0.7	Humic Surface- and Groundwater Gleys	Histic Stagnosols, Histic Gleysols
Gleys	0.4	Typical Surface- and Groundwater Gleys, Alluvium, Marsh	Stagnosols, Gleysols, Fluvisols
Podzols	0.2	Podzols	Podzols
Free-draining soils	0.1	Brown Earths, Luvisols,	Cambisols, Luvisols
Not categorised	undefined	Water body, Urban, Rock, Island	Includes Gleysols, Leptosols, Technosols, Histosols

4.5.Acceptable level of total annual nitrogen leaching ($N_{le(acc)}$)

The acceptable nitrogen leaching flux (Nle(acc)) depends on the 'harmful effects' that should be avoided. Leaching is the process of the washing out of soluble ions and compounds (e.g., nitrates) by water draining through the soil. In general, it is not the nitrogen leaching flux itself that is 'harmful', but the concentration of nitrogen in the leaching flux (CLRTAP 2017). The acceptable nitrogen leaching (in eq ha^{-1} $year^{-1}$) is calculated as:

$$N_{le\,(acc)} = Q \times [N]_{acc} \qquad (3)$$

Where:
[N]acc = the acceptable nitrogen concentration (eq m^{-3})
Q is the precipitation surplus (m^3 ha^{-1} yr^{-1})

A soil solution nitrogen concentration of 0.2 mg N L^{-1} (=0.0143 eq m^{-3}) was used as the value recommended to avoid nutrient imbalances in managed woodlands (Johnson et al., 2016). Q is the precipitation surplus of rainfall minus evapotranspiration derived from the Met Éireann Reanalysis (MÉRA) model.

4.6.Critical loads for managed woodlands

The final calculation of critical loads for managed conifer forests and managed deciduous and mixed forest are shown in Figure 5 below.

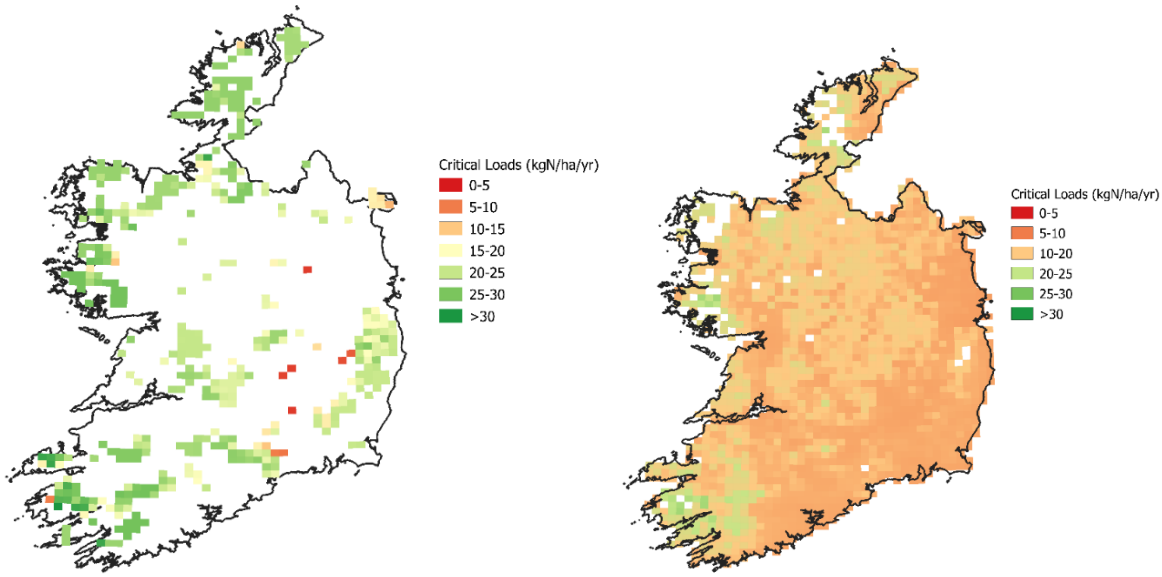

Figure 5. Left: Critical loads of nutrient nitrogen for managed coniferous forest based on the SSMB approach (kg N ha-1 year-1). Right: Critical loads of nutrient nitrogen for managed deciduous and mixed forest based on the SSMB approach (kg N ha-1 year-1).

5. Developing Critical Load for Acidity Maps

Critical Loads for Acidity (CLA) were assigned and calculated using different methods, depending on the habitat and also on the broad class of soil. For the purpose of assigning base-cation weathering classes, mapped habitats were mainly assumed to occur on the dominant soil type within each 1km grid square. Bog habitats are an exception and were assumed to only occur on peat soil. Rain-fed peats (which constitute the majority of peatland habitats in Ireland) do not receive any alkalinity inputs from base cation weathering, and so the soil solution pH is largely governed by the chemistry of rainfall (Cresser 2000). Base cation are positively charged ions of alkaline metals (e.g. sodium Na, calcium Ca, potassium K, and manganese Mg). The CLA for ombrotrophic peats were therefore defined as CLA = Q * [H+] where Q is the runoff or precipitation surplus in metres per year, and [H+] is the hydrogen ion concentration equivalent to a critical pH value of 4.4. Runoff Q is the total precipitation minus evapotranspiration and was calculated using the most recent MÉRA[10] evapotranspiration model for peat soils, paired with the best available national rainfall dataset[11].

On mineral and organic soils, for semi-natural habitats other than woodlands, CLA was defined using the base cation weathering based on Skokloster classes[12], minus the critical limit for leaching of Acid Neutralising Capacity (ANC). From previous work by Aherne and Farrell (2000), one of five "Skokloster" critical load classes was assigned based on the dominant mineralogy and weathering rate of the dominant soil type in each grid square. Each class is associated with a range of critical load values based on the amount of acid deposition that could be neutralised by the base cations produced by mineral weathering (Nilsson and Grennfelt 1988). ANC leaching is chosen as the chemical criterion set with a specified limit to protect the receptor ecosystem from long-term damage. The ANC is based on both the critical aluminium ([AL]crit) and hydrogen ion ([H]crit) concentration and the precipitation surplus (Q). A critical load of potential acidity is therefore obtained by setting a critical ANC leaching value – above which harmful effects occur, the critical limit (Aherne, 2000). For woodlands on mineral and organic soils, CLA was defined using a SSMB approach. Calculating SSMBs for woodlands building on the work of Johnson et al. (2015) and Johnson et al. (2016), who developed budgets of nutrient cations and nitrogen for forests.

The Critical Load Function (CLF), developed under the UNECE CLRTAP (Posch et al., 1999; Posch & Hettelingh, 1997; Posch et al., 1995; Hettelingh et al., 1995), defines combinations of sulphur and nitrogen deposition that will not cause harmful effects. The acidity critical load function is described by the values ClmaxS, ClminN and ClmaxN which are defined as follows.

- ClmaxS is calculated from CLA, but also takes into account the net base cation deposition to the soil system (Bcdep) and base cation removal from the system (Bcu).
- ClminN is the sum of the long-term nitrogen removal processes from the soil and vegetation including nitrogen uptake (removal), nitrogen immobilisation, and denitrification
- ClmaxN is calculated as ClmaxN = ClminN + ClmaxS

This report shows the CLmaxS and CLminN maps for habitats assuming that habitat is found in every grid square. There are five CLmaxS maps (managed conifer, managed deciduous, unmanaged deciduous, heathland and all other habitats). This is due to non-marine base cation deposition having three separate outputs – forest, heath and others. Forests are further divided based on the base cation uptake (BC_u) which differs for managed conifer and deciduous. For CLminN there are only three maps based on managed conifer, managed deciduous and all other habitats.

[10] https://www.met.ie/climate/available-data/mera

[11] https://data.gov.ie/dataset/1981-2010-rainfall-grids

[12] Skokloster - a classification based on the rate of base-cation release from weathering of mineral soils. These classifications were defined at a UNECE workshop on Critical Loads for Sulphur and Nitrogen in Skokloster, Sweden, March 1988. See Appendix 2

Critical loads for acidity (CL_A) were assigned and calculated using different methods, depending on the broad class of soil, detailed in sections 5.1 and 5.2.

5.1.Assigning Critical Loads of Acidity for Peat Soils

Rain-fed peat soils (which constitute the majority of peatland habitats in Ireland) do not receive any alkalinity inputs from base cation weathering, and so the soil solution pH is largely governed by the chemistry of rainfall (Cresser 2000). The critical load for acidity (CL_A) (in equivalents m^{-2} yr^{-1}) for ombrotrophic peats was calculated as

$$\boldsymbol{CL_a = Q \times [H^+]} \qquad (4)$$

Where:
Q (precipitation surplus) is the volume of percolating water in the root zone (i.e. precipitation minus evapotranspiration) in cubic metres per hectare per year
[H+] is the hydrogen ion concentration (in equivalents L^{-1}) corresponding to a critical pH value.

Critical loads of acidity for peat soils were set to the value corresponding to the amount of acid deposition that would give rise to an effective rain pH value of 4.4 (Calver, 2003; Calver et al., 2004; Skiba and Cresser, 1989) The choice of threshold pH value reflects the buffering effects of organic acids on peat drainage water pH.

The precipitation surplus Q is the amount of water percolating from the root zone. It is calculated as the difference between precipitation and actual evapotranspiration. It should be averaged annually from multiple years (CLRTAP, 2017). Q was calculated using Met Eireann's modelled rainfall data and MÉRA evapotranspiration model and is shown in Figure 6.

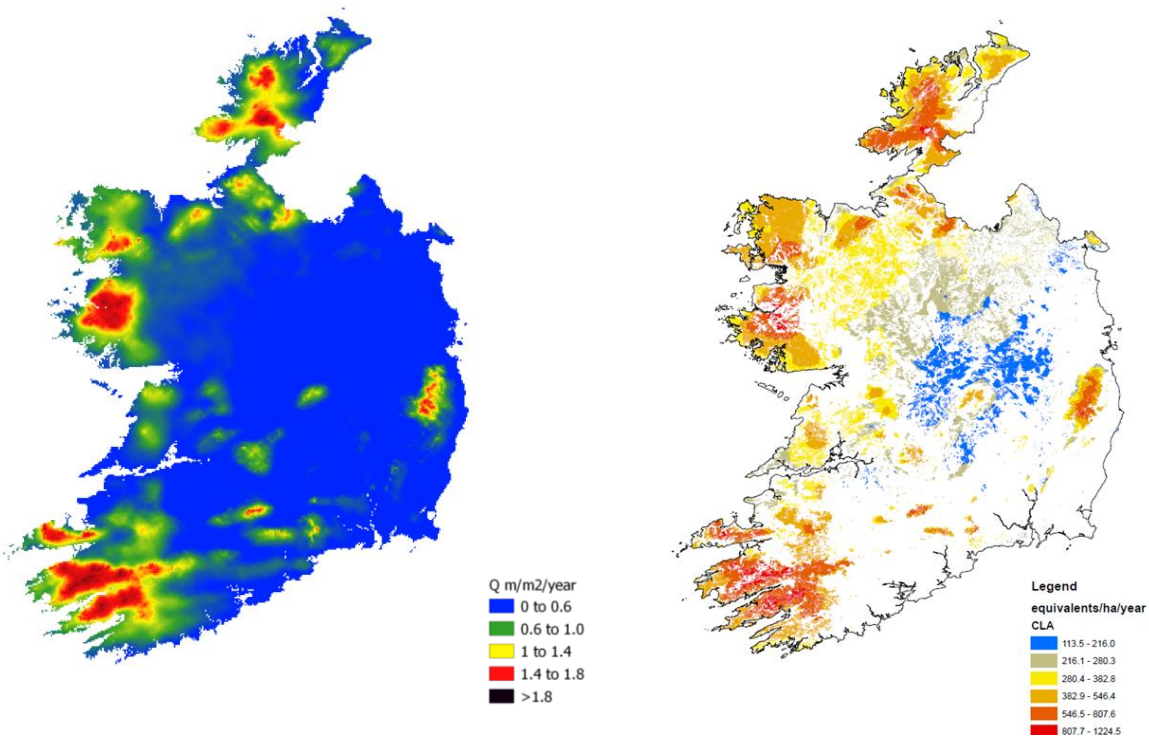

Figure 6 Left: Precipitation surplus 'Q' for Ireland derived from precipitation minus evapotranspiration. Right: Critical loads of acidity for Peat soils based on SSMB approach.

5.2.Assigning Critical Loads of Acidity for Mineral Soils

For mineral soils critical load for acidity is defined as:

$$\boldsymbol{CL(A) = BC_w - ANC_{le,crit}} \qquad (5)$$

Where:
BCw = base cation weathering (derived Skokloster classes)
ANCle,crit = the critical limit for leaching of Acid Neutralising Capacity

The process for preparing acidity critical loads for mineral soils is detailed in full in Appendix 2.

5.3.Critical Loads of Acidity

Final map of CL(A) for both Peat and Mineral soils is shown in Figure 7 in equivalents per hectare per year. The areas (purple) contain the peat type soils and are the most sensitive.

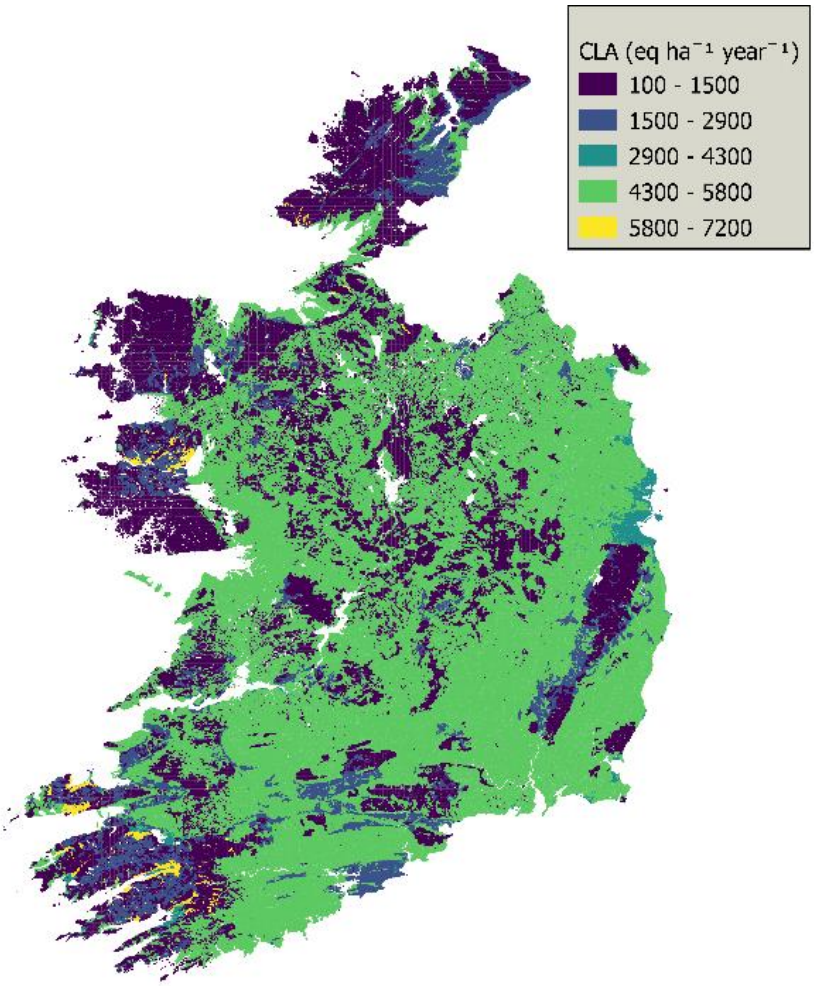

Figure 7. Final Critical Loads for Acidity map for Ireland including critical loads based on mineral soils and peat soils.

5.4.Critical Load Function of acidity

The Critical Load Function (CLF), developed under the UNECE CLRTAP (Posch et al., 1999; Posch & Hettelingh, 1997; Posch et al., 1995; Hettelingh et al., 1995), defines combinations of sulphur and nitrogen deposition that will not cause harmful effects. The acidity critical load function is described in graphical form as nitrogen deposition (x-axis) versus sulphur deposition (y-axis). In simple terms the critical load can be defined by a 45-degree diagonal line (Figure 8. Left). At each point along the line including the area under the line, the critical load for acidity is thus defined by varying combinations of nitrogen and sulphur deposition. To allow for the long-term nitrogen removal processes by the soil and through harvesting of vegetation, the simple diagonal line is shifted along the nitrogen axis to increase the nitrogen values across the entire function graph (Figure 8. Right). More nitrogen can then be deposited before the acidity critical load is exceeded. There are no similar removal processes that need to be considered for sulphur.

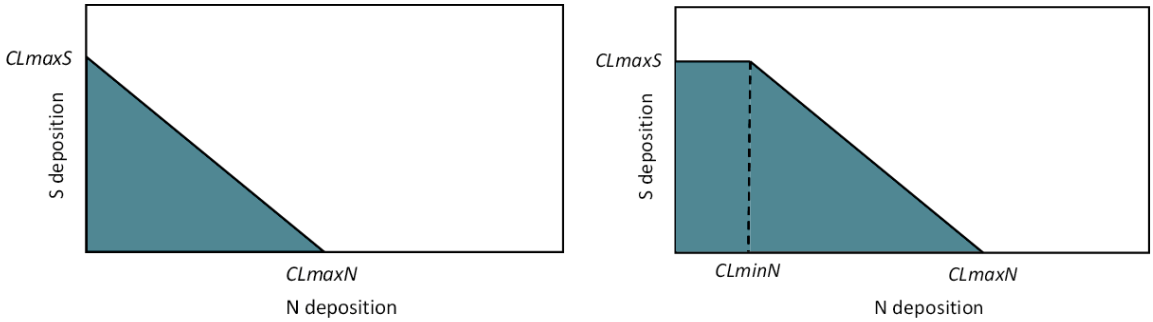

Figure 8. Left: Simple 45º critical load with no removal processes of nitrogen. Right: The full critical load function with nitrogen removal processes in place. The shaded area below the line denotes N/S deposition that are below the critical load (i.e., critical load is not exceeded).

