20th International Congress on Modelling and Simulation, Adelaide, Australia, 1–6 December 2013
www.mssanz.org.au/modsim2013

Application of a protectability index to assess habitat eutrophication in designated areas

T. Oxley[a], H.M. ApSimon[a] and J. Hall[b]

[a] *Centre for Environmental Policy, Imperial College, South Kensington, London SW7 1NA, England*
[b] *Centre for Ecology & Hydrology (CEH), Deniol Road, Bangor, Gwynedd LL57 2UW, Wales*
Email: t.oxley@imperial.ac.uk

Abstract: Under the UNECE LRTAP Convention protection of ecosystems is routinely evaluated in integrated assessment by calculating exceedance of critical loads, defined as the maximum levels of deposition sustainable without adverse effects. Such assessments using the UK Integrated Assessment Model are able to quantify the extent of exceedance regionally for different broad habitat categories. Although this provides an aggregated view useful for policy development, it cannot quantify impacts upon individual sites of special scientific interest (SSSI) or other sites designated under the Habitats Directive or the Birds Directive of the European Union.

Compilation of critical load data for designated sites by JNCC has enabled a more detailed consideration of those ecosystem areas of concern, leading to the development of a “protectability index” which indicates different degrees of risk for different habitats within designated sites, ranging from “protected with a high level of confidence” to “un-protectable” where exceedance is so large that reducing deposition to eliminate it is not feasible.

As designated sites are often nearby, or adjacent to agricultural livestock, they can be unduly affected by short-range dry deposition of ammonia emissions. We evaluate current (2010) and projected (2020) impacts upon a range of habitats in designated sites which display very low to very high sensitivities to nitrogen deposition. With agricultural emissions of ammonia consistently difficult to reduce, we compare these impacts with an hypothetical scenario in which dry deposition of ammonia – which is dominated by local sources – has been reduced, indicating where local control measures may be useful. We conclude that local mitigation measures may present an effective means for reducing eutrophication in designated sites.

Keywords: *Critical Load Exceedance, Eutrophication, Designated Sites (SSSI), Protectability Index*

1. INTRODUCTION

The protection of ecosystems is assessed in the UK Integrated Assessment Model (UKIAM) [Oxley *et al.*, 2013] by calculating exceedance of critical loads, defined as the maximum levels of deposition sustainable without adverse effects. The standard approach used in integrated assessment modelling and under the UNECE LRTAP Convention is to consider areas of exceedance integrated over all ecosystems. For the UKIAM this has involved use of critical load data for acidification and eutrophication for the UK provided at a detailed 1x1km resolution across the UK, and corresponding to the UK data submitted to the Coordinating Centre on Effects [Hall 2003; Hall *et al.*, 2008]. Emissions scenarios assessed by the UKIAM involve dispersion of the emitted pollutants utilising source-receptor relationships – which capture the effects of atmospheric chemistry – calculated by the Lagrangian FRAME model for UK sources [Fournier *et al.*, 2004; 2005; Dore *et al.*, 2007; 2009] and the Eulerian EMEP model for non-UK sources [Simpson *et al.*, 2012], with the consequent deposition patterns used to calculate exceedance of critical loads for different broad habitat types.

Aggregated statistics focussing on broad habitat types provide useful metrics for assessing overall progress towards ecosystem protection in the context of national and international policy making. However, such statistics do not indicate the extent of protection of designated sites which may contain multiple habitats displaying differing sensitivities to deposition.

Why focus on designated sites?

Spatial definition of designated areas and critical loads of acidity and eutrophication for designated features and habitats have been collated by CEH and the UK Government Joint Nature Conservation Committee (JNCC) (http://www.jncc.gov.uk/) for Sites of Special Scientific Interest (SSSI) or European Natura 2000 sites, which include Special Areas of Conservation (SAC) designated under the EC Habitats Directive (92/42/EEC) and Special Protection Areas (SPA) protected by the EC Birds Directive (2009/147/EC)), providing the basis of EU Biodiversity Policy. With 42% of European terrestrial ecosystems projected to remain at risk of nitrogen eutrophication in 2020, with consequent biodiversity loss [Posch *et al.*, 2011; Reis *et al.*, 2012], it is becoming increasingly important to focus upon designated sites as opposed to broad habitat classes. Since nutrient nitrogen deposition is difficult to reduce because of agricultural NH_3 emissions, local mitigation measures may be necessary in order to effectively protect sensitive habitats [Dragosits *et al.*, 2006].

