Research Repository UCD

Title	Mapping ammonia risk on sensitive habitats in Ireland
Authors(s)	Kelleghan, David B., Hayes, Enda T., Everard, Mark, Curran, Thomas P.
Publication date	2019-02-01
Publication information	Kelleghan, David B., Enda T. Hayes, Mark Everard, and Thomas P. Curran. "Mapping Ammonia Risk on Sensitive Habitats in Ireland" 649 (February 1, 2019).
Publisher	Elsevier
Item record/more information	http://hdl.handle.net/10197/10306
Publisher's statement	This is the author's version of a work that was accepted for publication in Science of The Total Environment. Changes resulting from the publishing process, such as peer review, editing, corrections, structural formatting, and other quality control mechanisms may not be reflected in this document. Changes may have been made to this work since it was submitted for publication. A definitive version was subsequently published in Science of The Total Environment (649, (2018)) https://doi.org/10.1016/j.scitotenv.2018.08.424
Publisher's version (DOI)	10.1016/j.scitotenv.2018.08.424

Downloaded 2023-04-07T10:52:29Z

The UCD community has made this article openly available. Please share how this access benefits you. Your story matters! (@ucd_oa)

© Some rights reserved. For more information

Title: Mapping ammonia risk on sensitive habitats in Ireland.

Authors: David B. Kelleghan¹, Enda Hayes², Mark Everard³, Thomas P. Curran¹

¹*UCD School of Biosystems and Food Engineering, University College Dublin, Belfield, Dublin 4, Ireland.*

²*Air Quality Management Resource Centre, University of the West of England, Frenchay Campus, Coldharbour Lane, Bristol BS16 1QY, UK.*

³*International Water Security Network, University of the West of England, Frenchay Campus, Coldharbour Lane, Bristol BS16 1QY, UK.*

Corresponding Author: david.kelleghan@ucdconnect.ie

Abstract

The aim of this study was to provide a simple, cost-effective, risk-based map of terrestrial areas in Ireland where environmental quality may be at risk from atmospheric ammonia. This risk-based approach identifies Natura 2000 sites in Ireland at risk from agricultural atmospheric ammonia, collating best available data using Geographical Information Systems (GIS). In mapping ammonia risk on sensitive habitats (MARSH), the method identifies sources of ammonia, classifying them on a scale of risk from 0 – 5. These sources are subsequently summed based on a weighting determined by their contribution to national emissions divided by their potentially impacted area. A Pearson's correlation coefficient of 0.72 allows for concentrations from United Kingdom's FRAME modelling to be applied to the MARSH model, which are corrected based on recent monitoring. Applying Designation Weighted Indicators (DWI), the MARSH model predicts that 80.7, 34.3 and 5.9% of Natura 2000 sites in Ireland may exceed ambient concentrations of 1, 2, and 3 $\mu\text{g}/\text{m}^3$, respectively. A Nitroindex map of Ireland based on available lichen records was also developed and is presented as part of this study. This Nitroindex was used to identify areas where impacts have already been recorded, thus informing the classification of sites "at-risk". The combination of both the MARSH and Nitroindex models ascertains which Natura 2000 sites are most at risk, thereby providing valuable data to relevant authorities. The MARSH model acts as a first step towards screening and assessing Natura 2000 sites most at risk from atmospheric ammonia, providing a tool to demonstrate compliance with the National Emissions Ceilings Directive.

Keywords MARSH, Ammonia, Risk, Natura 2000, Agriculture, National Emissions Ceilings Directive, Habitats Directive

Highlights

- A GIS risk-based approach gauges atmospheric NH₃ impacts in Ireland
- Integrates best available agricultural data to identify “at-risk” areas in Ireland
- Provides stakeholders with an atmospheric ammonia risk map for Ireland
- 80.7% of Natura 2000 sites likely to exceed critical level of 1 µg/m³
- 5.9% of Natura 2000 sites likely to exceed critical level of 3 µg/m³

1. Introduction

The European Union's (EU) Habitats Directive (92/43/EEC) (European Economic Commission, 1992) and Birds Directive (2009/147/EC) (European Commission, 2009) require EU Member States to identify and maintain the Natura 2000 network of designated sites in "favourable conservation status". Natura 2000 sites comprise Special Areas of Conservation (SAC) and Special Protection Areas (SPA) designated under the Habitats and Birds Directives respectively to protect internationally sensitive habitats and species. Ireland is comprised of both the Republic of Ireland (ROI) and Northern Ireland (NI). The Natura 2000 network covers 13.3% of ROI (Directorate-General Environment, 2018) and 7.1% of NI (OpenDataNI, 2016); it is reported that 91% and 62% of these sites have "unfavourable conservation status" in the ROI (Department of Culture Heritage and the Gaeltacht, 2017) and NI respectively (Joint Nature Conservation Committee, 2013). The conservation status of a site is assessed on the basis of a number of parameters, including "range, population, habitat area, suitable habitat for species, structure and functions of habitats, and future prospects" (European Commission, 2015).

Atmospheric nitrogen pollution, specifically in the form of ammonia (NH_3), is a substantial threat to global biodiversity (Payne et al., 2017; Phoenix et al., 2006; Butchart et al., 2010). Significant and pervasive links have been found between nitrogen pollution and species decline in several studies (Hernández et al., 2016; Aherne et al., 2017; Henry and Aherne, 2014; Bobbink et al., 2010; Maskell et al., 2010). Impacts from the eutrophication, acidification or direct toxicity of atmospheric ammonia can contribute to species community changes in a number of habitat types, including grasslands (Henry and Aherne, 2014), uplands (Stiles et al., 2017), woodlands (Wilkins et al., 2016) and bogs (Sutton et al., 2011).

The ROI has experienced continuously increasing ammonia emissions since 2011, exceeding limits set by the National Emissions Ceilings Directive (NECD) (2016/2284) (European Union, 2016) of 116 kt for the first time in 2016 (Environmental Protection Agency, 2018). Under the NECD, the ROI and the United Kingdom (UK) are required to reduce ammonia emissions by

1% and 8% by 2020 and 5% and 16% by 2030, respectively. (Environmental Protection Agency, 2016). NI produces 11.9% of the UK's ammonia emissions (MacCarthy et al., 2012), which have already reduced by 13% compared to 1990 figures (Wakeling et al. 2018). Both the ROI and NI aim to expand their agricultural food production under “Food Wise 2025” and “Going for Growth”, respectively (Department of Agriculture Food and the Marine, 2015; Department of Agriculture, Environment, and Rural Affairs, 2017). Unmitigated increases in agricultural production will further exacerbate existing impacts from atmospheric ammonia (Stoate et al., 2009).

The contribution of agriculture to national atmospheric ammonia emissions varies between 80 and 100% across European Member States, while in the ROI it comprises 98% and 91% in NI (European Environment Agency, 2016). A national level assessment of potential impacts from atmospheric ammonia is not possible without detailed concentration and deposition models. Recent amendments to the NECD (2016/2284/EU) requires monitoring of harmful gases, including ammonia, on sensitive Natura 2000 sites. Guidance for the implementation of Article 9 of the NECD (2016/2284/EU) requires a cost-effective, risk-based approach to interpolate between existing monitoring sites ensuring coverage of vulnerable ecosystems (European Commission, 2016). The UK has developed and used an atmospheric ammonia concentration and deposition model to identify Natura 2000 sites at risk of impacts (Hallsworth et al., 2010), known as FRAME (Fine Resolution Atmospheric Multi-pollutant Exchange); this particular assessment covers NI but not ROI.