The intercepts of the CLF on the sulphur and nitrogen axes (Figure 8) define the following terms and equations (Figure 9):

- $CL_{max}S$ is calculated from CL_A, but also takes into account the net base cation deposition to the soil system (BC_{dep}) and base cation removal from the system (BC_u).
- $CL_{min}N$ is the sum of the long-term nitrogen removal processes from the soil and vegetation including nitrogen uptake (removal), nitrogen immobilisation, and denitrification
- $CL_{max}N$ is calculated as $CL_{maxN} = CL_{min}N + CL_{max}S$

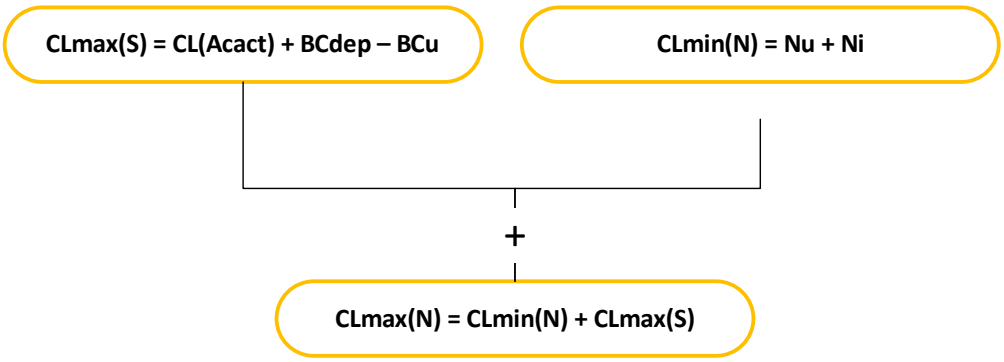

Figure 9. Calculation of CLF elements CLmaxS, CLminN and CLmaxN.

Details on calculation of CL_{maxN}, $CL_{min}N$ and $CL_{max}S$ are provided in Appendix 3.

Figures 10 - 12 below show the CLmaxS and ClminN maps for habitats assuming that habitat is found in every grid square. There are five ClmaxS based on managed conifer, managed deciduous, unmanaged

deciduous, heathland and all other habitats. This is down to the non-marine base cation deposition having three separate outputs – forest, heath and others, and the base cation uptake (BC_u) having outputs for managed conifer and deciduous and all other habitats. For ClminN there are only three maps based on managed conifer and deciduous and all other habitats.

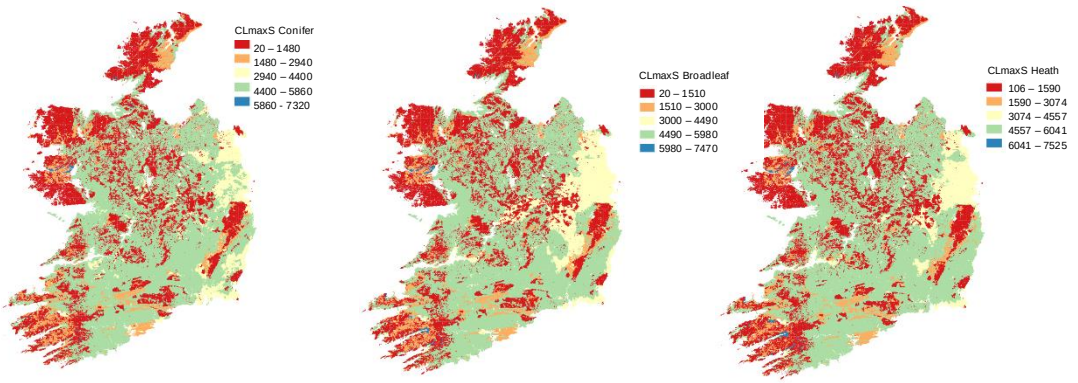

Figure 10. Left: ClmaxS for managed coniferous forest (eq $ha^{-1}year^{-1}$). Middle: ClmaxS for managed deciduous forest (eq $ha^{-1}year^{-1}$). Right: ClmaxS for heathlands (eq $ha^{-1}year^{-1}$)

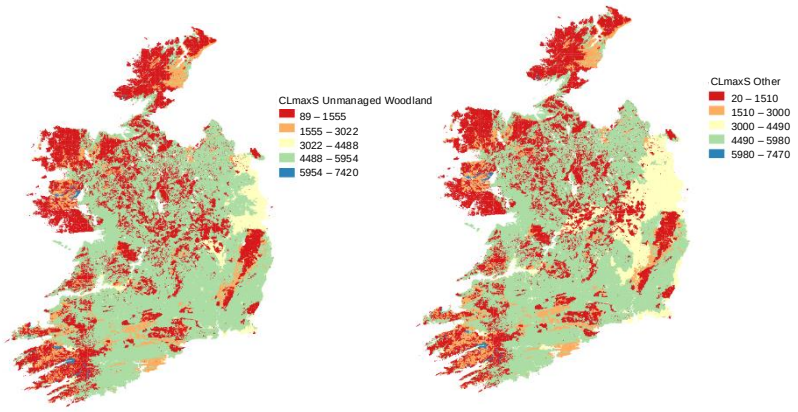

Figure 11. Left: ClmaxS for all unmanaged woodlands (eq $ha^{-1}year^{-1}$). Right: ClmaxS for all other habitats (eq $ha^{-1}year^{-1}$)

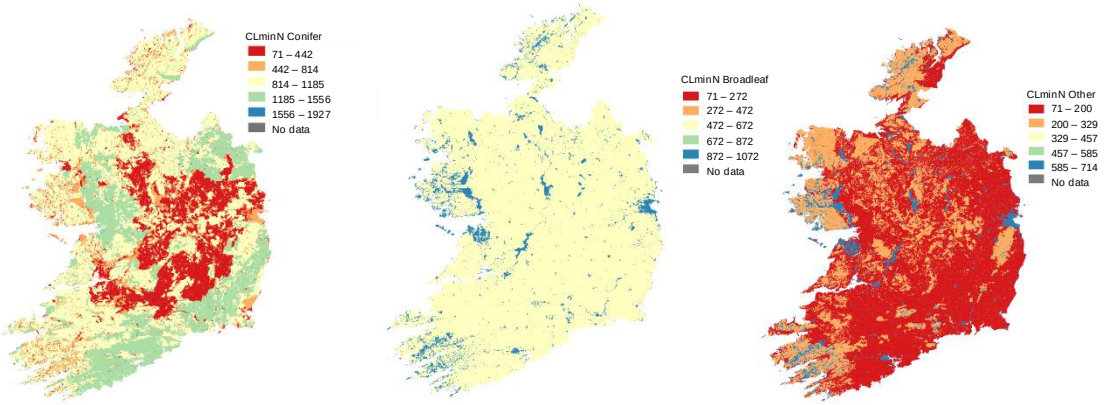

Figure 12. Left: ClminN for managed coniferous forest (eq $ha^{-1}year^{-1}$). Middle: ClminN for managed deciduous forest (eq $ha^{-1}year^{-1}$). Right: ClminN for all other habitats (eq $ha^{-1}year^{-1}$).

6. Modelling Pollutant Concentration and Deposition

6.1.Background

The EMEP-WRF model is an Atmospheric-Chemistry Transport Model (ACTM) based on the EMEP MSc-W model[13] , using the Weather Research Forecast (WRF)[14] model as the meteorological driver. The EMEP-WRF UK, also named EMEP4UK, is a photochemistry model able to represent the atmospheric composition in high detail, with a capability to simulate hourly air pollution interactions over decadal scales at high horizontal resolution. An output for the whole EMEP-WRF Irish domain (named EMEP4IE) at 1x1 km^2 grid resolution (Figure 13) was produced using the best available emission data (MapEIre) (see Section 6.2), with hourly averaged output for chemistry (EMEP4IE) and hourly for meteorology (WRF). The run produced a Republic of Ireland atmospheric composition of pollutant deposition for nitrogen and sulphur (including habitat specific depositions), and concentrations of ammonia and also PM_{10} for human receptor assessment in SCAIL-Agriculture.

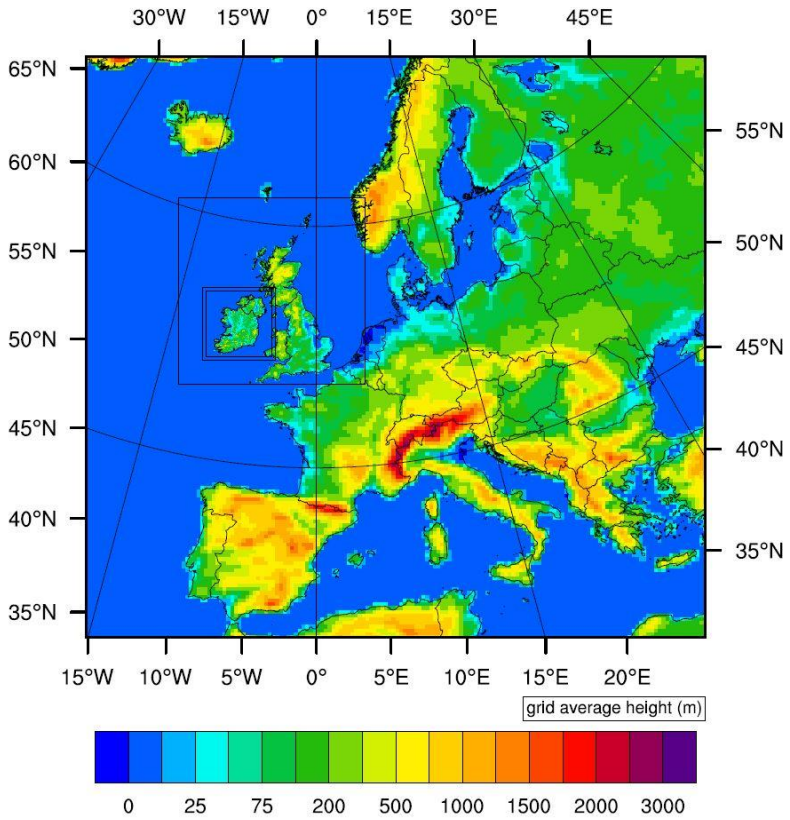

Figure 13. The model extent for Republic of Ireland (0.011° x0.011° (1.23 x 1.23 km^2 at the equator)) is nested within Britain and Ireland (0.033° x 0.033°) and the coarser EU model (resolution of 0.1° x 0.1°).

A typical set up for EMEP includes the following:

- Meteorology drivers from the Weather Research Forecast model (WRF 4.1.1 www.wrf-model.org)
- Vertical domain from surface (~45 m) up to an atmospheric pressure of 100hPa (~16 km altitude)

[13] https://github.com/metno/emep-ctm

[14] www.wrf-model.org

- Global emissions HTAPv2, ECLIPSE v6a, EU emission EMEP, UK emissions NAEI, Irish emissions compiled under MapEire[15] (e.g. NO_x, SO_x, NMVOC, NH_3 and $PM_{2.5}$) and the UN Framework Convention on Climate Change), and international shipping emissions from the Finnish Meteorological Institute.
- Detailed 3D meteorology output (e.g. wind speed, temperature, wind direction, precipitation)
- Detailed 3D outputs for more than 80 chemical species, including:
  - ammonia
  - nitrogen deposition
  - ozone
  - nitrogen dioxide
  - particulate matter
  - secondary inorganic and organic aerosols

6.2.Emission Models

Emissions of air pollutants in the Republic of Ireland were spatially distributed at a 1km x 1km resolution (TM65/Irish Grid projection) under the MapEire project for the years 2015 and 2016 (reporting submissions 2017 and 2018 respectively). The distribution was undertaken using the Danish SPREAD model (Plejdrup et al., 2018) which drew on both Irish and international sources of data. Following re-gridding to the required 0.1° x 0.1° resolution and required sectoral aggregation, the spatial distribution was reported to the Convention on Long-Range Transboundary Air Pollution (CLRTAP). The spatial distribution for the livestock sector was based on data from 2010 (CSO,2010), where the locations of intensive pig and poultry farms were of those identified up to 2015 (Kelleghan et al., 2020). As the latest emissions distributions at the time this project was completed for the Republic of Ireland were in 2016 (inventory submission 2018), sector level scaling using the totals in the national emissions inventory prepared by the EPA are submitted annually to the European Commission under NECD and to the UN-ECE under CLRTAP. For the EMEP4IE modelling, the MapEire emission grids were processed to a 0.01° x 0.01° resolution and the Selected Nomenclature for sources of Air Pollution (SNAP) reporting system. In the emissions maps that follow ammonia emissions are situated where the main agricultural areas are modelled to be, the highest emissions of oxides of nitrogen can be seen to follow the road patterns and urban areas while emissions of sulphur dioxide, much reduced from the 1990s, are situated over industrial sites (such as energy transformation industries etc.) but include urban areas due to residential heating.

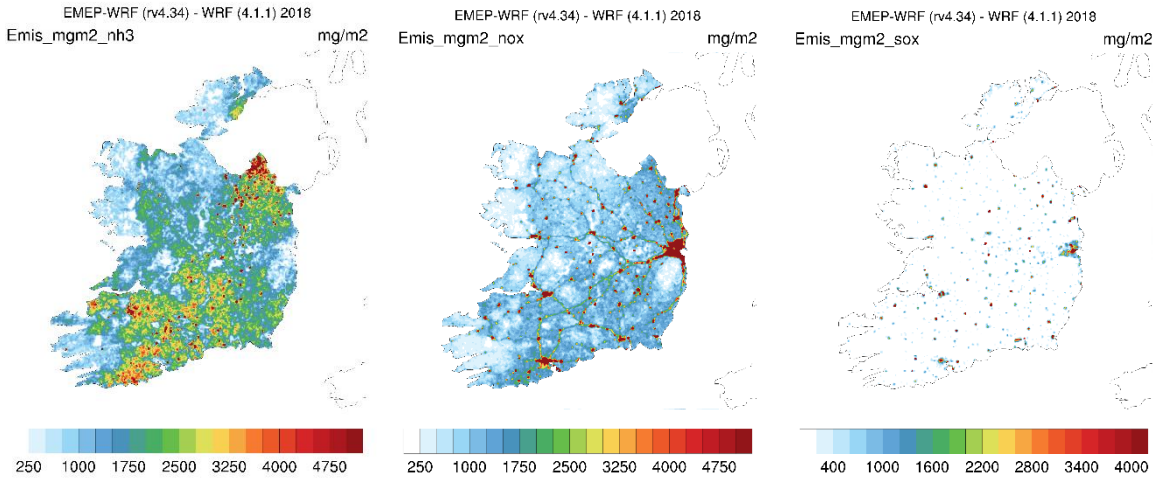

Figure 14. Left: Annual ammonia emissions for Ireland 2018 (mg m^{-2}) Middle: Annual oxides of nitrogen emissions for Ireland 2018 (mg m^{-2}). Right: Annual sulphur dioxide emissions for Ireland 2018 (mg m^{-2}).

[15] https://projects.au.dk/mapeire/

6.3.Concentration & Deposition Models

Concentrations of ammonia have been mapped over the last two decades. Maps have primarily been based measurements taken across the country and interpolating them via kriging[16]. Comparisons with previous maps are detailed in Appendix 5 Model Verification. Figure 15 highlights the increased spatial heterogeneity within the EMEP4IE model representing more the nature of ammonia hot-spots across the landscape.

Modelled ammonia concentrations shown in Figure 15, were compared with available ambient monitoring; this is detailed in Appendix 5. The correlation between the EMEP4IE modelled ammonia concentrations is moderate with that of the 1999 measurements (Doyle et al., 2017) shown below (R^2 0.49), but high with respect to the 2013-2014 measurements (R^2 0.79) and very high compared with the three Northern Ireland sites used for comparison as part of the UK ammonia network (R^2 0.89)[17].

Comparisons between EMEP4IE modelled wet deposition of ammonium (NH_4^+) and nitrate (NO_3^-) and measurements of ion rainfall concentrations are also detailed in Appendix 5. Current 2018 data for wet chemistry is limited to only four sites, therefore there are not enough points to derive a R-square value. Appendix 5 shows the EMEP4IE model outputs compared to the observation data. It should be noted that this analysis is based only on four monitoring locations. The National Ecosystem Monitoring Network (NEMN) monitors ecological impacts from nitrogen deposition. Increased monitoring under Ireland's NEMN will allow for better comparison between monitored and modelled data.

A full set of maps are available in Appendix 4 for other pollutants listed below;

- Annual ozone concentrations
- Annual nitric acid concentrations
- Annual PM fine concentrations (all PM <2.5 microns)
- Annual Primary $PM_{2.5}$ fine concentrations
- Annual sulphate concentrations
- Annual total nitrate concentrations
- Annual aerosol optical depth at 550 nm
- Annual deposition of isoprene (bio-natural)

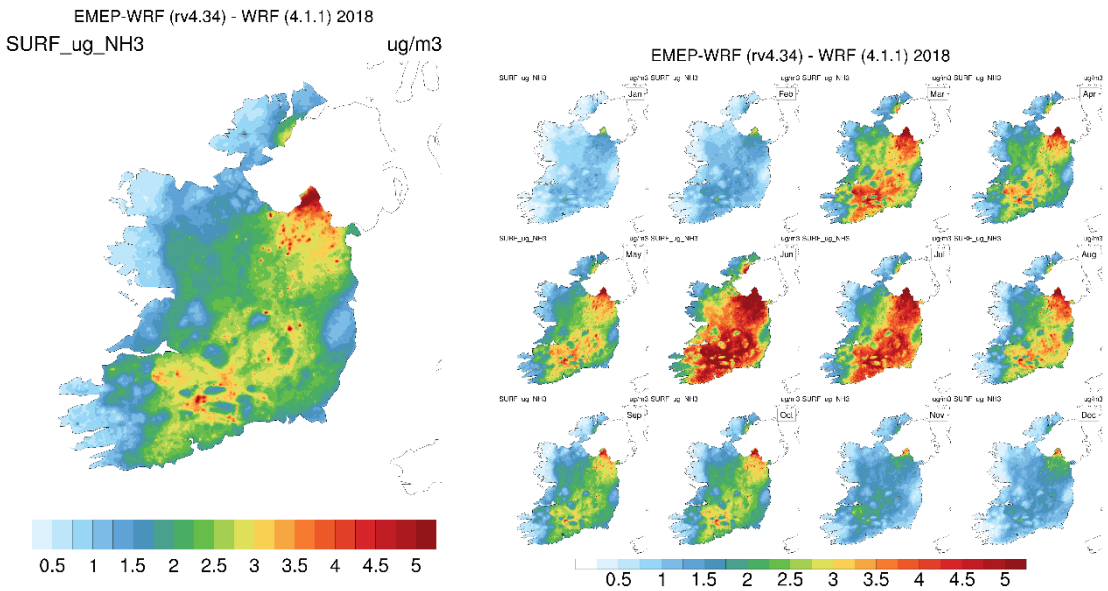

Figure 15. Left: Mean annual concentrations of ammonia (µg m^{-3}) across Ireland. Right: mean monthly concentrations of ammonia (µg m^{-3}) across Ireland.