2. BROAD HABITATS & DESIGNATED SITES

The purpose of the UK Integrated Assessment Model is to evaluate the potential impacts of emission abatement strategies based upon future projections of emissions. In relation to impacts on the natural environment, the model determines the extent and spatial distribution of both acid and nutrient nitrogen deposition and uses these deposition rates to calculate exceedance of critical loads for acidity and eutrophication for different broad habitat classes. These definitions of critical loads and distributions of broad habitat classes are consistent with the representations used by the Coordinating Centre for Effects [Posch *et al.*, 2012], ensuring that evaluations of the impacts of policies at the national scale remain consistent with assessments carried out at transboundary (European) scales (see, for example, Amann et al. (2011)).

The results of such national scale assessments can be represented both spatially as maps (see Figure 1) and with tabulated statistics (see Table 1). These outputs highlight the spatial variations in exceedance together with 'hot-spots' as can be observed in East Anglia where NH_3 emissions

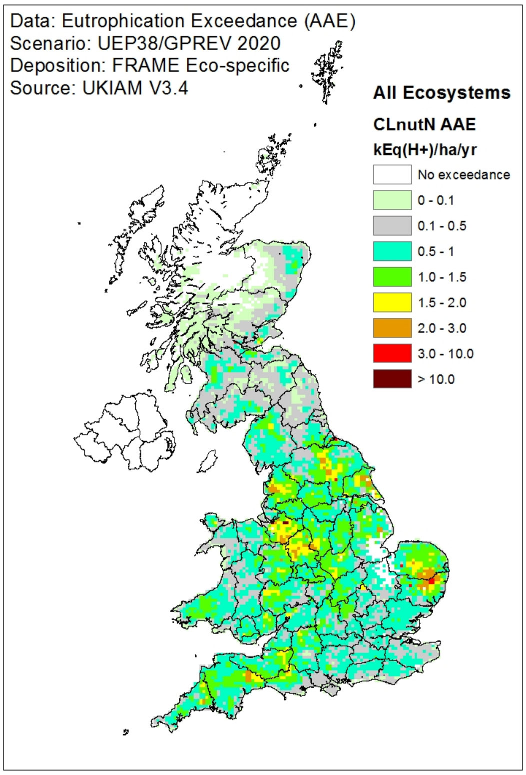

Figure 1 - Spatial distribution of exceedance of nutrient-N critical loads in 2020 including the effects of the revised Gothenburg Protocol

are dominated by poultry, and provide an aggregated numerical representation which allows policy makers to quickly evaluate progress relative to current conditions or alternative abatement strategies. Compared with a corresponding simulation of the current (2010) situation, Table 1 reflects a 7.5% reduction in the total percentage area exceeded, and a 15% reduction in accumulated exceedance by 2020.

Such metrics provide useful information for policy makers to evaluate abatement strategies on a national scale, and in relation to the commitments made under the Gothenburg Protocol. However, they provide little or no indication of impacts upon individual ecosystems *within* these broad habitat classes. In order to address the objectives of the Habitats Directive or the Birds Directive it is necessary to understand impacts upon sensitive habitats which these Directives are designed to protect with the objective of preventing further loss of biodiversity. With critical loads for designated sites becoming available (see above), the deposition patterns calculated for any given scenario can be applied to habitats and features in designated sites to provide additional statistics quantifying exceedances at each site (see Table 2); an uncertainty range is also provided by the definition of maximum and minimum critical loads for each habitat. Note that these results reflect exceedance of the most sensitive habitat on each site, whereas in reality there are likely to be several habitats present, each displaying a different sensitivity to deposition. This necessitates more detailed examination of the impacts *within* each site as habitats are currently assumed to be present throughout a site.