The FRAME model was used to model atmospheric ammonia concentrations across Ireland in 1996, where predicted ambient concentrations ranged from 0 to > 8.0 $\mu\text{g}/\text{m}^3$ (Fournier et al., 2002). Since then the FRAME model has gone through several iterations, where predicted concentrations across NI ranged 0.34 – 5.41 $\mu\text{g}/\text{m}^3$ for 2011 – 2013 (Dore, 2018, pers.comm.). The FRAME model in the UK is validated by annual monitoring carried out by the UK's National Ammonia Monitoring Network on 85 sites (Department for Environment Food and Rural Affairs, 2018). Monitoring of atmospheric ammonia has been carried out twice in the ROI, once

in 1999 - 2000 (de Kluizenaar and Farrell, 2000) and repeated in 2013 – 2014 (Doyle et al., 2017). In the 2013 – 2014 study, monitoring conducted at 25 locations measured annual mean concentrations of 0.48 – 2.96 $\mu\text{g}/\text{m}^3$. Deposition models have been created and are applied to the ROI, by interpolating concentrations from these two monitoring programmes (Henry and Aherne, 2014; Aherne et al., 2017). Doyle et al. (2017) intended to monitor ambient ammonia concentrations and thus intentionally excluded areas with intensive ammonia sources (primarily pig and poultry farms). As this approach intentionally excluded high concentration areas and is not representative of the high spatial variability associated with ammonia, the use of this monitoring data alone is not sufficient when conducting national assessments of risk.

The use of critical level exceedance has been used in the UK to identify Natura 2000 sites at risk from atmospheric ammonia (Hallsworth et al., 2010). Critical levels or “No Observable Effect Concentrations” (NOEC) are ambient ammonia concentrations above which visible impacts on habitats and species can be expected. Hallsworth et al. (2010) utilised predicted concentrations from the FRAME model across the UK Natura 2000 network to identify sites which exceeded either the critical level for lichens and moss ($1 \mu\text{g}/\text{m}^3$) or higher plants ($3 \pm 1 \mu\text{g}/\text{m}^3$) (Cape et al., 2009). The proposed approach in this study of Mapping Ammonia Risk on Sensitive Habitats (MARSH) aims to use best available data to identify areas at risk from atmospheric ammonia, as no current source apportioned concentration map exists for the ROI. The underlying principles used to build the MARSH model have been applied to a diverse range of risk assessment projects including assessing potential impacts from coal mining (Karan and Samadder, 2016); identifying areas susceptible to earthquakes (Sekac et al., 2016); identifying areas at risk from chemical factories (Heo et al., 2017) and identifying areas at risk from the spread of the invasive species Japanese Knotweed (*Fallopia japonica*) (Mackenzie, 2014). These projects all reclassify potential impact factors across a gradient (usually 0 or 1 to 5) and combine these using the raster calculator (allowing mathematical calculations on multiple raster images) in ArcGIS based on a predetermined weighting. This approach estimates a total perceived risk.

The contribution of all sources to national ammonia emissions is available from data submitted by the Irish Government to the European Environment Agency as part of the national emissions reported to the Convention on Long-range Transboundary Air Pollution (LRTAP Convention) (European Environment Agency, 2016). In 2010, each agricultural sector for both NI and the ROI can be categorised as emissions from cattle, synthetic fertiliser, pigs, poultry, sheep and horses. These categories contributed 74.4, 11, 7.3, 4.9, 1.5 and 0.9%, respectively, to Ireland's total ammonia emissions. As the most recent detailed agricultural census of the ROI was carried out in 2010 (Central Statistics Office, 2010), emissions contributions from that year were used to weight the MARSH model components.

Lichens are useful indicators of atmospheric nitrogen pollution, with a guide produced by the Field Studies Council in the UK to identify nitrogen-polluted areas (Air Pollution Information System, 2015). Numerous studies have linked lichen sensitivity to atmospheric ammonia concentrations (Wolseley et al., 2006; Frati et al., 2007; Frati et al., 2008). Nitrogen-sensitive species decrease when exposed to higher concentrations of ammonia, conversely nitrogen-tolerant species increase (Lindenmayer et al., 2015, Rihm et al., 2009). Past studies have allocated a value of -1 if nitrogen-sensitive and +1 if nitrogen-tolerant (Rihm et al., 2009). National lichen records for Ireland are collected and maintained by the Centre for Environmental Data and Recording (CEDaR). Mapping these records of nitrogen-sensitive and tolerant lichen species creates an indicative map of nitrogen impacts on lichen communities.

The primary aim of this paper was to develop a cost-effective, risk-based approach to identify Natura 2000 sites at risk of impact from atmospheric ammonia in Ireland, meeting the requirements of the EU NECD, Habitats Directive and Birds Directive. As such, this paper completes a comprehensive ecosystem assessment of Irish Natura 2000 sites, building on the current state of the environment in relation to Natura 2000 and implications of ammonia impacts.

2. Materials & methods

2.1. Overview of the MARSH model

The MARSH model was constructed with the intention of illustrating areas, at the best available resolution, that are at risk of impact from agricultural atmospheric ammonia. The MARSH model ranks contributing sources to an impact, and sums the resulting datasets based on a predetermined weighting. This approach has been applied to numerous risk assessment studies (e.g. Gómez et al., 2007; Wang and Wu, 2009; Heo et al., 2017).

The MARSH model deals solely with agricultural sources which contribute c. 98% of ROI's and 91% to NI's atmospheric ammonia emissions (European Environment Agency, 2016). Contributions from transport (1.42%) and industry (0.3%) were not included. Agricultural emissions were broken down into five model components: synthetic fertiliser; cattle; sheep; pigs; and poultry. Each of these were ranked based on relative intensity on a scale of 0 – 5, where 5 is representative of areas most likely “at-risk”.

Total emissions, and other data used for the ROI and NI were obtained from sources shown in Table 1.

Table 1. Data sources.

	Republic of Ireland	Northern Ireland
National emissions	European Environment Agency (European Environment Agency, 2016)	National atmospheric emissions inventory (MacCarthy et al., 2012)
Synthetic fertilisers	CORINE Landcover Animal numbers (Central Statistics Office, 2010)	CORINE Landcover Animal numbers (Northern Ireland Neighbourhood Information Service, 2016; 2010 data)
Cattle and sheep	Central Statistics Office (Central Statistics Office, 2010)	Northern Ireland Neighbourhood Information Service, 2016; 2010 data
Pigs and poultry	Irish Environmental Protection Agency	Department of Agriculture, Environment and Rural Affairs (Bruce, 2017, pers.comm.)
FRAME concentrations	Not Available	Centre of Ecology and Hydrology (Dore, 2018, pers.comm.)
Ambient monitoring	EPA monitoring (Doyle, et al. 2017).	Centre of Ecology and Hydrology
Natura 2000 site boundaries	NPWS (National Parks & Wildlife Service, 2017),	Northern Ireland Environment Agency (OpenDataNI, 2016).

2.1.1. Synthetic fertilisers

There are no publicly available data on areas where synthetic fertilisers are spread across Ireland. Therefore, the MARSH model presumes a potentially higher amount of synthetic fertiliser being spread in areas which produce less animal manure and have a high proportion of agricultural land (such as grass and arable land). The percentage of agricultural land was used as an indicator of areas where slurry could potentially be spread (Figure 2A). Density of livestock units including cattle, sheep, pigs and poultry was used as an indicator of areas which produce higher proportions of animal manure (Figure 2B). This presumes areas with high animal manure production would be less likely to require synthetic fertilisers. This approach weights areas with high proportions of agricultural land and low levels of manure production as having a high risk of synthetic fertiliser spreading. It does not consider the fertiliser requirements of different crops, and is hence a rough approximation of areas where synthetic fertiliser may be spread. The final risk map for areas at risk of impact from synthetic fertiliser spreading is presented in Figure 2C.

2.1.2. Cattle and sheep

Available cattle and sheep distribution data for the ROI (Central Statistics Office, 2010) and for NI (Northern Ireland Neighbourhood Information Service, 2016; 2010 data) were used. The number of cattle and sheep per area of each electoral division and ward was used to create indicative maps of cattle (Figure 2D) and sheep (Figure 2E) farming intensity. The total emissions for cattle and sheep were divided by the potentially impacted area of each model component to produce the final weighting for each component, presented in Table 2.

