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A decision framework to attribute atmospheric nitrogen deposition as a threat to or cause of unfavourable habitat condition on protected sites

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Developing a decision framework to attribute atmospheric nitrogen deposition as a threat to or cause of unfavourable habitat condition on protected sites

Annex 1: Strength of “theoretical/national” evidence - Work Package 1 report

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1 Introduction and objectives

This Annex covers the national and theoretical information available to ascertain the degree of confidence that nitrogen (N) deposition is exceeding the relevant critical load, for a particular habitat, at a particular site. It therefore includes the N deposition at the site together with a measure of certainty around that deposition, and how it relates to the critical load range for each Common Standards Monitoring (CSM) habitat and a measure of certainty around that critical load range. Since critical loads are defined for habitat types defined under the EUNIS classification scheme (Bobbink & Hettelingh 2011) rather than for CSM habitats, and since many EUNIS habitats do not have a defined critical load range, this Annex also describes the cross-matching process required to find the most appropriate proxy critical load for UK CSM habitats and to provide a measure of the uncertainty in that process. Lastly, we review UK evidence in the context of the wider international evidence, including that which has arisen since the UN-ECE critical loads workshop (Bobbink & Hettelingh 2011).

The work presented in this Annex was undertaken under Work Package (WP) 1 of the research contract to develop the matrix. The aim of WP1 was to provide scoring systems, based on rigorous criteria, to evaluate the certainty around the components which make up the theoretical/national evidence. These are: N deposition, the critical load range, cross-matching of CSM habitats to EUNIS to assign appropriate critical load ranges for all CSM habitats. The WP provided a methodology for combining this information into an overall 'Exceedance Score', which summarises the theoretical and national evidence that N deposition is likely to be impacting on the condition of a Habitat Feature at a site-specific level.

2 Overview of approach

2.1 Conceptual model of the sources of uncertainty

The problem defined above reveals three main sources of uncertainty in the process of deriving a theoretical/national Exceedance Score, which are summarised in Figure 1. These three sources of uncertainty co-vary and must all be taken into account in the assessment.

- The *first source of uncertainty* is around the level of N deposition which a site or a CSM feature is exposed to. This includes uncertainty in the grid-level (5 x 5km) estimates of N deposition, and sub-grid variation at finer scale, which are discussed in WP1.1 (Section 3).
- The *second source of uncertainty* has two components: (i) the reliability of the defined critical load ranges, since these are based on varying levels of evidence at the European scale in terms of the number of studies, the type of study and how well each was suited to the task of developing a critical load – this is described in WP1.2B (Section 4.2); and (ii) UK evidence in the context of the wider international evidence, including new evidence presented since the UN-ECE critical loads workshop (Bobbink & Hettelingh 2011), which together indicate that a CSM habitat may be more- or less- sensitive to N than the cross-matched critical load suggests – this is covered in WP1.2C (Section 4.3).
- The *third source of uncertainty* lies in whether the critical load we are using accurately reflects the N sensitivity of that CSM habitat. This also comprises two elements: (i) the cross-matching process used to align CSM habitats with EUNIS categories; (ii) the cross-matching process which allocates proxy critical loads at the EUNIS level to the CSM-EUNIS matched habitats, which is described in WP1.2A (Section 4.1).

The subsequent calculation of the Exceedance Score is based on where the N deposition lies in relation to the critical load used for a CSM habitat, taking into account the uncertainty in all of the components described above. This calculation is described in WP1.3 (Section 5).

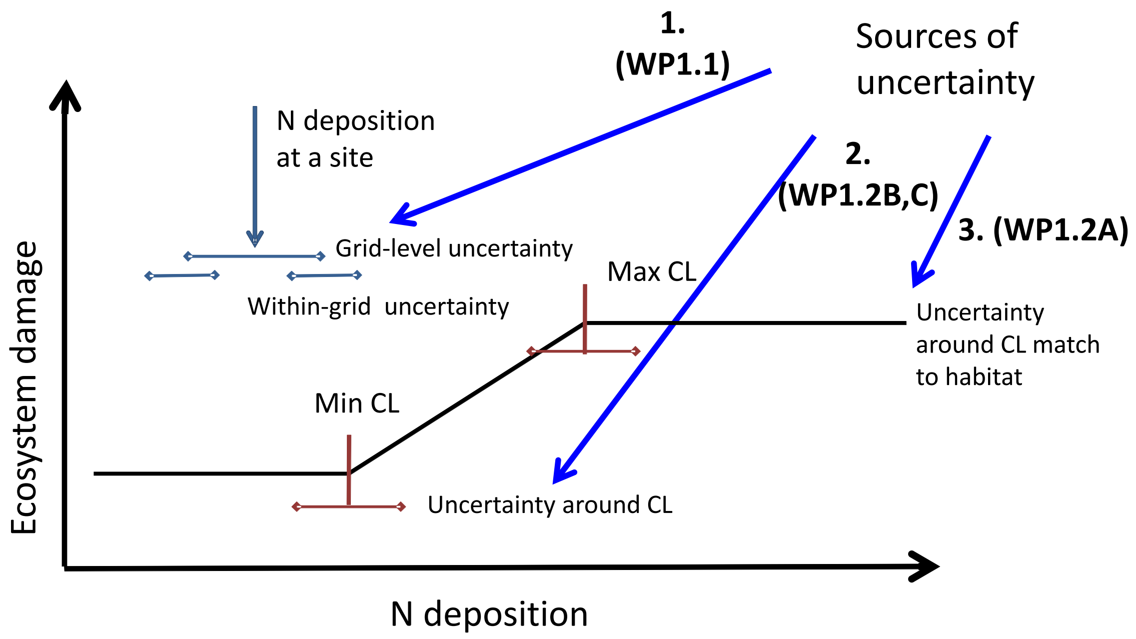

Figure 1. Schematic illustrating the three main sources of uncertainty in deriving an overall Exceedance Score by comparing N deposition with a critical load range. Black line symbolises ecosystem damage as N deposition exceeds the critical load (CL). Grey-blue lines represent N deposition and its associated uncertainty. Brown lines indicate CL bounds: Min CL = minimum of the critical load range, Max CL = maximum of the critical load range. Bright blue lines point out sources of uncertainty, numbered 1-3, and the relevant work packages identified where each is addressed. The y axis "ecosystem damage" refers to an increasing chance of significant adverse impacts from N on any individual site throughout critical load range.

2.2 How the sources of uncertainty can be combined

The components and their uncertainty are combined as illustrated schematically in Figure 2, and described below:

- The N deposition and its uncertainty (WP1.1) are used to calculate the likely N deposition range.
- The second and third sources of uncertainty which together capture the uncertainty around the critical load are covered as follows:
- The matching of CSM habitats to critical loads (WP1.2A) comprises two elements:
  i. the matching of the UK classification of CSM habitats to the European EUNIS classification (WP1.2Ai), and
  ii. the subsequent assignment of appropriate proxy EUNIS critical loads to those EUNIS habitats (WP1.2Aii).
- These are combined to give a certainty score that the critical load that has been matched to a CSM habitat is appropriate (WP1.2Aiii).
- This information is then combined with the certainty in the UN-ECE critical load ranges (WP1.2B) to produce an overall certainty that the critical load being used for a CSM habitat accurately reflects its N sensitivity (WP1.2D).
- The new UK evidence (WP1.2C) is used to identify particular cases where the CSM habitat may be more- or less- sensitive than the assigned CL. This information is not used to modify the assigned critical load, but is recorded to flag those habitats where

the assigned critical load may need to be reconsidered in future iterations of the framework.

- The combined certainty score from WP1.2D is used to adjust the critical load ranges which feed into the final calculation to produce an Exceedance Score for the CSM habitat at a site.

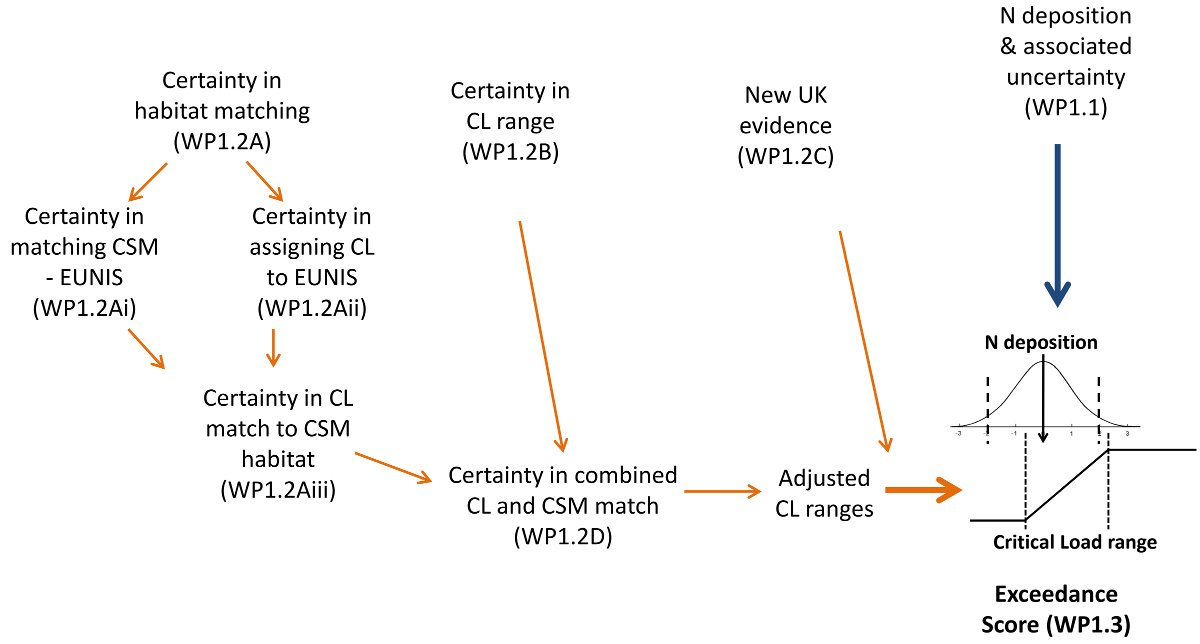

Figure 2. Schematic illustrating how the components of WP1 are combined to produce an Exceedance Score that summarises the degree to which a CSM habitat exceeds the critical load for N at a particular site, given the sources of uncertainty illustrated in Figure 1 and described in section 2.2.

2.3 Introduction to how the approach was implemented

The approach to calculate an Exceedance Score for a CSM habitat at a site is implemented within a spreadsheet. This requires entry of the N deposition for the site, for example as provided from the Air Pollution Information System (APIS: www.apis.ac.uk), and searching for the CSM habitat of interest to find the calculated Exceedance Score for that habitat, given the N deposition. The spreadsheet was pre-populated with all the information needed to obtain this information, and includes formulae which calculate the uncertainty around the N deposition, all the necessary intermediate scores illustrated in Figure 2, broken down by CSM habitat (and sub-habitat where appropriate) and the final Exceedance Score. In the sections below, but particularly in WP1.2A (section 4.1), further reference is made to how the spreadsheet is structured, and explanations for this structure are provided. A fuller description of how to use the spreadsheet is given in section 6 and the guidance in Appendix B.

3 WP1.1 Uncertainty around the N deposition to a site/CSM habitat

3.1 Aim

To incorporate the uncertainty in N deposition which subsequently determines the degree of confidence that N deposition at a site is exceeding the relevant N critical load.

3.2 Description of Approach

This WP describes the sources of uncertainty in N deposition, and the information supporting the choice of how uncertainty in N deposition is calculated within the framework. It also describes how this information is incorporated into the Framework spreadsheet.

3.3 N deposition and uncertainties

3.3.1 CBED deposition methodology and uncertainties

The CBED methodology generates regional scale maps, plotted at 5km x 5km resolution, of wet and dry deposition of sulphur, oxidised and reduced nitrogen, and base cations. It is based on measurements of air concentrations of gases and aerosols and concentrations of pollutants in precipitation from the UK Eutrophying and Acidifying Pollutants (UKEAP) network. The site-based measurements are used as a basis to generate maps of pollutant concentrations for the UK, principally using a kriging approach but including relevant additional spatial information where available. The gas and particulate concentrations are combined with estimates of vegetation-specific deposition velocities based on climate data (Smith *et al* 2000) to generate maps of deposition of SO_2, NH_3, NO_2 and HNO_3 gases and SO_4^{2-}, NH_4^+ and NO_{3-} aerosols (dry deposition). The precipitation ion concentrations and annual precipitation estimates from the UK Met Office are combined to generate estimates of pollutant deposition in rainfall (wet deposition) of SO_4^{2-}, NH_4^+ and NO_{3-}, Na^+, Cl^-, Ca^{2+} and Mg^{2+}. This includes an enhancement factor reflecting the increase in ion concentration within rainfall scavenged from orographically-enhanced cloud, relevant to higher elevation areas in the UK (Smith & Fowler 2001). Cloud droplets also deposit directly on vegetation and this deposition is estimated from the precipitation ion concentration (occult deposition). Maps of total pollutant deposition (dry, wet and occult) are generated for different land cover types: arable, grassland, moorland, forest and urban. The area of grassland is assumed to consist of one third improved grass (i.e. fertilised) and two thirds unimproved. The values used in APIS for terrestrial habitat types (and in national critical load exceedance calculations) are the values for “moorland”, which are deemed to be appropriate for all natural and semi-natural habitats with “low-growing” vegetation (0.2m high in winter to 0.5m high in summer, a leaf area index between 1.5 and 3, and an optimum growing temperature of 15^{o}C), and are used for all non-woodland habitats; there are also values for “woodland” (based on conifers with a 10m closed canopy and a leaf area index of 6) that are applied to all woodland habitats.

The N deposition values provided in APIS are the total habitat-specific deposition and include both oxidised N (NO_y) and reduced N (NH_x) components calculated by CBED. APIS recommends that additional data from local scale models and measurements are used where this is possible.

CBED provides values primarily for national scale estimation of UK deposition and budgets. Each 5km x 5km value provides typical deposition for the habitat and region in which the location occurs – it is <u>not</u> a site specific value. It is used to estimate the area of critical load exceedances in a broader region, as required for national policy development. Therefore any value of CBED deposition for a particular location does not generate a true critical load exceedance on its own; rather, by setting the location within the appropriate regional context, the relative area of exceedance for that habitat provides a probabilistic measure of the chances of the critical load being exceeded at this and any other local location of similar type. The reason for this interpretation of the deposition estimate is that many of the assumptions that underpin CBED are appropriate at a 10km – 50km scale and not at a 1m – 1,000m scale. Hence the output maps are plotted on a 5km x 5km grid, which is a reasonable geographical scale to interpret the information available. Therefore, there is no information in CBED about intra-grid variability.

There is some information available about intra-grid variability from other sources. Close to a local point source of ammonia (such as a poultry house, cattle shed, slurry pit, etc.), as you move away from the point source the air concentration of NH_3 is estimated to decrease by an order of magnitude, probably exponentially, over a distance of 200m - 300m (Pitcairn *et al* 2002; Jones *et al* 2013). However, these areal spikes in NH_3 concentration have little effect on the overall 'average' concentration in the 5km x 5km square – even if the concentration is, say, 10 times greater than the background within a circle of 50m of a source, then it would raise the average concentration in the 5km x 5km square by 0.3%, much less than the accuracy of the measurements. The 'true' spatial pattern of concentrations in an area and the closeness of the deposition value to the critical load will determine to what extent exceedances are underestimated (very close to sources) or overestimated (in areas of the 5km x 5km squares remote from sources) by CBED. Quantifying this scale dependence in general is not a trivial exercise, especially as the variability being assessed is at the scale of 10m. In the proximity of roads and urban areas, emissions of nitrogen oxides substantially raise NO_2 concentrations[1] up to 100m – 300m from the source, though the potential effects of NO_2 on vegetation are smaller than those of NH_3 at these concentrations. Further, deposition estimates are generally parameterised for notionally flat uniform landscapes, so effects of intermixing of multiple habitat types, elevation changes, or inclusion of hedges, buildings and small woods within the landscape are not represented. Hence the recommendation that the national scale (5km x 5km) data sets are complemented with more detailed information (e.g. local scale source-receptor tools such as SCAIL, or local scale atmospheric dispersion models) due to the large spatial variability of N at a landscape scale, especially with regard to point sources (e.g. large intensive livestock farms, industry) and line sources (e.g. busy roads) (Dragosits *et al* 2014).

Another scenario where local variation does occur and there is some quantification is in the complex terrain that occurs with hills and mountains. CBED builds in an orographic enhancement linked to the average rainfall in the 5km x 5km square (altitude is not an adequate proxy for rainfall, as most rainfall does not fall vertically in the UK). There is an additional challenge to any modification in that rainfall is extremely difficult to measure (or model) accurately at higher elevations, and only a probabilistic estimate of that variability would be possible at the present time. All rainfall is assumed to come from frontal systems, so deposition estimates to any location that experiences a substantial fraction of its rainfall from convective events (e.g. thunderstorms) will use an overestimate of the orographic enhancement. Likewise, although likely to be a small effect, estimates of cloud cover are from a national model. Local data on cloud cover and wind speeds at higher elevations could be used to improve estimates of occult deposition.