Table 1 - Nutrient nitrogen exceedances for the United Kingdom
(Scenario: UEP38/Gothenburg Revision (2020))

Broad Habitat	**Habitat Area (km^2)**	**Exceeded Area (km^2)**	**Percentage Area Exceeded**	**Accumulated Exceedance (kEq/year)**
Acid grassland	15,241	6,708	44.01	252,111
Calcareous grassland	3,577	2,254	63.00	72,445
Dwarf shrub heath	24,820	4,454	17.94	167,400
Bog	5,541	1,804	32.56	105,954
Montane	3,129	2,055	65.69	32,146
Coniferous woodland (managed)	8,385	6,084	72.56	367,844
Broadleaved woodland (managed)	7,482	7,053	94.27	624,555
Unmanaged woods (ground flora)	3,296	2,765	83.88	222,016
Atlantic oak (epiphytic lichens)	822	477	58.08	35,306
Supralittoral sediment	2,128	520	24.45	11,067
All habitats	**74,422**	**34,175**	**45.92**	**1,890,843**

Table 2 - Statistics describing exceedance of habitats and features at each designated site for each UK region.

CLnutN counts of sites/habitats exceeded

	Total			Exceeding CLmin			Exceeding CLmax		
Country	Sites	Features	Habitats	Sites	Features	Habitats	Sites	Features	Habitats
England	3070	4549	7777	2919	4261	7441	2098	2866	4820
Wales	701	1508	3841	693	1465	3612	540	978	1967
Scotland	970	1478	3004	671	913	1614	299	333	498
NIreland	158	227	452	149	210	407	110	151	264
UK	4899	7762	15074	4432	6849	13074	3047	4328	7549

CLnutN areas (hectares) of sites exceeded

	Total	Exceeding CLmin		Exceeding CLmax	
Country	Area	Area	AE	Area	AE
England	927,634	887,805	795,611	716,576	450,338
Wales	184,820	181,576	140,478	137,945	66,122
Scotland	896,750	574,496	166,687	161,803	42,201
NIreland	60,945	56,457	79,508	49,721	56,684
UK	2,070,149	1,700,334	1,182,284	1,066,045	615,345

Source: UKIAM V3.4
Scenario: **UEP38 2020**

3. PROTECTABILITY INDEX

Although the statistics shown in Table 2 provide additional information to policy makers at an aggregated level, they still do not indicate how protectable individual sites or habitats may be. This has resulted in a more detailed consideration of those ecosystem areas of greater concern, with development of a "protectability index". This index indicates different degrees of risk for different habitats within designated sites from "protected with a high level of confidence" to "un-protectable" where exceedance is so large that reducing deposition to eliminate it may not be feasible. Thus, each individual habitat (within features, within sites) can be evaluated in each designated site; where multiple habitats are examined, the greatest habitat exceedance will determine the site exceedance.

The protectability index is defined to highlight:

- Protected (No exceedance)
- Within CL uncertainty range (Exceedance > $CLnutN_{min}$ and < $CLnutN_{max}$)
- Unprotected (Exceedance > $CLnutN_{max}$)
- Difficult to protect (Exceedance > 1.5x $CLnutN_{max}$)
- Potentially not protectable (Exceedance > 2x $CLnutN_{max}$)

Whereas the first three bands are self-explanatory, the final two bands reflect simple multiples of deposition rates beyond the point of exceedance in order to highlight extreme situations. Based upon these protectability bands, habitats/sites which may require additional local measures to achieve protection can be highlighted, although it may still not be possible to protect some sensitive habitats in some sites.

Figure 2 shows a map illustrating this approach, where the colour indicates the "protectability" index for the most sensitive habitat with respect to eutrophication in each SSSI; based on deposition in 2020 and critical load data for SSSI's. CL_{min} and CL_{max} represent the minimum and maximum estimates of critical loads (ie. $CLnutN_{min}$ & $CLnutN_{max}$, respectively) as an indicator of uncertainty. Where nitrogen deposition is less than CL_{min}, the green areas, the level of protection is high. Between CL_{min} and CL_{max} the probability of protection decreases towards the higher value. Where deposition is not all that much higher than CL_{max} (yellow) it is possible that further measures to reduce deposition could lead to protection; but above 1.5x CL_{max} (orange) this is less likely to be possible, and for habitats with deposition greater than 2x CL_{max} (red) protection is, in practical terms, effectively impossible.