2.1.3. Pigs and poultry

In the ROI, the locations of Industrial Emissions Directive (IED) (2010/75/EU) (European Union, 2010) licensed pig and poultry farms are publicly available through the Environmental Protection Agency (Environmental Protection Agency, 2017). In NI, the locations of such farms are available on request from the Department of Agriculture, Environment and Rural Affairs;

these are farms which house more than 40,000 birds and more than 2,000 production pig or 750 sow places. The point locations of farms were converted into a density map using the quadratic kernel density estimation function (Spatial Analyst, ArcMap 10.4, ESRI). The potential impact area for pig and poultry farms for the MARSH model was set to the total area of land within 10 km of the farms, based on the recommended screening distance for atmospheric pollution used by the Department for Environment and Rural Affairs in the UK (Department for Environment Food & Rural Affairs, 2016). The total emissions for pigs and poultry in Ireland were divided by the potential impact area of each model component. This produced pig and poultry emissions per 10 km impact area was then used to calculate the percent contribution to potential impacts on the Natura 2000 ecological network (Table 2).

2.2. Defining risk categories

The final weighting was determined by each model component's relative contribution to total ammonia emissions per potentially impacted area (Table 2). The five ranked model components were multiplied by their final weighting (Table 2) and summed using the raster calculator (Spatial Analyst, ArcMap 10.4, ESRI). As risk posed to Natura 2000 sites can vary depending on the sites sensitivity to ammonia, the resulting risk scale was defined into risk categories based on concentrations predicted by the UK FRAME model for NI. These were subsequently refined by interpolating the difference between predicted and monitored concentrations from Doyle, et al. (2017), and subtracting the difference from the MARSH model using raster calculator (Spatial Analyst, ArcMap 10.4, ESRI).

Concentrations from the FRAME model in NI were provided by the Centre of Ecology and Hydrology (CEH) (Dore, 2018, pers.comm.). The MARSH model was correlated with FRAME-modelled concentrations using the R Statistical Programme (R Core Team, 2013). Figure 1 shows an x-y scatterplot where the y-axis presents the atmospheric ammonia concentration based on the UK FRAME model in NI on a 5 km grid, and the x-axis presents the corresponding MARSH risk categories in the same location. Pearson's correlation was used to test the similarity between the two datasets, for which a value of 0.72 indicates there is a

clear relationship between the two models. The line of best fit shown in Figure 1 ($y = 0.8801x + 0.6524$) was used to estimate atmospheric ammonia concentrations within the MARSH model.

Figure 1: Predicted ammonia (NH₃) concentration based on FRAME model (µg/m³) vs. modelled MARSH risk values for Northern Ireland. Pearson's correlation coefficient of 0.72 between both datasets, and p-value: < 0.005.

The predicted concentrations were subsequently corrected based on a full year of atmospheric ammonia monitoring conducted in 2013 - 2014 by the Ammonia2 project (Doyle et al., 2017) and three sites continuously monitored in NI by CEH. The difference between the monitored concentrations and predicted model concentrations was interpolated using the Inverse Weighted Distance (IDW) tool (Figure 3A) (Spatial Analyst, ArcMap 10.4, ESRI), which was subsequently subtracted from the proxy concentration values (Figure 2I) using raster calculator (Spatial Analyst, ArcMap 10.4, ESRI). This allowed for MARSH risk categories to be defined by likely concentrations of atmospheric ammonia. The MARSH risk categories of 1, 2, 3, 4 and 5 correspond to concentrations of 0 – 0.99, 1 – 1.99, 2 – 2.99, 3 – 3.99 and > 4 µg/m³ respectively. The classified MARSH model (Figure 3B) was used to identify areas likely at risk from atmospheric ammonia based on predicted concentrations.

2.3. Nitroindex model - using lichens as indicators of impacts

Records of nitrogen-sensitive and nitrogen-tolerant lichen species collected between 2000 and 2014 for species listed on the Field Studies Council's "Guide to using a lichen based index to nitrogen air quality" (Air Pollution Information System, 2015), were provided by the Centre for Environmental Data and Recording (CEDaR). Rihm et al. (2009) carried out surveys where the frequency of nitrogen-sensitive species were subtracted from nitrogen-tolerant species, and divided by the sum of all frequencies for the trees monitored as part of the study. This methodology was applied within 10 km grids using all available relevant records. These were then interpolated using IDW (Spatial Analyst, ArcMap 10.4, ESRI) presented in Figure 3C. The resulting map presents areas with less than 0 being predominantly sensitive species indicative of unaffected areas and those greater than 0 as being predominantly tolerant species indicative of impacted areas. The Nitroindex data was incorporated into the MARSH model to produce a bivariate map (Figure 3D), which indicates both areas "a-risk" from the MARSH and Nitroindex models.

2.4 Assessing risk to Natura 2000 sites

Natura 2000 site boundaries were obtained from sources shown in Table 1. A database of the qualifying features (e.g. Active raised bogs [7110], European dry heaths [4030], marsh saxifrage (*Saxifraga hirculus*) [1528], pearl mussel (*Margaritifera durrovensis*) [1990]) of the entire Natura 2000 network of sites was created by this project, to which the relevant critical level was assigned to each habitat/species. The critical levels assigned to each feature within this database was crosschecked against those used in the UK for each specific Habitats Directive Annex 1 habitat and species.

For SACs where a site contained a qualifying feature with a critical level of $1 \mu\text{g}/\text{m}^3$, this critical level was applied to the entire site. A critical level of $3 \mu\text{g}/\text{m}^3$ was applied to all other sites (Cape et al., 2009). There is a risk of secondary impacts to qualifying features of SPAs (birds) through impacts on their habitats. CORINE land cover was used to determine the habitats

potentially sensitive to ammonia (peat bogs, moors and heathland and natural grasslands) within SPAs. The MARSH and Nitroindex models were intersected (ArcMap 10.4, ESRI) with the Natura 2000 site boundaries. The spatial area of MARSH and Nitroindex risk categories within each Natura 2000 site was calculated using ArcGIS 10.4. These data were compiled and provided to the relevant authorities, in order to inform site specific risks.

Designation Weighted Indicators (DWI) have been recommended to summarise the exceedance of critical levels of atmospheric ammonia on Natura 2000 sites (Hallsworth et al., 2010). As DWIs are considered more appropriate for assessment under the Habitats Directive, this was the method used to summarise the risk for Natura 2000 sites across Ireland. If any portion of a Natura 2000 site exceeds a risk value, it was considered to have that level of risk associated with the entire site. The proportion of Natura 2000 sites which at some location fall within a MARSH risk category are summarised in Table 3. Exceedance values of all Natura 2000 sites are shown in Table 4.

3. Results

3.1. Compiling the MARSH & Nitroindex models

The total ammonia emissions for the sectors reported to the European Environment Agency for Ireland are presented in Table 2. The “Area Occupied” in Table 2 refers to electoral divisions or wards in which synthetic fertiliser, cattle and sheep are present, and the total area of 10 km buffers around pig and poultry farms. “Total Emissions/ha” shown in Table 2 was used to weight the model components shown in Figure 2 (C – G). Based on emissions per hectare, cattle contribute 51.3% of potential impacts where pigs and poultry contribute 24.9 and 15.1%, respectively. This approach compensates for the varying scale of impacts between diffuse (synthetic fertiliser, cattle and sheep) and point sources (pig and poultry) of atmospheric ammonia. Figure 2H shows the summed model components based on the weighting shown in Table 2, where 0 is representative of areas with low risk and 5 of areas with high risk of impacts.

Table 2: Breakdown of model source component ammonia emissions, the area occupied by each source component and final weighting of each source component in the MARSH model¹.