The above considerations lead to a conclusion that there are small sub-grid areas that will experience possibly considerably higher deposition than the estimate from CBED, but there will also be some areas where CBED overestimates deposition.

A full, quantitative, assessment of the uncertainties in UK CBED 5km x 5km deposition data sets has not been carried out. While it is relatively easy to undertake sensitivity analyses, there is a lack of any significant body of actual measurement data of N deposition across the UK landscape to validate an uncertainty analysis at a national scale (concentrations are widely measured, N deposition is not, except in precipitation). This is partly because N is so reactive within ecosystems and comprises many forms. The validations that support the use of CBED rely on other ions such as sulphur and chloride in situations where they can be

[1] NO_2 is about 80% of the NOx in rural areas. See http://uk-air.defra.gov.uk/assets/documents/reports/cat09/1310021025_AQD_DD4_2011mapsrepv0.pdf

tracked through terrestrial and freshwater systems (e.g. Reynolds et al, 1997). The extensive measurement studies used in deriving parameters that are used by CBED tend to concentrate on particular habitat types rather than the general landscape, and using these data both to find parameter values and compare with model outputs leads to a circular argument that results in underestimating the uncertainty. Without these data comparisons, any uncertainty assessment is effectively a propagation of possible errors exercise, and it makes the assumption that we properly know and can justify all parameter distributions, all correlations between parameters and all relationships between any variables and parameters used – certainly not a trivial task.

However the processes on which CBED is based are understood, and there is a body of evidence that supports the use of the equations within CBED including: process studies near various ammonia sources (Flechard *et al* 2013; Theobald *et al* 2012), the Great Dun Fell, Snowdon and Holme Moss experiments on wet and occult deposition (Fowler *et al* 1988; Choularton *et al* 1988; Gallagher *et al* 1988), and the ^{210}Pb studies (Fowler *et al* 1995) which integrate deposition over 20 years and allow the spatial structure in wet and aerosol deposition to be quantified. Deposition measurements at the EMEP supersite at Auchencorth Moss validate the use of these methods for all of the components of N deposition at one specific location and habitat type. Catchment studies measuring sulphur outputs at Beacon Hill in the English Midlands and in upland catchments in Central Wales (Plynlimon) allow integration of deposition estimates at annual and catchment scales and allow validation of CBED for these catchments. There are also areas of the UK where there are fewer complicating processes, i.e. no local sources and simple topography, where we believe CBED estimates are more representative of the local area and can in principle be downscaled. However, the field experiments needed to measure the fine scale structure in deposition and concentration within a range of 5km x 5km grid squares of the UK landscape has not been attempted, despite attempts to secure the necessary funding. Such experiments are needed to provide the validation of estimates of deposition at the sub-5km scale.

It is possible to provide subjective (expert opinion) assessments of uncertainty. In a study into uncertainties in critical loads and their exceedances, Heywood *et al* (2006) state "a subjective assessment by the relevant UK deposition experts suggests a normal distribution with a coefficient of variation (CV) of 25% for the national 5km sulphur and N deposition data". In the absence of a more comprehensive study, the CBED experts consulted within this project (Ron Smith, David Fowler) suggest this is used as a guideline figure for uncertainty in N deposition nationally. The CV is the standard deviation divided by the mean and expressed as a percentage. A 95% confidence interval is approximately twice the CV. Therefore, a CV of 25% equates to an uncertainty range of +/- 50%, i.e. 0.5*mean to 1.5*mean. This uncertainty has been applied to each 5x5km value of the CBED deposition. Although uncertainty is likely to vary spatially across the UK, data on the spatial variability in the uncertainty does not yet exist, and therefore the same uncertainty is applied to all locations in the UK within the N Decision Framework. It is also assumed that there is no systematic bias to the uncertainty among or within habitats. Figure 3 and Figure 4 show the potential ranges in N deposition to moorland and woodland based on a CV of 25%; these maps show that the potential range in N deposition is large and can span entire critical load ranges.

Potential sources of uncertainty in the deposition values include:

- Measured concentration data
- Generation of UK concentration maps
- Rainfall data used for generating wet deposition
- Weather
- Habitat maps

- Parameters used in calculating deposition estimates, such as those related to weather variables and plant physiology
- Scale, both in space and in time (e.g. the time step used in the calculations)

But this list is not exclusive. Within a 5km x 5km grid square deposition will depend on topography, landscape complexity, the weather experienced by the particular habitat, and the presence of local emission sources (e.g. pig or poultry farms, cattle or extensive sheep grazing). Uncertainty within a grid square could either be smaller or larger than the uncertainty in the 5km x 5km national data. The variations are likely to be smaller where conditions are homogeneous across the grid square, and larger where the conditions are more complex. However, data are not available to enable sub-grid uncertainty to be taken into account in the Framework.

3.3.2 Uncertainty in other measurements or models for estimating N deposition

All measurements and models for deriving N deposition values will have uncertainties associated with them. The CV of 25% for CBED data is in the same range of uncertainty as other deposition models. Cellier *et al* (2011) looked at uncertainties in estimates of concentrations and deposition in models used to assess N impacts to Natura 2000 sites. Their conclusions include:

- Uncertainty in deposition predictions is significantly larger than that of concentration predictions because (a) deposition rates are usually calculated from modelled concentrations; (b) deposition processes are less well understood and more complex than atmospheric dispersion processes; (c) this means deposition is modelled or parameterised in very different ways; (d) deposition predictions are more difficult to validate than concentration predictions.
- Although detailed uncertainty analyses have not been carried out for the models, validation studies provide an estimate of average prediction uncertainty of approximately ± 20% for concentrations, when using measured emission data and on-site meteorological data.
- Specifying uncertainty estimates for N deposition is much more difficult due to a lack of validation studies. The assessment approach used in Denmark reported an uncertainty estimate of ± 35-70% for total N deposition.
- Based on expert judgement the [working] group agreed that uncertainties in N deposition estimates of regulatory models lay in the range of ± 50-100%.

Theobald *et al* (2014) compared two atmospheric dispersion models (ADMS and AERMOD) to simulate the short-range dispersion of ammonia emitted from pig farms to assess the suitability of these models in situations with frequently calm meteorological conditions. They carried out Monte Carlo analysis based on the inputs deemed to be the most uncertain for their case study, and estimated a prediction uncertainty of ± a factor of two for both models (i.e. -50% to +100%), with most of the uncertainty due to uncertainties in emission rates.

These studies highlight the magnitude of uncertainties in estimates of N concentrations and deposition using both national and local-scale models.

Although it is recommended that CBED N deposition values from APIS are used in the N Decision Framework, deposition values from other sources, if available, could be entered into the spreadsheet, together with the associated uncertainty in the values for the measurements or model used. However, there are likely to be very few sites for which this information is available. If using deposition data from sources other than CBED for the N Framework, the following points need to be considered:

- For measurements of concentrations and deposition; what are the uncertainties in the techniques and equipment used?
- Do the measurements include deposition from all sources (wet and dry) and take deposition velocity to different vegetation types into account? Sutton *et al* (2004) suggest measuring the components that are locally highly variable (e.g. NH_3, NO_x wet deposition in hill areas) and using data from the national networks and maps for those components that only vary significantly at the regional scale (HNO_3 aerosols NH_4^+, NO_3^-, wet deposition in low altitude areas).
- Are there sufficient measurements to derive annual mean values? Concentrations and deposition of atmospheric N compounds vary substantially over daily, monthly and seasonal scales, indicating a requirement for measurements over many months (Sutton et al, 2004). As critical loads are expressed as annual N deposition fluxes (i.e. kg N ha^{-1} $year^{-1}$), it is important that the deposition used to calculate exceedances is also an annual flux.
- Can, or have, the uncertainties in the measurements be quantified? The N Framework requires an estimate of uncertainty in the deposition values used.
- If using atmospheric dispersion models what is known about the uncertainties in the model input data (emissions, meteorological data), parameterisation and model performance?
- Can, or have, the uncertainties in the modelled deposition values be quantified? The N Framework requires an estimate of uncertainty in the deposition values used.

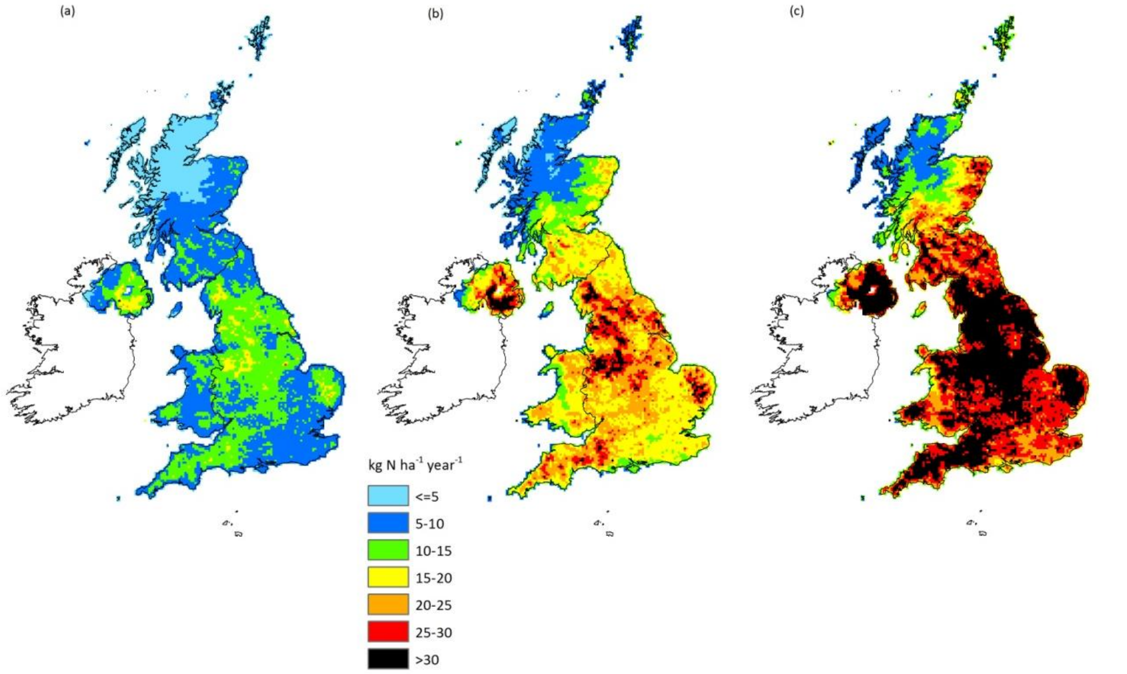

Figure 3. CBED 2010-12 deposition to moorland incorporating +/- 50 % uncertainty: (a) minimum potential N deposition; (b) mean potential N deposition (i.e. mapped CBED deposition); (c) maximum potential N deposition.

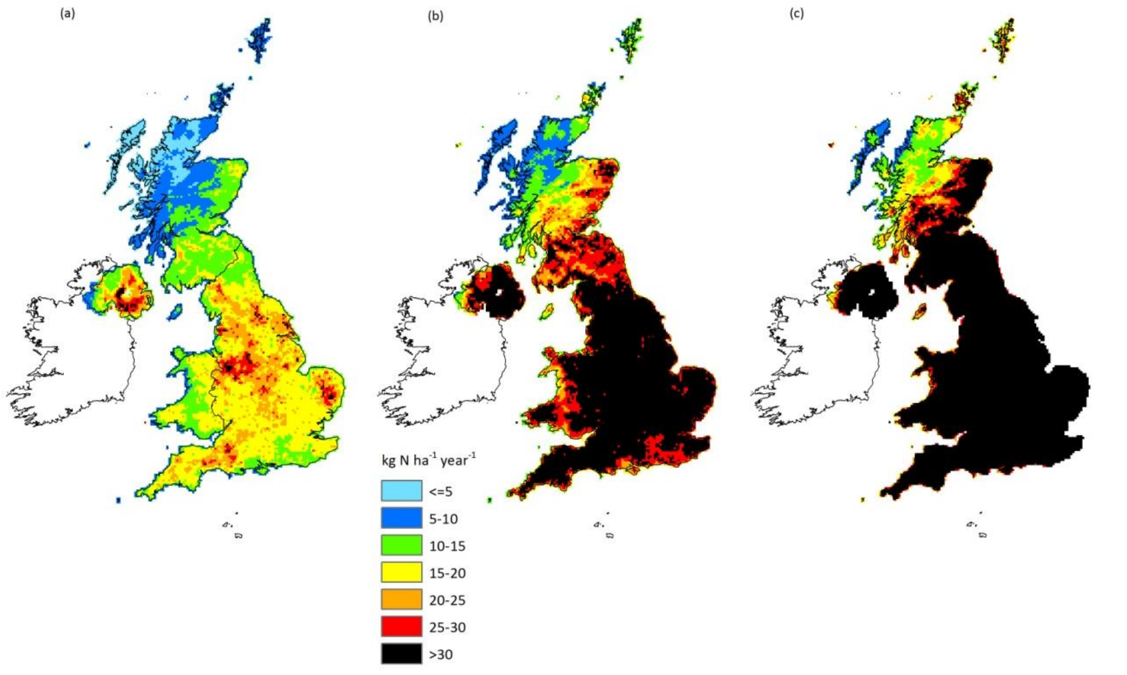

Figure 4. CBED 2010-12 deposition to woodland incorporating +/- 50 % uncertainty: (a) minimum potential N deposition; (b) mean potential N deposition (i.e. mapped CBED deposition); (c) maximum potential N deposition.

3.4 Applying uncertainty in N deposition in the Framework

The Framework requires N deposition values for the site and habitat(s) of interest. CBED N deposition values can be obtained using different search tools on APIS. The most appropriate deposition value will be that for the location of the habitat of interest within the site; this can be obtained by entering the grid reference into the APIS “Search by location” tool. Using a deposition value for a single point within a site (e.g. site “centre”) could, in some circumstances, lead to an inappropriate (or less appropriate) value being used. For example, large sites may cover tens or hundreds of square kilometres, and therefore the deposition may vary from one 5km x 5km square to another; or small sites may also cross the “boundary” between different 5km x 5km grid squares that may have the same or different deposition values. To illustrate this some examples are shown in Table 1 below. Alternatively if the grid reference of the habitat of interest within a site is not known, the APIS “site relevant critical loads” tool can be used to search for habitats within SACs, SPAs and A/SSSI, and this will display the minimum, maximum and mean deposition values across the entire site.

Table 1. Examples to illustrate potential variability in N deposition across sites of different sizes, e.g. where sites are covered by more than one 5km x 5km grid square, using CBED total N deposition for 2010-12 to moorland.

Site name	Area (km^2)	N deposition (kg N ha^{-1} $year^{-1}$)		
		Minimum	Maximum	Mean
Devil’s Dyke	0.08	17.4	17.4	17.4
Aston Rowant	3.83	20.0	20.0	20.0
Godrevy Head to St Agnes	3.84	8.5	19.7	14.2
Burnham Beeches	3.83	16.1	17.2	16.4
South Pennine Moors	3249	22.0	37.0	26.5
Migneint-Arenig Dduallt	2197	15.8	24.1	20.0
Snowdonia	4539	14.7	27.9	22.8

Deposition values to moorland and to woodland also vary (see Section 3.3.1 and Figure 3 and Figure 4 above) and therefore the appropriate value for the habitat being considered should be used. In the APIS “search by location” tool selecting any non-woodland habitat at the specified location will provide the “moorland” deposition value; and selecting any woodland habitat at the specified location will provide the “woodland” deposition value. Once these two values are entered into the Framework spreadsheet, the uncertainty in deposition (i.e. minimum and maximum values incorporating the uncertainty) is automatically calculated and fed into the Exceedance Score (WP1.3). If the user wishes to input deposition values from an alternative source and has an associated estimate of uncertainty, then the alternative deposition and uncertainty can be entered into the spreadsheet and the scores will automatically be generated as before. The formulae in the Framework spreadsheet are set up to work with uncertainty expressed as a percentage, e.g. ± 50%.

3.5 Gaps in knowledge related to uncertainty in N deposition

- Quantitative information on the uncertainty in wet and dry oxidised and reduced deposition at the national scale.
- Spatial information on the variation in uncertainty in wet and dry oxidised and reduced deposition across the UK.
- Within-grid square uncertainty in deposition; this will vary by location, sources and local topography, land cover, meteorological conditions.

- There are proposals to reduce the number of monitoring sites in the national UK Eutrophying and Acidifying Pollutant (UKEAP) monitoring networks (NAMN, AGANet, PrecipNet). A final decision on the number and location of the remaining sites is still to be confirmed; an analysis of the impacts of including or excluding different sites across the county has been submitted to Defra for their consideration (Smith *et al* 2014).

4 WP1.2 Assessing the confidence around matching of CSM habitats and critical loads

This WP assesses (i) the uncertainty in the cross-matching and assigning of critical loads to CSM habitats (WP1.2A); (ii) the reliability scores around established critical loads for EUNIS habitats (WP1.2B); and (iii) additional UK evidence of N deposition impacts and whether this indicates that the cross-matched N critical loads may be too high or too low (WP1.2C). This WP provides much of the content for the assessment spreadsheet which is used to calculate the overall Exceedance Score (WP1.3).

4.1 WP1.2A Assess the confidence around cross-matching of habitats and the assigned critical loads for those habitats

4.1.1 Aim

To assess the level of confidence/certainty between the CSM habitats included in the project and a EUNIS class for which an N critical load is set.