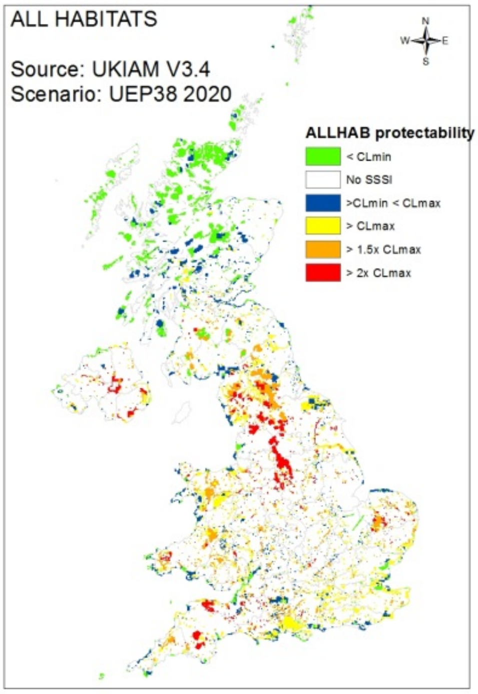

Figure 2 - Spatial distribution of SSSI's reflecting the protectability band each site lies in; all habitats included

Habitat Selection

Clearly, Table 2 and Figure 2 would present a different picture if the analyses were carried out for individual habitats. Therefore, a selection of habitats were assessed in order to capture the range of sensitivities displayed across different habitats. The habitats were selected to reflect a range of sensitivities from 'very low' to 'very high' so that the benefits of alternative emission scenarios could be further evaluated. The habitats selected were:

- NCL017_SALTMARS (Salt Marsh) - very low sensitivity (2.14<CLnutN<2.86kEq/ha)
- NCL007_GRASNELO (Lowland Grass) - low sensitivity (1.43<CLnutN<2.14)
- NCL009_FENLOW (Lowland Fens) - mid sensitivity (1.07<CLnutN<1.79)
- NCL025_WOODBL (Broadleaf Woodland) - high sensitivity (0.71<CLnutN<1.07)
- NCL019_BOGLOW (Lowland Bog) - very high sensitivity (0.35<CLnutN<0.71)

4. DEPOSITION SCENARIOS

The potential utility of the protectability index for assessing alternative policy scenarios in relation to biodiversity protection is investigated through definition of three related but contrasting emission scenarios. These scenarios were also evaluated in order to assess the progress towards habitat protection up to 2020, and to understand the potential for protection using local abatement measures. The three scenarios are:

I.	Baseline 2010	- Current state of protectability
II.	UEP38 (2020)	- Projected state of protectability
III.	UEP38 excl. Dry NH_X Dep. (2020)	- Potential for local measures

The third scenario, which reflects Scenario II but with dry deposition from agricultural sources removed, reflects an extremely speculative scenario whereby *all* agricultural NH_3 emissions are assumed to be mitigated by local measures. In reality this will never happen, and detailed spatial relationships between areas of emissions and the sensitive areas within SSSI's will be crucial for local impacts. However, this scenario facilitates assessment of *where* such local mitigation efforts may be most beneficial in relation to habitat protection, and where more detailed consideration of local measures including spatial planning and shelter belts is likely to be effective. This is because dry deposition of ammonia is highly concentrated close to the source, and hence changing local sources can have a large effect on nitrogen deposition as reflected in the dry deposition patterns.

These scenarios reflect contrasting deposition patterns (see Figure 3), with a noticeable reduction in nitrogen deposition between 2010 (Scenario I) and 2020 (Scenario II), and a large additional reduction evident in Scenario III.