	Ammonia Emissions				Area Occupied	Weighting
Source	Northern Ireland (Gg)	Republic of Ireland (Gg)	Total (Gg)	Total (%)	Hectares (million ha)	Total Emissions/ha (%)
Synthetic Fertiliser	2	12.9	14.9	11	8.4	7.6
Cattle	20.5	79.9	100.4	74.4	8.4	51.3
Sheep	0.6	1.4	2	1.5	8	1.1
Pigs	2	7.9	9.9	7.3	1.7	24.9
Poultry	3.8	2.8	6.6	4.9	1.9	15.1
Total	29	105.9	134.9	100	28.3	100

¹ Horses were excluded as their numbers are not available through the Northern Ireland Neighbourhood Information Service (NINIS) website (Northern Ireland Neighbourhood Information Service, 2016). Horses contribute 0.9% to total emissions.

Figure 2A shows the risk of ammonia impact based on the proportion of agricultural land, using CORINE landcover. Figure 2B displays areas more likely to use synthetic fertiliser based on lower livestock units of cattle, sheep, pigs and poultry. Figure 2A and Figure 2B, when integrated form Figure 2C which presents areas with a risk from the proportion of agricultural land, and the likelihood for synthetic fertiliser to be used. A band of high risk areas is visible along the eastern coast of Ireland.

Figures 2D and E show areas at risk from cattle and sheep production respectively. Here the higher risk of 5 is representative of electoral districts or wards with higher cattle and sheep populations per unit area. Risk associated with cattle farming is highest in the south and north of Ireland. The areas at risk from sheep production is much lower, with areas reaching the risk category of 1 – 2, in the north with small sections at risk in the west and south east of Ireland. Figures 2F and G show areas at risk from pig and poultry production respectively. These are based on the density of IED licensed farms within 10 km of each other, higher densities have higher predicted impacts. Pig production is visible down the centre of Ireland, whereas poultry production is concentrated in the north. Figure 2H illustrates the total risk following the summation of Figures 2C – G. based on the weightings in Table 2. This shows a large proportion of Ireland falling within the MARSH risk category of 1, with sections of 2 in the north and south. Correlating this data with FRAME concentrations classifies this risk based on potential concentrations (Figure 2I), where the risk classification has visibly increased. Significantly more of Ireland is now presumed to exceed concentrations of $1 \mu\text{g}/\text{m}^3$ (MARSH Risk Category 1) and $3 \mu\text{g}/\text{m}^3$ (MARSH Risk Category 3).

Figure 2. A. Risk based on total agricultural density from CORINE landcover. B. Risk based on likelihood of synthetic fertiliser use. C. Areas at risk from synthetic fertiliser spreading. D. Areas at risk from cattle production. E. Areas at risk from sheep production. F. Areas at risk from pig production. G. Areas at risk from poultry production. H. Model components summed based on weighting in Table 2. I. FRAME concentrations applied to Figure 2H.

3.2. Defining risk categories

Risk categories were defined for MARSH by predicting likely concentrations. The line of best fit shown in Figure 1 was used to apply a proxy concentration value to both NI and the ROI, using FRAME concentrations modelled in the UK for NI. This is shown in Figure 2I, which overestimates concentrations based on local monitoring carried out in 2013 – 2014 on a scale of 0.2 to 0.6 $\mu\text{g}/\text{m}^3$ (Figure 3A). Raster calculator (ArcMap 10.4, ESRI) was used to subtract the difference (Figure 3A) from proxy concentrations (Figure 2. I.). As monitored concentrations were consistently lower than those modelled, Figure 3A was used to correct Figure 2I, producing a final MARSH risk map presented in Figure 3B. The highest overestimation of concentration was along the west coast of Ireland, where concentrations are lower due to decreased agricultural activity (see Figure 2A – H.).

3.3. Integrated MARSH and Nitroindex results

By considering both the likelihood of impacts based on sources (MARSH – Figure 3B)) and recorded ecological impacts (Nitroindex – Figure 3C), the number of potential risk categories increases from five to twenty. Figure 3C shows the Nitroindex map created using existing national lichen records collected between the years 2000 and 2014. This is presented on a scale where the value of +1 is interpreted as an area that has a lot of nitrogen tolerant species and is thereby impacted, whereas a value of -1 represents an area that has predominantly nitrogen sensitive species and is thereby not impacted. The Nitroindex was divided into four risk categories -1 to -0.49 (“no-risk”), -0.5 to -0.01 (“low-risk”), 0 to 0.49 (“at-risk”) and 0.5 to 1 (“high-risk”). This presents best available data for recorded ecological impacts on a national scale. The Nitroindex presents areas unaffected by atmospheric ammonia along the west coast, and a portion of the east coast. This coincides with the areas of little agricultural activity shown in Figure 2. C – G. A number of additional areas throughout Ireland have small pockets where the Nitroindex is low, likely representative of bogs or other sensitive habitats where indicator species reflected no impact.

Subsequently, a bivariate map (Figure 3D) bringing both the MARSH model and Nitroindex model data together allows for a more detailed interpretation of potential risks to Natura 2000 sites. Figure 3D shows areas “at-risk” both from predicted risk and recorded impacts, where high risk areas are visible in the south and midlands, in addition to the very high risk areas in the north where the MARSH risk category of 4 indicates extensive exceedance of $3 \mu\text{g}/\text{m}^3$. Both the MARSH and Nitroindex model align on the low risk posed along the west coast of Ireland.

Figure 3: A. Interpolated difference between recent monitoring (Doyle et al., 2017) and predicted concentrations; B. Final MARSH model; C. Final Nitroindex model; D. Bivariate map of both the MARSH and Nitroindex Models.

3.4. Using MARSH and Nitroindex to gauge risk to Natura 2000 sites

Figure 4A shows SACs and their corresponding critical level at which impacts are likely on that site. This highlights that the majority of SACs have a qualifying feature that is sensitive to atmospheric ammonia with a critical level of $1 \mu\text{g}/\text{m}^3$. SACs with a critical level of $3 \mu\text{g}/\text{m}^3$ are primarily coastal sites on which ammonia impacts are not likely. In the case of oceanic SACs, they have been excluded entirely from this assessment. The percentage area within each SPA that could potentially include a habitat with a critical level of $1 \mu\text{g}/\text{m}^3$ was calculated and mapped (Figure 4B). SPAs with greater than 51% coverage of habitats that potentially have a critical level of $1 \mu\text{g}/\text{m}^3$ roughly correspond with the low risk areas of the MARSH and Nitroindex models, whereas a number 11 – 50% and 0 – 10% of SPAs are in medium to high risk areas.

Figure 4. A. Critical level of the most sensitive qualifying feature of each SAC, B. Proportion of landcover likely to have a critical level of $1 \mu\text{g}/\text{m}^3$ within each SPA.

SACs are more vulnerable to impacts from atmospheric ammonia when compared to SPAs due to a potential for direct impacts on qualifying features. Hallsworth et al. (2010) recommended applying the highest concentration recorded on a site to the whole site. This logic was applied to assigning the critical levels of SAC sites, where if a SAC had a qualifying feature with a critical level of $1 \mu\text{g}/\text{m}^3$ this was applied to the whole site. Using this approach, 68% of SACs were assigned a critical level of $1 \mu\text{g}/\text{m}^3$ (Figure 4A). Sensitivity of SPAs was defined based on the proportion of habitats within each site that had a potential critical level of $1 \mu\text{g}/\text{m}^3$, presented as a percentage of the total site area. These sites were divided into three categories, 0 – 10%, 11 – 50%, and 51 – 100%, which contained 72%, 16% and 11% of all SPAs respectively (Figure 4B).

By mapping the sensitivity of Natura 2000 sites, identification of potential risks is enhanced. The breakdown of SACs and SPAs based on sensitivity of sites and MARSH risk values is presented in Table 3. This shows the percentage of Natura 2000 sites that in some location on that site fall within the MARSH risk categories. The majority of sites within the Natura 2000 ecological network are exposed to concentrations exceeding the critical level of $1 \mu\text{g}/\text{m}^3$, with 67% of all sites overlapping with concentrations of $1 - 2 \mu\text{g}/\text{m}^3$. As concentrations increase, the number of sites exposed decreases with $2 - 3 \mu\text{g}/\text{m}^3$ occurring on 33.4% of sites and $3 - 4 \mu\text{g}/\text{m}^3$ on 5.9% of sites.