4.1.2 Description of Approach

Nitrogen critical loads (Bobbink & Hettelingh, 2011) have been assigned to habitat classes of the EUNIS hierarchical classification scheme (Davies & Moss 2002). To assign critical loads to UK CSM habitats for which critical loads have not been defined, two steps have to be carried out: i) the relationships between each CSM habitat and the EUNIS classification have to be established; and ii) the most appropriate critical load identified for that EUNIS habitat. This WP describes the cross-matching and critical load allocation work that was been undertaken, and the resulting spreadsheet which incorporates all this information.

4.1.3 How the CSM habitats are structured in the spreadsheet

The list of 47 CSM habitats provided in the Invitation to Tender formed the basis for this work package. These are the habitats for which there is a standardised table of guidance with attributes and targets in the appropriate guidance document. The National Vegetation Classification (NVC) communities and Habitats Directive Annex I habitats that are included within each CSM habitat type were taken from the latest published versions of the relevant guidance sections (http://jncc.defra.gov.uk/page-2199).

The spreadsheet is populated with CSM habitat types and their corresponding NVC classes, Annex I habitats, EUNIS classes, as well as the SSSI reporting categories and the APIS “NCL codes” and “NCL classes”. NVC-based categories can be matched against the list of NVC communities. Filters were added to the spreadsheet so it can be searched by any of these categories. **In addition, for this application the CSM habitats were sub-divided where different critical loads would apply and/or different certainty scores from CSM to EUNIS type or from EUNIS type to EUNIS critical load (see section below) would apply. The corresponding classes in the other classifications are also shown**. There are 94 types or sub-types. The sub-divisions were therefore determined by EUNIS classification and/or critical load categories rather than sub-divisions within the CSM guidance or other habitat categories, e.g. BAP priority habitats. Sub-types have been named for easy reference back to the parent CSM category, but should be used in conjunction with the corresponding NVC types for clarification.

For certain CSM habitats the relevant guidance tables refer users to other sections of the guidance, e.g. for “mire grasslands and rush pastures (upland)”, users are referred to the guidance for “lowland purple moor grass and rush pastures”, and the same approach has been adopted in the spreadsheet here. There are several habitat types which are SSSI and/or SAC features but are not specifically included in the CSM habitat tables. Additional sub-types have been created for these, under the relevant CSM habitat (and coded x, y or z), e.g. Dunes with *Hippohae rhamnoides* (Habitat code in the spreadsheet: 5y).

4.1.4 Relating CSM habitats to EUNIS habitat classes (WP1.2Ai)

Relating NVC classes and Annex I habitats to EUNIS classes was achieved by building upon earlier work on developing site-relevant critical loads (APIS: www.apis.ac.uk) and work on a manual of EUNIS habitats in Scotland for SNH (Strachan 2015)[2] and, where necessary, using the habitat classification correspondence tables developed by JNCC[3].

Correspondences were determined to EUNIS level 3 and/or 4. The cross match between the CSM and the corresponding EUNIS class(es) was assigned a certainty score using the criteria in Table 2 below. For the Medium and Low categories brief notes have been added to the spreadsheet to indicate any individual reasons for assigning these scores. Eighty percent of matches are classed as High, 10% as Medium and 10% as Low. The reasons for M and L scores are indicated in column K of the spreadsheet. The major cause of uncertainty is a lack of clarity regarding the scope of certain EUNIS habitat types. In some cases the EUNIS descriptions are inadequate e.g. H3.42 Northern wet inland cliffs (to which type 46 *Yellow saxifrage bank* has been matched), in others the descriptions at different levels are inconsistent e.g. type 34 *Montane willow scrub* fits the description of EUNIS type F2.1 at level 3, but F2.323 at Level 5. In this case the CSM type has been matched to F2.1 but with a score of Medium.

Generally the CSM types are well defined. A few types are poorly known or described e.g. 2 *Soft maritime cliff and slope*, 25c *Serpentine heath (upland)* and 47z *Dry lowland scrub*. In other cases the breadth of the CSM type gives rise to uncertainty. Usually in such cases the CSM type has been split into subtypes to remove the uncertainty, but for habitats such as *Bog woodland* and *Juniper scrub* there is a complete gradation from woodland/scrub to open habitat. This is reflected in the cross-matching score of Low for these habitats.

Table 2. Certainty scores for the match between CSM habitats and EUNIS classes (WP1.2Ai).

Certainty score (WP1.2Ai)	**Criteria and reasoning**
High (EUNIS includes CSM habitat)	Confident that all of the CSM habitat is included within the matching EUNIS class.
Medium (Ambiguous CSM match)	Ambiguous or overlapping definitions/descriptions in EUNIS mean that some or the entire CSM habitat could be assigned elsewhere in the EUNIS classification, but this would not affect the corresponding critical load or the certainty score.
Low (Very ambiguous CSM	Ambiguous or overlapping definitions/descriptions in EUNIS mean that some or the entire CSM habitat could be assigned

[2] http://www.snh.gov.uk/publications-data-and-research/publications/search-the-catalogue/publication-detail/?id=2207
[3] http://jncc.defra.gov.uk/page-1425, http://jncc.defra.gov.uk/page-4532

match)	elsewhere in the EUNIS classification, and this would alter the corresponding critical load or certainty score; or the CSM habitat is poorly or broadly defined and/or overlaps EUNIS categories (e.g. Bog woodland).

4.1.5 Allocating critical loads to EUNIS habitats (WP1.2Aii)

Critical loads have been assigned to a wide range of different habitat types (Bobbink & Hettelingh 2011) but are not available for all EUNIS classes. Where a critical load exists for the EUNIS class corresponding to the CSM habitat, this has been used[4]. Where critical loads do not exist for the EUNIS class corresponding to the CSM habitat, a critical load for an ecologically similar EUNIS class has been applied where possible. This cross-matching takes into account the characteristics of the CSM habitat as well as the proxy EUNIS habitat cross-matched to it in WP1.2Ai to select the most appropriate EUNIS habitat critical load for that CSM habitat. If no appropriate critical load is available, none has been applied (this applies to eight habitats). There are four habitats that are not sensitive to eutrophication and these are clearly marked and again no critical loads are assigned. Where no critical loads can be assigned the Exceedance Score cannot be determined.

In some cases it has been necessary to sub-divide the CSM habitats to take account of the different sensitivity to N deposition at a sub-CSM habitat level, and apply different critical loads. For example, where a habitat may occur on calcareous or non-calcareous substrate (e.g. lowland calaminarian grasslands) and critical loads for different EUNIS classes are applied, or different parts of the critical load range for a single EUNIS class are applied (e.g. fixed dune grassland). Note that the CSM Woodland habitat has also been sub-divided to enable the appropriate critical load value to be applied to the woodland type on a site; if the woodland type is unknown or not listed separately in the spreadsheet, then the category for "Broadleaved deciduous woodland (general)" (47k) should be selected. The Framework spreadsheet includes a "Note for users" column to assist the user in selecting an appropriate sub-division of the CSM habitat where this is required. The allocation of the critical load to each CSM habitat (and sub-division of) has been assigned a certainty score based on the criteria given in Table 3.

Table 3. Certainty scores for the allocation of critical loads to EUNIS habitats (WP1.2Aii).

Certainty score (WP1.2Aii)	Criteria and reasoning
High (critical load for defined EUNIS class)	Habitat is included within the EUNIS class for which there is a critical load.
Medium (critical load defined for similar EUNIS class)	Habitat is ecologically similar; therefore similar sensitivity to N is expected to the EUNIS class for which there is a critical load.
Low (critical load inferred from different EUNIS class)	Habitat is broadly similar in ecology (e.g. both are dry coastal habitats, or both are grasslands), but there may be ecological differences which alter sensitivity to N (e.g. different soil pH). Therefore, there is lower certainty that the critical load is appropriate.
None (No critical load available)	No comparable habitat with established critical load estimate available. NB. For CSM/EUNIS habitats with this score the Exceedance Score cannot be determined.

[4] For habitats 22a (*Carex saxatilis* mire) and 40b (upland calcareous springs), although EUNIS equivalents are sub-types of D4.1, they have both been assigned the critical load for D4.2 because both habitats are ecologically closer to D4.2 in the UK.

4.1.6 Scoring certainty that the critical load cross-matched to the CSM habitat is appropriate (WP1.2Aiii)

This component combines the certainty scores in the CSM to EUNIS match (WP1.2Ai) and the EUNIS critical load to EUNIS habitat match (WP1.2Aii) described above. The resulting certainty scores (Table 4) reflect the certainty that the critical load cross-matched to the CSM habitat is appropriate. Where there is no appropriate critical load (WP1.2Aii score = “None”), the certainty cannot be scored. Slightly more weight is given to the Aii score. The effect of the Ai score depends on the degree to which the uncertainty about matching CSM to EUNIS actually influences the critical load match (see examples below). A Medium score for Ai indicates (as defined) that there is uncertainty but this doesn’t affect the critical load assigned to it, therefore the overall score for habitats with Ai M scores should be the same as the relevant Aii score; whereas a Low score for Ai should reduce the overall uncertainty (unless Aii is also Low). Some examples are worked through below:

Type 34 *Montane willow scrub* fits the description of EUNIS type F2.1 at level 3, but F2.323 at Level 5. Type 34 is therefore matched to F2.1, with a score of Medium. The EUNIS habitat to critical load score is High and so the overall score should be High.

For type 8 *Machair* the match is to EUNIS type B1.9 Machair. The full definition of both types is uncertain, as it is unclear to what extent wet grassland and cultivated/fallow habitats are included in both; however the ‘core’ machair habitat (NVC SD8 dune grassland) is included in both types and is always the main component of the feature, so the Ai score is Medium. The critical load match is to B1.4 Coastal stable dune grassland (grey dunes), and the Aii score is Medium because it is ecologically close but not exact. The overall score should therefore be Medium.

Table 4. Scoring of the certainty that the critical load matched to a CSM habitat is appropriate (WP1.2Aiii).

	Certainty in the match between CSM habitat and EUNIS habitat (WP1.2Ai, section 4.1.4, Table 2)		
Certainty of the EUNIS critical load match to the EUNIS habitat (WP1.2Aii, section 4.1.5, Table 3)	**Low** (Very ambiguous CSM match)	**Medium** (Ambiguous CSM match)	**High** (EUNIS includes CSM habitat)
None	No match	No match	No match
Low (critical load inferred from different EUNIS class)	Low	Low	Low
Medium (critical load defined for similar EUNIS class)	Low	Med	Med
High (critical load for defined EUNIS class)	Med	High	High

4.1.7 Gaps in knowledge related to matching CSM habitats to EUNIS classes

- Critical loads are generally set at EUNIS classification levels 2 or 3 (e.g. D1, B1.5), whereas CSM habitats can typically be described at a more detailed level of EUNIS e.g. type 21 *Alpine dwarf-shrub* heath corresponds to EUNIS type F2.25 (Boreo-alpine & arctic heaths), whereas the equivalent EUNIS type with an established critical load is F2 (Arctic, alpine & subalpine scrub). It is assumed in such instances that the critical load is valid for all ‘lower’ units in the EUNIS classification. Further work would be useful to test this assumption.

- Critical loads are not available for all habitats. Critical loads for EUNIS types equivalent to or broader than CSM (sub-) habitats are available for 42 types. For 25 types (e.g. no. 42 *Tall herbs (upland),* no. 12 *Lowland meadows,* no. 31 *Juniper scrub*) critical loads have been matched based on comparable habitats with established critical load estimates. Eight habitats had no critical load. Of these, four types are considered not to be sensitive to eutrophication (4a. Strandline (sand), 9a. Shingle beach driftlines and open shingle vegetation, 17d. Lowland swamps, 47b. Alluvial woodland), while the remaining four types (*Hard and soft maritime cliff communities, Hippophae scrub* and *Inland salt meadows*) had no comparable habitats with established critical load estimates. Experimental or survey work to establish critical loads for some of these habitats, notably *Maritime cliffs and slopes*, is recommended.

4.2 WP1.2B Reliability scores for critical load ranges

4.2.1 Aim

To assign a confidence score to the critical load for each EUNIS habitat based on the published "reliability" scores of Bobbink & Hettelingh (2011).

4.2.2 Description of approach

Each of the published ranges of N critical loads is accompanied by a qualitative "reliability score" (Bobbink & Hettelingh 2011) according to the evidence underpinning the values. The three levels of reliability are scored as high, medium and low as in Table 5 below.

Table 5. Certainty scores for critical load ranges (WP1.2B).

Confidence score	Qualitative reliability score from Bobbink & Hettelingh (2011)
High (Reliable)	When a number of published papers of various studies showed comparable results.
Medium (Quite reliable)	When the results of some studies were comparable.
Low (Expert judgement)	When no empirical data were available for the ecosystem; critical loads based upon expert judgement and knowledge of ecosystems which were likely to be comparable with this ecosystem.

4.2.3 Gaps in knowledge related to matching CSM habitats to EUNIS classes

There are no additional knowledge gaps here in this component.

4.3 WP1.2C Assessing UK evidence

4.3.1 Aim

This WP aims to assess whether national (UK) evidence sources demonstrate impacts of N deposition on CSM habitats in line with or at different levels to the assigned N critical load. The findings identify where critical loads currently matched to CSM habitats may be too high or too low, but are not used to adjust the framework at this stage.

4.3.2 UK evidence within the critical loads international process

Evidence of N impacts from N-manipulation experiments, gradient surveys and modelling studies across a wide range of habitats has been extensively reviewed through an international process, following an established methodology and using strict criteria, documented in Bobbink & Hettelingh (2011). They are periodically reviewed at international workshops, the latest of which was in Noordwijkerhout, The Netherlands in 2010. This is the latest update of a long-established process, started by European N experts in 1985 when the concept of critical loads and critical levels was defined, and which was first brought into the international Convention on Long-Range Transboundary Air Pollution (CLRTAP) in 1988 (Nilsson and Grennfelt 1988).

Results from UK studies features heavily in this body of evidence and provide essential evidence underpinning the empirical N critical loads for a large number of EUNIS habitats. This is mainly due to an extensive programme of experimental research on N impacts funded by Defra over an 18-year period as part of the UKREATE research programme (experiments reviewed in Phoenix *et al* 2012).

Previous experience over the long history of the development of critical loads has shown that the effects of relatively large experimental applications in short-term experiments are often a useful proxy for the effects of smaller deposition rates over a long period. Experience has shown that as evidence about impacts accumulates for a particular habitat, the critical load is revised downwards (see e.g. the critical loads tables in the front of Bobbink & Hettelingh (2011) which show the critical loads in 2003 and after revision in 2010). To our knowledge, the critical load has never been revised upwards in the light of new evidence.

The critical loads concept is a risk-based methodology. The critical load is the level of N deposition below which adverse impacts on ecosystems are not expected to occur, according to present knowledge. These adverse impacts may still take many decades to become apparent. They are caused by a variety of mechanisms, including direct toxicity, competition-mediated effects and via altered soil processes, including accumulation of N pools, increased available N, and acidification of poorly buffered habitats as a result of N leaching. The mechanisms of impact and their consequences have been extensively reviewed and described (e.g. Bobbink *et al* 2010; Rowe *et al* 2013; Jones *et al* 2014; Stevens *et al* 2006; ROTAP 2012). The effects of excess N deposition in semi-natural ecosystems are rarely as dramatic as the frequently cited conversion of Dutch heathlands to grassland (Heil & Diemont 1983). Nonetheless, although subtle and difficult to detect without carefully designed experiments or gradient studies which adequately account for confounding factors such as rainfall, temperature, and effects of other co-correlated pollutants such as sulphur deposition, the effects of N in the UK environment appear to be far-reaching.

4.3.3 Description of approach

This section reviews UK evidence on N deposition impacts in the context of existing international evidence, and particularly considers new evidence which has emerged since the Noordwijkerhout workshop (Bobbink & Hettelingh 2011). It focuses on the evidence for impacts on conservation objectives, making the assumption that critical load exceedance will have a direct or indirect impact on those conservation objectives (see section 5.2 for wider discussion on this issue).

The UK evidence is synthesised and collated, by habitat, in two places in this report for slightly different purposes. The key UK evidence for N impacts in a habitat is collated in the WP2.1 spreadsheets for each habitat, where it is used to back up the scoring of targets as possible indicators of N impact. The UK evidence is also summarised in the context of its utility in defining the most appropriate critical load range for each CSM habitat in Table A1 in Appendix A of this report. The reader is directed to these places for a summary of UK evidence on N impacts in each habitat.

i. Methodology

The critical load for each CSM habitat type was assessed according to UK evidence in the context of the international evidence that was used to set the empirical critical load for habitats in the UN-ECE workshop held in Noordwijkerhout (Bobbink and Hettelingh, 2011), and the UK “mapping values” derived from those critical load values (Hall *et al* 2011). Evidence from other sources was also considered, including species-level studies (e.g. Emmett *et al* 2011; Stevens *et al* 2011), habitat-level surveys and monitoring studies (e.g. Field *et al* 2014; Maskell *et al* 2010) and experimental N addition studies (e.g. studies described in Phoenix *et al* 2012) from the UK. The schema used to evaluate the evidence is summarised in Figure 5. Essentially this asked whether UK evidence, including that which was not included in the UN-ECE workshop discussions at Noordwijkerhout, is inconsistent with the critical load, i.e. showed effects at deposition rates below critical load or no effects at rates above critical load.