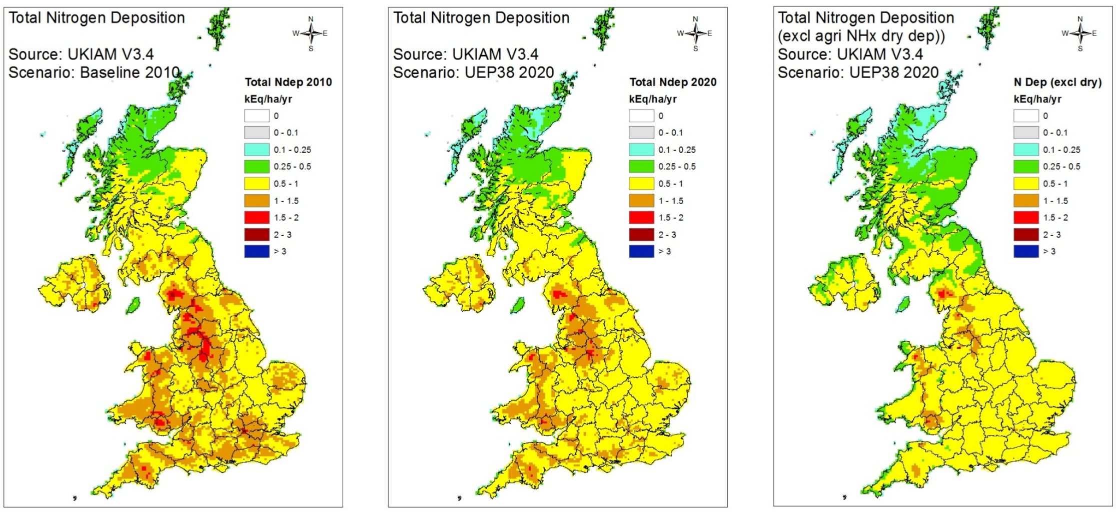

Figure 3 - Spatial representation of nutrient nitrogen deposition for the three scenarios investigated.

5. RESULTS

A selection of results from these scenarios are presented in Figure 4 in the form of histograms highlighting the number of habitats falling into each protectability band and identifying regionally where these habitats are located. The histograms give a break down for the different regions of how many sites fall in each category. This sort of display is useful for comparing scenarios, and understanding the extent to which further abatement and/or mitigation measures can improve ecosystem protection. Statistics can also be produced for individual habitats, showing how the distribution across different levels of protectability differs from less sensitive habitats to the most sensitive ones, and in which areas it appears impossible to achieve protection of any given habitat.

The results in Figure 4 provide an aggregated perspective (all habitats included) together with an individual habitat displaying very high sensitivity (Lowland Bog), for each of the three scenarios. The most striking feature in both cases is that there is only a marginal shift towards further protection between Scenario I (2010) and Scenario II (2020). However, the extreme Scenario III – where local dry deposition of ammonia from agricultural livestock is assumed to be fully mitigated by local measures – shows a significant shift