Table 3: Percentage of Natura 2000 sites which at some location fall within MARSH risk categories presented.

MARSH Risk Category	1	2	3	4	5
Proxy Ammonia concentration	< 1 µg/m³	1 -2 µg/m³	2 – 3 µg/m³	3- 4 µg/m³	> 4 µg/m³
SAC critical level of 1 µg/m³	30.7%	66%	33.7%	5.5%	0.3%
SAC critical level of 3 µg/m³	22.9%	66%	28.8%	4.6%	0%
All SACs	28.2%	66%	32.2%	5.2%	0.2%
SPA critical level of 1 µg/m³ (1-10%)	24.2%	69.5%	39.8%	8.6%	0%
SPA critical level of 1 µg/m³ (11 - 50%)	35.7%	78.6%	35.7%	3.6%	0%
SPA critical level of 1 µg/m³ (51 – 100%)	50%	60%	20%	10%	0%
All SPAs	29%	69.9%	36.9%	8%	0%
All Natura 2000 sites	28.4%	67%	33.4%	5.9%	0.2%

Concentrations above a critical level of 3 µg/m³ can impact higher plants present within Natura 2000 sites; 5.9% of all Natura 2000 sites exceed this value. These are sites that should be considered as having the highest overall risk. When critical levels of 1 µg/m³ are exceeded, impacts can be observed on lichen and moss communities and other sensitive habitats; 80.7% of all Natura 2000 sites are likely to exceed this concentration using DWI. These analyses are summarised in Table 4 below, which also details exceedances in SACs and SPAs separately.

Table 4: Proportion of Natura 2000 sites which exceed proxy atmospheric concentration values based on DWI.

Critical Level	Total no.	> 1µg/m ³	> 2 µg/m ³	> 3 µg/m ³
SAC count	482	389	161	25
SPA count	176	142	65	14
All Natura 2000 count	658	531	226	39
All Natura 2000 (%)	-	80.7%	34.3%	5.9%

Areas within the Nitroindex values of -1.0 to -0.5 can be considered relatively unaffected, compared to those at 0.5 to 1.0 that, with high numbers of nitrogen tolerant species, are likely impacted. Though lichens have not been recorded on all Natura 2000 sites, by interpolating the data using IDW tools, lichen species recorded nearby will contribute to the Nitroindex values in the vicinity of Natura 2000 sites.

Table 5 presents the overlap of Natura 2000 site data and the Nitroindex model. Separating the Nitroindex model into four categories allows for easy interpretation of the data. The Nitroindex risk category of -1.0 to -0.5, the areas with most nitrogen sensitive species occurs in the lowest number (23.7%) of Natura 2000, whereas a value of 0.5 to 1.0 indicative of the most impacted areas occurs in more than half (55%) of Natura 2000 sites.

Table 5: Percentage of Natura 2000 sites which at some location fall within Nitroindex risk categories presented.

Nitroindex Value	- 1.0 to -0.5	-0.5 to 0.0	0.0 to 0.5	0.5 to 1.0
SAC critical level of 1 µg/m³	28.3%	51.1%	25.2%	55.3%
SAC critical level of 3 µg/m³	14.4%	30.7%	28.1%	56.2%
All SACs	23.9%	44.6%	26.1%	55.6%
SPA critical level of 1 µg/m³ (1- 10%)	16.4%	43.8%	42.2%	54.7%
SPA critical level of 1 µg/m³ (11 -50%)	35.7%	71.4%	46.4%	53.6%
SPA critical level of 1 µg/m³ (51 – 100%)	50%	100%	65%	75%
All SPAs	23.3%	50%	41.5%	53.4%
All Natura 2000 sites	23.7%	46%	30.2%	55%

4. Discussion

4.1. Final MARSH model

The Republic of Ireland urgently requires a detailed atmospheric ammonia concentration model, similar to the FRAME model used in the UK. Without such detailed modelling, it is extremely difficult to identify Natura 2000 sites potentially at risk from impacts arising from atmospheric ammonia. The MARSH model infers concentration values based on agricultural activity converted to ammonia concentrations using FRAME data that were verified and adjusted using monitored atmospheric ammonia data gathered across Ireland. MARSH categorises risk based on potential concentrations; however, the model is not intended to act as a concentration model, but instead as a risk assessment screening tool to work towards compliance with the risk-based approach recommended by the NECD. Meteorology, topography, non-regulated agricultural facilities and other non-agricultural sources of ammonia are currently not accounted for in the MARSH model; inclusion of these variables is considered likely to modify the findings.

Currently, the best tool available to assess impacts from new agricultural developments is the screening tool known as SCAIL (Simple Calculation of Atmospheric Impact Limits). The SCAIL tool allows for assessment of sites in the ROI and NI, however it currently utilises interpolated values from the 1999 – 2000 monitoring program conducted on behalf of the EPA (de Kluizenaar and Farrell, 2000) as background atmospheric concentrations (Hill et al., 2014). This excludes the contribution of intensive point sources such as pig and poultry farms as monitoring sites were intentionally placed at some distance from such sources. If modelling, such as FRAME, was extended to include the ROI, it would account for all contributions to atmospheric ammonia and could incorporate other variables that the MARSH model has not included. An emissions map for the ROI with a resolution of 1 x 1 km for ammonia emissions has recently been produced (Nielsen et al., 2017). The creation of this map is an important step in the process of building a concentration model. Using this dataset to represent areas at risk from impacts arising from atmospheric ammonia is not ideal as the modelled emissions

are limited to within 1 km of their source. In reality, these emissions can spread much further with 10 km screening distance recommended in the UK (Department for Environment Food & Rural Affairs, 2016).

A detailed summary of the proportion of all Natura 2000 sites across Ireland within each MARSH and Nitroindex risk category can be used by relevant authorities to assist in identifying Natura 2000 sites at risk from atmospheric ammonia. These resources collectively are intended to guide the responsible authorities in terms of assessing “at-risk Natura 2000 sites”, particularly ones that require atmospheric ammonia monitoring under the NECD. Critical load exceedance is often the primary tool used by countries to gauge impacts of atmospheric nitrogen on sensitive habitats (Hicks, 2011; Aherne et al., 2017). However, in order to accurately create a deposition model, a concentration model is first required. Irish deposition models have been relying on the use of interpolated monitoring locations (Doyle et al., 2017; de Kluizenaar and Farrell, 2000).

4.2. MARSH model source components

Impact scales used in this paper are relative, with a value of 5 assigned to the most impacted area for that model component and 0 assigned to the least impacted area. Integrating more recent data from the Land Parcel Information System (LPIS) would benefit future modelling (Zimmermann et al., 2016), in addition to the locations of below IED-threshold pig and poultry farms. While the MARSH model accounts for potential cumulative impacts of IED licensed pig and poultry farms, it is important to consider the potential influence of sub IED threshold farms which contribute to a cumulative impact. As the locations of these farms are currently unavailable, using such density maps is the best means to account for their contribution to impacts. The data used as inputs are similar to those used by the UK AENAID model (Hellsten et al., 2008), which is the primary input for the FRAME concentration and deposition model (Dore, 2009). The novel approach taken in MARSH provides a potentially low cost risk-assessment methodology for atmospheric ammonia. Improvement of data availability would enhance the analytical and predictive capabilities of similar models in future. For example, the

current lack of details of any areas where animal manure spreading occurs needs to be addressed. Estimating areas based on low animal stocking rates but with high areas of agricultural land is currently the best method for creating a risk map of areas where synthetic fertiliser is likely to be spread. The MARSH model also assumes that animal manure is spread in the electoral division or ward in which it is generated. In reality, animal manure can be transported to other areas.