[16] A method of spatial interpolation to estimate values at un-monitored locations.

[17] https://uk-air.defra.gov.uk/networks/network-info?view=nh3

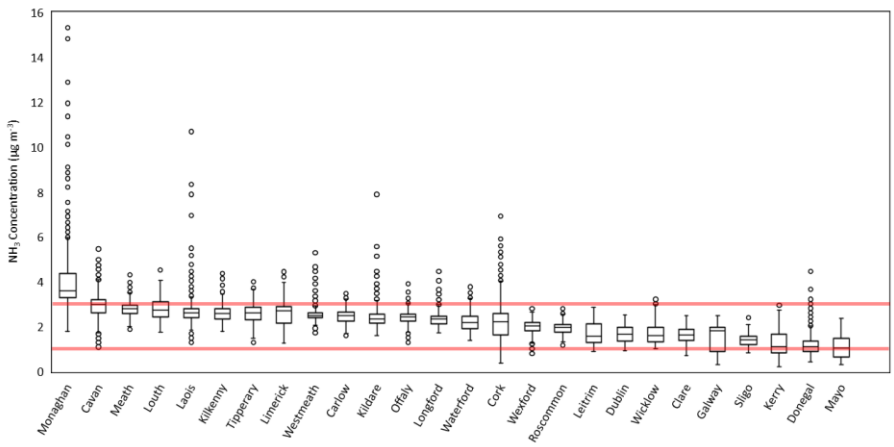

Figure 16. Modelled annual average ammonia concentrations summarised across each county in the Republic of Ireland. Red lines represent critical levels of 1 and 3 µg m^{-3}.

Figure 16 summarises concentrations present across the counties in the Republic of Ireland average annual concentrations are highest in Co. Monaghan and lowest in Co. Mayo. Despite a number of counties with grid cells exceeding the higher critical level of 3 µg m^{-3} for higher plants, Co. Monaghan is the only county which exceeds this on average across the county with an average concentration of 3.9 µg m^{-3}. Counties Cavan, Meath, Louth, Laois, Kilkenny, Tipperary, Limerick and Westmeath all come close with average concentrations across the counties above 2.5 µg m^{-3}, with Cavan being 2.8 µg m^{-3}. The average concentrations across all remaining counties exceeds the lower critical level of 1 µg m^{-3} with the lowest concentration in Co. Mayo of 1.1 µg m^{-3}. Spatial heterogeneity within the counties needs to be considered when carrying out critical level exceedance. As shown in Figure 15, even with 1 km grid resolution many locations within the counties can fall below the thresholds for impacts, thus site and habitat specific assessments are required to adequately gauge impacts. These are discussed further in Section 7 Exceedance of Thresholds.

Nitrogen and sulphur deposition that was modelled nationally for 2018 (Figures 17 – 21).

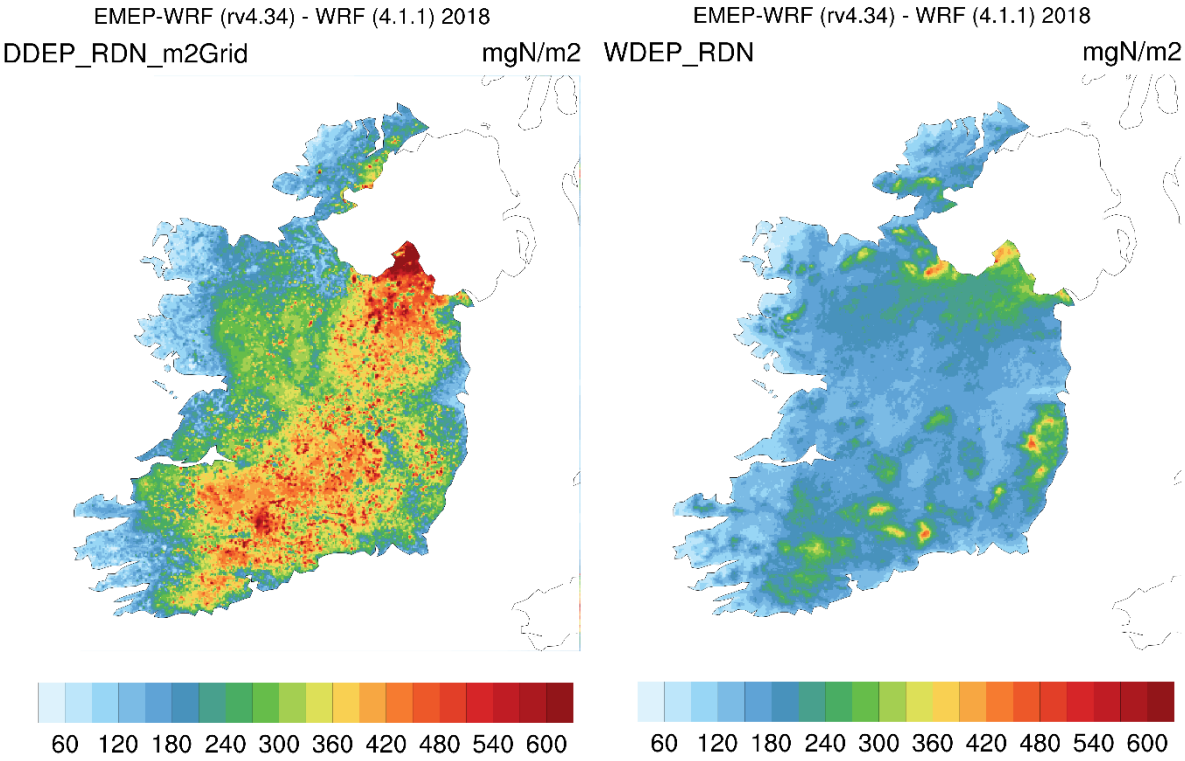

Figure 17. Left: Mean annual dry deposition of reduced nitrogen (mg N m^{-2} $year^{-1}$) across Ireland. Right: mean annual wet deposition of nitrogen (mg N m^{-2} $year^{-1}$) across Ireland. Deposition is presented in mg N m^{-2} $year^{-1}$, dividing by 100 will provide the values in. kg N ha^{-1} $year^{-1}$.

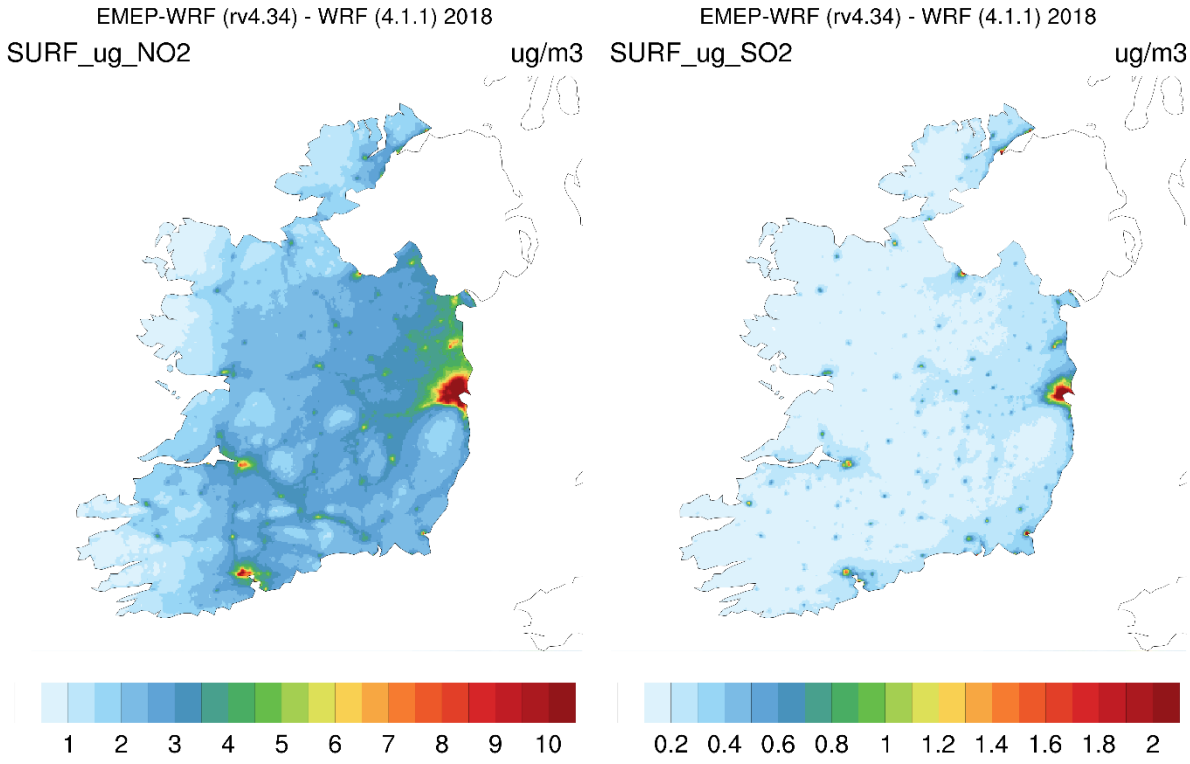

Figure 18. Left: Mean annual concentrations of nitrogen dioxide (µg m^{-3}) across Ireland. Right: Mean annual concentrations of sulphur dioxide (µg m^{-3}) across Ireland.

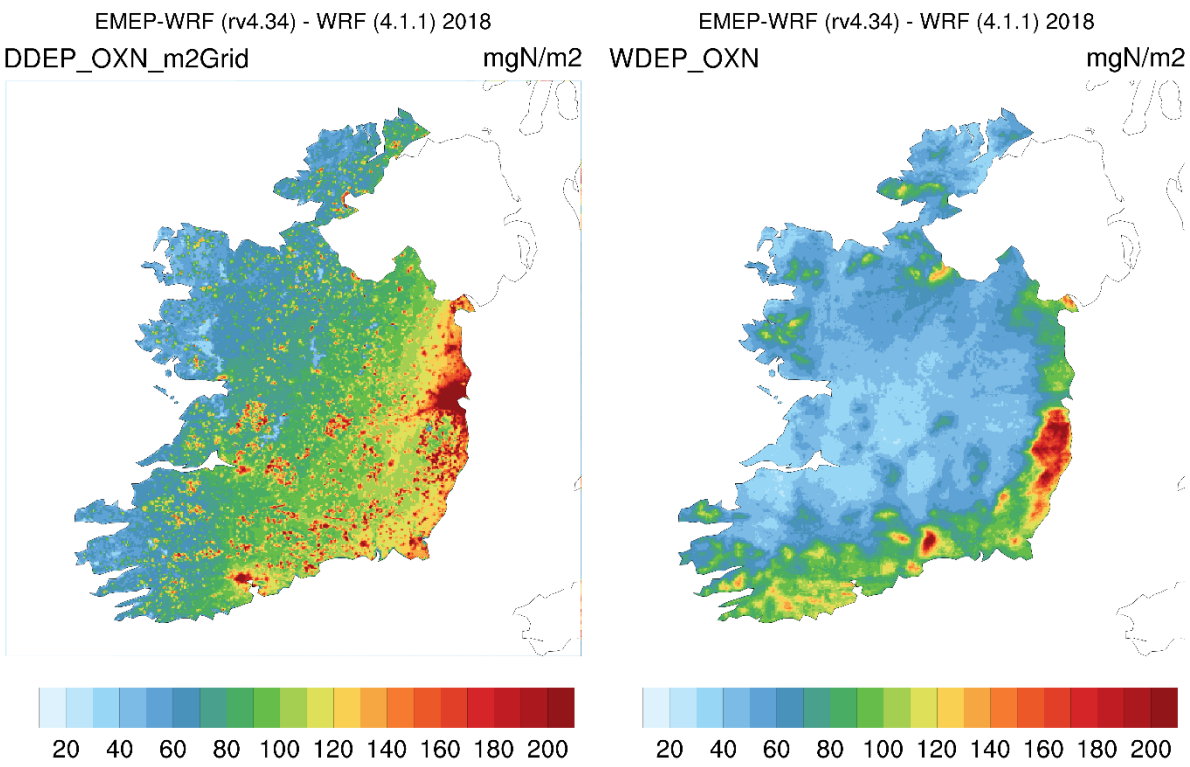

Figure 19. Left: Mean annual dry deposition of nitrogen oxides (mg N m^{-2} $year^{-1}$) across Ireland. Right: Mean annual wet deposition of nitrogen oxides (mg N m^{-2} $year^{-1}$) across Ireland. Deposition is presented in mg N m^{-2} $year^{-1}$, dividing by 100 will provide the values in kg N ha^{-1} $year^{-1}$.

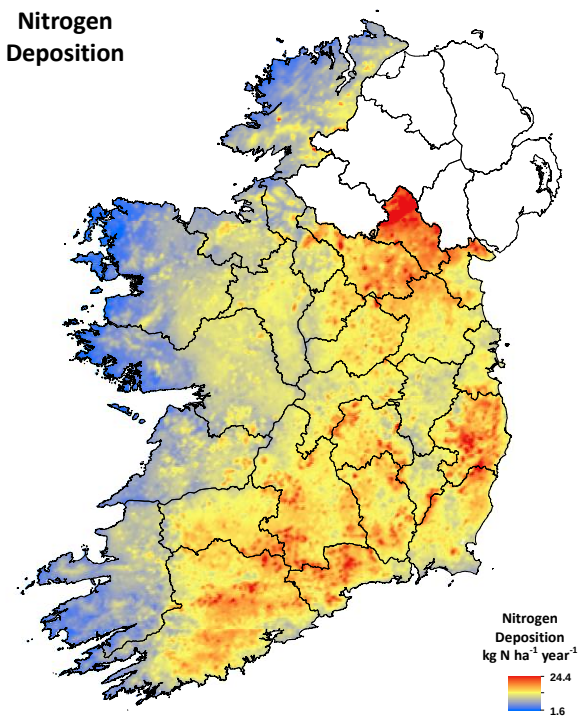

Figure 20. Total Nitrogen Deposition in kg N ha^{-1} $year^{-1}$ for 2018.

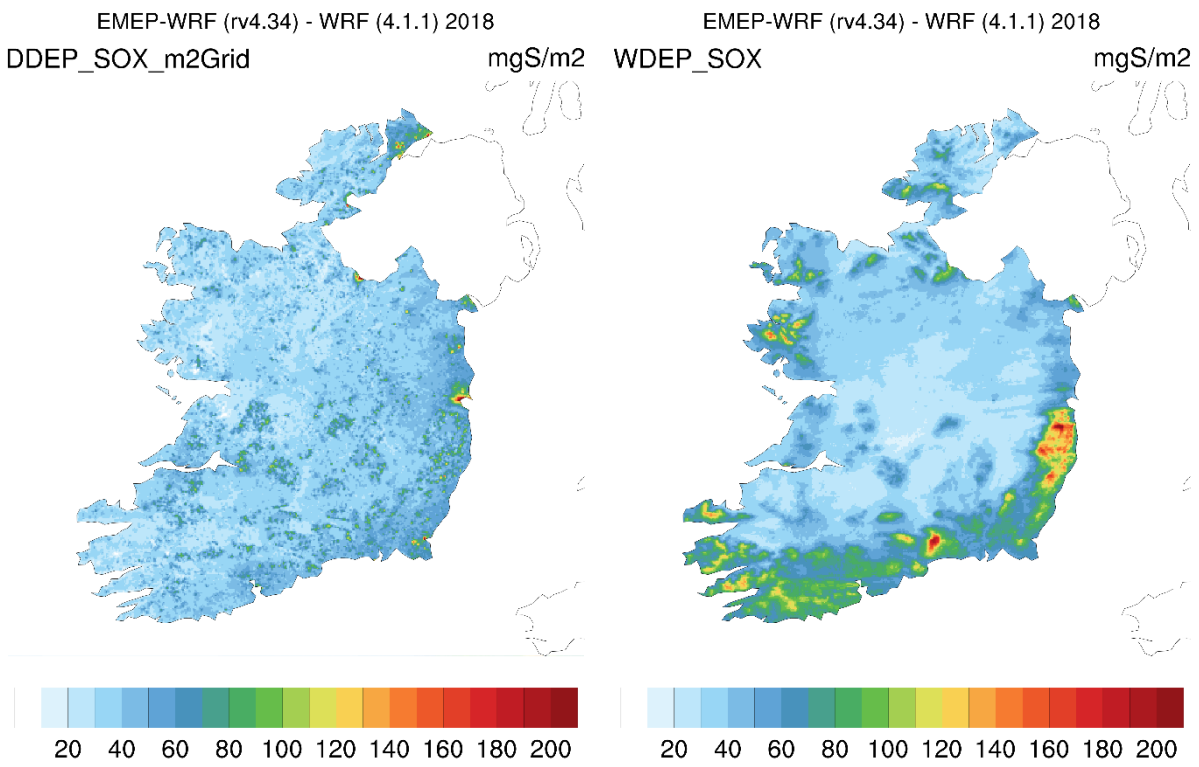

Figure 21. Left: mean annual dry deposition of oxides of sulphur (mg S m^{-2} $year^{-1}$) across Ireland. Right: Mean annual wet deposition of oxides of sulphur (mg S m^{-2} $year^{-1}$) across Ireland. Deposition is presented in mg S m^{-2} $year^{-1}$, dividing by 100 will provide the values in kg S ha^{-1} $year^{-1}$.