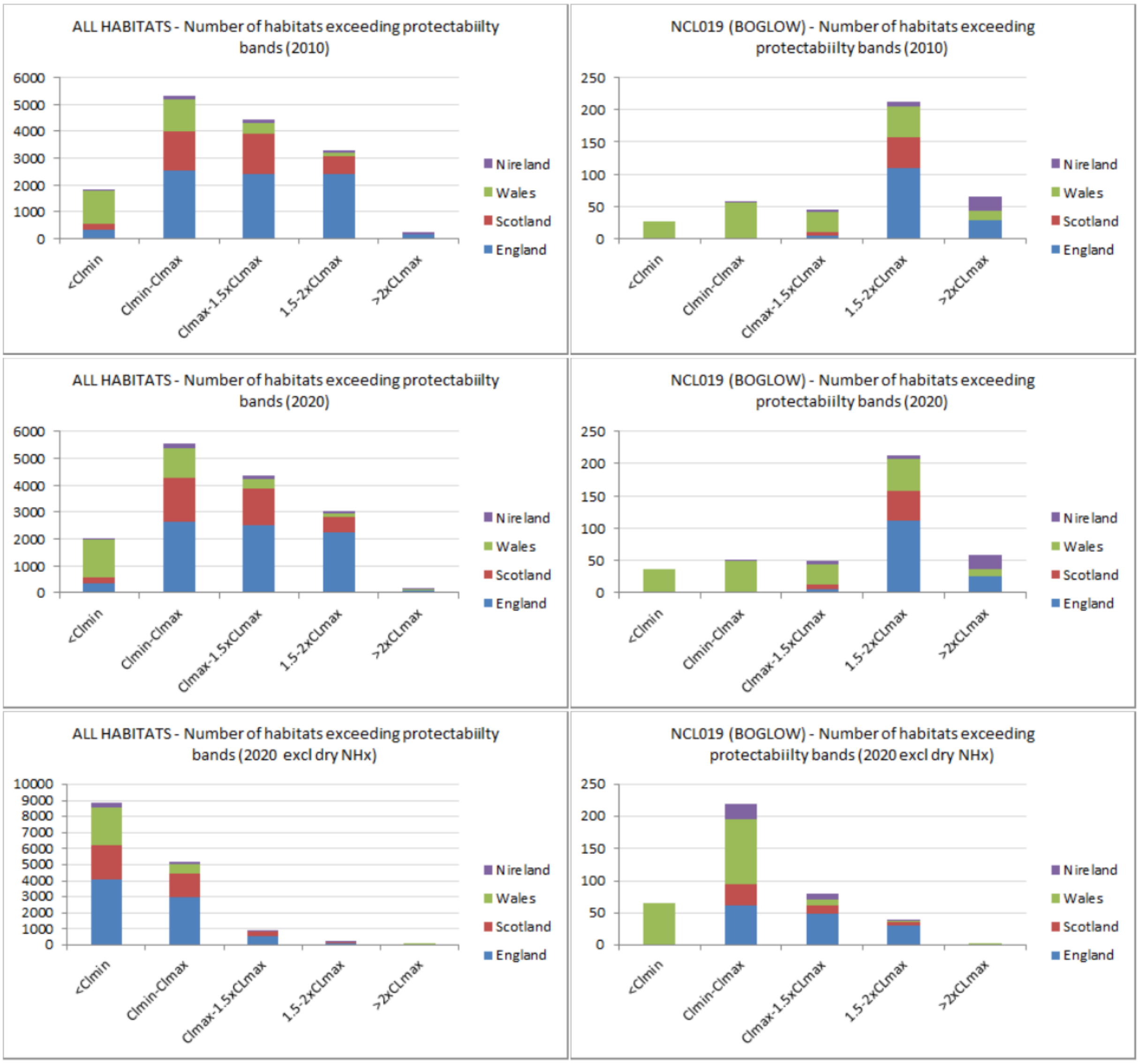

Figure 4 - Selected results from the three scenarios, showing all habitats (exceedance is determined by the most sensitive habitat) and showing lowland bog habitats only

towards habitat protection, with the majority of habitats either protected or now within the uncertainty range of the critical loads. In the case of lowland bogs (very high sensitivity), even assuming the extreme scenario, the majority of sites (219) are now within the uncertainty range of the critical loads (ie. may be protected), although 122 sites are still unprotected (with a quarter of those remaining in the highest bands). 65 lowland bog sites are protected, which compares with 26 protected in 2010 and 36 in 2020 (Scenario II).

6. DISCUSSION & CONCLUSIONS

Clearly, both the aggregated broad habitat perspective and the assessment of exceedances in designated sites in relation to protectability bands can provide useful understanding and statistics for policy makers tasked with developing emission abatement strategies which will protect the natural environment. However, it is only the latter which can effectively address issues of biodiversity protection, whereas the former remains beneficial for assessment of general ecosystem impacts.

The findings from this work can be summarised as follows:

- Increased protection of habitats in 2020 is modest, relative to 2010, and mainly a result of reduced NO_X emissions since there are only small changes in agricultural NH_3 emissions;

- Further *abatement* (~15%) of NH_3 emissions is possible, but the measures required to achieve this may not be applicable everywhere (eg. in Nitrate Vulnerable Zones), and/or may be expensive to implement;
- Significant increases in habitat protection may be possible with *mitigation* of NH_3 emissions by local measures (ie. no assumed change in emissions);
- Some habitats (very low sensitivity – SALTMARS, GRASSNELO) are either already protected or lie within the uncertainty range for the critical loads (ie. between CL_{min} and CL_{max});
- Sensitive habitats (eg WOODBL, BOGLOW) are very difficult to protect, at best remaining within the CL uncertainty range;
- Some sensitive habitats appear to be un-protectable, even if local mitigation measures are considered;
- Additional scenarios are needed to investigate the impact of different livestock sectors upon dry NH_X deposition, and thus assess the potential for local measures; this should be coupled with more detailed studies of areas for priority sites where local sources are likely to be important;
- Where habitats appear to be un-protectable, the spatial distribution of the habitat should be re-mapped to determine precisely where this habitat is located within a designated site;