4.3. Nitroindex

Lichens were inevitably under-recorded in some areas, hence the currently available dataset used in this study is an imperfect indicator of risk by itself. Incorporating it as an aspect of the bivariate map to identify risk areas in conjunction with the MARSH model ensures that risk is not based solely on potentially under-recorded lichen species. This approach encourages future national and local lichen surveys, which can contribute to building detailed impact maps. In addition, work currently being carried out surveying and analysing nitrogen content within moss species in Ireland will provide invaluable data in identifying areas with heavy loads of nitrogen deposition (Cathcart and Wilkins, 2015).

4.4. Risk to Natura 2000 sites

The MARSH model predicts that 80.7, 34.3 and 5.9% of Natura 2000 sites in Ireland may exceed ammonia concentrations of 1, 2, and 3 $\mu\text{g}/\text{m}^3$, respectively. The primary benefit of using the MARSH model rather than interpolated monitored concentrations or existing deposition maps to identify risk on Natura 2000 sites is that it offers enhanced spatial resolution concerning areas with higher emissions, which may have been unaccounted for previously (Doyle et al., 2017). Incorporating all best available data, the MARSH methodology therefore represents the most cost-effective approach to identifying Natura 2000 sites at risk from atmospheric ammonia without additional targeted monitoring.

The risk to Natura 2000 sites using DWI should be re-evaluated once a detailed concentration model for Ireland is produced. Some nationally important or undesignated sites are often

excluded from such assessments. In the ROI, for example, a large number of Natural Heritage Areas are designated to conserve nationally important bogs, which are particularly sensitive to impacts from atmospheric ammonia. Irish Natura 2000 sites already experience a range of impacts, including for example turf cutting (O' Riordan et al., 2015) which directly removes sensitive bog habitats and causes the bogs to dry. Research conducted on heathlands suggests that ammonia can further exacerbate impacts on heathlands such as drying (Sheppard et al., 2008). It is hence important to consider all impacts when determining sites at risk. Consequently, site-specific nitrogen management plans for sites should be created and integrated with existing monitoring and modelling of impacts on such sites.

4.5. Critical Levels & Critical Loads

A critical level is defined by Posthumus (1988) as 'the concentration in the atmosphere above which direct adverse effects on receptors, such as plants, ecosystems or materials, may occur according to present knowledge'. Posthumus (1988) describes a critical load as 'a quantitative estimate of deposition of one or more pollutants below which significant harmful effects on specified elements of the environment do not occur according to present knowledge'. Whether gauging impacts by using critical levels or critical loads, a concentration map is required to either directly assess impacts using critical levels based on the concentration, or to build a deposition model with which critical load exceedance can be applied. All modelling of critical loads in the ROI thus far is based on the deposition of interpolated concentration values (Henry and Aherne, 2014; Aherne et al., 2017). As this methodology intentionally excludes the contribution of licensed pig and poultry farms, in addition to unmonitored high concentration areas, it is flawed in terms of identification of risks to Natura 2000 sites. The MARSH model acts as the first source-apportioned concentration model for Ireland since first modelled in 2001, using data from 1996 by the UK's FRAME model (Fournier et al., 2002). Until a more detailed model is produced, the MARSH approach acts as a concentration model which may assist future deposition models for Ireland. MARSH may therefore be particularly useful for assessing the exceedance of new lower critical loads for Ireland defined by Wilkens et al.

(2016), which will benefit the long-term management of Natura 2000 sites. Research conducted in Ireland suggests that the critical loads as currently applied (Bobbink and Hettelingh, 2011) may be too high to represent ecological impacts of nitrogen (Wilkins et al., 2016). Similarly, although critical levels of 1 and $3 \pm 1 \mu\text{g}/\text{m}^3$ are based on best available evidence from a number of international studies (Cape et al., 2009), there have been recorded instances where critical levels for impacts were observed at concentrations below $1 \mu\text{g}/\text{m}^3$ (Sutton et al., 2009; Pinho et al., 2014). Further research may be required in order to test the validity of these critical levels transferred into an Irish context.

5. Conclusions

This GIS-based methodology applied to best available data for ammonia sources and nitrogen vulnerability provides an approximation of risk from atmospheric ammonia impacts. Identification of risk categories based on FRAME concentrations and locations monitored for atmospheric ammonia enhanced the ability of the MARSH model to predict areas at risk from ammonia deposition. The methodology used is a cost-effective approach utilising existing datasets to provide a relatively simple approach to identifying “at-risk” areas, and may be applicable in other Member States should suitable data exist. Though containing considerable stated uncertainties and assumptions, this methodology has nevertheless generated a list of Natura 2000 sites based on the likelihood of potential risk, fulfilling the requirement of the EU NECD to use a risk-based approach to identify sites that require monitoring. Understanding areas at risk will allow the relevant stakeholders to identify national monitoring programmes that overlap with “at-risk” areas, and which can be used to further enhance the cost-effectiveness of future monitoring in compliance with the NECD. This paper recommends future lichen surveys, on both a national and site-specific level, in addition to production of an atmospheric concentration model such as FRAME for the ROI.

6. Acknowledgements

This research was undertaken as part of the AmmoniaN2K Project funded by the Irish Environmental Protection Agency through the STRIVE Programme. The authors would like to acknowledge the support of the AmmoniaN2K Project Steering Committee, the Centre of Ecology and Hydrology (CEH) and the Centre for Environmental Data and Recording (CEDaR).

7. References

- Aherne, J., Henry, J. & Wolniewicz, M. 2017. Development of Critical Loads for Ireland: Simulating Impacts on Systems (SIOS). (2008-CCRP-4.1a). CCRP Report. EPA, Johnstown Castle, Ireland.
- Air Pollution Information System. 2015. *Monitoring air quality using lichens - field guide and app* [Online]. Air Pollution Information System. Available online: <http://www.apis.ac.uk/nitrogen-lichen-field-manual> (Accessed March 2018).
- Bobbink, R. & Hettelingh, J. 2011. Review and revision of empirical critical loads and dose–response relationships: Proceedings of an Expert Workshop, Noordwijkerhout, 23–25 June 2010. Available online: http://www.iap.ch/publikationen/bobbink_hettelingh_2010_empirical_critical_loads.pdf (Accessed March 2018).
- Bobbink, R., Hicks, K., Galloway, J., Spranger, T., Alkemade, R., Ashmore, M., Bustamante, M., Cinderby, S., Davidson, E., Dentener, F., Emmett, B., Erisman, J. W., Fenn, M., Gilliam, F., Nordin, A., Pardo, L. & De Vries, W. 2010. Global assessment of nitrogen deposition effects on terrestrial plant diversity: a synthesis. *Ecological Applications*, 20, 30-59.
- Butchart, S. H. M., Walpole, M., Collen, B., Van Strien, A., Scharlemann, J. P. W., Almond, R. E. A., Baillie, J. E. M., Bomhard, B., Brown, C., Bruno, J., Carpenter, K. E., Carr, G. M., Chanson, J., Chenery, A. M., Csirke, J., Davidson, N. C., Dentener, F., Foster, M., Galli, A., Galloway, J. N., Genovesi, P., Gregory, R. D., Hockings, M., Kapos, V., Lamarque, J.-F., Leverington, F., Loh, J., Mcgeoch, M. A., Mcrae, L., Minasyan, A., Morcillo, M. H., Oldfield, T. E. E., Pauly, D., Quader, S., Revenga, C., Sauer, J. R., Skolnik, B., Spear, D., Stanwell-Smith, D., Stuart, S. N., Symes, A., Tierney, M., Tyrrell, T. D., Vié, J.-C. & Watson, R. 2010. Global Biodiversity: Indicators of Recent Declines. *Science*, 328, 1164 – 1168.