7. Exceedance of Thresholds

7.1. Critical Level exceedance for ammonia concentrations across Natura 2000 network

Atmospheric concentrations of ammonia across Natura 2000 sites in the Republic of Ireland are shown in Figure 22, with Table 4 summarising this. Table 4 presents concentration in terms of their critical levels; but does not consider the sensitivity of the sites. Work is ongoing to develop Natura 2000 site specific thresholds for Ireland, funded by the EPA. Once this data is available, they should be assessed against ammonia concentration and nitrogen deposition models carried out as part of this project. For Table 5 the data is further divided into the percent of sites which at some location thereon, exceeded the thresholds for impact and the percent of the full network exceeding thresholds. Noting, with improved modelling the estimated number of Natura 2000 sites exposed to concentrations above 1 µg m^{-3} has increased from 60% during previous assessment (Kelleghan et al., 2019) to 80.9% during this assessment.

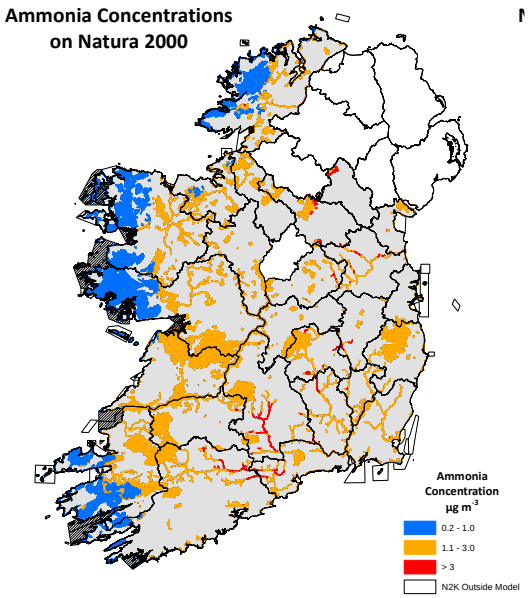

Figure 22. EMEP4IE modelled Natura 2000 site exceedances of critical levels for atmospheric ammonia.

Table 4. EMEP4IE modelled critical level exceedances across Natura 2000 sites which overlap with output model.

	Critical level	Percent (%)	
	µg m^{-3}	Special Areas of Conservation	Special Protection Areas
Sites with an exceedance	1	80.9	77.7
	3	3.8	8.8
Proportion of network exceeding	1	40.2	82.5
	3	0.7	0.9

7.2. Critical Load exceedance for nitrogen deposition at SACs

To be able to estimate the impacts of air pollutants on designated sites, the notified interest features (i.e., the features for which the site is designated) need to be assigned the most relevant critical load. The site-relevant critical load (SRCL) for a designated site links the habitat feature interest to a suitable empirical critical load class based on EUNIS. Revisions to the recommended empirical critical loads were applied to all habitats based on Aherne et al., (2021). The recommended values from Aherne et al., (2021) were based on two approaches to assessing the influence of nitrogen deposition on plant species diversity within Annex I habitats: a gradient approach (threshold indicator species analysis) and an approach using the PROPS species-niche model. Annex I habitats have been assigned critical loads from previous work and through site

relevant critical loads under the UK Air Pollution Information System (APIS) tool and SCAIL-Agriculture. Based on Aherne 2021 these new revisions have been applied to all Annex I habitats in Ireland as set out in Appendix 6. Where Aherne has not given a suitable critical load APIS values have been assigned. Some habitats were deemed not to be sensitive to nitrogen inputs. These were mainly habitats submerged (or partially submerged) by tidal waters, and some river and riverine habitats where other nutrient inputs are more dominant. There are a few habitats that are sensitive to atmospheric inputs of nitrogen but no comparable empirical critical class can be assigned. A full list of Annex 1 habitats, their names and links are given in Appendix 6.

The EMEP4IE modelled data for total nitrogen deposition (kg N ha^{-1} $year^{-1}$) was compared with the empirical critical loads for SAC Annex I features outlined in Appendix 6. The EMEP4IE 1km grid for total nitrogen deposition was applied over all of the SAC boundaries for Ireland using the National Parks and Wildlife Service Designation Viewer[18]. Total nitrogen deposition for three vegetation types (deciduous, semi-natural, and an area weighted grid average of all other habitats which includes arable, water and urban surfaces) were used by matching to the habitat type. Grid-average deposition was used as a default for comparing freshwater habitats as no unique deposition set was available for this habitat type. It should be noted that grids with urban and arable land use within the grid cell will receive less deposition than unfertilised habitats (e.g. habitats at protected sites), and grid-average deposition is generally less than the deposition to short-vegetation. However, outside these areas using the grid-average was seen as a good proxy for freshwater habitats to obtain suitable statistics for exceedance calculations. Freshwaters themselves are flat surfaces and deposition to freshwaters are less than short-vegetation habitats.

Figure 23 shows SACs which are receiving reactive nitrogen deposition above and below their critical load. Where the critical load assigned is based on the most sensitive feature at each SAC site (i.e. the feature with the lowest minimum critical load). Areas of exceedance were calculated together with percentage area exceeded at each site based on total site area (hectares). This data is summarised in Table 5. Despite this being the most sensitive model yet produced for nitrogen deposition in Ireland there remains a potential loss of potential detail, as emissions are averaged over 1 km grids. Consideration should be given to site specific variation of nitrogen deposition, accompanied by habitat specific assessments. It is highly likely that deposition and exceedances across sites will be more spatially heterogeneous than within the 1 km grids provided.

[18] https://dahg.maps.arcgis.com/apps/webappviewer/index.html?id=8f7060450de3485 fa1c1085536d477ba

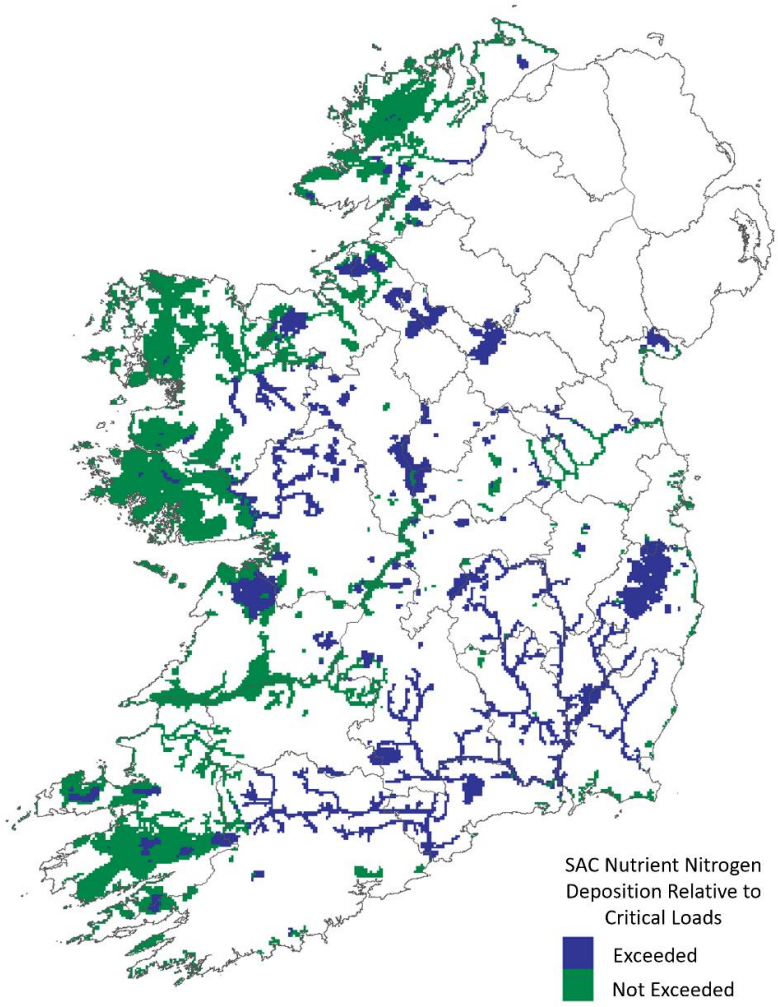

Figure 23. Critical Load exceedance across the SAC network (kg N ha^{-1} $year^{-1}$). Blue cells indicate an exceedance of the empirical nitrogen critical loads.

Figure 23 shows the exceedance of critical loads for reactive nitrogen across the SAC network with blue indicating exceedances. In general, sites to the east of the country and midland areas are exceeded while in general to the west side of the country they are not exceeded.

Table 5 shows the number and area of sites exceeded for nitrogen deposition. A total of 439 SAC sites are designated across the Ireland with 408 of those having an Annex I habitat – the other 31 sites had only Annex II species listed. 327 sites had at least one habitat sensitive to nitrogen deposition and of those 128 had part of its site exceeding the critical load for the most sensitive feature. For some sites there were occasionally more than one habitat with the minimum critical load at a site. Just under 40% of SACs with sensitive habitats exceeded their critical loads, which **is 29% of the entire SAC network. The total** area exceeded was just under 200k hectares representing 11% of the SAC network. Though many sensitive Annex I habitats may represent relatively small areal coverage, specifically active raised bogs which are particularly sensitive, in areas likely to be impacted and represent only a small proportion covered by the SAC network.

Table 5: Critical load exceedance of SACs across Ireland, based on Figure 23.

Total SACs	439
SAC with Annex 1 Habitats	408
Number of nitrogen Sensitive Sites	327
Sites Exceeded based on most sensitive habitat	128
% of sensitive sites exceeded	39%
% of entire SAC network exceeded	29%

7.3. Critical Load exceedance of selected habitats

Once habitat specific critical loads have been set (e.g. Figures 4 and 5), the total nitrogen deposition model (Figure 20) was used to assess selected habitats which receive sufficient nitrogen deposition to illicit an impact. Selected habitats include bogs, heaths, seminatural grasslands, marshes, fens, sand dunes, woodlands & forests. Figure 24 below shows the exceedance of both empirical and mass balance nutrient nitrogen critical loads for all habitats assessed within this report. This highlights 36% of the area selected habitats occupy, exceeds its critical load for nitrogen deposition.

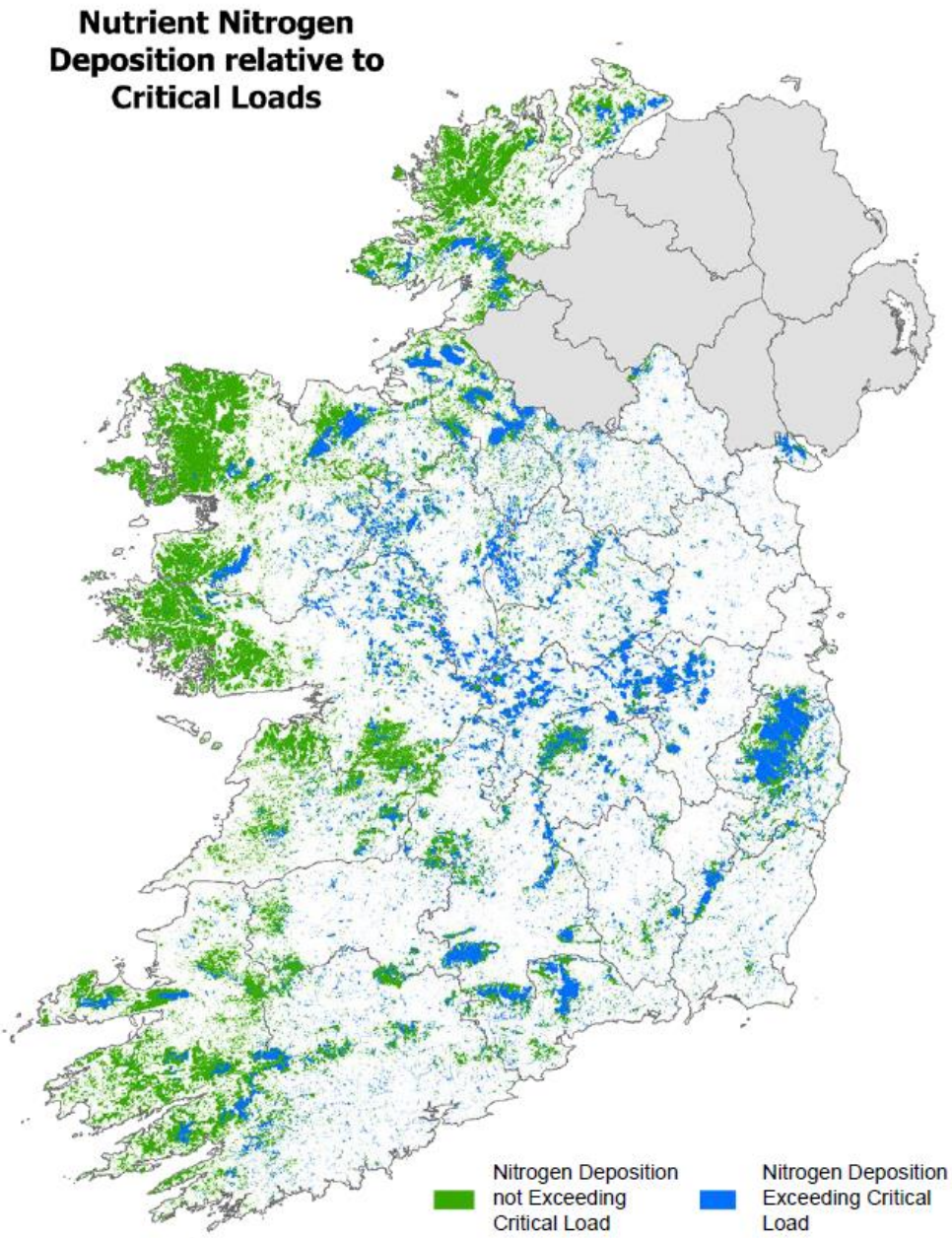

Figure 24: Above and below exceedance of both empirical and mass balance nutrient nitrogen critical loads for all habitats assessed.

8. Conclusions and Recommendations

8.1. Significance of project

This report highlights the number and area of SACs sites exceeded for atmospheric nitrogen deposition. A total of 439 such sites are designated across Ireland with 408 of those having an Annex I habitat – the other 31 sites had only Annex II species listed. A total of 327 sites had at least one habitat sensitive to nitrogen deposition and, of those, 128 had part of its site exceeding the critical load for the most sensitive feature. For some sites there were occasionally more than one habitat with the minimum critical load at a site. Just over 29% of SACs exceeded their critical loads. Critical loads were exceeded over 36% of the area selected habitats occupied (including habitats outside the Natura 2000 network). Similarly, 81% and 78% of the SAC and SPA network were modelled to exceed the critical level for atmospheric ammonia of 1 µg m^{-3}. The critical level for higher plants was modelled to exceed 4% and 9% of SACs and SPAs respectively.

Outputs from this project have already been adapted into SCAIL-Agriculture, a tool used to assess ammonia contribution of EPA licensed pig and poultry farms to Natura 2000 sites. The ammonia concentration and nitrogen deposition models have been integrated into this tool to improve environmental assessments by using a more realistic model for background concentration and deposition. This is relevant to the EPA licensing team, who review and approve assessments of such developments under IPC and IED. This is a requirement under the EU Habitats Directive (92/43/EEC), as sources of ammonia need to be assessed in light of impacts the site is already receiving, specifically under cumulative impacts. While this work focused on SACs where the qualifying features themselves can be sensitive to nitrogen deposition, further consideration should be given to potential secondary impacts to both species within SACs and birds protected within SPAs.

Other models generated through this project should be considered as part of future relevant projects, including models of; annual ozone concentrations, annual nitric acid concentrations, annual PM fine (all PM < 2.5 microns) concentrations, annual primary $PM_{2.5}$ concentrations, annual sulphate concentrations, annual total nitrate concentrations, annual aerosol optical depth at 550 nm and annual deposition of isoprene (bio-natural).

8.2. Improve concentration and deposition modelling

The national ammonia concentration map, and subsequent nitrogen deposition map were derived from the EPA-funded gridded emission data submitted under CLRTAP, developed under the MapEire project. Though the emissions had been updated to represent those of 2018, updated spatial distribution of livestock through the 2020 Census of Agriculture needs to be incorporated into future models. A Department of Agriculture, Food and Marine funded research project (entitled 'Abating Ammonia in Agriculture') is currently compiling updated gridded emission data for livestock emissions using the recently captured 2020 census data.

These models need to be assessed against designated critical levels and loads for Natura 2000 sites, set by National Parks and Wildlife Service. These thresholds are currently being set through collaboration between the EPA and the NPWS by inclusion of Ireland within the Air Pollution Information System (APIS). The output of such an assessment should be integrated into an open access interactive map, either on the EPA map viewer, or potentially feature on the development of the NEMN webpage. The site-specific critical levels and loads data will be made available through the APIS website and will be available for future assessments. Critical level and load exceedances of Natura 2000 sites have been generated and are publicly available to better inform environmental assessments through APIS.

8.3. Incorporate new landcover map

This work utilised the best available habitat maps at the time in order to apply critical loads across the country, principally the Habitats Assets Register from the National Parks and Wildlife Service. The more detailed the national habitat map, the more precisely habitat specific critical loads for impacts can be applied. Updated critical load maps using national land use maps generated using the new EPA/ Tailte Éireann National Land Cover Map will improve the assignation of critical loads across Irish habitats. Efforts should be made within

submissions under CLRTAP to increase the resolution of mapping available to ensure all appropriate habitats are adequately assessed for impacts.

8.4. Critical loads for freshwater ecosystems

Atmospheric pollution by nutrient nitrogen is generally considered to have limited effects on freshwater systems (because many such systems are phosphorus-limited, and because nitrogen pollution of freshwaters is mainly due to leaching of nitrogen through soils), so nutrient-N critical loads will not be calculated for freshwaters. Acidity pollution of freshwaters is however an important and ongoing issue. Acidity critical loads have previously been calculated for a selection of acid-sensitive freshwater sites under previous EPA contracts. While this does not include all acid-sensitive freshwater sites in Ireland, the network is representative, and provides good links to empirical data. This was not carried out as part of this project, but should be considered for future work. Similarly, the relative contribution of atmospheric deposition and runoff to freshwater habitats such as lakes and rivers needs to be developed further; clarifying their contribution to freshwater declines across the country.