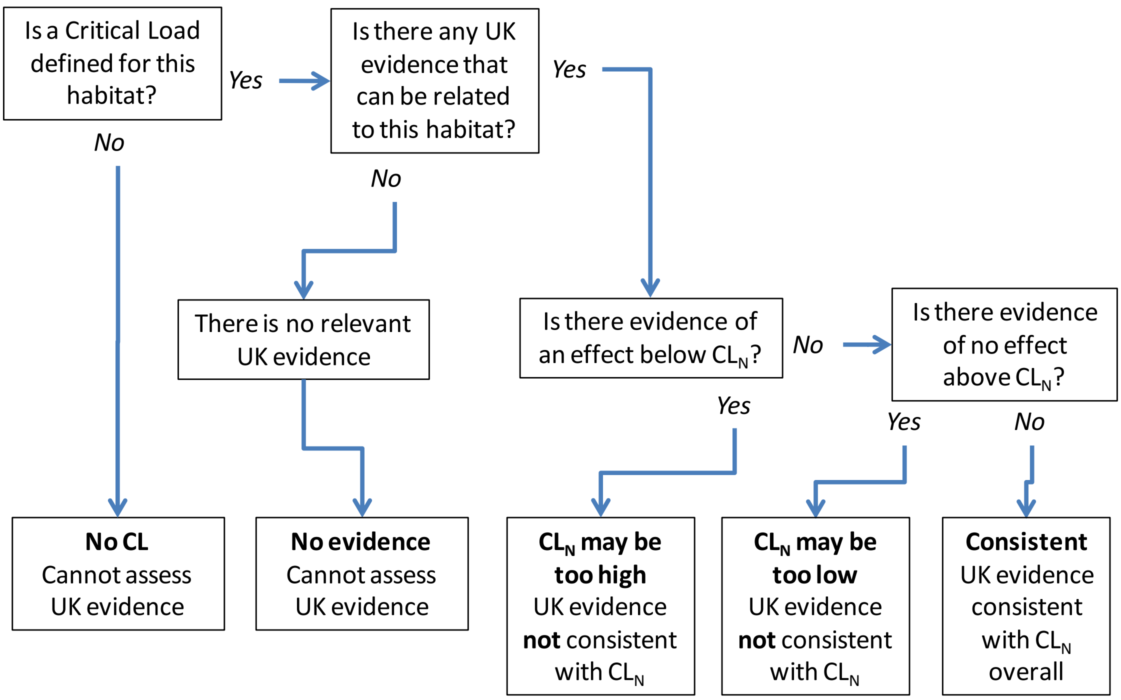

Figure 5. Flowchart for assessing whether or not UK evidence is consistent with the assigned empirical critical load for nitrogen (CL_N).

Species-level evidence was considered relevant to a habitat where a species that showed a response to N was listed in the floristic tables for the NVC communities[5] which occur in the habitat (as defined by the EUNIS class). However, in some cases a species considered to be too infrequent and/or localised (according to expert judgement) across the habitat of relevance was not included. Evidence for these species was not used and this was noted in Table A1 in Appendix A. For example, rock-growing species that were recorded within mire habitats were assumed to have been present at localised micro-sites, and evidence related to such species was not included in the assessment of mire habitats.

[5] http://jncc.defra.gov.uk/page-4265

The species-level evidence that was assessed derives from an analysis of plant and lichen occurrence datasets (Emmett *et al* 2011; Stevens *et al* 2011), in which responses were assessed within four major habitat-classes (Acid Grassland, Calcareous Grassland, Heathland and Bog). In that study, 83 species showed significant positive or negative responses to N deposition. In view of the lack of evidence that species responses to N show significantly different responses between habitats, and the theoretical and practical difficulties with adopting an alternative approach, species-level evidence was in general considered relevant whether or not it came from the same habitat (following the caveats above). However, in woodlands, although the effects of the tree canopy on N deposition rate can be accounted for, the amount of N reaching the ground flora is uncertain because of canopy uptake and throughfall processes. This means that N deposition rates are not comparable between woodlands and open habitats, so the species-level evidence that was obtained from open habitats in Stevens *et al* (2011) and Emmett *et al* (2011) was not considered relevant in woodlands, except for the open-canopy woodland type ‘47x. Bog woodland’.

In some cases, the characteristics of certain habitats vary greatly across Europe. In particular, *Nardus* grasslands occur on acid soils across a wide range of moisture and climate and include several species-rich subtypes in the mountains of central Europe, whereas in the UK *Nardus* grasslands are often species-poor and are comparatively insensitive to N pollution. Evidence from Alpine *Nardus* grasslands is therefore of doubtful relevance to the UK.

An overall judgement was made as to whether the assigned critical load for the CSM habitat type was consistent with UK evidence. The basis for this judgement is summarised in Table 6. The UK evidence was considered to be “not consistent” with the critical load only when there were clear inconsistencies with the international evidence. For habitats for which no critical load has been defined, or for which there is no relevant UK evidence the consistency of UK evidence with the critical load was judged “not applicable”. As described in the aim for this section, this evidence is used to identify instances where the matched critical load may be too high or too low, but is not currently used to modify the assessment.

Table 6. Basis for assessing whether UK evidence was consistent with the international evidence that was used to set the empirical critical load for nitrogen in reviews by Achermann & Bobbink (2003), Bobbink & Hettelingh (2011) and Hall *et al* (2011).

Conclusion as to consistency of UK evidence with international studies	**Criteria and reasoning**
Consistent	• The UK evidence is considered compatible with the critical load range that was derived from international evidence, unless there is clear evidence to the contrary (see ‘Not Consistent’). The UK evidence may differ in the type of study (e.g. experiments, targeted or non-targeted gradient studies, or studies of species prevalence in relation to N deposition), or the N loads to those observed in the international evidence, but still be deemed consistent. For example, the critical load for saltmarsh is set at 20-30 kg N ha^{-1} yr^{-1} based on expert judgement (Bobbink & Hettelingh 2011). A saltmarsh manipulation experiment in the UK (Jefferies and Perkins 1977) showed adverse impacts of additions of 66 kg N ha^{-1} yr^{-1}. Although lower application rates were not included in the Jefferies study, the results were consistent with impacts at lower rates. In Bobbink & Hettelingh (2011), based on experience from previous experiments, impacts observed over short timescales at

	high N loads were assumed to be indicative of effects of smaller N loads over longer timescales.
Not consistent. -Critical load may be too high; -Critical load may be too low	• There is UK evidence which suggests adverse impacts of N deposition at a rate below the critical load established using international evidence (i.e. **the critical load may be too high**). • Or, all relevant UK evidence shows no adverse impacts of N deposition within and below the critical load range. (i.e. **the critical load may be too low**). For example, the critical load for a habitat is 10-20 kg N ha^{-1} yr^{-1}, but evidence from well-designed UK experiments with treatments of 5, 10, 20 and 30 kg total N ha^{-1} yr^{-1} does not show any impact until deposition reaches 30 kg total N ha^{-1} yr^{-1}, i.e. above the critical load range, and no other UK evidence shows impacts within the critical load range.
No critical load	• No critical load has been defined for the habitat.
No evidence	• There is no relevant UK evidence. This includes cases where the international evidence was derived from an example of the habitat that is dissimilar to UK examples.

4.3.4 Discussion of outcomes from considering UK evidence

Of the 94 CSM habitats and sub-divisions according to likely N sensitivity, the UK evidence was found to be consistent for 38 habitats, while no evidence was found for 34 habitats (the remaining either had no critical load (n=7), were not sensitive to N (n=4), or the critical load may be too high (n=11)). This illustrates that despite the substantial body of evidence from experiments, gradient studies and species-level assessments, we still lack any primary evidence on which to base N sensitivity of over one third of CSM habitats.

The assessment of UK evidence led to the conclusion that the critical load may be too high for the following 11 habitats:

- 10b. Lowland open dry acid grasslands (U1)
- 11a. Lowland calcareous grasslands (Mesobromion)
- 11b. Lowland calcareous grasslands (Xerobromion);
- 14a. Lowland calaminarian grasslands (calcareous)
- 14b. Lowland calaminarian grasslands (acidic)
- 15a. Lowland dry heaths (not on dunes)
- 15b. Coastal dune heath
- 16a. Lowland wet heath (without *Erica ciliaris*)
- 26a. Calcareous grassland (upland on limestone)
- 31a. Juniper heath and scrub (upland acidic)
- 45. Wet heath (upland)

The UK evidence did not suggest that the critical load was too low in any habitat. As previously noted, it is difficult to observe impacts of experimental addition at sites where the critical load has already been exceeded for several decades (as is the case for most of the UK). Grasslands and heathlands are the habitats where N impacts have been studied most intensively. Despite this, or perhaps because there is so much data that more sophisticated analyses are now possible, the emerging evidence suggests that the critical load values currently used may have to be reduced for these habitats. This is likely to apply to more habitats as additional evidence is obtained in future. This reinforces the observation that a lack of evidence of impacts should not be seen as evidence that there are not impacts.

4.3.5 Gaps in knowledge related to assessing UK evidence

- Despite considerable UK data, there is a lack of any primary evidence on which to base assessment of N-sensitivity for 34 of the 94 CSM habitats or sub-divisions.
- Consideration of the UK evidence suggests that new survey evidence since Noordwijkerhout and more sophisticated analysis of existing survey data in some cases points to a need to consider revising some critical load ranges downwards.

4.3.6 Recommendations

- Given the lack of primary evidence for N impacts on one-third of the CSM habitats or sub-divisions, and the lack of habitat-level (rather than species-level) evidence for considerably more of the CSM habitats, there is an urgent need for more well-designed experimental or survey-based studies to provide this evidence. This should concentrate on habitats with reasonable UK coverage or geographical distribution rather than extremely rare habitats. Suggested priorities at broad habitat level where there is little or no UK evidence include coastal habitats such as saltmarsh and shingle, many upland habitats, neutral and damp grassland habitats. Although woodlands have received some study, the evidence is conflicting and further work also needs to be done in this habitat type.

4.4 WP1.2D Scoring certainty that the critical load assigned to the CSM habitat accurately reflects its sensitivity to N deposition

4.4.1 Aim

The aim of this WP was to devise and apply an approach to combine the scores from WP1.2A and WP1.2B to derive a certainty score that the critical load matched to the CSM habitat reflects the N sensitivity of that habitat, such that deposition will, in time, lead to an impact on the conservation objectives of the habitat. This feeds into a further step of adjusting the critical loads to take account of the certainty scores (section 4.5).

4.4.2 Description of approach

The decision matrix shown in Table 7 combines the certainty around critical load ranges from the Bobbink & Hettelingh (2011) reliability scores (WP1.2B) and the certainty in the matching of critical load to CSM habitats (WP1.2A). This score reflects the certainty that the critical load matched to the CSM habitat reflects the N sensitivity of that habitat.
Where the certainty in the critical load (WP1.2B score) is ‘High’ or ‘Medium’ (i.e. where the Bobbink & Hettelingh (2011) critical load ranges are based on at least several peer-reviewed studies which are suitable for defining a critical load, equating to Reliable and Quite Reliable scores respectively), then the certainty in the cross-matching of critical load to CSM habitats (WP1.2Aiii score) remains the same, resulting in certainty outcomes of High, Medium and Low accordingly. However, where the critical load is based on expert judgement only, scored as ‘Low’ certainty in WP1.2B, then there is less certainty that the critical load matched to those CSM habitats accurately reflects the sensitivity of that habitat to N deposition. The corresponding certainty outcomes are modified downwards accordingly.

Table 7. Decision matrix for WP1.2D, which combines WP1.2B and WP1.2Aiii certainty scores. Cells show the certainty that the critical load (CL) matched to the CSM habitat accurately reflects the N sensitivity of that habitat.

		Certainty in CL (WP1.2B)		
		Low	**Med**	**High**
Certainty in CL match to CSM features (WP1.2Aiii, section 4.1.6, Table 6,)	**No match**	*No match*	*No match*	*No match*
	Low	*Low*	*Low*	*Low*
	Med	*Low*	*Med*	*Med*
	High	*Med*	*High*	*High*

4.5 Adjusting critical load ranges in the assessment to account for uncertainty and UK evidence

4.5.1 Aim

This section describes how the critical load ranges used in the calculation of an Exceedance Score (section 5) should be adjusted to take account of the certainty scores arrived at in WP1.2D (section 4.4).

4.5.2 Description of approach

Uncertainty in the critical load range was implemented in a quantitative way using the expert judgement of the project team. Note that this uncertainty encapsulates the elements of uncertainty in the cross-matching process, as illustrated in Figure 1, and not just the critical load reliability scores (WP1.2B). Previous attempts to implement a measure of uncertainty in critical loads have applied a fixed amount of N (e.g. adding +5 or +10 kg N ha^{-1} yr^{-1}) above and below the critical load range according to the critical load reliability score (Hall et al, 2003). However, applying a fixed value to the edges of the range does not capture the way critical load ranges work. The framework aims to reproduce what a realistic critical load would be if the CSM habitat was in reality more sensitive, or less sensitive than the habitat to which it is currently cross-matched. The critical load range would also differ depending on whether there is medium or low certainty that the proxy critical load accurately reflects the N sensitivity of that CSM habitat. These changes are summarised in Table 8**Error! Reference source not found.**, for all the possible critical load lower bound (Min CL) values and all the possible critical load upper bound (Max CL) values.

If there is a high certainty (derived in WP1.2D, e.g. see Table 7) that the critical load accurately reflects the N sensitivity of the CSM habitat, then it is assumed the critical load range does not change, and the default critical load range is used. If there is a medium certainty, then the critical load may be a bit lower or a bit higher than the proxy critical load. If there is only a low certainty that the critical load accurately reflects the N sensitivity of the CSM habitat, then we might expect the critical load to shift rather more, usually by up to 10 kg N ha^{-1} yr^{-1} upwards or downwards. These shifts are fairly clear within the suite of typical critical load ranges, but become less clear at the extremes. The lowest possible critical load is set at 3 kg N ha^{-1} yr^{-1}, to match the lowest EUNIS critical load available, and the shifts become slightly compressed at the lower end of the critical loads. The highest possible critical load is set at 40 kg N ha^{-1} yr^{-1}, 10 kg N ha^{-1} yr^{-1} above the highest EUNIS critical load available.

Therefore, where the certainty in the critical load is medium or low (as derived from WP1.2D), these new Min CL and Max CL values are used in combination with the N deposition uncertainty to calculate the Exceedance Score.

Where it is deemed the critical load may be set too high (as an outcome from assessing the UK evidence in WP1.2C) in principle the minimum critical load value could be shifted downwards. However, pending more detailed evidence, in the current version of the framework the critical load is not adjusted.

Table 8. Implementing uncertainty in critical load ranges under WP1.2D High, Medium and Low certainty scores.

	Minimum CL Bound (Default = High Certainty)		
Certainty in CL (section 4.4.2, Table 7)	High Certainty	Medium Certainty	Low Certainty
Range of possible **Min CL** values (kg N $ha^{-1} yr^{-1}$)	5	4	3
	8	5	4
	10	8	5
	15	10	8
	20	15	10
	Maximum CL Bound (Default = High Certainty)		
Certainty in CL (section 4.4.2, Table 7)	High Certainty	Medium Certainty	Low Certainty
Range of possible **Max CL** values (kg N $ha^{-1} yr^{-1}$)	10	15	20
	15	20	25
	20	25	30
	25	30	35
	30	35	40

5 WP1.3 Deriving an Exceedance Score (Factor 1 score)

5.1 Aim

The aim of this WP is to devise and justify an approach for combining the outcomes from WP1.1 and WP1.2, to calculate an overall Exceedance Score (Factor 1 score), which summarises the degree to which the critical load is exceeded at a site and will therefore result in impacts which would be detrimental to the nature conservation objectives for the habitat. This Exceedance Score will then be used in the decision framework (see Annex 3).

5.2 Discussion of how N deposition affects conservation objectives

This section discusses the assumptions about how N deposition and critical load exceedance would be expected to affect conservation objectives.