- Cape, J. N., Van Der Eerden, L. J., Sheppard, L. J., Leith, I. D. & Sutton, M. A. 2009. Evidence for changing the critical level for ammonia. *Environmental Pollution*, 157, 1033-1037.
- Cathcart, H. & Wilkins, K. 2015. Hunting high and low for *Hylocomium* in Ireland *Field Bryology*, 114, 32 - 35.
- Central Statistics Office. 2010. Census Of Agriculture 2010. *Central Statistics Office*. Dublin, Ireland.
- de Kluizenaar, Y. & Farrell, E. P. 2000. Ammonia Monitoring In Ireland: A Full Year Of Ammonia Monitoring. *R&D Report Series No. 8. Dublin: Forest Ecosystem Research Group, University College Dublin*, 66.
- Department for Environment Food & Rural Affairs. 2016. *Air emissions risk assessment for your environmental permit* [Online]. <https://www.gov.uk/>. Available: <https://www.gov.uk/guidance/air-emissions-risk-assessment-for-your-environmental-permit> (Accessed January 2018).
- Department for Environment Food & Rural Affairs. 2018. *UKEAP: National Ammonia Monitoring Network* [Online]. <https://uk-air.defra.gov.uk>. Available: <https://uk-air.defra.gov.uk/networks/network-info?view=nh3> (Accessed June 2018).
- Department of Agriculture, Environment, and Rural Affairs. 2017. *Going for Growth - a strategic action plan in support of the NI agri-food industry* [Online]. Crown Copyright. Available: <https://www.daera-ni.gov.uk/publications/going-growth-strategic-action-plan-support-ni-agri-food-industry> (Accessed May 2018).
- Department of Agriculture Food and the Marine 2015. Food Wise 2025. *Department of Agriculture, Food and the Marine*. Dublin, Ireland.
- Department of Culture Heritage and the Gaeltacht. 2017. National Biodiversity Action Plan 2017 - 2021. *Department of Culture, Heritage and the Gaeltacht*. Dublin, Ireland.

- Directorate-General Environment. 2018. Nature Newsletter Natura 2000 No. 43. *In: European Commission Nature and Biodiversity Newsletter*, Brussels, Belgium.
- Dore, A., Kryza, M., Hallsworth, S., Matejko, M., Hall, J., Van Oijen, M., Zhang, Y., Bealey, B., Vieno, M., Tang, S., Smith, R., Dragosits, U., Sutton, M.A. 2009. Modelling the Deposition and Concentration of Long Range Air Pollutants: Final Report. <http://www.uk-pollutantdeposition.ceh.ac.uk/frame>.
- Doyle, B., Cummins, T., Augustenborg, C. & Aherne, J. 2017. Ambient Atmospheric Ammonia in Ireland, 2013-2014. (2012-CCRP-MS.8). CCRP Report. EPA, Johnstown Castle, Ireland.
- Environmental Protection Agency. 2016. Ireland's Environment 2016 - An Assessment. *Environmental Protection Agency*. Johnstown Castle, Co. Wexford.
- Environmental Protection Agency. 2017. *EPA Map Viewer* [Online]. Environmental Protection Agency. Available online: <http://gis.epa.ie/Envision> (Accessed September 2017).
- Environmental Protection Agency. 2018. Ireland's Transboundary Gas Emissions 1990 - 2016. *Environmental Protection Agency*. Johnstown Castle, Wexford.
- European Commission. 2009. Directive 2009/147/EC of the European Parliament and of the Council of 30 November 2009 on the conservation of wild birds. Official Journal of the European Union L20/7, 26/01/2010. Brussels, Belgium.
- European Commission. 2015. The State of Nature in the European Union. *European Commission*. Brussels, Belgium.
- European Economic Committee. 1992. Council directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora. Official Journal of the European Communities, L206/7, 22/07/1992. Brussels, Belgium.

European Union. 2016. Directive (EU) 2016/2284 of The European Parliament and of the Council of 14 December 2016 on the reduction of national emissions of certain atmospheric pollutants, amending Directive 2003/35/EC and repealing Directive 2001/81/EC. Official Journal of the European Union, L344/1, 17/12/2016. Brussels, Belgium.

European Union. 2010. Directive (EU) 2010/75/EU of The European Parliament and of the Council of 24 November 2010 on industrial emissions (integrated pollution prevention and control) (Recast). Official Journal of the European Union, L334/17, 17/12/2010. Brussels, Belgium.

European Environment Agency. 2016. *National emissions reported to the Convention on Long-range Transboundary Air Pollution (LRTAP Convention)* [Online]. *European Environment Agency*. Available Online: <http://www.eea.europa.eu/data-and-maps/data/national-emissions-reported-to-the-convention-on-long-range-transboundary-air-pollution-lrtap-convention-10/#parent-fieldname-title> (Accessed January 2017).

Fournier, N., Pais, V. A., Sutton, M. A., Weston, K. J., Dragosits, U., Tang, S. Y. & Aherne, J. 2002. Parallelisation and application of a multi-layer atmospheric transport model to quantify dispersion and deposition of ammonia over the British Isles. *Environmental Pollution*, 116, 95-107.

Fрати, L., Brunialti, G. & Loppi, S. 2008. Effects of reduced nitrogen compounds on epiphytic lichen communities in Mediterranean Italy. *Science of The Total Environment*, 407, 630-637.

Fрати, L., Santoni, S., Nicolardi, V., Gaggi, C., Brunialti, G., Guttova, A., Gaudino, S., Pati, A., Pirintsos, S. A. & Loppi, S. 2007. Lichen biomonitoring of ammonia emission and nitrogen deposition around a pig stockfarm. *Environmental Pollution*, 146, 311-6.

- Gómez, A., Ondiviela, B., Juanes, J., Revilla, J., García, A., Vargas, A., Álvarez, C. & Puente, A. 2007. A risk assessment approach to contaminant emissions in seaport areas: methodological procedure to calculate susceptibility. Fourth International Conference on Port Development and Coastal Environment, Varna, Bulgaria.
- Hallsworth, S., Dore, A. J., Bealey, W. J., Dragosits, U., Vieno, M., Hellsten, S., Tang, Y. S. & Sutton, M. A. 2010. The role of indicator choice in quantifying the threat of atmospheric ammonia to the 'Natura 2000' network. *Environmental Science & Policy*, 13, 671-687.
- Hellsten, S., Dragosits, U., Place, C. J., Vieno, M., Dore, A. J., Misselbrook, T. H., Tang, Y. S. & Sutton, M. A. 2008. Modelling the spatial distribution of ammonia emissions in the UK. *Environmental Pollution*, 154, 370-379.
- Henry, J. & Aherne, J. 2014. Nitrogen deposition and exceedance of critical loads for nutrient nitrogen in Irish grasslands. *Science of The Total Environment*, 470, 216-223.
- Heo, S., Kim, M., Yu, H., Lee, W.-K., Sohn, J. R., Jung, S.-Y., Moon, K. W. & Byeon, S. H. 2017. Chemical accident hazard assessment by spatial analysis of chemical factories and accident records in South Korea. *International Journal of Disaster Risk Reduction*, 27, 37 -47.
- Hernández, D. L., Vallano, D. M., Zavaleta, E. S., Tzankova, Z., Pasari, J. R., Weiss, S., Selmants, P. C. & Morozumi, C. 2016. Nitrogen Pollution Is Linked to US Listed Species Declines. *BioScience*, 66, 213-222.
- Hicks, W. K., Whitfield, C.P., Bealey, W.J. , & Sutton M.A. 2011. Nitrogen Deposition and Natura 2000 Science and Practice in Determining Environmental Impacts. *COST729/Nine/ESF/CCW/JNCC/SEI Workshop Proceedings, published by COST. Available at: <http://cost729.ceh.ac.uk/n2kworkshop>.*