8.5. Improved model verification

Where this work has modelled ammonia concentration and nitrogen deposition across the Republic of Ireland, the National Ecosystem Monitoring Network (NEMN) a requirement under the National Emissions reduction Commitment Directive (2016/2284/EU) co-ordinated by the EPA will monitor these impacts on sensitive ecosystems. Such monitoring can be used to validate future models, improving our understanding of air pollution effects to ecosystems in Ireland. Concentration, deposition and critical load models generated by this project can also be used to improve the required risk-based design of sites included within the NEMN. The nitrogen deposition models used within the initial NEMN design were on an 8.3 km^2 resolution, where this model is 1 km^2. As ammonia and, as a result, nitrogen deposition are so spatially variable, increasing the resolution will improve the appropriate assignation of risk across habitats. Such modelling is an important method to extrapolate monitoring taking place as part of the NEMN across all sensitive Irish ecosystems. Despite this being the most sensitive model yet produced for nitrogen deposition in Ireland there remains a potential loss of potential detail from averaging emissions over 1 km grids. Consideration should be given to site specific variation of nitrogen deposition, accompanied by habitat specific assessments. It is highly likely that deposition and exceedances across sites will be more spatially heterogeneous than within the 1 km grids provided.

9. Acknowledgements

This report was written for the EPA as part of an EPA funded contract covering the Determination of Critical Loads for Ireland and a call for data from the Coordination Center for Effects (CCE) of the International Cooperative Programme on the Modelling and Mapping of Critical Levels and Loads, and Air Pollution Effects, Risks and Trends. The authors would like to acknowledge the support of the EPA contacts Patrick Byrne, Brendan Wall, Yvonne English, Aisling O'Connor, Niamh O'Donoghue, Bernard Hyde, Ian Marnane, and Brian Donlon.

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11. Appendix 1. Receptor Ecosystem Classification

The Habitat Asset Register was translated into Level 1 EUNIS categories for Irish habitats based on most similar habitat description. The subsequent process of sorting and aggregating these habitats went through a series of stages (Figure 25):

i. Habitats that are not deemed sensitive to nutrient nitrogen and acidity were excluded.
ii. Simple associations with relevant critical load habitats were made.
iii. Using the national soil map natural grasslands were assigned as calcareous or acid grassland.
iv. Woodlands.
v. Oligotrophic waters.
vi. Moss and lichen dominated ridges.

Habitats which are not sensitive to nitrogen deposition were first removed from the dataset, these included built environment, improved agricultural grassland, bare ground, etc. A full list of habitats deemed “not sensitive” is presented in. A number of habitats from within the habitats assets register were combined in order to form a habitat type to which a relevant critical load could be applied, including for example saltmarsh, intertidal flats and salt meadows to which the critical load for salt marsh was applied. The same was done for sand dunes, where beaches, dunes, sands, sand dune and machair were combined. Similarly, blanket bogs, peat bogs and raised bogs were combined and simplified to bogs. For both dry heath and wet grassland, habitats were already mapped for these definitions and so amendments were necessary. Calcareous and dry acid grasslands required further analysis, where habitats classed as natural grasslands, semi-natural dry grassland or semi-natural grassland were combined and overlaid with soil types; the combined grasslands overlaying calcareous soils were identified as calcareous grassland, and dry acid grassland over other soil types.

In order to apply empirical critical loads to woodlands and forests, the numerous different habitat types needed to be categorised into managed and unmanaged woodlands for both broadleaves and conifers. It was presumed any and all conifer plantations in Ireland are to some extent managed, hence the two relevant habitat types coniferous woodland and coniferous forest were combined to form managed conifers. Splitting broadleaf habitats into managed and unmanaged is slightly more complex, due to the diversity of associated woodlands. Initially, broad leaved forest, broadleaved woodland, mixed woodland and woodland were combined, these habitats were then overlaid with quadrats collected during National Native Woodland Surveys, pockets of woodland which had no quadrats and were therefore excluded from the native woodland survey were presumed to be managed. This approach was applied by Aherne et al. (2020) to also distinguish managed from unmanaged woodlands. The woodlands within which quadrats were collected, were subsequently combined with scattered woodland, transitional woodland scrub and wet woodland as habitats more likely to be unmanaged.

Oligotrophic waterbodies also required the application of other data sources in order to identify potential natural oligotrophic lakes. The decision to classify such habitats was based on underlying bedrock, where the bedrock underlying oligotrophic to mesotrophic waterbodies classified within Natura 2000 sites in Ireland were used to identify other waterbodies over the same bedrock type.

In order to identify areas where the critical load for moss and lichen dominated ridges could be applied, a combination was made of areas classed as being bare rock, vegetated rocky slope, vegetated scree, sparsely vegetated and alpine heath. A digital elevation model was then used to exclude any sections mapped as these habitats below 300m.

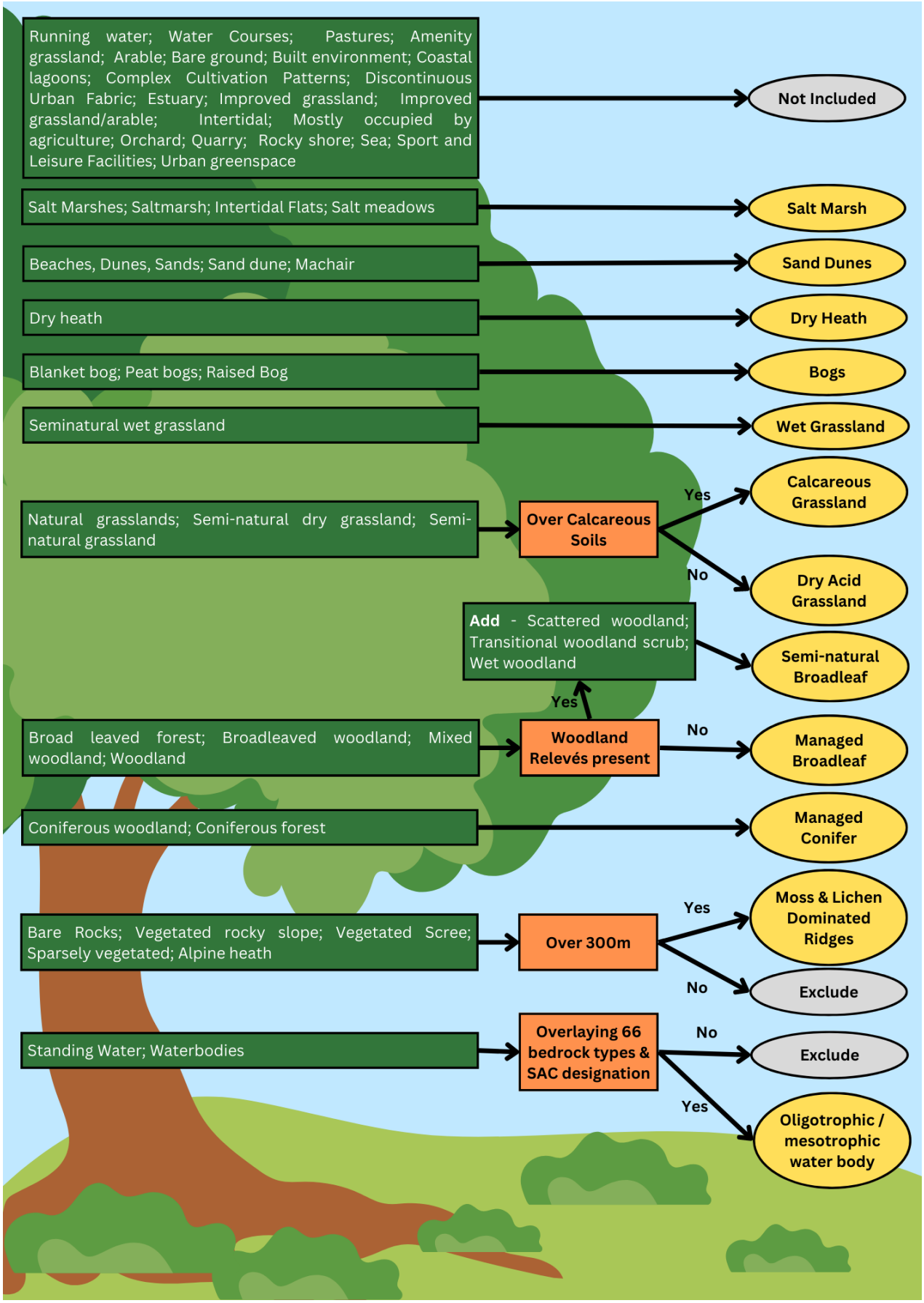

Figure 25. Process for assigning critical load habitats to the NPWS Irish Habitats Asset Register habitats.

Table 6. Habitat classes, with EUNIS codes, mapped for acidity and for nutrient nitrogen critical loads.

Habitat	EUNIS code	Mapped for nutrient nitrogen	Mapped for acidity
Bogs	D1	Yes	Yes
Dry Acid grassland	E1.7	Yes	Yes
Wet Acid grassland	E3.52	Yes	Yes
Dry Calcareous grassland	E1.26	Yes	Yes
Dry heath	F4.2	Yes	Yes
Wet heath	F4.11	Yes	Yes
Marsh and fen	D2	Yes	No
Moss and lichen-dominated mountain ridges > 300m	E4.2	Yes	Yes
Oligotrophic and Mesotrophic Water bodies	C1	Yes	Yes
Salt Marsh	A2.5	Yes	No
Sand Dunes	B1.4	Yes	No
Unmanaged Broadleaf Woodland	G1.8	Yes	Yes
Managed Broadleaf Woodland	G1	Yes	Yes
Managed Coniferous woodland	G3.1	Yes	Yes

12. Appendix 2. Assigning Critical Loads of Acidity for Mineral Soils Process

12.1. Assign Skokloster weathering classes

The Critical Loads Workshop at Skokloster (Nilsson and Grennfelt 1988) outlined a method to make rough estimates of the weathering rate of a mineral soil. While not suitable for detailed, or site-based estimation it is appropriate for such national assessments. The Skokloster approach assigns mineral soils to one of five classes, based on the dominant weatherable and weathering mineral. Approaches build on the ICP M&M Manual (CLRTAP 2017) Chapter V dated 18-September 2017 (Figure 26).

Table 7. Adapted from Table V.17 from the ICP M&M Manual (CLRTAP 2017) Chapter V dated 18-September 2017 showing weathering rates of certain soil types.

	% content of minerals	100%	30%	3%	0.3%
Mineral class	**Type of soils**	**Weathering, 10^3 eq ha^{-1} $year^{-1}$**			
Very fast weathering	**Calcareous soils, fine-grained dark mineral dominated soils, basic basaltic, mafic minerals**	25	15	10	3
Fast weathering	**Dark mineral dominated soils, basic basaltic, mafic minerals, traces of carbonate minerals from deeper layers**	15	10	3	0.3
Intermediate	**Fine-grained normal soils, brown soils, rich soils for agriculture, very fine-grained granitic soils**	5	2	0.2	0.05
Slow weathering	**Granitic and gneissic materials, most coarse soils. Old weathered soils**	2	0.6	0.2	0.02
Near inert	**Tropical weathered soils, quartzitic soils, high content of quartz and slow weathering minerals**	0.3	0.2	0.05	0.01

Critical-load ranges are assigned to the classes. Soil map units are described as soil associations, assigning the first-listed soil series, which occupies the greatest land area, as if it covered the full extent of that polygon. Outline criteria for inferring weathering rates are (1) rocks contributing to parent material, (2) soil type, with (3) landscape as a plausibility check.

Table 8. Skokloster classes with relevant parent material, soil type and weathering rates.

Class	Weathering	Rock influence in soil parent material	WRB	Landscape, Ireland
5	Very fast	Limestone, basalt	Rendzic Leptosol	Limestone plain, kames
4	Fast	Mixed lithologies	Cambisol, Luvisol	Fertile agricultural lands
3	Intermediate	Fine-grained granitic	Cambisol, Podzol	Foothills, siliceous
2	Slow	Granite	Podzol	Siliceous uplands
1	Near Inert	Quartzite	Leptosol	Devonian sandstone, Quartzite peaks
9	Not assessed			

Modifications of Skokloster classes are suggested in Table V.4 of the Mapping Manual (CLRTAP 2017), and are reproduced here. No modifications due to soil sulphate absorption capacity, base-cation deposition, low precipitation, or vegetation are suggested.

Table 9. Modifying factors adapted from Table V.4 of the Mapping Manual (CLRTAP 2017).

Modifying Factor	Effect on critical load	
	Decrease	Increase
Precipitation	High	Low
Vegetation	Coniferous Forest	Deciduous Forest
Elevation, slope	High	Low
Soil texture	Course-sandy	Fine
Soil drainage	Free	Impeded
Soil sulphate adsorption capacity	Low	High
Base cation deposition	Low	High

Following the sequence of the World Reference Base (WRB) key to Reference Soil Groups, the process of assigning WRB Reference Soil Groups (RSGs) to Skokloster classes is described here. The initial assignment is by of mineralogy of parent materials, and the dominating and most-weatherable minerals in the fine-particulate matrix and clasts. Modifications are made using criteria identified in Table 9 above.

Non-assessed classes In the Skokloster method, **Histosols** are not classified.

Anthrosols These soils are recognised as Anthropic subgroups only in the Teagasc soil map. The Ross Carbery Association is represented by an Anthrosol profile, with pH > 8.0 and sand, which coupled with the history of sanding of these soils, indicates an Anthrosol created by adding calcareous sea sand.

Technosols may be associated with mapped urban areas and assigned to Class 5 because settlement nuclei are typically located in low-altitude, low-rainfall, low-slope areas, commonly fluvial and estuarine sediments, and especially the widespread incorporation of artefactual materials especially lime building materials into anthropogenic deposits and observation of high pH in urban soils. Teagasc mapping does not deal with urban soils except as a miscellaneous category.

Leptosols may be divided into those derived from carbonate-bearing rocks, as Rendzic Leptosols, assigned to Skokloster Class 5, and those from carbonate-free and quartz-dominated rocks, Dystric Leptosols, in Skokloster Class 1. Areas on the soil map categorised as rock, and on limestone as interpreted from Geological Survey Ireland 500k mapping, are assigned to Class 5, while all other areas mapped as rock are in Class 1.

Podzols identified by Teagasc are assigned to Class 2 based on dominance of silica, and of slowly-weathering minerals derived from granite, gneiss, and schist (quartz, K-feldspar, and micas). The soils identified by Teagasc as Brown Podzolics, but which would be classified under WRB as Podzols, having a Bs but no overlying E horizon, are assigned to Class 3 as, while having similar parent materials, have been cultivated and limed, or, where identified with coarse texture, Class 2.

Gleysosols and Stagnosols Gley soils were initially separated between Class 4 where siliceous stones dominate, and Class 5 where limestone clasts dominate. Impeded drainage was used to modify those Stagnosol and Gleysol soils dominated by siliceous clasts by one class, so all the Gley soils are in Class 5.

Luvisols are assigned to Class 5 on the basis of carbonate presence. Soil thickness, lowland landscapes, and free drainage would all support the presence of Luvisols in Class 5.

Cambisols are separated and divided into Class 5 where there is evidence of carbonate presence, and Class 4 where carbonates are not indicated. Modification of –1 class is applied for coarse texture. Stagnic subgroups are not modified on the basis of drainage, as this distinction is slight in these soils, and they tend to be in low-rainfall areas.

Arenosols are assigned to Class 5 as having a carbonate content due to presence of seashell fragments. They are also typically thick, freely-drained soils. Arenosols are found in coastal locations, and typically have at least a small proportion of calcareous particles derived from seashells. This material was widely used for land improvement in the near-coastal areas of the south and west during the 19th century, giving Anthrosols from former weathered soils of many types. An area in Co. Wexford may qualify as Arenosols, derived from sands of mixed lithology and low lime content. They are assigned to Class 2 on the basis of low lime, low pH and CEC, and excessive drainage; this area requires clarification for mapping, as there is a mismatch between the soil map and the survey report from which it apparently derives, with the soil map showing Rendzinas and pH above 8, while the Wexford soil bulletin shows pH 5 with Podzols in unmanaged areas.

Fluvisols include river, lake, and marine alluvium, and are assigned to Class 5. These are all strictly terrestrial soils within the scope of the soil map, with subaqueous soils not recognised.

Regosols include mechanically redistributed soils in urban areas, which are included in Class 5 based on low landscape positions, and thick soil cover. No soil association on the soil map recognises these soils.

Critical load ranges (mol± ha^{-1} $year^{-1}$) associated with dominant mineral classes (also shown as Table V.2 from the Mapping Manual (CLRTAP 2017) with). Values are shown in Table 10 and Figure 26. Mapping values are the mid-points for classes 2–4 but for class 5 it is set to 4000 eq ha^{-1} yr^{-1} for carbonate type soil.

Table 10. Assigned weathering rates to Skokloster classes

Skokloster class	Minerals controlling weathering	Usual parent material Weathering rate	(molc ha^{-1} $year^{-1}$)	Mapping keq ha^{-1} $year^{-1}$	Mapping eq ha^{-1} $year^{-1}$
1	Quartz K-feldspar	Granite quartzite	< 200	0.1	100
2	Muscovite plagioclase biotite (<5%)	Granite gneiss	200–500	0.35	350
3	Biotite amphibole (<5%)	Granodiorite greywacke shale schist gabbro	500–1000	0.75	750
4	Pyroxene epidote olivine (<5%)	Gabbro basalt	1000–2000	1.5	1500
5	Calcite dolomite	Limestone marlstone	> 2000	4.0	4000

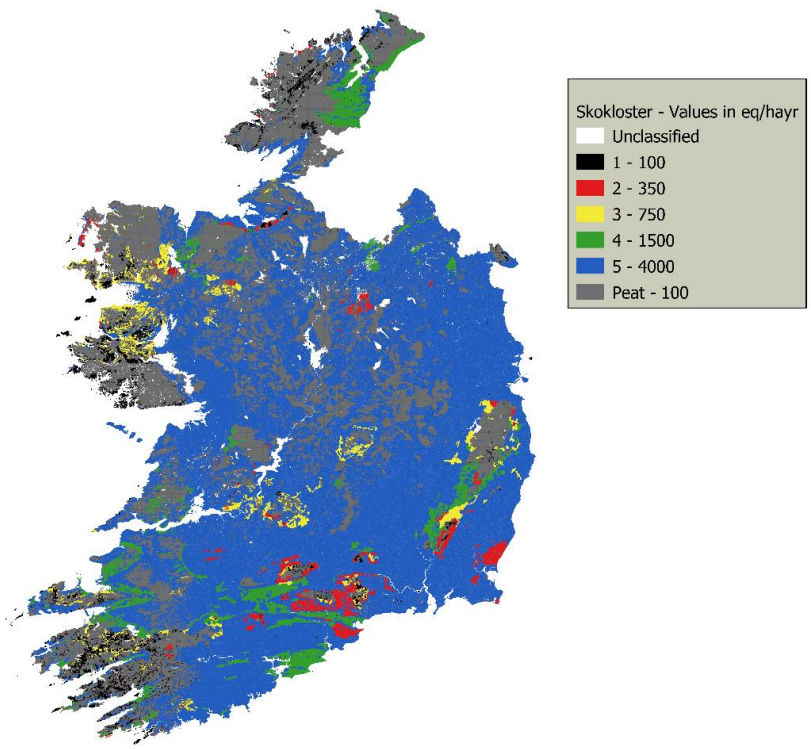

Figure 26. Skokloster map for Ireland with classes.