Finally, an equivalent protectability index for acidity cannot be derived in the same way owing to the multi-pollutant influences on acidity (which includes Sulphur deposition); however, achieving significant reductions in exceedance of nutrient-N critical loads will also (significantly) reduce exceedance of acidity critical loads.

REFERENCES

Amann, M., Bertok, I., Borken-Kleefeld, J., Cofala, J., Heyes, C., Hoglund-Isaksson, L., Klimont, Z., Nguyen, B., Posch, M., Rafaj, P., Sandler, R., Schöpp, W., Wagner, F. & Winiwarter, W., 2011, Cost-effective control of air quality and greenhouse gases in Europe: modelling and policy applications, *Environmental Modelling & Software*, 26(12), 1489-1501

Dore, A. J., Vieno, M., Tang, Y. S., Dragosits, U., Dosio, A., Weston, K. J. & Sutton, M. A., 2007, Modelling the atmospheric transport and deposition of sulphur and nitrogen over the United Kingdom and assessment of the influence of SO_2 emissions from international shipping. *Atmospheric Environment*, 41 (11), 2355-2367.

Dragosits, U., Theobald, M.R., Place, C.J., ApSimon, H.M. & Sutton, M.A., 2006, The potential for spatial planning at the landscape level to mitigate the effects of atmospheric ammonia deposition, *Environmental Science & Policy* 9, 626-638

Fournier, N., A.J. Dore, M. Vieno, K.J. Weston, U. Dragosits & Sutton, M.A., 2004, Modelling the deposition of atmospheric oxidised nitrogen and sulphur to the United Kingdom using a multi-layer long-range transport model. *Atmospheric Environment*, 38(5), 683-694.

Fournier, N., K.J. Weston, A.J. Dore & Sutton, M.A., 2005, Modelling the wet deposition of reduced nitrogen over the British Isles using a Lagrangian multi-layer atmospheric transport model. *Quarterly Journal of the Royal Meteorological Society*, 131, 703-722.

Hall, J. (ed.), 2003, Status of UK Critical Loads: Critical Loads Methods, Data and Maps. UK National Focal Centre, Centre for Ecology & Hydrology, February 2003, http://cldm.defra.gov.uk/

Hall, J., Evans, C., Rowe, E. & Curtis, C., 2008, UK National Focal Centre report. In: Hettelingh, J-P., Posch, M., Slootweg, J. (eds.) Critical load, dynamic modelling and impact assessment in Europe: CCE Status Report 2008, Coordination Centre for Effects, Netherlands Environmental Assessment Agency, 211-216 (http://wge-cce.org/)

Oxley, T., Dore, A.J., ApSimon, H.M., Hall, J. & Kryza, M., 2013, Modelling future impacts of air pollution using the multi-scale UK Integrated Assessment Model (UKIAM), *Environment International*, Vol 61C, 17-35, DOI: 10.1016/j.envint.2013.09.009

Posch, M., Aherne, J. & Hettelingh, J-P., 2011, Nitrogen critical loads using biodiversity-related critical limits, *Environmental Pollution*, 159(10), 2223-2227

Posch, M., Slootweg, J. & Hettelingh, J-P., (eds.) 2012, Modelling and Mapping of Atmospherically-induced Ecosystem Impacts in Europe, CCE Status Report 2012, Coordination Centre for Effects, Report 680359004, ISBN 978-90-6960-262-2 (http://wge-cce.org/)

Reis, S., Grennfelt, P., Klimont, Z., Amann, M., ApSimon, H., Hettelingh, J-P., Holland, M., LeGall, A-C., Maas, R., Posch, M., Spranger, T., Sutton, M. & Williams, M., 2012, From acid rain to climate change, *Science*, 338, 1153-1154

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