- Hill, R., Bealey, B., Johnson, C., Ball, A., Simpson, K., Smith, A., Theobald, M. R., Braban, C. F., Magaz, I. & Curran, T. P. 2014. SCAIL-Agriculture update. Sniffer ER26 Final Report.
- Joint Nature Conservation Committee. 2013. *Habitat Conservation Status Reports - 3rd UK Habitats Directive Reporting 2013* [Online]. Available online: <http://jncc.defra.gov.uk/article17>. Monkstone House, City Road, Peterborough, PE1 1JY: JNCC. (Accessed April 2018).
- Karan, S. K. & Samadder, S. R. 2016. Reduction of spatial distribution of risk factors for transportation of contaminants released by coal mining activities. *Journal of Environmental Management*, 180, 280-290.
- Lindenmayer, D., Barton, P. & Pierson, J. 2015. *Indicators and Surrogates of Biodiversity and Environmental Change*. Clayton South: CSIRO Publishing.
- MacCarthy, J., Thistlethwaite, G., Salisbury, E., Pang, Y. & Misselbrook, T. 2012. Air Quality Pollutant Inventories for England, Scotland, Wales and Northern Ireland: 1990 – 2010. Report for Department of Environment, Food and Rural Affairs. UK: AEA Didcot.
- Mackenzie, C. 2014. Knotweed Vulnerability Analysis. Kitsap County, Washington State. *Tufts GIS Poster Expo*. Medford, Massachusetts: Tufts GIS Center.
- Maskell, L. C., Smart, S. M., Bullock, J. M., Thompson K., Stevens, C. J. 2010. Nitrogen deposition causes widespread loss of species richness in British habitats. *Global Change Biology*, 16, 671-679.
- National Parks & Wildlife Service. 2017. *Download boundary data* [Online]. www.npws.ie. Available online: <https://www.npws.ie/maps-and-data/designated-site-data/download-boundary-data> (Accessed July 2017).

- Nielsen, O.-K., Plejdrup, M. S., Gyldenkærne, S., Christensen, J. H. & Bruun, H. G. 2017. *MapElre Project results* [Online]. Aarhus, Denmark: Aarhus University. Available online: <http://projects.au.dk/mapeire/project-results/> (Accessed October 2017).
- Northern Ireland Neighbourhood Information Service. 2016. *Farm Census* [Online]. Northern Ireland: Northern Ireland Neighbourhood Information Service. Available online: <http://www.ninis2.nisra.gov.uk/InteractiveMaps/Agriculture%20and%20Environment/Agriculture/Farm%20Census/atlas.html> (Accessed May 2018).
- O' Riordan, M., Mahon, M. & McDonagh, J. 2015. Power, Discourse and Participation in Nature Conflicts: The Case of Turf Cutters in the Governance of Ireland's Raised Bog Designations. *Journal of Environmental Policy & Planning*, 17, 127-145.
- OpenDataNI. 2016. *Protected Sites* [Online]. Northern Irish Environment Agency. Available online: <https://www.opendatani.gov.uk/dataset?tags=Protected+Sites> (Accessed March 2018).
- Payne, R. J., Dise, N. B., Field, C. D., Dore, A. J., Caporn, S. J. & Stevens, C. J. 2017. Nitrogen deposition and plant biodiversity: past, present, and future. *Frontiers in Ecology and the Environment*, 15, 431-436.
- Phoenix, G. K., Hicks, W. K., Cinderby, S., Kuylensstierna, J. C. I., Stock, W. D., Dentener, F. J., Giller, K. E., Austin, A. T., Lefroy, R. D. B., Gimeno, B. S., Ashmore, M. R. & Ineson, P. 2006. Atmospheric nitrogen deposition in world biodiversity hotspots: the need for a greater global perspective in assessing N deposition impacts. *Global Change Biology*, 12, 470-476.
- Pinho, P., Llop, E., Ribeiro, M. C., Cruz, C., Soares, A., Pereira, M. J. & Branquinho, C. 2014. Tools for determining critical levels of atmospheric ammonia under the influence of multiple disturbances. *Environmental Pollution*, 188, 88-93.

- Posthumus. 1988. Critical levels for effects of ammonia and ammonium. Proceedings of the Bad Harzburg Workshop, Umweltbundesamt Berlin, 117-127.
- R Core Team 2013. *R: A language and environment for statistical computing*, Vienna, Austria, R Foundation for Statistical Computing.
- Rihm, B., Urech, M. & Peter, K. 2009. Mapping Ammonia Emissions and Concentrations for Switzerland - Effects on Lichen Vegetation. *In: Sutton, M. A., Reis, S. & Baker, S. (eds.) Atmospheric Ammonia: Detecting emission changes and environmental impacts.* Dordrecht: Springer Netherlands.
- Sekac, T., Jana, S. K., Pal, I. & Pal, D. K. 2016. GIS Based Evaluation in Earthquake Hazard Micro-Zonation-A Case Study of Madang and Morobe Province, Papua New Guinea. *International Journal of Advanced Engineering Research and Science*, 3, 95-104.
- Sheppard, L. J., Leith, I. D., Crossley, A., Van Dijk, N., Fowler, D., Sutton, M. A. & Woods, C. 2008. Stress responses of *Calluna vulgaris* to reduced and oxidised N applied under 'real world conditions'. *Environmental Pollution*, 154, 404-413.
- Stiles, W. a. V., Rowe, E. C. & Dennis, P. 2017. Long-term nitrogen and phosphorus enrichment alters vegetation species composition and reduces carbon storage in upland soil. *Science of The Total Environment*, 593, 688-694.
- Stoate, C., Báldi, A., Beja, P., Boatman, N. D., Herzon, I., Van Doorn, A., De Snoo, G. R., Rakosy, L. & Ramwell, C. 2009. Ecological impacts of early 21st century agricultural change in Europe – A review. *Journal of Environmental Management*, 91, 22-46.
- Sutton, M., Leith, I., Bealey, W., Van Dijk, N. & Tang, Y. 2011. 3.6 Moninea Bog-Case study of atmospheric ammonia impacts on a Special Area of Conservation. *Nitrogen deposition and Natura 2000: Science and Practice in Determining Environmental Impacts*. COST, Brussels, 59 - 71.

- Sutton, M. A., Wolseley, P. A., Leith, I. D., Van Dijk, N., Tang, Y. S., James, P. W., Theobald, M. R. & Whitfield, C. 2009. Estimation of the Ammonia Critical Level for Epiphytic Lichens Based on Observations at Farm, Landscape and National Scales. *In*: Sutton, M. A., Reis, S. & Baker, S. M. H. (eds.) *Atmospheric Ammonia: Detecting emission changes and environmental impacts*. Dordrecht: Springer Netherlands.
- Wakeling, D., Passant, N., Murrells, T., Pang, Y., Thistlethwaite, G., Walker, C., Brown, P., Del Vento, S., Hunter, R., Wiltshire, J., Broomfield, M., Watterson, J., Pearson, B., Rushton, K., Hobson, M., Dore, C. & Misselbrook, T. 2018. UK Informative Inventory Report (1990 to 2016). Ricardo Energy & Environment.
- Wang, J. & Wu, J. 2009. Occurrence and potential risks of harmful algal blooms in the East China Sea. *Science of The Total Environment*, 407, 4012-4021.
- Wilkins, K., Aherne, J. & Bleasdale, A. 2016. Vegetation community change in Atlantic oak woodlands along a nitrogen deposition gradient. *Environmental Pollution*, 216, 115-24.
- Wolseley, P. A., James, P. W., Theobald, M. R. & Sutton, M. A. 2006. Detecting changes in epiphytic lichen communities at sites affected by atmospheric ammonia from agricultural sources. *The Lichenologist*, 38, 161-176.
- Zimmermann, J., Fealy, R. M., Lydon, K., Mockler, E. M., O'brien, P., Packham, I., Smith, G. & Green, S. 2016. The Irish Land-Parcels Identification System (LPIS)—Experiences in ongoing and recent environmental research and land cover mapping. *Biology and Environment: Proceedings of the Royal Irish Academy*, 116B, 53-62.