12.2. The critical limit for leaching of Acid Neutralising Capacity

The Acid Neutralising Capacity (ANC) leaching is chosen as the chemical criterion set with a specified limit to protect the receptor ecosystem from long-term damage. A critical load of potential acidity is therefore obtained by setting a critical ANC leaching value - a value above which harmful effects occur (Aherne, 2000).

$$\boldsymbol{ANC_{le,crit}} = -\boldsymbol{Q} \times ([\boldsymbol{AL}]_{\boldsymbol{crit}} + [\boldsymbol{H}]_{\boldsymbol{crit}}) \qquad (6)$$

Where:
[Al]crit = critical aluminium concentration
[H]crit = critical hydrogen ion concentration,
[square] brackets denote concentrations (molc m^{-3}). Critical refers to a critical limit, above which damage occurs.
Q = Precipitation surplus is the water leaving the root zone or net water flux through a soil horizon (m^3 ha^{-1} $year^{-1}$).

The H^+ concentration limit was set to a pH of 4.2 with pristine conditions seen as pH 5.0 (Aherne, 2000) and that at pH lower than 4.2, Al_3^+ is brought into solution (Ulrich 1987). The H^+ concentration limit can then be used to estimate the Al_3^+ critical limit via the gibbsite equilibrium relationship (Werner and Spranger, 1996):

$$[\boldsymbol{AL_{crit}} = \boldsymbol{K_{gibb}} \times ([\boldsymbol{H}]_{\boldsymbol{crit}})^{\boldsymbol{3}} \qquad (7)$$

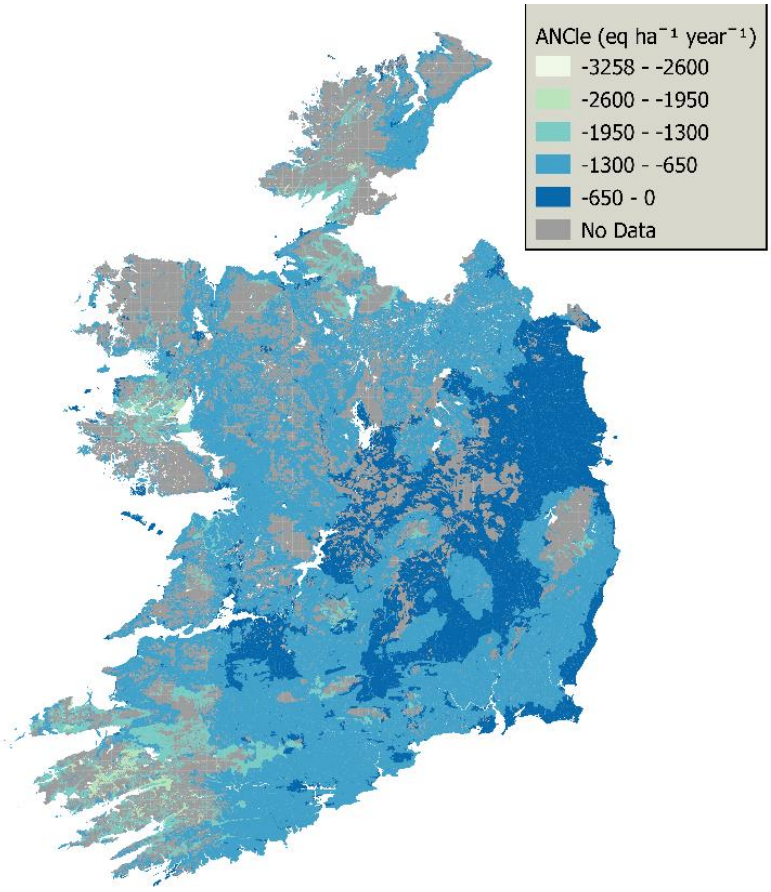

Figure 27. $ANC_{le,crit}$ values for Ireland. Note the values are negative. 'No Data' areas include Peat soils which uses a different method of critical load for acidity calculation. White areas are freshwaters.

12.3. The Gibbsite Equilibrium Constant

Following V.3.2.3.1 of the Mapping Manual (CLRTAP, 2017) Chapter V, the equilibrium constant that relates aluminium concentration in soil solution to soil-solution pH, the Gibbsite equilibrium constant, varies with soil type, or more specifically with organic content of soil types. Transformations of K_{gibb} are $-pK_{gibb}$ and $log_{10}KAl_{ox}$, the latter numerically identical.

On this basis of organic content, and with interpretations noted below for some soils, K_{GIBB} and $logKAl_{OX}$ are assigned to Irish Soil Information System soil map units using the field Assoc_1 (Figure 28).

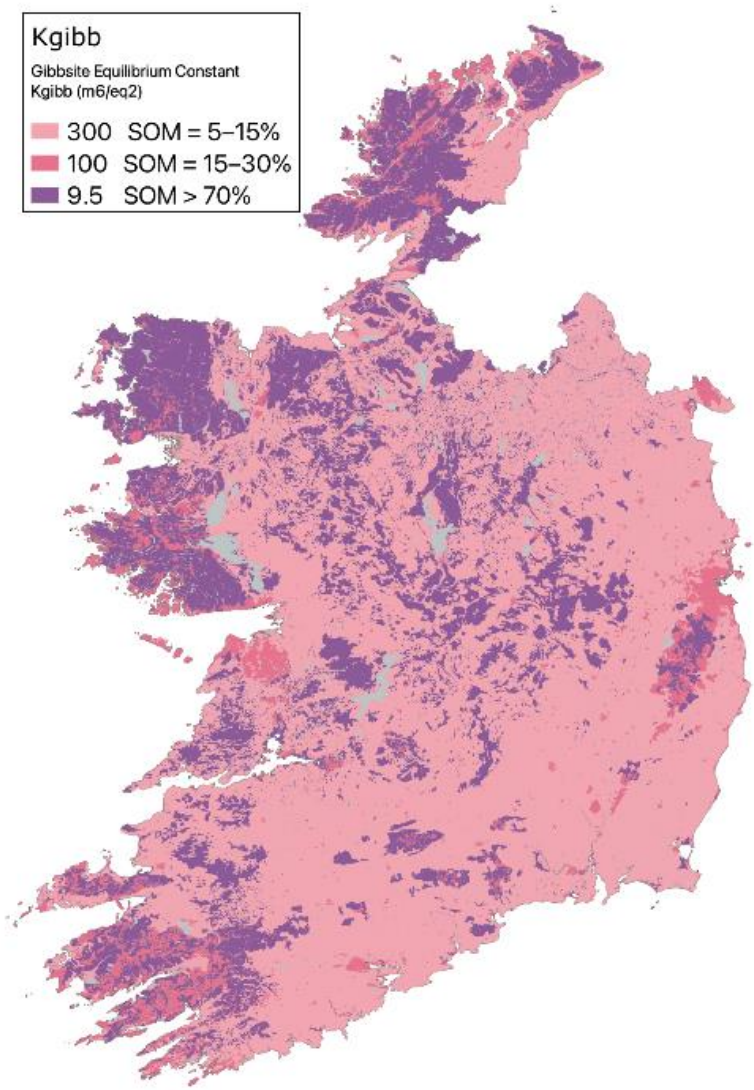

Figure 28. Kgibb equilibrium constant values based on three types of soil organic matter. Units are m^6 eq^-

13. Appendix 3. Calculation of $CL_{min}N$ & $CL_{max}S$

13.1. Calculation of $CL_{max}S$

The acceptable critical load for acidity (CL(Acact)) is defined by the critical loads calculated in the previous sections for peat and mineral soils and shown in Figure 27. Non-marine base cation deposition (BC_{dep}) has been calculated from sampling points of base cation ion concentration in rainfall and interpolated across Ireland. Filter factors are applied for certain vegetation types – forest (x2), heath (x1.5) and 'the rest' (x1) (Aherne 2000). Non-marine base cations are then calculated based on the amount of sodium in rainfall via a sea-salt correction factor. Base cation uptake (BC_u) (eq ha^{-1} $year^{-1}$) for managed forests (conifer and deciduous) was estimated from the minimum of base cation availability (BC_{avail}) and base cation net uptake (BCnet). BC_{avail} is the available base cation flux estimate according to:

$$\boldsymbol{BC_{avail}} = \boldsymbol{BC_{we}} + \boldsymbol{BC_{dep}} + \boldsymbol{BC_{leaching}} \qquad (8)$$

Where:
BCleaching was set equal to 0.002 eq m–1 (see CLRTAP, 2017)

BCnet is the net permanent uptake removal for managed forests (coniferous, deciduous, and mixed) under stem only harvesting, according to:

$$\boldsymbol{BC_u} = \mathbf{YC} \times \text{fÏ} \times \boldsymbol{C_{Ca}} \qquad (9)$$

where :
BCu= nitrogen uptake (eq ha^{-1} yr^{-1})
YC is yield class or annual growth rate (m3 ha-1 year-1)
fÏ is the density of stem wood (kg m3)
CCa is the content of calcium in stems (molc kg-1) . All base cation uptake was assigned to calcium uptake

BCu for managed deciduous is based on Aherne 2017 where YC = 6; *f*Ï = 550 kg m^{-3} and C_{ca} = 0.062 eq kg^{-1}. Base cation uptake by conifer forests was based on calculations from the ForSite project (Johnson, 2016) where calcium uptake represented the above-ground biomass above-ground whole-tree harvesting (Figure 29). For native woodlands, grasslands, bogs (lowland, upland) and heathlands an uptake of 45 eq ha^{-1} a^{-1} was set to account for uptake from grazing.

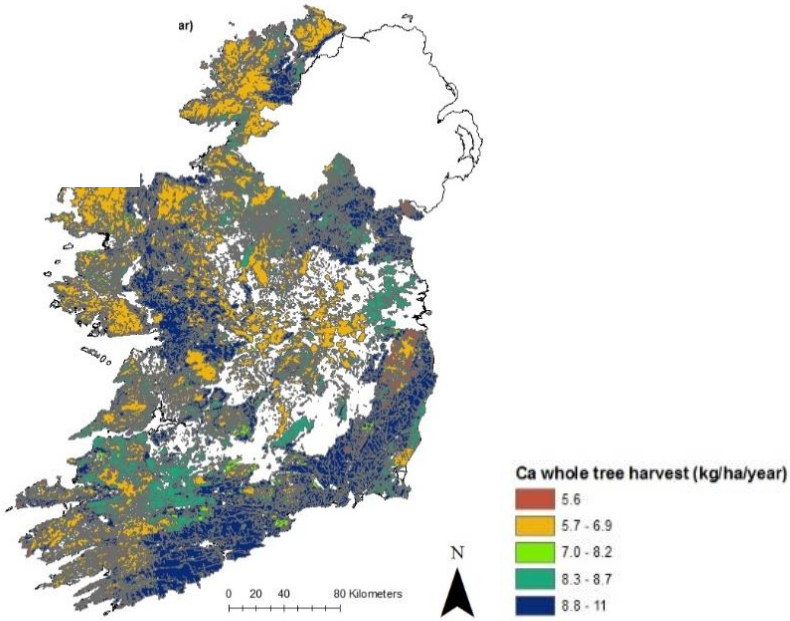

Figure 29: Calcium uptake in woody stems by managed coniferous forest (Johnson et al 2016).

13.2. Calculation of $CL_{min}N$

$CL_{min}N$ is the sum of the long-term nitrogen removal processes from the soil and vegetation, and is calculated as:

$$\boldsymbol{CL_{min}N = N_u + N_i} \qquad (10)$$

Where:
Nu = nitrogen uptake (removal)
Ni = nitrogen immobilisation

For managed forests (conifer and deciduous) the same approach and maps and values were used.

13.3. Critical Load Function by habitat (select habitats)

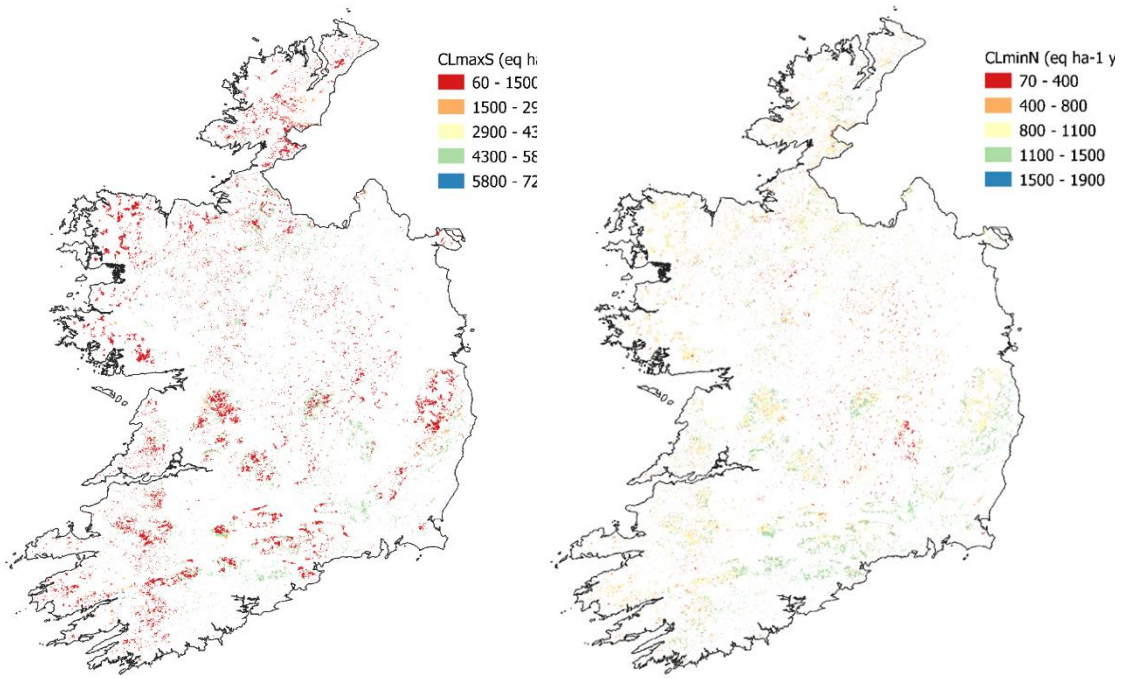

Figure 30: Left: CLmaxS for managed coniferous woodlands. Right: CLminN for managed coniferous woodlands

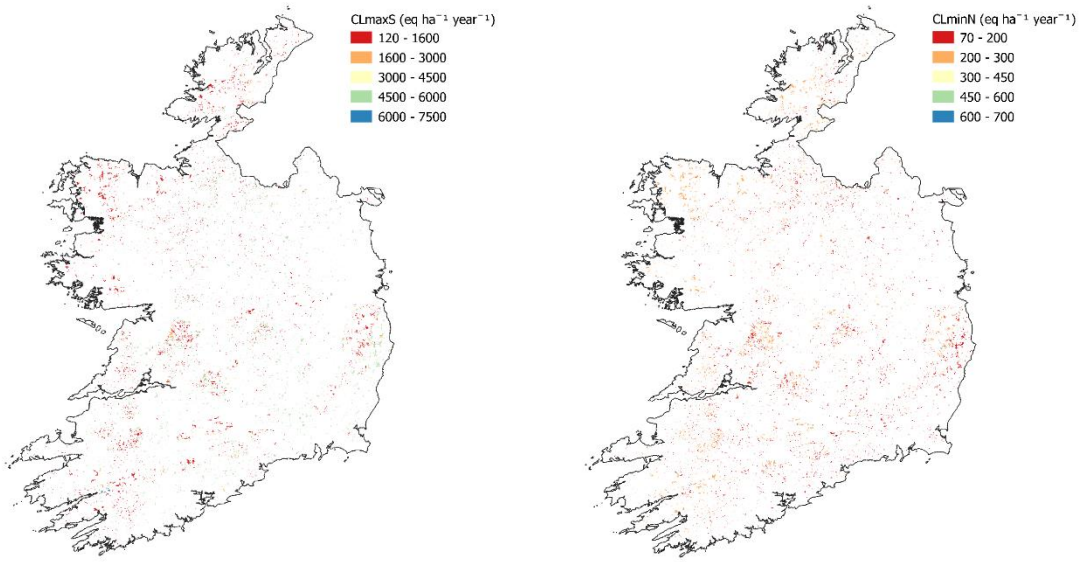

Figure 31: Left: CLmaxS for unmanaged deciduous and mixed forest woodlands. Right: CLminN for unmanaged deciduous and mixed forests.