5.2.1 What is the critical load and why is there a range?

As discussed in Section 4.3.2, the empirical critical loads are defined as "***A quantitative estimate of exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge" (Nilsson and Grennfelt 1988)***.

i. The logical extension of this statement, discussed and agreed with Roland Bobbink one of the original proponents of the critical load concept and who led the last two international revisions of the empirical critical loads (Achermann & Bobbink 2003; Bobbink & Hettelingh 2011), is that "we might expect damage to occur at any point above the CL (damage to one or more receptors representing ecological structure or function)" (see also point iii and Figure 7 and section 5.2.2)

ii. The critical load is expressed as a range for a number of reasons:
   a. to reflect variability among sites in the point at which that threshold occurs. This variability occurs due to factors which moderate sensitivity to N. Such factors include: **rainfall** (in some habitats, higher rainfall means greater flushing of nutrients from the system, lower solute concentrations, and reduced N sensitivity), **soil pH** (calcareous habitats are well buffered and less likely to suffer from acidification effects), **site management** (appropriate grazing, cutting or burning regimes for example may mitigate some effects of N on habitat suitability (Stevens *et al* 2013)), **nutrient limitation** (may prevent many competitive species taking full advantage of the excess N). The red double arrow in Figure 6 shows how variability in N sensitivity due to these and other factors is revealed in survey data of plant species richness for a given level of N deposition.
   b. to reflect uncertainty in the information used to derive the critical loads. This includes uncertainty in the precise N load at which damage occurs due to the difficulty of adequately covering the appropriate N range in N manipulation experiments, as well as uncertainty in the assessment of N deposition at the experimental or survey sites.

iii. The upper bound of the range therefore represents the point above which adverse ecological impacts on at least one sensitive ecosystem component are likely to occur in the majority of examples of that habitat. Figure 7 illustrates responses of one measure of ecosystem condition "plant species richness" to N in four UK habitat types. This shows that in acid grasslands, dune grasslands, upland and lowland heathlands, the highest observed species richness above the upper bound of the critical load is lower than almost all sites below the minimum of the critical load range. For bogs, it is not possible to make this comparison because there are no sites in the UK below the minimum critical load. Note also that this is just one measure of impact, and other measures may reveal damage at the sites which appear to be in relatively good condition with respect to species richness.

iv. This suggests that, even though damage may not yet have occurred at all sites above the critical load, in practice, damage is already visible at almost all sites included in these surveys.

5.2.2 Relating critical load exceedance to conservation objectives

The evidence reviewed to define critical loads is based on observed changes in two aspects of the structure and functioning of ecosystems. Firstly, on changes in "species abundance, composition and/or diversity" (Bobbink & Hettelingh 2011, p25), i.e. direct or indirect impacts on plant or animal species themselves. Secondly, on changes in functioning (e.g. nitrate leaching, decomposition or mineralisation rate). These impacts occur on the underlying processes which influence species composition. For example, while nitrate leaching may not appear to have an obvious impact on conservation objectives, it is one of the main processes driving soil acidification (ROTAP 2012), and in the longer term will directly lead to species change in acidic or in poorly buffered habitats. Similarly, even though changes in a particular species may not have occurred yet, the fact that N cycling has been accelerated due to N means that the underlying conditions may no longer be suitable for that species to persist in the long term. Therefore, for both impacts on species and impacts on function there is a potential impact of N on the conservation objectives.

These impacts can be substantial. Data from Field *et al* (2014) in a series of well-designed gradient studies illustrate this impact on plant species richness across a suite of semi-habitat types. They showed major reductions in plant richness in acid grasslands, where richness at 20 kg N ha^{-1} yr^{-1} was only 35% that of the level in unpolluted sites; in upland and lowland heaths where richness was reduced to roughly 40%; in sand dune grasslands where it was reduced to 50%; and in bogs which were least affected but still showed a significant reduction. Data from national monitoring programmes (Countryside Survey) in the wider countryside outside of protected areas show a similar pattern, with declines in species richness observed in broad habitats across the UK (Maskell *et al* 2010). Species-level, rather than habitat-level, studies have also shown responses of individual species along N gradients, with 83 species showing significant responses to N deposition in particular types of habitats (Emmett *et al* 2011; Stevens *et al* 2011).

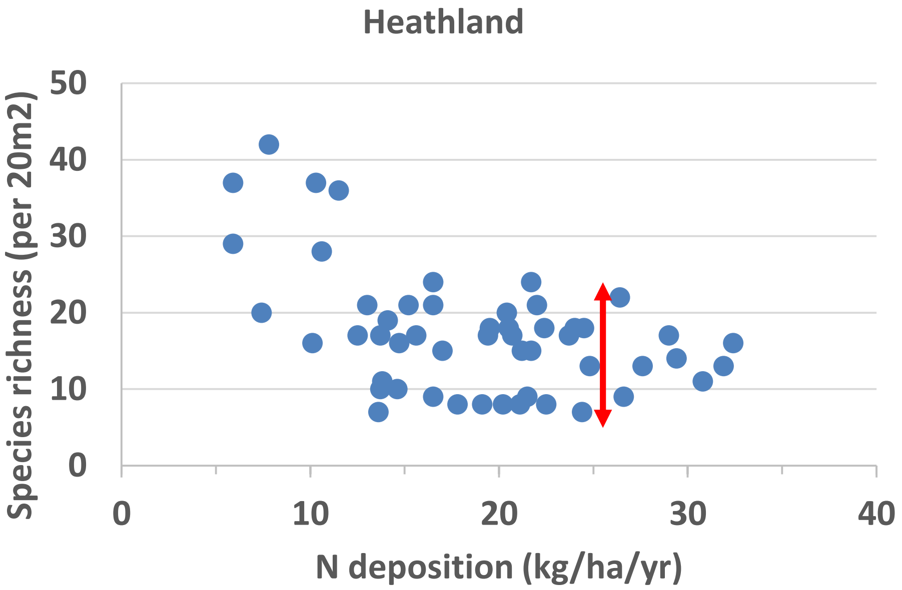

Figure 6. Variability in response of plant species richness to N deposition in upland and lowland heathlands from survey data. Red arrow illustrates the range of ecological response at a given level of N, due to site-specific factors such as climate, soil pH, management, etc. Data from Field *et al* (2014).

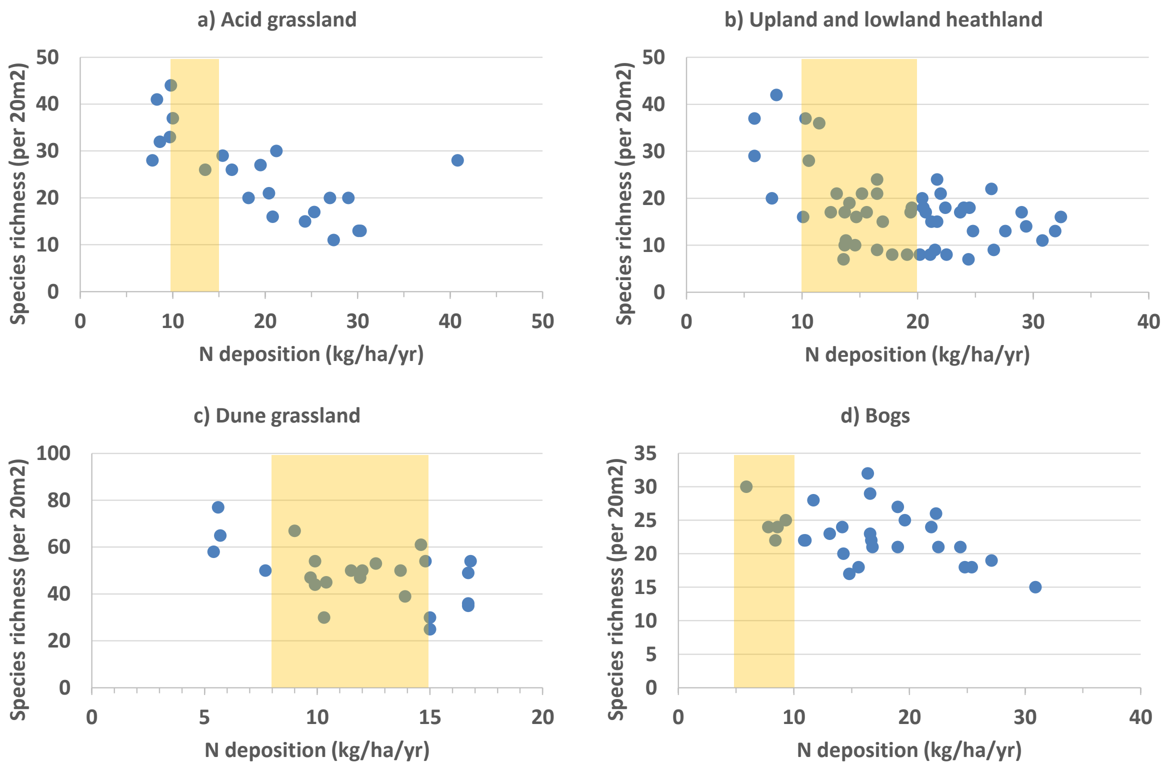

Figure 7. Plant species richness in four UK habitats, showing response in relation to the critical load bounds (yellow shaded box) for a) acid grassland, b) upland and lowland heathlands, c) dune grassland and d) bogs. Data from Field *et al* (2014).

Two aspects of critical loads are important to note with respect to N:

a) Nitrogen is tightly cycled in most ecosystems (i.e. it is not easily lost from the system), so its effects can be cumulative and persistent.

b) Much of the UK has received elevated N inputs for an extended period, particularly over the last half of the 20th century. This means that the more N-sensitive species are likely already to have been lost from particular sites. It also explains why evidence from surveys generally shows considerably stronger effects of N than experimental evidence – as at most, if not all, experimental sites, the effects of N addition are somewhat masked by the effects of previous N pollution.

Critical loads therefore incorporate an element of response over time, since not all impacts of N occur immediately, and some may be latent or dependent on interactions with other factors. Thus, even if not apparently affected at present, impacts are more likely to occur in the future, e.g. in response to secondary triggers such as a severe drought or frost (Sheppard *et al* 2008), increased herbivory from pest outbreaks (Heil and Diemont 1983), or due to increases in disease incidence (Strengbom *et al* 2002). This means that interpreting damage to conservation objectives should not only take into account current visible impacts, but should also consider the latent impacts of excess N above the which has already accumulated in the system. Excess N starts to accumulate in plants and soil above the minimum of the critical load (Rowe *et al* 2013). The excess N can only be removed by management techniques such as cutting which remove large quantities of biomass from the site (Stevens *et al* 2013), or if N deposition drops below the critical load such that natural leakage via leaching or denitrification is greater than the atmospheric inputs. If deposition is reduced, but remains above the critical load, N will continue to accumulate but at a slower rate. Dynamic modelling is the only way to predict the long term effects of this accumulated N. Studies have shown that accumulated N will cause long term changes in plant composition over decades (Rowe *et al* 2011) and, even if N deposition reduces below the critical load, can take many decades to recover (Rowe *et al* 2013). Some biological components such as moss and lichen abundance can recover much faster, within a few years (Jones 2005), while soil processes and changes in vascular plants can take decades to recover (Rowe *et al* 2013).

It should also be noted that different components of an ecosystem are sensitive to N deposition at different loads. For example, impacts on bryophytes and epiphytic lichens are likely to occur at lower N deposition loads, closely followed by impacts on other plant species. However, impacts on the underlying processes may only become apparent at higher deposition loads as the soil system becomes more N-saturated. Therefore, although critical load exceedance can usually be demonstrated by impacts at the low end of the critical load range, as deposition and critical load exceedance increase, the impacts become more severe, and affect a wider range of species and processes.

5.2.3 Reference condition for conservation objectives

The fact that N-sensitive species are likely to have already been lost from many sites in high deposition areas, perhaps decades previously, raises questions about the reference-point used for setting conservation objectives and CSM targets. As a result, at some sites, features that have been lost or diminished by N deposition, such as the lichen flora in lowland woods or dwarf shrub cover of lowland heathland, may not be included in the site condition assessment. This could be because: (i) the CSM targets do not consider such features; (ii) the generic CSM targets already accommodate N impacts or any locally set CSM targets (indicators of local distinctiveness) do the same; or (iii) the generic CSM target thresholds (or locally set targets) have been adjusted to accommodate (perhaps unknowingly) N impacts. This is a complex issue, which is difficult to disentangle. It is hampered by a lack of information on the historical species composition and the extent to which N deposition has impacted on a site. It is also unclear to what extent such impacts should be accepted, while noting that CSM targets are <u>not</u> meant to be set at levels which seek to achieve substantial improvements to the feature beyond that needed to maintain their biological interest <u>at the time of selection</u>, apart from in certain exceptional circumstances where the feature was selected with the specific view to improving it to a better state (e.g. degraded raised bogs).

5.2.4 Summary of ecological N impacts occurring above the critical load

This section describes what it means when N deposition is below, within, or above the critical load in terms of likely impacts of N deposition in the context of the consequences for habitat conservation objectives. It summarises information presented elsewhere in the three Annex reports and in the habitat spreadsheets.

Increasing critical load exceedance has two general implications: the severity and number of N impacts is likely to increase for any individual Habitat Feature, and the probability increases that all examples of that Habitat Feature in the UK will be impacted.

i. N deposition below the critical load:
Below the minimum critical load bound, in principle there should be no N impacts and no conservation objectives should be affected. However, because critical loads are only based on evidence to date, they may not reflect the true N sensitivity of the habitat due to incomplete evidence, therefore some of the effects described in the following paragraph may occur below the specified critical load.

ii. N deposition above the critical load:
As N deposition rises above the critical load, and critical load exceedance begins, the following types of N impact start to occur (note some of these may be habitat specific):

- Reduced viability of N-sensitive lower plants (mosses, liverworts, lichens – especially many epiphytic lichens), such that some species may be lost from the community, or at least reduced in abundance (cover) or frequency (e.g. Pearce *et al* 2003).
- Small stature slow-growing vascular plants are outcompeted by more vigorous species – these may be lost from the community, or at least reduced in abundance (cover) or frequency (Emmett *et al* 2011).
- Grasses increase in cover and height at the expense of flowering herbaceous species (forbs), increasing the ratio of the percentage cover of grasses to forbs resulting in an overall loss of plant species richness (van den Berg *et al* 2016).
- Nitrophilic species (both lower plants and vascular species) are more likely to establish and become dominant (e.g. Jones *et al* 2013; Pitcairn *et al* 2009), particularly if there is a local seed source and if disturbance creates areas for them to establish.
- Reduced flowering of many grassland species as they allocate more resources to vegetative growth (e.g. Basto *et al* 2015). However, flowering of Calluna in heathlands may increase.
- The life cycle of Calluna is accelerated meaning the shrubs reach their senescent phase more rapidly (e.g. Power *et al* 1998).
- Many ericoid shrubs and tree species becoming more sensitive to pathogens, herbivory, and to weather extremes such as severe drought or frost, all of which may become apparent as damage to foliage and plant canopies (e.g. Strengbom *et al* 2002).
- Nitrogen accumulation in the soil can lead to nutrient imbalances and reduced tree growth rates (e.g. Aber *et al* 1998)
- Nitrogen accumulation in the soil can also lead to nitrate leaching, which drives soil acidification and subsequent changes in plant communities.

Species and ecological processes respond to N at different loads. As critical load exceedance increases, a greater proportion of N-sensitive species are likely to be affected, whilst conditions become more suitable for nitrophilic species, and the number and severity of other adverse effects will likely increase. With increasing critical load exceedance therefore, these effects become more numerous and more apparent. Note also that, although some sites may show impacts at different N loads, UK survey evidence across a wide range of habitats suggests that some sites will start responding at (or even below) the current minimum critical load, and as N deposition increases, the proportion of sites which show an impact increases (e.g. refer to Figures 7 and 8).

In some cases, the impacts of N on plant community composition or structure may not necessarily be visible at present. However, with a raised N deposition load, and despite increases in the quantity of N lost through processes such as denitrification, leaching or management, the majority of the extra N will continue to accumulate in the plant and soil N pools (Rowe *et al* 2013).

This accumulated N can also constitute damage to conservation objectives since it affects the underlying processes and conditions necessary for many plant species to persist. These effects include: more available nitrate in the soil, faster mineralisation (i.e. breakdown of soil organic matter), increased tissue N concentrations in plant material, nutrient imbalances in the soil, a build-up of soil N stocks and N saturation in soils. In this situation N deposition is reducing the resilience of the system and there is potential for infrequent major events, such as severe drought, severe frost, fire or insect pest outbreaks, to trigger sudden ecological change. The cause of change is likely to be rapid remobilisation of part of the accumulated soil N pool.

iii. Increasing N deposition above the critical load:
Above the maximum critical load bound, it is expected that the majority of examples of that habitat will be impacted by N (see for example Figure 7) and the consequences of that exceedance will be more severe. As discussed above, there may still be cases where the impacts of N on plant community composition or structure are not apparent, but N is still accumulating in the vegetation and soil of those habitats, and is expected to cause future ecological impact.

iv. Interpretation with respect to conservation objectives
It should be recognised that critical loads represent the first point at which damage starts to occur. By contrast, the target thresholds in CSM assessments define the point at which a site is judged to be in unfavourable condition. Notwithstanding issues of historical N deposition impact prior to site designation, and whether CSM targets are adequate to detect N impacts, there is potentially a difference between the N deposition loads at which damage starts to occur, and the point at which the Habitat Feature is deemed in unfavourable condition. **In effect, a certain level of damage to the habitat due to N is likely to occur before the thresholds defined in CSM targets fail, even for those targets which have been scored as strong N indicators (see Figure 8, and section 5.2.5 below)**. At this point, there is already damage to species composition and ecological condition, and N is also accumulating within the vegetation and soil system (e.g. Plassmann *et al* 2009; Rowe *et al* 2011; Rowe *et al* 2013), with longer term consequences.

5.2.5 Recommendations

- There is a research need to quantitatively assess the UK survey (and experimental) evidence to identify the point at which conservation objectives (as manifest in the CSM targets) are affected by N deposition, and how this relates to current critical load bounds. One example is illustrated in Figure 8, using a CSM target for forb cover in acid grassland – *Vegetation composition: More than 10% of the vegetation cover should consist of forbs*. The target fails if forb cover is less than 10%. Figure 8 examines survey data from Field *et al* (2014) and shows that, assuming cover is either forbs or grasses, the target will only fail once the upper end of the critical load has already been exceeded, yet at this point there has already been a substantial loss in species richness, and that these changes in species richness are associated with much lower grass/forb ratios around 0.7-0.8.