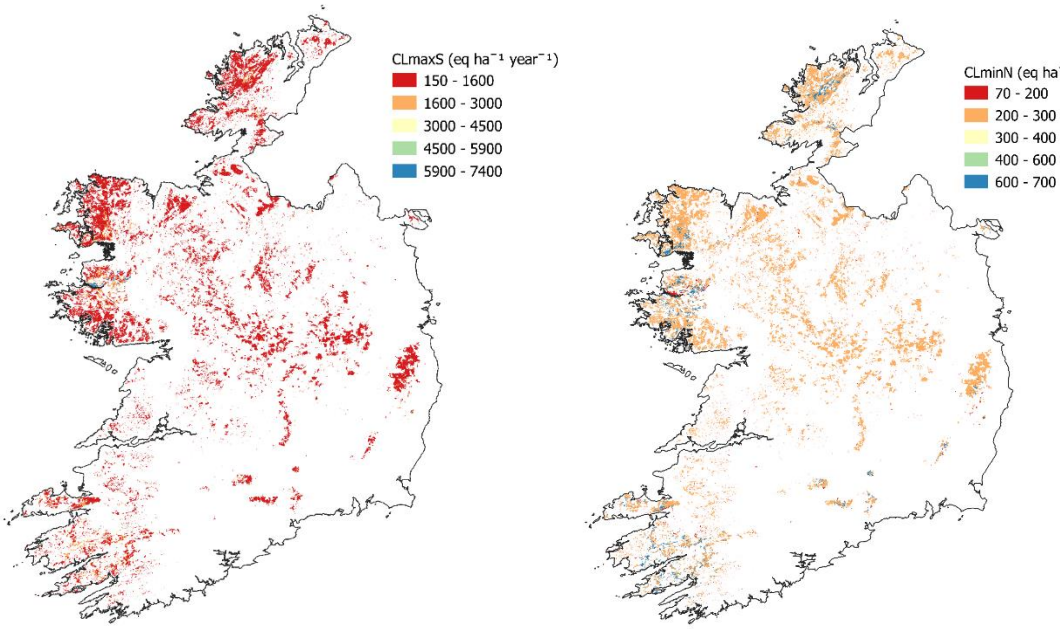

Figure 32. Left: CLmaxS for Bogs. Right: CLminN for Bog.

14. Appendix 4. Other Concentration Models

All models below were run for 2018 using EMEP4IE.

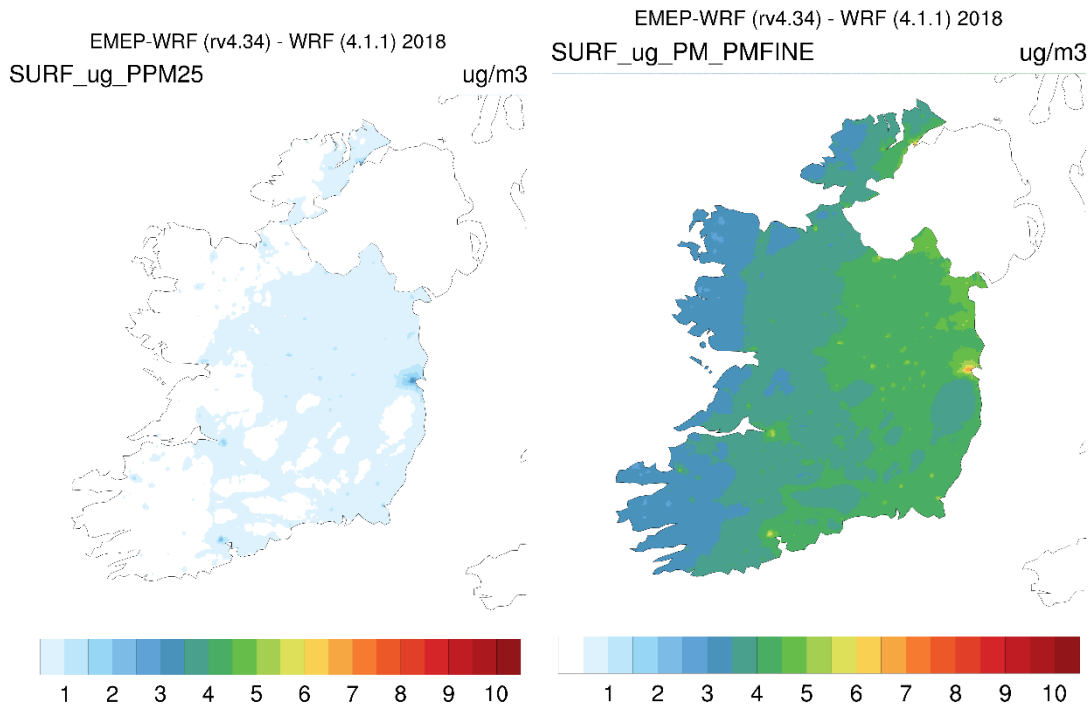

Figure 33. Left: Mean annual concentrations of primary particulate matter 2.5 microns (µg m^{-3}) across Ireland. Right: Annual PM fine concentrations ug m^{-3} (all PM <2.5 microns)

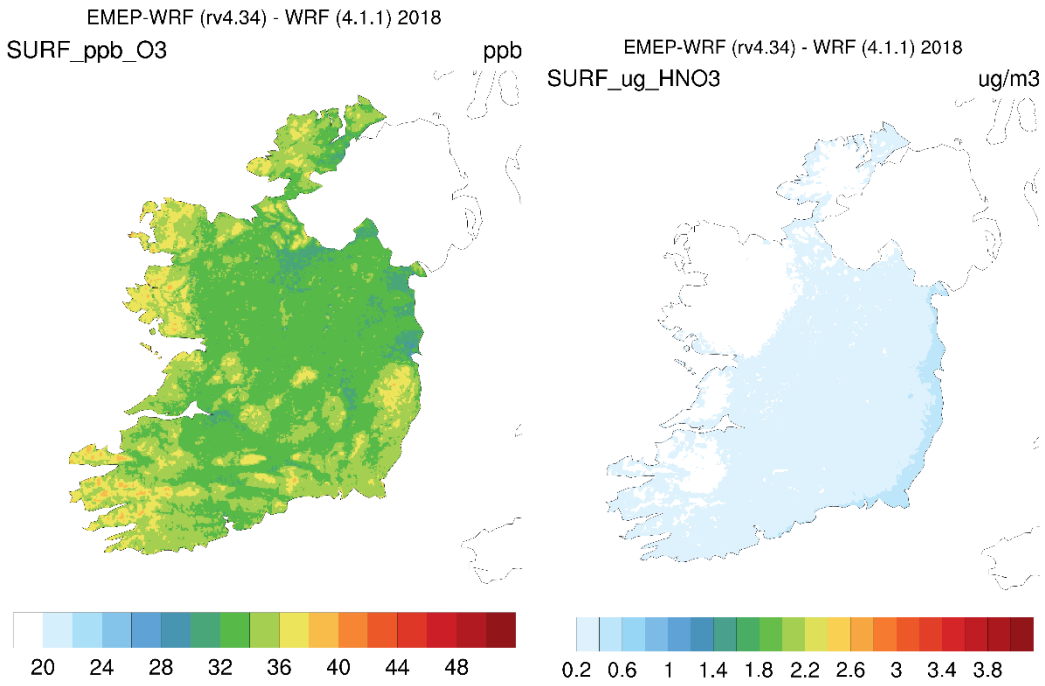

Figure 34. Left: Annual ozone concentrations ppb. Right: Annual nitric acid concentrations ug m^{-3}.

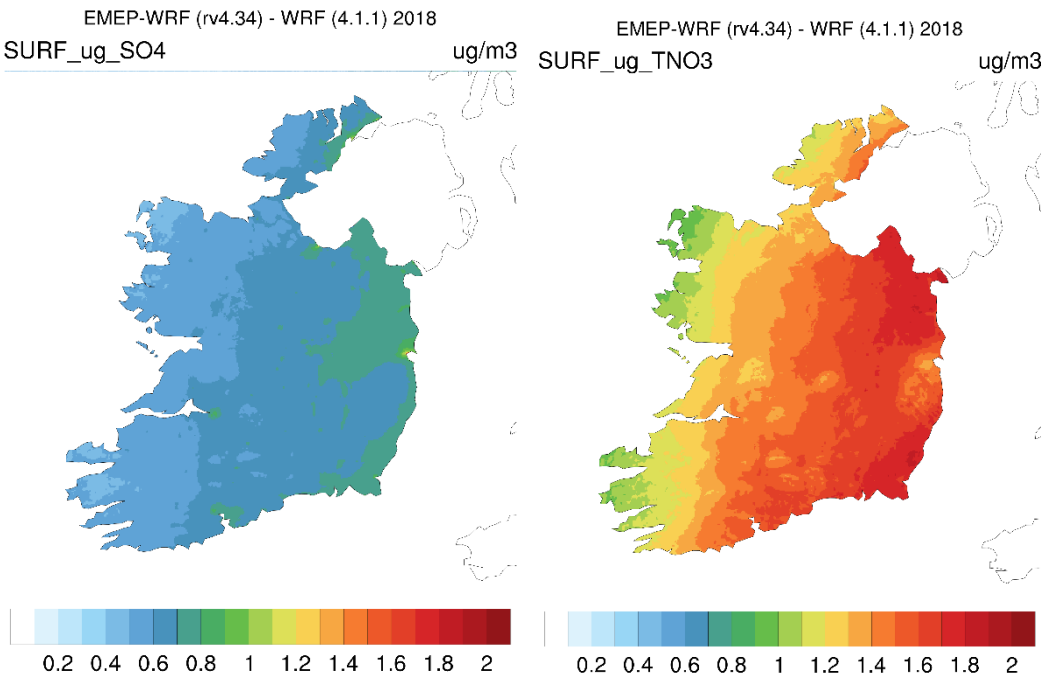

Figure 35. Left: Annual sulphate concentrations ug m^{-3}. Right: Annual total nitrate concentrations ug m^{-3}.

15. Appendix 5. Model Verification

15.1. Ammonia Concentrations

Comparisons between EMEP4IE modelled concentrations of ammonia and measurements are shown in Table 11 and Figures 36 and 37. The correlation between the EMEP4IE modelled ammonia concentrations is moderate with that of the 1999 measurements shown below (R^2 0.49), but high with respect to the 2013-2014 measurements (R^2 0.79) and very high compared with the three Northern Ireland sites used for comparison as part of the UK ammonia network (R^2 0.89).

Table 11. Ammonia measurement sites in the Republic of Ireland three reporting periods 1999 and 2013-2014 (Doyle et al, 2017). Three Northern Irish (NI) sites are included for QA/QC and 2018 (UKEAP).

Site name	Easting (m)	Northing (m)	Altitude (m)	NH_3 1999 (µg m^{-3})	NH_3 2013-2014 (µg m^{-3})	UK Ammonia network 2018 (µg m^{-3})	EMEP4IE 2018 (µg m^{-3})
Glenties	181531	393744	63	0.25	0.7	-	1.05
Killarney	96952	86347	41	0.27	0.65	-	1.08
Straide	126050	297867	21	1.21	1.1	-	1.55
Derrygreenagh	249402	238163	100	1.48	1.99	-	2.37
Littleton	220376	151178	136	1.58	1.53	-	2.28
Clonroche	282386	133109	118	1.62	2.83	-	2.33
Shannon Airport	137213	160815	12	1.63	1.53	-	1.91
Springfield Castle	135214	122368	106	2.06	2.29	-	3.10
Ballincurrig	186255	84300	175	2.43	2.04	-	2.30
Naas	286354	217152	84	3.37	1.67	-	2.20
Coleraine (NI)	288306	420989	33	-	-	4.19	3.15
Lough Naver (NI)	206515	354543	130	-	-	0.50	1.26
Hillsborough (NI)	324349	357677	120	-	-	2.71	2.99

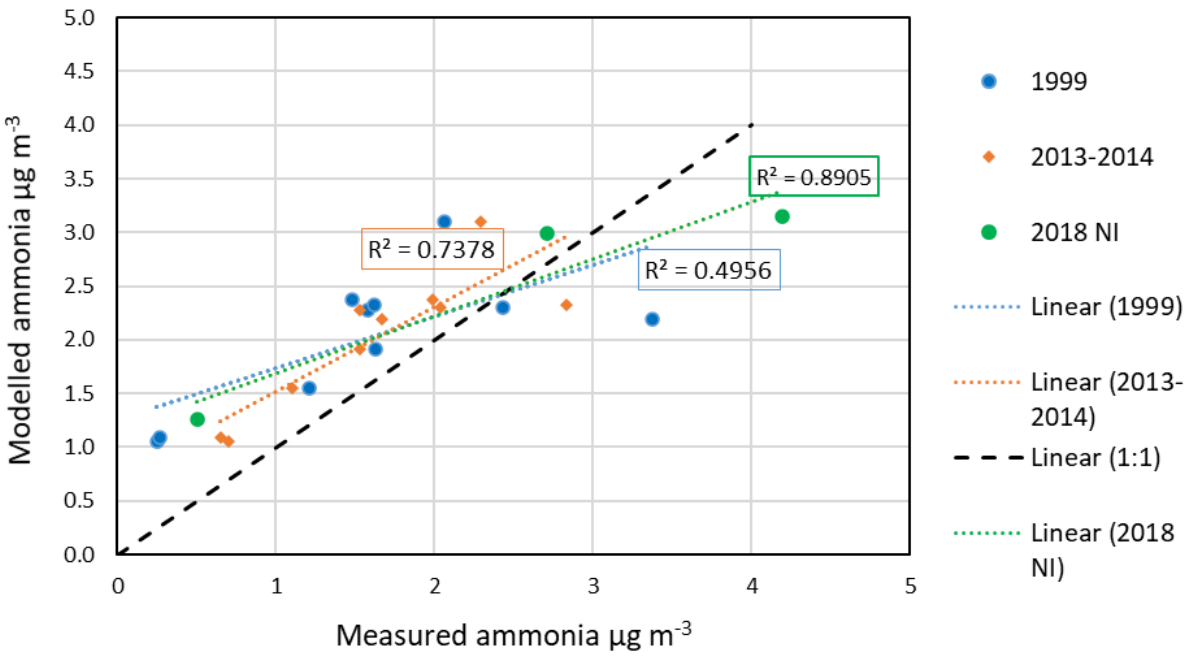

Figure 36. Measured concentrations of ammonia plotted against modelled EMEP4IE based on 3 sets of data and 13 measurement points.

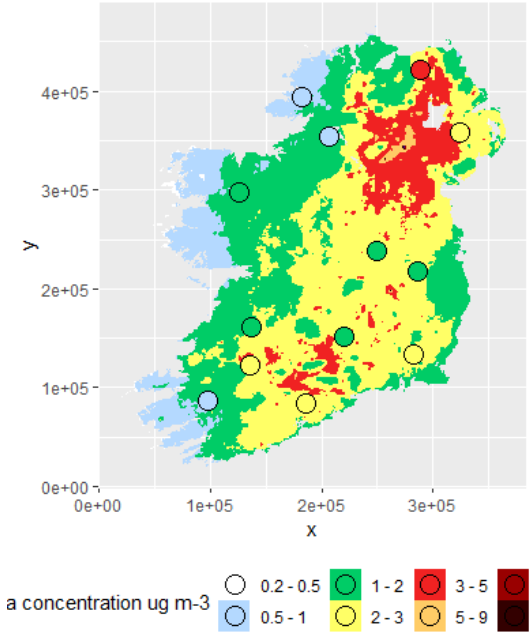

Figure 37. Map of ammonia concentrations from EMEP4IE compared with monitoring sites (circles) from year 2013-2014 and UK ammonia network 2018 for Northern Ireland sites (see Table 11). Northern Irish modelled data and monitored values are included for model QA/QC.

Concentrations of ammonia have been mapped over the last two decades. Maps have primarily been based on taking measurements across the country and interpolating them via kriging[19]. Figure 38 left and middle shows ammonia across Ireland based on measurement points which provide smooth isolines in the map. This is compared with the EMEP modelled approach which is based on emissions, meteorology and chemistry within the model. Figure 38 right from the EMEP4IE model provides more spatial heterogeneity in the maps representing more the nature of ammonia hot spots in the landscape. Areas of low concentrations to the south of the country and interspersed hot spots which the kriged maps do not capture.

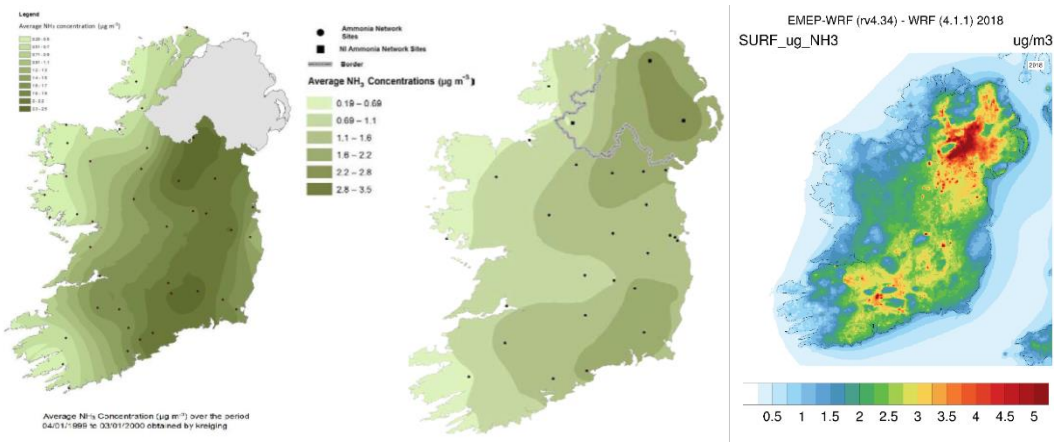

Figure 38. Left: Mean annual ammonia concentrations 1999 (ug^{m-3}) from 40 measurement sites. Middle: Mean atmospheric ammonia concentrations (ug^{m-3}), interpolated from measurements at 25 sites in Ireland and 3 sites in Northern Ireland between June 2013 and July 2014 (Doyle et al. 2017). Right: EMEP4IE ammonia concentrations

15.2. Nitrogen Deposition

Comparisons between EMEP4IE modelled wet deposition of ammonium (NH_4^+) and nitrate (NO_3^-) and

[19] A method of spatial interpolation to estimate values at un-monitored locations.

measurements of ion rainfall concentrations are shown in Table 12 and Figure 39. Current 2018 data for wet chemistry is limited to a handful of sites, therefore there are not enough points to derive a R-square value.

Table 12. Modelled wet deposition of ammonium and nitrate compared to measurement network ion concentrations in rainfall and derived deposition (kg N ha^{-1} yr^{-1}). VWM equates to the volume weighted mean as an annual average concentration (mg l^{-1}).