- Further analysis of existing data along these lines would substantially improve our understanding of the extent to which current conservation objectives accurately reflect N deposition impacts for the well-studied UK habitats for which data exist, and would allow limited extrapolation to other similar CSM habitats.

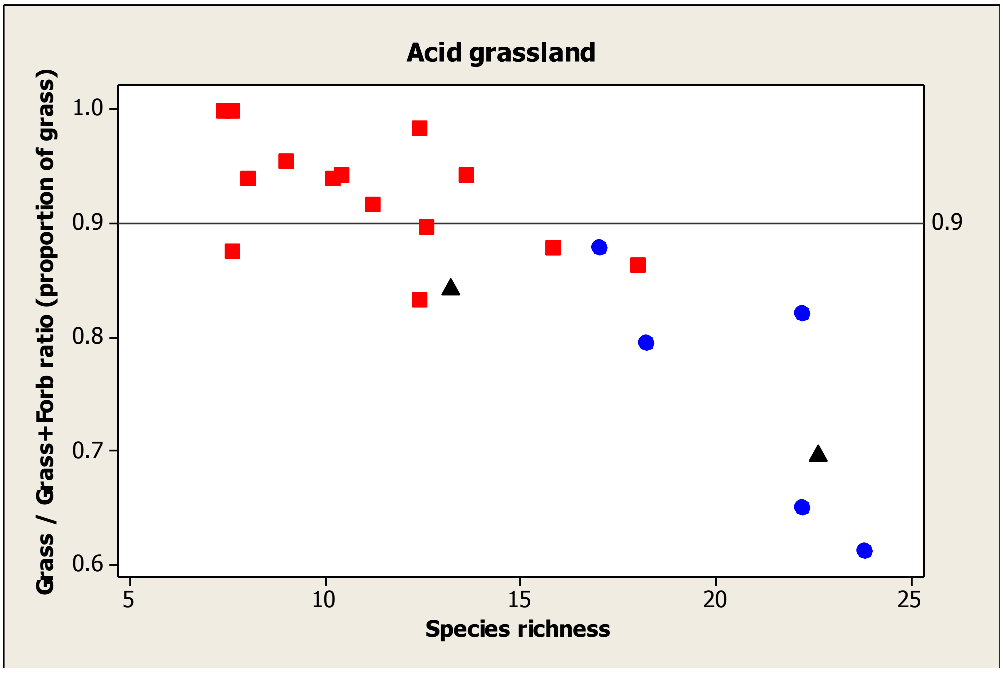

Figure 8. Plot of grass/forb ratio against average species-richness in 2x2m quadrats for acid grasslands. Line at 0.9 on y axis shows current equivalent CSM target for 10% forb cover. Blue circles show acid grassland sites below the minimum critical load bound, black triangles are within the critical load range, red squares are sites above the maximum critical load bound. Data from Field *et al* (2014).

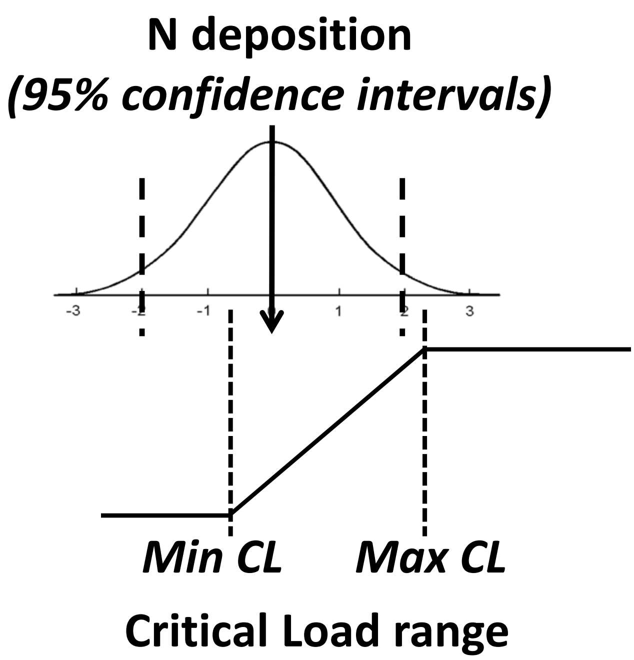

Figure 9. Illustration of how the Exceedance Score uses information on the quantity of N deposition, including associated uncertainty quantified as 95% confidence intervals (upper part of diagram), relative to the critical load range (lower part of diagram). The positions shown represent those for the Medium-Low Exceedance Score class in Table 1 and Figure 5.

Table 9. Description of Exceedance Score classes generated in WP1.3. These reflect differences in the N deposition range relative to the N critical load range and are illustrated in Figure 9.

Exceedance Score	Description
Very Low	The full deposition range, including 95% confidence intervals falls entirely below the minimum critical load.
Low	The specified deposition value falls below the minimum critical load, but the upper confidence interval lies somewhere between the minimum and the maximum critical load.
Medium-Low	Both the specified deposition value and the upper confidence interval lie between the minimum and the maximum critical load, but the lower confidence interval is lower than the minimum critical load.
Medium	The deposition range, including the upper and lower 95% confidence intervals lies between the minimum and maximum critical load.
Medium-High	The specified deposition value lies below the maximum critical load, while the upper confidence interval lies above the maximum critical load. The position of the lower confidence interval is not important in this outcome[6].
High	Both the specified deposition value and the upper confidence interval lie above the maximum critical load.
Very High	The full deposition range, including 95% confidence intervals lies entirely above the maximum critical load.

5.3 Description of approach

This section describes how the Exceedance Score is calculated, taking into account the amount of N deposition and associated uncertainty (Step 1), and uncertainty in the critical load ranges and in the habitat cross-matching (which together form Step 2 and are described as ‘certainty in the critical load’). The N deposition range, including its 95% Confidence Interval is assessed against the critical load range to derive different Exceedance Score classes, as described above Table 9 and illustrated in Figure 9.

6 How this is implemented in the framework (WP1 spreadsheet)

A spreadsheet has been designed and populated with the CSM habitat classes, their corresponding classes in other habitat classifications and their cross-matched critical loads. The individual user, or automated process carrying out the assessment, will need to look up values of N deposition for the location of the site, or location of a particular habitat within the site. The N deposition values for the 5x5km grid square for any location in the UK can be obtained from the Air Pollution Information System (APIS: www.apis.ac.uk).

The relevant N deposition value is entered into the spreadsheet and the Exceedance Score will automatically be calculated for each CSM habitat, taking account of uncertainties in the N deposition and in the cross-matched critical loads. The user or automated process subsequently only needs to look up the relevant CSM habitat of interest, to find the resulting

[6] A further possibility exists, with the specified N value within the critical load range, but both the lower and upper 95% confidence intervals for the deposition lie outside it (e.g. critical load range 10-20, certainty high, deposition 15, so range 7.5-22.5). This would also be classified as medium-high (since the position of the lower bound is not crucial to this category).

Exceedance Score for that habitat at that site. Guidance for this procedure can be found in Appendix B.

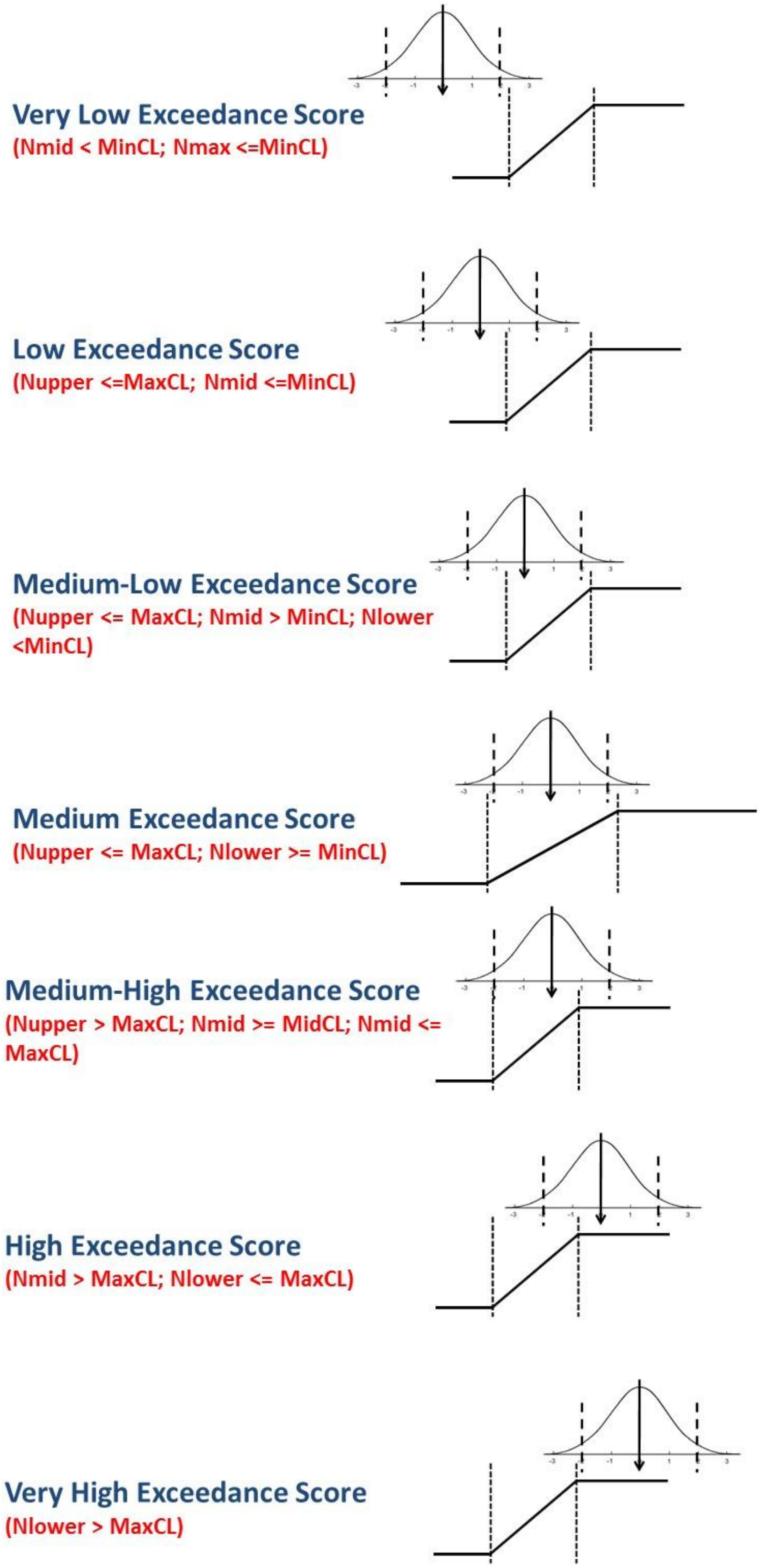

Figure 10. Illustration of the Exceedance Score classes generated in WP1.3. These reflect differences in the N deposition range relative to the N critical load range and are described in Table 9.

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8 Appendices

Appendix A. Documentation of consistency of UK evidence with the cross-matched critical loads for CSM habitats.

Table A1. Assessment for each CSM/critical load habitat type of whether UK evidence is consistent with the international evidence used to set the critical load for nitrogen (CL). N/A = not applicable.. Some old species names were used in Emmett *et al* (2011) and have been updated here: *Cladonia impexa* is now *Cladonia portentosa*; and *Cornicularia aculeata* is now *Cetraria aculeata*. Habitats in bold are CSM types, those not in bold are sub-divisions created for this assessment where different critical loads apply.

CSM / CL Habitat Type	Critical Load	Relevant UK evidence	Notes	Evidence of no effect, or an effect only above CL?	Evidence of an effect below CL?	Outcome
1a. Maritime grassland and rock-crevice communities	None	No	There is no CL for this habitat class.	N/A	N/A	No CL
2. Soft maritime cliff and slope	None	No	There is no CL for this habitat class.	N/A	N/A	No CL
3a. Saltmarsh (pioneer/low-mid)	20-30	No	There is no UK evidence related to this specific habitat class.	No	No	No evidence
3b. Saltmarsh (mid-upper)	20-30	Yes	International evidence used to set CL for saltmarsh showed impacts in experiments with 50 kg N addition ha^{-1} yr^{-1}, with further long-term monitoring of site-based evidence in The Netherlands suggesting possible impacts at 15-20 kg N_{tot} ha^{-1} yr^{-1}, and CL for saltmarsh was set to 20-30 kg N_{tot} ha^{-1} yr^{-1} based on Expert Judgement. In a review of N impacts on saltmarshes, Boorman & Hazelden (2012) were required not to challenge CL values, but concluded that inputs of N in excess of CL are likely to be needed for significant changes to occur to the vegetation. However, this conclusion was largely based on the fact that N stocks are large in relation to the input rate at CL, and perhaps takes insufficient account of the difference between relatively inert soil N pools and recently deposited reactive N. A manipulation experiment on upper saltmarsh in the UK (Jefferies et al. 1977) showed adverse impact at treatments of 66 kg N ha^{-1} yr^{-1}. Lower application rates were not included in the Jefferies study, but results were not inconsistent with impacts at lower rates.	No	No	Consistent
3c. Saltmarsh (scrub/driftline)	20-30	No	There is no UK evidence related to this specific habitat class.	No	No	No evidence
4a. Strandline (sand)	None	No	There is no CL for this specific habitat class.	N/A	N/A	No CL
4b. Embryo and mobile dunes	10-20	Yes	Increases in above-ground biomass of *Ammophila arenaria* were observed in semi-fixed dunes within the range of 7-29 kg N_{tot} ha^{-1} yr^{-1} (Jones et al., 2004). UK evidence is consistent with the CL range.	No	No	Consistent

CSM / CL Habitat Type	Critical Load	Relevant UK evidence	Notes	Evidence of no effect, or an effect only above CL?	Evidence of an effect below CL?	Outcome
5a. Fixed dune grassland (calcareous)	10-15	Yes	A decline in species-richness was observed in a mixture of calcareous and acidic fixed-dune grasslands over a short range of N deposition, 5-17 kg N_{tot} ha^{-1} yr^{-1} (Field et al., 2014). The study does not propose a threshold for the effect, but visual inspection of the data suggests there may be a decline within the 5-10 kg N_{tot} ha^{-1} yr^{-1} range. However, for consistency with the Bobbink & Hettelingh (2011) conclusion that acidic dunes are more sensitive than calcareous dunes we retain the distinction here and UK evidence is deemed consistent with the CL range.	No	No	Consistent
5b. Fixed dune grassland (acidic)	8-10	Yes	Field et al. (2014) suggest that acidic fixed-dune grasslands are more sensitive to N pollution than calcareous fixed-dune grasslands. This is reflected in the lower CL for more acidic grasslands.	No	No	Consistent
5x. Coastal dunes with *Juniper* spp	10-20	No	There is no UK evidence related to this specific habitat class.	No	No	No evidence
5y. Dunes with *Hippophae rhamnoides*	None	No	There is no CL for this specific habitat class.	N/A	N/A	No CL
6a. Humid dune slacks (calcareous)	15-20	Yes	UK evidence was cited in Bobbink & Hettelingh (2011) to justify a reduction in the CL for dune slacks. Although few effects on soil or vegetation were observed in surveys of dune slacks across N deposition gradients of 7-29 kg N_{tot} ha^{-1} yr^{-1} (Jones et al., 2004) or 4-20 kg N_{tot} ha^{-1} yr^{-1} (Jones, 2007), cover of *Carex arenaria* and *Hypochaeris radicata* increased with total N deposition, and a treatment of ca. 15 kg N_{tot} ha^{-1} yr^{-1} was observed to affect dune slack seedbanks (Plassmann et al., 2008).	No	No	Consistent
6b. Humid dune slacks (non-calcareous)	10-15	Yes	There is no separate evidence for this category, but the notes under 6a Calcareous humid dune slacks also apply here. Neutral to acid humid dune slacks are more susceptible to acidifying effects of N, so have been given a lower CL range. UK evidence is consistent with this range.	No	No	Consistent
7. Dunes with *Salix repens*	10-20	No	There is no UK evidence related to this specific habitat class.	No	No	No evidence
8. Machair	8-15	Yes	There is no specific evidence related to machair. The term can include both wet and dry calcareous dune grasslands, but biogeochemical conditions are most often similar to those in calcareous fixed-dune grassland. By analogy with that habitat, evidence presented by Field et al. (2014) suggests that effects may begin at rates below 15 kg N_{tot} ha^{-1} yr^{-1}. The proposed CL range here is 8–15 kg N_{tot} ha^{-1} yr^{-1}, therefore the UK evidence is consistent with this range.	No	No	Consistent
9a. Shingle beach driftlines and open shingle vegetation	None	No	There is no CL for this specific habitat class.	N/A	N/A	No CL

CSM / CL Habitat Type	Critical Load	Relevant UK evidence	Notes	Evidence of no effect, or an effect only above CL?	Evidence of an effect below CL?	Outcome
9b. Shingle grasslands	8-15	Yes	There is no UK evidence related to this specific habitat class, but vegetated shingle banks are analogous to acidic fixed-dune grassland in that they are free-draining with little buffering capacity for acid and nutrient inputs.	No	No	Consistent
10a. Lowland closed dry acid grasslands (U3/U4)	10-15	Yes	Extensive field surveys of upland and lowland acid grassland, spanning the range of ambient deposition in the UK, show changes in species composition, soil and plant tissue chemistry, and plant species richness (Field et al., 2014; Maskell et al., 2010; Stevens et al., 2006; Stevens et al., 2004). Although none of these studies established a threshold N deposition rate that caused significant change, the responses presented, e.g. Stevens et al. (2006) Fig. 1, suggest that changes may begin to occur at rates below 10 kg N_{tot} ha^{-1} yr^{-1}. Other studies have too few sites with sufficiently low deposition to strengthen this finding. Two species which occur in this habitat, *Cladonia portentosa* and *Leucobryum glaucum*, were affected by N in heathland at 5-10 kg N_{tot} ha^{-1} yr^{-1} (Emmett et al., 2011). It is likely that these species will also be affected in this habitat at these deposition rates, which are below the current CL. However, these species are infrequent or localised within this habitat so this evidence was not considered relevant.	No	No	Consistent
10b. Lowland open dry acid grasslands (U1)	10-15	Yes	There is no specific evidence for open dry acid grassland, but the notes above for closed lowland acid grasslands apply here also. Open grasslands are more likely than closed grasslands to support low-growing, light-demanding species that are vulnerable to N pollution (Hautier et al., 2009; Hodgson et al., 2014). This is reflected in a slightly larger list of species occurring in this habitat that were affected by N at 5-10 kg N_{tot} ha^{-1} yr^{-1}: *Cerastium arvense* and *Cetraria aculeata* in acid grassland and *Cladonia portentosa* and *C. uncialis* in heathland (Emmett et al., 2011). It is likely that these species will also be affected in this habitat at these deposition rates, which are below the current CL.	No	Yes	CL may be too high
10x. Inland dunes	8-15		There is no UK evidence related to this specific habitat class.	No	No	No evidence

CSM / CL Habitat Type	Critical Load	Relevant UK evidence	Notes	Evidence of no effect, or an effect only above CL?	Evidence of an effect below CL?	Outcome
11a. Lowland calcareous grasslands (Mesobromion)	15-25	Yes	UK evidence from a range of investigations shows negative impacts of N addition on species composition, plant tissue chemistry and soil processes (Haworth et al., 2007; Unkovich et al., 1998). Monitoring suggests that increases in abundance of *Brachypodium pinnatum* are not always as apparent as in other areas of Europe (Bryant, 1998; Hewins and Link, 1998; Pitcairn et al., 1991; Wells et al., 1993). National surveys in calcareous grasslands demonstrate changes in species composition and increases in Ellenberg N values under elevated N deposition (Bennie et al., 2006; Maskell et al., 2010; Van den Berg et al., 2011). None of these studies established a threshold N deposition rate that caused significant change. However, there is strong species-level evidence of impacts at rates below CL. Four species which occur in this habitat (*Bromopsis erecta*, *Carlina vulgaris*, *Centaurea scabiosa* and *Daucus carota*) were affected by N in calcareous grassland at 5-10 kg N_{tot} ha^{-1} yr^{-1}, with an additional species, *Ononis repens*, affected at 10-15 kg N_{tot} ha^{-1} yr^{-1} (Emmett et al., 2011). These deposition rates are below the current CL.	No	Yes	CL may be too high
11b. Lowland calcareous grasslands (Xerobromion)	15-25	Yes	The notes under 11a Lowland calcareous grasslands (Mesobromion) are mostly applicable to this sub-class, although the species found within this sub-class differ slightly. *Carlina vulgaris*, *Centaurea scabiosa* and *Daucus carota* do occur in this sub-class and the negative responses of these species to 5-10 kg N_{tot} ha^{-1} yr^{-1} (Emmett et al., 2011) suggest that changes are likely to occur to this habitat at rates below the current CL.	No	Yes	CL may be too high
12a. Lowland meadows	20-30	Yes	UK evidence from the long-running Park Grass Experiment (ammonium sulphate or sodium nitrate addition 48 kg N ha^{-1} yr^{-1}) showed decreases in diversity and species richness with a few grasses becoming dominant over time, particularly where the effects of acidification were apparent (Crawley et al., 2005; Dodd et al., 1995; Johnston et al., 1986; Silvertown et al., 1994; Silvertown et al., 2006). In a national survey Maskell et al. (2010) found a weak decline in species richness with increasing N deposition. None of these studies established a threshold N deposition rate that caused significant change. One species that occurs in this habitat, *Bromopsis erecta*, was affected in calcareous grasslands at 5-10 kg N_{tot} ha^{-1} yr^{-1} (Emmett et al., 2011), but this species is very infrequent and/or localised within lowland meadows, so this evidence was not considered relevant.	No	No	Consistent

CSM / CL Habitat Type	Critical Load	Relevant UK evidence	Notes	Evidence of no effect, or an effect only above CL?	Evidence of an effect below CL?	Outcome
12b. Upland hay meadows	20-30	Yes	The studies described under 12a Lowland meadows included upland sites that are also relevant to this habitat. There was no species-level evidence related to this habitat.	No	No	Consistent
12x. Other lowland neutral grasslands (MG9-13)	20-30	Yes	UK evidence from Tadham Moor showed that N loads from approximately 45 kg N_{tot} ha^{-1} yr^{-1} reduced richness and changed species composition with forbs showing the greatest reduction in abundance (Kirkham et al., 1996; Mountford et al., 1994).	No	No	Consistent
13a. Lowland rush pastures	20-30	No	There is no UK evidence related to this specific habitat class.	No	No	No evidence
13b. Lowland purple moor-grass pastures	15-25	No	There is no UK evidence related to this specific habitat class.	No	No	No evidence
14a. Lowland calaminarian grasslands (calcareous)	15-25	Yes	There is no survey or experimental UK evidence related to this specific habitat class. However, some forms of calaminarian grasslands are defined by the presence of particular bryophytes and/or lichens, and there is evidence that many lichens and bryophytes are particularly sensitive to N since the lack of a well-developed cuticle means they can absorb pollutants across their surface area, and also because productivity increases in vascular plants may lead to increased shading and reduction in understorey species (Phoenix et. al. 2012). Declining abundance of lichens has been recorded at application rates of 7.7-10 kgN/ha/yr (Phoenix et. al. 2012). Bobbink & Hettelingh (2010) quote references to CLs of less than 10 kgN/ha/yr depleting lichens in alpine communities and heaths. These deposition rates are below the current CL.	No	Yes	CL may be too high
14b. Lowland calaminarian grasslands (acidic)	10-15	Yes	There is no survey or experimental UK evidence related to this specific habitat class. However, some forms of calaminarian grasslands are defined by the presence of particular bryophytes and/or lichens, and there is evidence that many lichens and bryophytes are particularly sensitive to N since the lack of a well-developed cuticle means they can absorb pollutants across their surface area, and also because productivity increases in vascular plants may lead to increased shading and reduction in understorey species (Phoenix et. al. 2012). Declining abundance of lichens has been recorded at application rates of 7.7-10 kgN/ha/yr (Phoenix et. al. 2012). Bobbink & Hettelingh (2010) quote references to CLs of less than 10 kgN/ha/yr depleting lichens in alpine communities and heaths. These deposition rates are below the current CL.	No	Yes	CL may be too high

CSM / CL Habitat Type	Critical Load	Relevant UK evidence	Notes	Evidence of no effect, or an effect only above CL?	Evidence of an effect below CL?	Outcome
15a. Lowland dry heaths (not on dunes)	10-20	Yes	UK N addition experiments in lowland dry heath at Thursley Common and Budworth Common have found significant effects of N. Nitrogen has been found to increase growth and alter phenology of the main heathland plant, *Calluna vulgaris,* above 20 kg N_{tot} ha^{-1} yr^{-1} (Power et al., 1998; Power et al., 1995). In a sub-experiment at Thursley, lichen cover was also significantly reduced above 15 kg N_{tot} ha^{-1} yr^{-1} (Barker, 2001) and grass incursion increased following management (Barker et al., 2004; Power et al., 2006). Significant field scale evidence supports the experimental data, with changes in plant and soil chemistry above 13 kg N_{tot} ha^{-1} yr^{-1} (Jones and Power, 2012) and declines in species richness and increases in cover of grasses above 7 kg N_{tot} ha^{-1} yr^{-1} (Southon et al., 2013). *Cladonia portentosa* and *Hylocomium splendens* were also found to decline above 16 kg N_{tot} ha^{-1} yr^{-1} in a survey of Lowland Heaths (Field et al., 2014). However, Southon et al. (2013) suggests that effects occur below the current CL, and this is supported by species-level evidence. *Cladonia portentosa* and *C. uncialis* were affected by N in Lowland dry heathland at 5-10 kg N_{tot} ha^{-1} yr^{-1} (Emmett et al., 2011). These deposition rates are below the current CL.	No	Yes	CL may be too high

CSM / CL Habitat Type	Critical Load	Relevant UK evidence	Notes	Evidence of no effect, or an effect only above CL?	Evidence of an effect below CL?	Outcome
15b. Coastal dune heath	10-20	Yes	The habitat “Coastal dune heaths” has not been specifically studied in experiments or surveys, but other acidic dune habitats have (Remke et al. 2009), and it is closely related to the other heathland types with components of general heathland vegetation with *Calluna vulgaris* often dominant, so responses are expected to be similar with reductions in lower plant (moss, lichen and liverwort) diversity and cover. The other significant component of this habitat is the sedge *Carex arenaria*, this has been found to increase in cover in response to N in targeted surveys of sand dune systems (Jones et al., 2004), supporting the theory that graminoid cover responds to N and the likely outcome of reduced lower plant diversity. A similar study on European coastal dunes (Remke et al., 2009) also found increases in the cover of *Carex arenaria* and reductions in the species richness of forbs and lichens at modest N_{tot} ha^{-1} yr^{-1} <10 kg. UK N addition experiments in lowland dry heath at Thursley Common and Budworth Common have found significant effects of N. N has been found to increase growth and alter phenology of the main heathland plant, *Calluna vulgaris,* above 20 kg N_{tot} ha^{-1} yr^{-1} (Power et al., 1998; Power et al., 1995). In a sub-experiment at Thursley, lichen cover was also significantly reduced above 15 kg N_{tot} ha^{-1} yr^{-1} (Barker, 2001) and grass incursion increased following management (Barker et al., 2004; Power et al., 2006). Significant field scale evidence supports the experimental data, with changes in plant and soil chemistry above 13 kg N_{tot} ha^{-1} yr^{-1} (Jones and Power, 2012) and declines in species richness and increases in cover of grasses above 7 kg N_{tot} ha^{-1} yr^{-1} (Southon et al., 2013). *Cladonia portentosa* and *Hylocomium splendens* were also found to decline above 16 kg N_{tot} ha^{-1} yr^{-1} in a survey of Lowland Heaths (Field et al., 2014). However, Southon et al. (2013) suggests that effects occur below the current CL, and this is supported by species-level evidence. *Cladonia portentosa* and *C. uncialis* were affected by N in Lowland dry heathland at 5-10 kg N_{tot} ha^{-1} yr^{-1} (Emmett et al., 2011). These deposition rates are below the current CL.	No	Yes	CL may be too high

CSM / CL Habitat Type	Critical Load	Relevant UK evidence	Notes	Evidence of no effect, or an effect only above CL?	Evidence of an effect below CL?	Outcome
16a. Lowland wet heath (without *Erica ciliaris*)	10-20	Yes	In the UK, lowland wet heath, lowland dry heath, and upland dry and wet heaths, are closely related habitats along an edaphic gradient driven by changes in climate, hydrology and altitude. Responses of lowland wet-heath to N are therefore thought to be similar to those of lowland dry heath and upland wet heath covered elsewhere in this table, although there might be some differences in N response because of the different soils, growing conditions, etc.. Experimentation in the early 1990's on Dutch *Erica tetralix*-dominated lowland heath found large-scale conversion of heaths to grasslands dominated by *Molinia caerulea*, albeit at experimentally N deposition above 150 kg (Berendse and Aerts, 1984) The critical load for this specific habitat was formulated by expert judgment based on the responses observed in other heathland types. *Cladonia portentosa* and *Hylocomium splendens* were also found to decline above 16 kg N_{tot} ha^{-1} yr^{-1} in a survey of Lowland Heaths (Field et al., 2014). However, Emmett et al (2011) found that *Cladonia portentosa*, *C. uncialis*, *C. verticillata* and *Leucobryum glaucum*, were affected by N in Lowland wet heaths (without *Erica ciliaris*) at 5-10 kg N_{tot} ha^{-1} yr^{-1}. These deposition rates are below the current CL.	No	Yes	CL may be too high

CSM / CL Habitat Type	Critical Load	Relevant UK evidence	Notes	Evidence of no effect, or an effect only above CL?	Evidence of an effect below CL?	Outcome
16b. Lowland wet heath (with *Erica ciliaris*)	10-20	Yes	*Erica ciliaris* heath is a nationally rare habitat confined mainly to Dorset, extending into Cornwall. In the UK, lowland wet heath, lowland dry heath, and upland dry and wet heaths, are closely related habitats along an edaphic gradient driven by changes in climate, hydrology and altitude. Responses to N of lowland wet-heath are therefore thought to be similar to those of lowland dry heath and upland wet heath covered elsewhere in this table, although there might be some differences in N response because of the different soils, growing conditions, etc. Experimentation in the early 1990's on Dutch *Erica tetralix*-dominated lowland heath found large-scale conversion of heaths to grasslands dominated by *Molinia caerulea*, albeit at experimentally very high N deposition above 150 kg (Berendse and Aerts, 1984) The critical load for this specific habitat was formulated by expert judgment based on the responses observed in other heathland types. *Cladonia portentosa* was also found to decline above 16 kg N_{tot} ha^{-1} yr^{-1} in a survey of Lowland Heaths (Field et al., 2014). However, *Cladonia portentosa*, *C. uncialis*, *C. verticillata* and *Leucobryum glaucum* were affected by N in heaths at 5-10 kg N_{tot} ha^{-1} yr^{-1} (Emmett et al., 2011). These deposition rates are below the current CL. However, it is deemed there is not sufficient UK evidence for this particular heathland type to consider modifying the CL, given the differences in base status for this heathland type on serpentine soils.	No	No	Consistent
17a. Lowland fens (base-poor/transitional)	10-15	Yes	Two lichen species that can occur in lowland poor fens, *Cladonia portentosa* and *C. uncialis*, declined in prevalence at N deposition rates of 5-10 kg N_{tot} ha^{-1} yr^{-1} in heathlands (Emmett et al., 2011). However, these species are infrequent and/or localised within lowland poor fens, so this evidence was not considered relevant.	No	No	Consistent
17b. Lowland fens (base-rich)	15-30	No	There is no UK evidence related to this specific habitat class.	No	No	No evidence
17c. Lowland *Filipendula* mires (M27/28)	15-30	No	There is no UK evidence related to this specific habitat class.	No	No	No evidence
17d. Lowland swamps	None	No	There is no CL for this specific habitat class.	N/A	N/A	No CL
17x. Inland salt meadows	None	No	There is no CL for this specific habitat class.	N/A	N/A	No CL

CSM / CL Habitat Type	Critical Load	Relevant UK evidence	Notes	Evidence of no effect, or an effect only above CL?	Evidence of an effect below CL?	Outcome
18. Lowland raised bog and lowland blanket bog	5-10	Yes	The CL for lowland and upland bog was set to 5-10 kg N_{tot} ha^{-1} yr^{-1} based mainly on Swedish evidence (Gunnarsson et al., 2002). The lowest deposition observed to affect lowland bog habitats in UK experiments was 16 kg N_{tot} ha^{-1} yr^{-1}, which caused an initial increase (Sheppard et al., 2004) and later stabilisation (Sheppard et al., 2014) of *Sphagnum* growth, but there is no habitat-level evidence that rates of 5-10 kg N_{tot} ha^{-1} yr^{-1} do not cause change. However, species responses suggest that 5-10 kg N_{tot} ha^{-1} yr^{-1} reduced prevalence of two species in lowland bog: *Anastrophyllum minutum* and *Odontoschisma denudatum* (Emmett et al., 2011), which is consistent with the CL	No	No	Consistent
19a. Upland acid grassland (dry U2-5*)	10-15	Yes	UK evidence from long-term N addition experiments at total N loads (addition + background) of approximately 65, 100 and 170 kg N ha^{-1} yr^{-1} show changes in species composition, soil chemistry, plant tissue chemistry and soil processes (Arroniz-Crespo et al., 2008; Carroll et al., 2003; Carroll et al., 2000; Horswill et al., 2008; Morecroft et al., 1994; Phoenix et al., 2012). Evidence from an upland grassland in Wales found negative effects on lichens at 10 kg N ha^{-1} yr^{-1} and on bryophytes and other changes in species composition at 20 kg N ha^{-1} yr^{-1} (Emmett, 2007; Emmett et al., 2001). Extensive field surveys (upland and lowland acid grassland) spanning the range of ambient deposition in the UK show changes in species composition, soil and plant tissue chemistry, and plant species richness (Field et al., 2014; Maskell et al., 2010; Stevens et al., 2006; Stevens et al., 2004). All of these surveys show impacts at the lowest levels of deposition in the UK although the scarcity of sites below the lower end of the critical load makes it difficult to say there is an effect at these low levels. None of these studies established a threshold N deposition rate that caused significant change. Three species that occur in this habitat, *Cladonia portentosa*, *C. uncialis* and *Vaccinium vitis-idaea*, were affected in upland heathland at 5-10 kg N_{tot} ha^{-1} yr^{-1} (Emmett et al., 2011). These deposition rates are below the current CL. These species are infrequent or localised within this habitat so this evidence was not considered relevant.	No	No	Consistent