Site name	Easting (m)	Northing (m)	Altitude (m)	precipitation wet only sampler mm	NH_4 VWM mg l^{-1}	NO_3 VWM mg l^{-1}	kg NH_4- N ha^{-1} yr^{-1}	EMEP4IE Kg NH_4^-N ha^{-1} yr^{-1}	kg NO_3^- N ha^{-1} yr^{-1}	EMEP4IE NO_3^-N ha^{-1} yr^{-1}
Oak Park	272451	180257	59	519	0.32	0.10	1.28	1.45	0.41	0.46
Valentia Observatory	45723	78743	11	1859	0.09	0.06	1.28	0.82	0.86	0.63
Johnstown Castle	301627	117368	62	492.4	0.21	0.11	0.81	1.18	0.41	1.72
Malin Head	241710	458867	20	1053.3	0.22	0.08	1.80	1.02	0.67	0.47

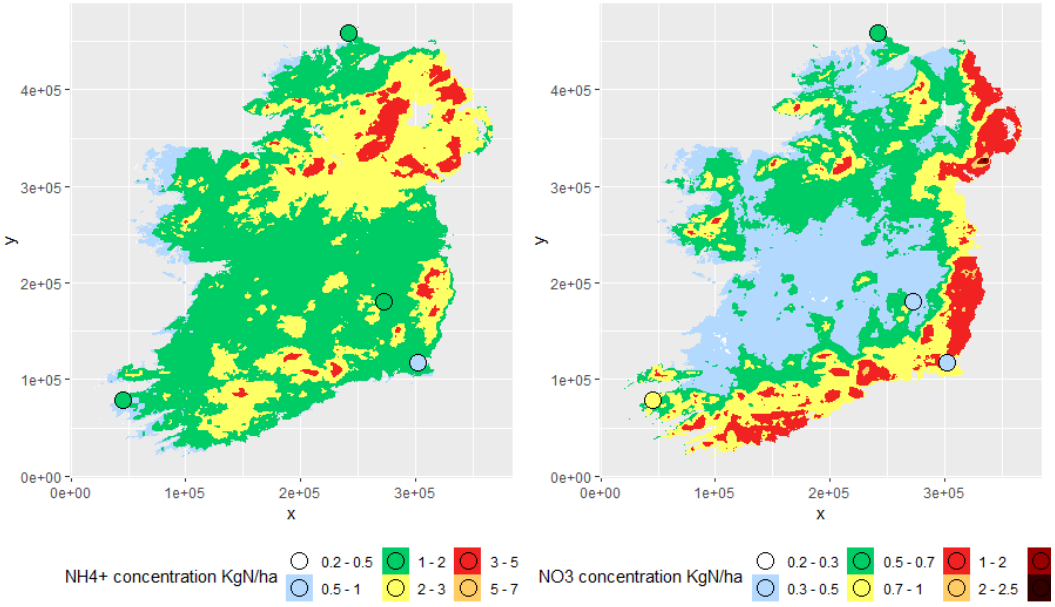

Figure 39. Northern Irish modelled data and monitored values are included for model QA/QC. Left: Underlying map of ammonium NH_4^+ wet deposition from EMP4IE model and monitoring station points (circles) from ion concentrations in rainfall. Monitoring data is from EMEP database for the year 2018. Right: Underlying map of nitrate NO_3^- wet deposition from EMP4IE model and monitoring station points (circles) from ion concentrations in rainfall. Monitoring data is from EMEP database for the year 2018.

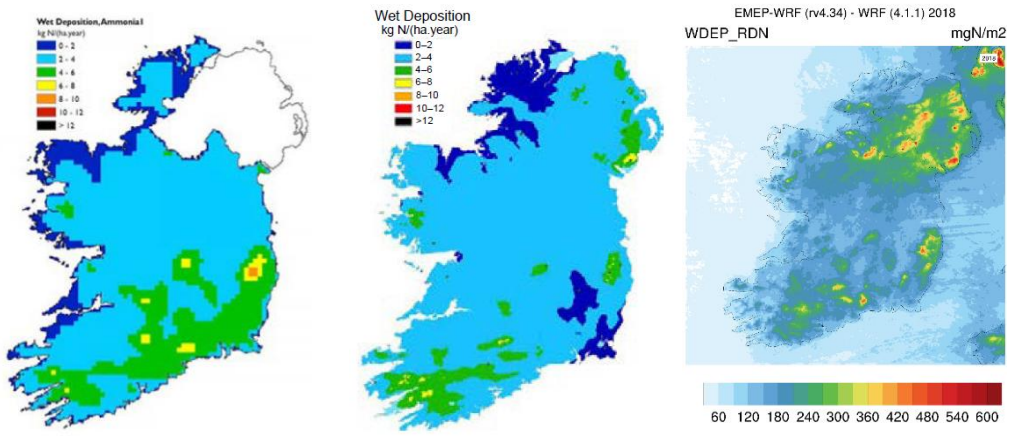

Figure 40. Left: 1999 Wet deposition of ammonium (kg N ha^{-1} year). Middle: 2013-2014 Wet deposition of ammonium (kg N ha^{-1} $year^{-1}$) (Doyle et al., 2017). Right: EMEP4IE 2018 mean annual wet deposition of ammonia (mg N m^{-2} $year^{-1}$) across Ireland.

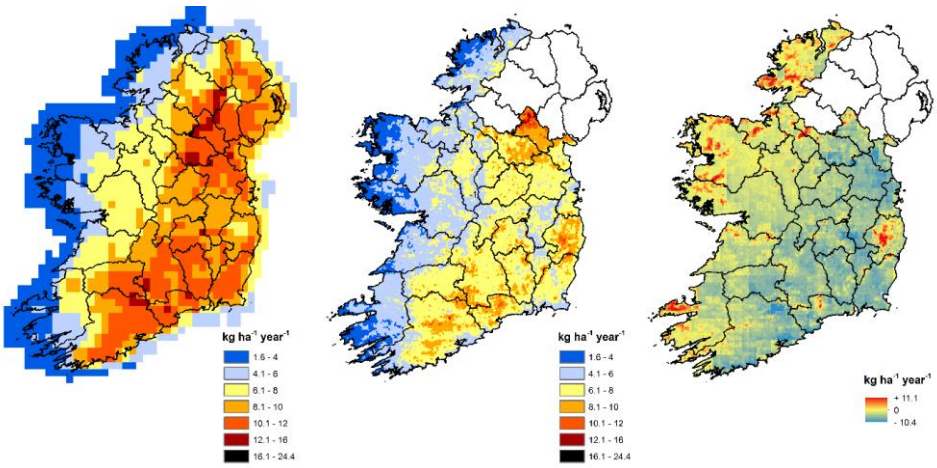

Figure 41. Left: 2018 EMEP Total Nitrogen Deposition (NMI, 2019) Middle: Updated 2018 EMEP model from this study. Right: Difference between both models.

Figures 40 and 41 shows the most recent national deposition modelling available for Irish wet and total nitrogen deposition prior to this project. In Figure 41 the coarser resolution in the 2018 model does not provide as much detail as the updated 1 km^2 EMEP4IE model for the same year. Comparing both models it is clear that deposition in the uplands was likely underestimated in the EMEP model, where an additional 11.1 kg N ha^{-1} $year^{-1}$ is apparent across a number of uplands in the most recent model. Across the Republic of Ireland the 2020 EMEP4IE estimates 13.8% less of the country receiving the lowest modelled deposition rate of 1.6 – 4 kg N ha^{-1} $year^{-1}$. This is accompanied with an increase in the amount of land receiving between 4 and 8 kg N ha^{-1} $year^{-1}$, with a total increase of 41%.. Modelled deposition of between 8.1 – 16 kg N ha^{-1} $year^{-1}$ saw a cumulative reduction in cover of 27.3% whereas the new model identified for the first-time areas where deposition exceeded 16.1 kg N ha^{-1} $year^{-1}$.

Table 13. Percent cover of nitrogen deposition rates across the Republic of Ireland, derived from Figure 41. comparing modelling results from 2018 and 2020.

Total Nitrogen (N) Deposition	**% of National Model**		**Difference**
Kg N ha^{-1} $year^{-1}$	**2018 (NMI, 2019)**	**2018 (Current Model)**	
1.6 - 4	25.6	11.8	-13.8
4.1 - 6	15.3	36.2	+20.9
6.1 - 8	20.6	40.7	+20.1
8.1 - 10	19.7	9.8	-9.9
10.1 - 12	17.2	1.2	-16
12.1 - 16	1.6	0.2	-1.4
>=16.1	0	0.02	+0.02

16. Appendix 6. Empirical Critical Loads of Nutrient Nitrogen for Annex I habitats

Feature Code	Feature Name	Sensitive to N?	CLempN (Noordwijkerhout 2010*)	EUNIS	Min CLempN	Max CLempN	CLempN Mapping Value (APIS)	CLempN range (Aherne 2021)	CLempN Revised Mapping Value
1110	Sandbanks which are slightly covered by sea water all the time	No	Designated feature/feature habitat not sensitive to eutrophication						
1130	Estuaries	Yes	Pioneer, low-mid, mid-upper saltmarshes	A2.54; A2.55; A2.53	20	30	25	5-10	7.5
1140	Mudflats and sandflats not covered by seawater at low tide	Yes	No comparable habitat with established critical load estimate available						
1150	Coastal lagoons	Yes	Pioneer, low-mid, mid-upper saltmarshes	A2.54; A2.55; A2.53	20	30	25	5-10	7.5
1160	Large shallow inlets and bays	No	Designated feature/feature habitat not sensitive to eutrophication						
1170	Reefs	No	Designated feature/feature habitat not sensitive to eutrophication						
1180	Submarine structures made by leaking gases	No	Designated feature/feature habitat not sensitive to eutrophication						
1210	Annual vegetation of drift lines	No	Designated feature/feature habitat not sensitive to eutrophication						
1220	Perennial vegetation of stony banks	Yes	Coastal stable dune grasslands	B1.4	8	15	11.5	5-10	7.5
1230	Vegetated sea cliffs of the Atlantic and Baltic coasts	Yes	No comparable habitat with established critical load estimate available						
1310	Salicornia and other annuals colonising mud and sand	Yes	Pioneer, low-mid, mid-upper saltmarshes	A2.54; A2.55; A2.53	20	30	25	5-10	7.5
1330	Atlantic salt meadows (*Glauco-Puccinellietalia maritimae*)	Yes	Pioneer, low-mid, mid-upper saltmarshes	A2.54; A2.55; A2.53	20	30	25	5-10	7.5
1410	Mediterranean salt meadows (*Juncetalia maritimi*)	Yes	Pioneer, low-mid, mid-upper saltmarshes	A2.54; A2.55; A2.53	20	30	25	5-10	7.5
1420	Mediterranean and thermo-Atlantic halophilous scrubs (*Sarcocornetea fruticosi*)	Yes	Pioneer, low-mid, mid-upper saltmarshes	A2.54; A2.55; A2.53	20	30	25	5-10	7.5
2110	Embryonic shifting dunes	Yes	Shifting coastal dunes	B1.3	10	20	15	5-10	7.5
2120	Shifting dunes along the shoreline with *Ammophila arenaria* (white dunes)	Yes	Shifting coastal dunes	B1.3	10	20	15	5-10	7.5
2130	Fixed dunes with herbaceous vegetation (grey dunes) (acid type)	Yes	Coastal stable dune grasslands	B1.4	8	10	9	5-10	7.5
2130	Fixed dunes with herbaceous vegetation (grey dunes) (calcareous type)	Yes	Coastal stable dune grasslands	B1.4	10	15	12	5-10	7.5

Feature Code	Feature Name	Sensitive to N?	CLempN (Noordwijkerhout 2010*)	EUNIS	Min CLempN	Max CLempN	CLempN Mapping Value (APIS)	CLempN range (Aherne 2021)	CLempN Revised Mapping Value
2140	Decalcified fixed dunes with *Empetrum nigrum*	Yes	Coastal dune heaths	B1.5	10	20	15		15
2150	Atlantic decalcified fixed dunes (*Calluno-Ulicetea*)	Yes	Coastal dune heaths	B1.5	10	20	15		15
2170	Dunes with Salix repens ssp. argentea (*Salicion arenariae*)	Yes	Moist to wet dune slacks	B1.8	10	20	15	5-10	7.5
2190	Humid dune slacks (acid type)	Yes	Moist to wet dune slacks	B1.8	10	15	12.5	5-10	7.5
2190	Humid dune slacks (calcareous type)	Yes	Moist to wet dune slacks	B1.8	15	20	17.5	5-10	7.5
3110	Oligotrophic waters containing very few minerals of sandy plains (*Littorelletalia uniflorae*)	Yes	Permanent oligotrophic waters: Softwater lakes	C1.1	5	10	7.5		7.5
3130	Oligotrophic to mesotrophic standing waters with vegetation of the *Littorelletea uniflorae* and/or of the *Isoëto-Nanojuncetea*	Yes	Permanent oligotrophic waters: Softwater lakes	C1.1	3	10	6.5		6.5
3140	Hard oligo-mesotrophic waters with benthic vegetation of *Chara* spp.	Yes	No comparable habitat with established critical load estimate available						
3150	Natural eutrophic lakes with *Magnopotamion* or *Hydrocharition*-type vegetation	Yes	No comparable habitat with established critical load estimate available						
3160	Natural dystrophic lakes and ponds	Yes	Permanent dystrophic lakes, ponds and pools	C1.4	3	10	7.5		7.5
3180	Turloughs	Yes	No comparable habitat with established critical load estimate available						
3260	Water courses of plain to montane levels with the *Ranunculion fluitantis* and *Callitricho-Batrachion* vegetation	Yes	No comparable habitat with established critical load estimate available						
3270	Rivers with muddy banks with *Chenopodion rubri* p.p. and *Bidention* p.p. vegetation	Yes	No comparable habitat with established critical load estimate available						
4010	Northern Atlantic wet heaths with *Erica tetralix*	Yes	Northern wet heath: Erica tetralix dominated wet heath	F4.11	10	20	10	5-10	5
4030	European dry heaths	Yes	Dry heaths	F4.2	10	20	10	5-10	7.5
4060	Alpine and Boreal heaths	Yes	Arctic, alpine and subalpine scrub habitats	F2	5	15	10	5-10	5
5130	*Juniperus* communis formations on heaths or calcareous grasslands	Yes	Dry heaths	F4.2	10	20	10	5-10	7.5
6130	Calaminarian grasslands of the *Violetalia calaminariae*	Yes	Sub-atlantic semi-dry calcareous grassland	E1.26	15	25	15		15
6210	Semi-natural dry grasslands and scrubland facies: on calcareous substrates (*Festuco-Brometalia*)	Yes	Sub-atlantic semi-dry calcareous grassland	E1.26	15	25	15	5-15	10
6230	Species-rich Nardus grassland, on siliceous substrates in mountain areas (and submountain areas in continental Europe)	Yes	Non-mediterranean dry acid and neutral closed grassland	E1.7	10	15	10	5-15	5
6410	Molinia meadows on calcareous, peaty or clayey-silt-laden soils (*Molinion caeruleae*)	Yes	Moist and wet oligotrophic grasslands: Molinia caerulea meadows	E3.51	15	25	20	5-15	10
6430	Hydrophilous tall herb fringe communities of plains and of the montane to alpine levels	Yes	Alpine and subalpine grasslands	E4.3; E4.4	5	10	7.5	5-15	10

Feature Code	Feature Name	Sensitive to N?	CLempN (Noordwijkerhout 2010*)	EUNIS	Min CLempN	Max CLempN	CLempN Mapping Value (APIS)	CLempN range (Aherne 2021)	CLempN Revised Mapping Value
6510	Lowland hay meadows (*Alopecurus pratensis, Sanguisorba officinalis*)	Yes	Low and medium altitude hay meadows	E2.2	20	30	25	5-15	10
7110	Active raised bogs	Yes	Raised and blanket bogs	D1	5	10		5-10	7.5
7120	Degraded raised bogs still capable of natural regeneration	Yes	Raised and blanket bogs	D1	5	10		5-10	5
7130	Blanket bogs	Yes	Raised and blanket bogs	D1	5	10		5-10	7.5
7140	Transition mires and quaking bogs	Yes	Valley mires, poor fens and transition mires	D2	10	15	12.5		12.5
7150	Depressions on peat substrates of the *Rhynchosporion*	Yes	Valley mires, poor fens and transition mires	D2	10	15	12.5		12.5
7210	Calcareous fens with *Cladium mariscus* and species of the *Caricion davallianae*	Yes	Rich fens	D4.1	15	30	22.5		22.5
7220	Petrifying springs with tufa formation (*Cratoneurion*)	Yes	Mountain rich fens	D4.2	15	25	20		20
7230	Alkaline fens	Yes	Rich fens	D4.1	15	30	22.5	5-10	7.5
8110	Siliceous scree of the montane to snow levels (*Androsacetalia alpinae* and *Galeopsietalia ladani*)	Yes	Arctic, alpine and subalpine scrub habitats	F2	5	15	10		10
8120	Calcareous and calcshist screes of the montane to alpine levels (*Thlaspietea rotundifolii*)	Yes	Arctic, alpine and subalpine scrub habitats	F2	5	15	10		10
8210	Calcareous rocky slopes with chasmophytic vegetation	Yes	Alpine and subalpine grasslands	E4.3; E4.4	5	10	7.5		7.5
8220	Siliceous rocky slopes with chasmophytic vegetation	Yes	Arctic, alpine and subalpine scrub habitats	F2	5	15	10	5-10	7.5
8240	Limestone pavements	Yes	Alpine and subalpine grasslands	E4.3; E4.4	5	10	7.5	5-10	7.5
8310	Caves not open to the public	No	Designated feature/feature habitat not sensitive to eutrophication						
8330	Submerged or partially submerged sea caves	No	Designated feature/feature habitat not sensitive to eutrophication						
21A0	Machairs	Yes	Coastal stable dune grasslands - calcareous type	B1.4	10	15	12	5-10	7.5
91A0	Old sessile oak woods with *Ilex* and *Blechnum* in the British Isles	Yes	Acidophilous Quercus-dominated woodland	G1.8	10	15	10	10-15	10
91D0	Bog woodland	Yes	Raised and blanket bogs	D1	5	10			7.5
91OE	Alluvial forests with *Alnus glutinosa* and *Fraxinus excelsior* (*Alno-Padion, Alnion incanae, Salicion albae*)	No	Designated feature/feature habitat not sensitive to eutrophication						
91J0	*Taxus baccata* woods of the British Isles	Yes	Coniferous woodland	G3	5	15	12		12

* http://www.rivm.nl/bibliotheek/rapporten/680359002.pdf