CSM / CL Habitat Type	Critical Load	Relevant UK evidence	Notes	Evidence of no effect, or an effect only above CL?	Evidence of an effect below CL?	Outcome
19b. Upland acid grassland (wet U5b/U6)	10-20	Yes	The habitat-level evidence described under 19a. Upland acid grassland (dry) is also relevant to this habitat. Some upland acid grasslands dominated by *Nardus* may not be as species rich as European counterparts and may be less sensitive to N deposition inputs but there is insufficient evidence to draw conclusions about this in relation to the critical load. Three species that occur in upland acid grassland were shown to respond to N by Emmett et al. (2011): *Cetraria aculeata* at 5-10 kg N_{tot} ha^{-1} yr^{-1} in acid grassland, *Cladonia portentosa* at 5-10 kg N_{tot} ha^{-1} yr^{-1} in heathland, and *Racomitrium lanuginosum* at 10-15 kg N_{tot} ha^{-1} yr^{-1} in acid grassland. Two of these deposition rates are below the current CL. These species are infrequent or localised within this habitat so this evidence was not considered relevant.	No	No	Consistent
20. Alkaline fen (upland, excluding alpine flushes)	15-30	No	There is no UK evidence related to this specific habitat class.	No	No	No evidence
21. Alpine dwarf-shrub heath	5-15	Yes	Evidence from a UK experiment on *Calluna-Cladonia* heath (part of EUNIS class F2.2; the CL is set for F2. Arctic, alpine & subalpine scrub as a whole) found increases in growth of *Calluna vulgaris* in response to 20 kg N_{tot} ha^{-1} yr^{-1} (background 10 kg N ha^{-1} yr^{-1} plus 10 kg N ha^{-1} yr^{-1} addition) and subsequent reductions in lichen species richness and % cover (Britton and Fisher, 2007; Britton and Fisher, 2008). These experimental findings fed directly into the recent updating of critical loads. European experimentation found declines in the shrub *Empetrum hermaphroditum*, in response to N additions of 50 kg N ha^{-1} yr^{-1} (52 kg N_{tot} ha^{-1} yr^{-1}), and rapid increases in cover of the grass *Deschampsia flexuosa* were also observed (Nilsson et al., 2002). Declines in the cover of mosses and lichens were also observed. *Cladonia portentosa* and *C. uncialis* were affected by N in Alpine dwarf-shrub heaths at 5-10 kg N_{tot} ha^{-1} yr^{-1} and *Racomitrium lanuginosum* was affected by 10-15 kg N_{tot} ha^{-1} yr^{-1} (Emmett et al., 2011). These rates are consistent with the CL.	No	No	Consistent
22a. Alpine flush (*Carex saxatilis* mire)	15-30	Yes	The moss *Racomitrium lanuginosum*, which can occur in Alpine Flushes, was shown to decrease in prevalence in acid grassland at N_{tot} ha^{-1} yr^{-1} rates of 10-15 kg N_{tot} ha^{-1} yr^{-1} (Emmett et al., 2011). However, although this species occurs within Alpine flushes (*Carex saxatilis* mire), there is only evidence from this species so this evidence was not considered sufficient to be inconsistent with the current CL.	No	No	Consistent

CSM / CL Habitat Type	Critical Load	Relevant UK evidence	Notes	Evidence of no effect, or an effect only above CL?	Evidence of an effect below CL?	Outcome
22b. Alpine flush (not *Carex saxatilis* mire)	15-25	Yes	The moss *Racomitrium lanuginosum*, which can occur in this habitat, was shown to decrease in prevalence in acid grassland at N_{tot} ha^{-1} yr^{-1} rates of 10-15 kg N_{tot} ha^{-1} yr^{-1} (Emmett et al., 2011). However, this species is infrequent and/or localised within Alpine flush, so this evidence was not considered to be inconsistent with the current CL.	No	No	Consistent
23a. *Juncus trifidus* and *Carex-Racomitrium* heaths	5-10	Yes	A UK experiment on *Carex bigelowii-Racomitrium* heath found declines in the cover of the moss *Racomitrium lanuginosum* in response to N_{tot} deposition above 28 kg ha^{-1} yr^{-1} (background 18 kg, N addition 10 kg) (Pearce et al., 2003). The moss *Racomitrium lanuginosum*, an important component of this habitat, was also found to be affected by even very low rates of N deposition in a survey that included UK sites (Armitage et al., 2012). Leaf N concentrations increased most rapidly in the 0-5 kg N_{tot} ha^{-1} yr^{-1} range. However, this physiological change is not necessarily related to conservation objectives for this habitat, so was not considered to be inconsistent with the current CL. Several species which occur in this habitat (*Cladonia portentosa, C. uncialis, Cetraria aculeata* and *Vaccinium vitis-idaea*), were affected in heathland at 5-10 kg N_{tot} ha^{-1} yr^{-1} (Emmett et al., 2011), providing supporting evidence for the current CL.	No	No	Consistent
24a. Blanket bog (upland)	5-10	Yes	Similarly to 18 Lowland bog , the CL was set to 5-10 kg N_{tot} ha^{-1} yr^{-1} based mainly on Swedish evidence. Effects of N on the prevalence of 11 upland bog species were reported in Emmett et al. (2011), and two of these, *Odontoschisma denudatum* and *Anastrophyllum minutum*, were affected at 5-10 kg N_{tot} ha^{-1} yr^{-1} (Stevens et al., 2011), providing supporting evidence for the current CL.	No	No	Consistent
24b. Valley bog (upland M21)	10-15	Yes	A single species, *Cladonia portentosa*, was shown to be affected in bog habitats by N_{tot} ha^{-1} yr^{-1} of 15-20 kg (Emmett et al., 2011). This species was shown to be affected in heathland at a lower rate, 5-10 kg, but this was not considered to be sufficient evidence to reduce the CL.	No	No	Consistent
25a. Calaminarian grassland (upland calcareous)	15-25	No	There is no UK evidence related to this specific habitat class.	No	No	No evidence
25b. Calaminarian grassland (upland acidic)	10-15	No	There is no UK evidence related to this specific habitat class.	No	No	No evidence

CSM / CL Habitat Type	Critical Load	Relevant UK evidence	Notes	Evidence of no effect, or an effect only above CL?	Evidence of an effect below CL?	Outcome
25c. Serpentine heath (upland)	10-20	Yes	Two species that occur in this habitat were shown to be affected in by N deposition rates of 5-10 kg ha^{-1} yr^{-1}: *Cladonia portentosa* in heathland and *Daucus carota* in calcareous grassland (Emmett et al., 2011). It is likely that these species will also be affected in this habitat at these deposition rates, which are below the current CL. However, there was not deemed enough UK evidence to change the CL for this habitat.	No	No	Consistent
26a. Calcareous grassland (upland on limestone)	15-25	Yes	In a national survey (upland and lowland) Maskell et al. (2010) found significant changes in species composition consistent with eutrophication which could be caused by N deposition. None of these studies established a threshold N deposition rate that caused significant change. Three species that occur in this habitat were affected at 5-10 kg N_{tot} ha^{-1} yr^{-1} (Emmett et al., 2011): *Carlina vulgaris* in calcareous grassland, and *Cetraria aculeata* and *Vaccinium vitis-idaea* in upland heathland. *Vaccinium vitis-idaea* isinfrequent and/or localised within calcareous grassland, so this evidence was not considered relevant. However, the other two species could be retained. These deposition rates are below the current CL.	No	Yes	CL may be too high
26b. Calcareous grassland (upland not on limestone)	10-15	Yes	The habitat-level evidence described under 19a. upland acid grassland (dry) is also relevant to this habitat. Two species that can occur in this habitat were affected by 5-10 kg N_{tot} ha^{-1} yr^{-1} in heathland: *Cladonia uncialis* and *Vaccinium vitis-idaea* (Emmett et al., 2011). However, these species are infrequent and/or localised within calcareous grassland, so this evidence was not considered relevant.	No	No	Consistent
26c. Calcareous dwarf-herb snowbed (CG12)	5-10	Yes	Two species that occur in this habitat were affected by 5-10 kg N_{tot} ha^{-1} yr^{-1} in heathland: *Cladonia uncialis* and *Vaccinium vitis-idaea* (Emmett et al., 2011). These responses are consistent with the current CL.	No	No	Consistent
26d. Upland *Dryas* mats	5-15	Yes	Three species that occur in this habitat were affected by 5-10 kg N_{tot} ha^{-1} yr^{-1}: *Arctostaphylos uva-ursi* and *Vaccinium vitis-idaea* in heathland and *Daucus carota* in calcareous grassland (Emmett et al., 2011). Although the CL range extends higher than this to 15 kg N_{tot} ha^{-1} yr^{-1}, these responses were considered consistent with the current CL.	No	No	Consistent
27. Calcareous rocky slope	5-10	No	There is no UK evidence related to this specific habitat class.	No	No	No evidence
28. Calcareous scree	5-15	Yes	One species which occurs in this habitat, *Vaccinium vitis-idaea*, was shown to be affected in heathland at a rate of 5-10 kg N_{tot} ha^{-1} yr^{-1} (Emmett et al., 2011). }. The CL range extends slightly higher than this to 15 kg N_{tot} ha^{-1} yr^{-1}, but the evidence was considered consistent with the current CL.	No	No	Consistent

CSM / CL Habitat Type	Critical Load	Relevant UK evidence	Notes	Evidence of no effect, or an effect only above CL?	Evidence of an effect below CL?	Outcome
29. Fellfield	5-10	No	There is no UK evidence related to this specific habitat class.	No	No	No evidence
30. Fern-dominated snow-bed	5-10	No	There is no UK evidence related to this specific habitat class.	No	No	No evidence
31a. Juniper heath and scrub (upland acidic)	10-20	Yes	Two species which occur in this habitat, *Scapania gracilis* and *Vaccinium vitis-idaea*, were affected by N in other habitats: *S. gracilis* in acid grassland at 10-15 kg N_{tot} ha^{-1} yr^{-1} and *Vaccinium vitis-idaea* in heathland at 5-10 kg N_{tot} ha^{-1} yr^{-1} (Emmett et al., 2011). *Scapania gracilis* is infrequent and/or localised within this habitat, so this evidence was not considered relevant, but *V. vitis-idaea* is a widespread component of some subtypes of this habitat. It is likely that this species will also be affected in this habitat at 5-10 kg N_{tot} ha^{-1} yr^{-1}, which is below the current CL.	No	Yes	CL may be too high
31b. Juniper heath and scrub (upland calcareous)	15-25	Yes	Two species which occur in this habitat, *Scapania gracilis* and *Vaccinium vitis-idaea*, were affected by N in other habitats: *S. gracilis* in acid grassland at 10-15 kg N_{tot} ha^{-1} yr^{-1} and *V. vitis-idaea* in heathland at 5-10 kg N_{tot} ha^{-1} yr^{-1} (Emmett et al., 2011). However, both *Scapania gracilis* and V. vitis-idaea are infrequent and/or localised within this habitat (see also Atherton et al., 2010), so this evidence was not considered relevant.	No	No	No evidence
32. Limestone pavement	5-10	Yes	Five species that occur in this habitat were affected by 5-10 kg N_{tot} ha^{-1} yr^{-1} in other habitats: *Cetraria aculeata* in acid grassland, *Carlina vulgaris* and *Daucus carota* in calcareous grassland, and *Arctostaphylos uva-ursi* and *Vaccinium vitis-idaea* in heathland (Emmett et al., 2011). These responses are consistent with the current CL.	No	No	Consistent
33. Mire grasslands and rush pastures (upland)	None	No	There is no CL for this habitat class.	N/A	N/A	No CL
34. Montane willow scrub	5-15	Yes	Two species which occur in this habitat, *Racomitrium lanuginosum* and *Vaccinium vitis-idaea*, were affected by N in other habitats: *R. lanuginosum* in acid grassland at 10-15 kg Ntot ha^{-1} yr^{-1} and *V. vitis-idaea* in heathland at 5-10 kg Ntot ha^{-1} yr^{-1} (Emmett et al., 2011). The CL range extends slightly higher than this to 15 kg Ntot ha^{-1} yr^{-1}, but the evidence was considered consistent with the current CL.	No	No	Consistent
35a. Moss, dwarf-herb, and grass-dominated snow-bed (U11/13/14)	5-10	Yes	Three species which occur in this habitat, *Racomitrium lanuginosum*, *Cladonia uncialis* and *Vaccinium vitis-idaea*, were affected by N in other habitats: *R. lanuginosum* in acid grassland at 10-15 kg N_{tot} ha^{-1} yr^{-1} and both *C. uncialis* and *V. vitis-idaea* in heathland at 5-10 kg N_{tot} ha^{-1} yr^{-1} (Emmett et al., 2011), providing supporting evidence for the current CL.	No	No	Consistent

CSM / CL Habitat Type	Critical Load	Relevant UK evidence	Notes	Evidence of no effect, or an effect only above CL?	Evidence of an effect below CL?	Outcome
35b. *Nardus-Carex bigelowii* and *Carex-Polytrichum* heaths (U7/8)	5-10	Yes	Four species which occur in this habitat, *Cladonia portentosa, C. uncialis, Cetraria aculeata* and *Vaccinium vitis-idaea*, were affected by N in heathland at 5-10 kg N_{tot} ha^{-1} yr^{-1} (Emmett et al., 2011), providing supporting evidence for the current CL.	No	No	Consistent
35c. Snow-bed with *Salix herbacea* (U12)	5-15	Yes	Two species which occur in this habitat, *Cladonia uncialis* and *Cetraria aculeata*, were affected by N in heathland at 5-10 kg N_{tot} ha^{-1} yr^{-1} (Emmett et al., 2011), providing supporting evidence for the current CL.	No	No	Consistent
36. Short sedge acidic fen (upland)	10-15	No	There is no UK evidence related to this specific habitat class.	No	No	No evidence
37. Siliceous rocky slope	5-15	Yes	Three species which occur in this habitat, *Cladonia portentosa, C. uncialis* and *Cetraria aculeata*, were affected by N in heathland at 5-10 kg N_{tot} ha^{-1} yr^{-1} (Emmett et al., 2011). The CL range extends slightly higher than this to 15 kg N_{tot} ha^{-1} yr^{-1}, but the evidence was considered consistent with the current CL.	No	No	Consistent
38. Siliceous scree	5-15	Yes	Three species which occur in this habitat, *Cladonia portentosa, C. uncialis* and *Cetraria aculeata*, were affected by N in heathland at 5-10 kg N_{tot} ha^{-1} yr^{-1} (Emmett et al., 2011). The CL range extends slightly higher than this to 15 kg N_{tot} ha^{-1} yr^{-1}, but the evidence was considered consistent with the current CL.	No	No	Consistent
39. Soakway and sump (upland)	10-15	No	There is no UK evidence related to this specific habitat class.	No	No	No evidence
40a. Spring-head, rill and flush (upland non-calcareous)	10-15	Yes	One species which occurs in this habitat, *Racomitrium lanuginosum*, was shown to be affected in acid grassland at a rate of 10-15 kg N_{tot} ha^{-1} yr^{-1} (Emmett et al., 2011), providing supporting evidence for the current CL.	No	No	Consistent
40b. Upland calcareous springs	15-30	No	There is no UK evidence related to this specific habitat class.	No	No	No evidence
41. Subalpine dry dwarf-shrub heath	10-20	Yes	UK studies have often not distinguished dry from wet subalpine heath, and the notes under 45 Wet heath are also relevant to this habitat. Responses to N are expected to be similar with reductions in bryophyte and lichen diversity and cover. Three species which occurs in this habitat, *Vaccinium vitis-idaea*, *Cladonia portentosa* and *C. uncialis,* were shown to be affected by N in heathland at 5-10 kg N_{tot} ha^{-1} yr^{-1} (Emmett et al., 2011). These rates are below the CL.	No	Yes	Consistent
42a. Tall herbs (upland, base-rich)	5-10	No	One species which occurs in the NVC table for this habitat, *Vaccinium vitis-idaea*, was shown to be affected in heathland at a rate of 5-10 kg N_{tot} ha^{-1} yr^{-1} (Emmett et al., 2011). This would provide supporting evidence for the current CL. However, this species infrequent and/or localised within the habitat, so this evidence was not considered relevant.	No	No	No evidence

CSM / CL Habitat Type	Critical Load	Relevant UK evidence	Notes	Evidence of no effect, or an effect only above CL?	Evidence of an effect below CL?	Outcome
42b. Tall herbs (upland, base-poor)	5-15	No	Three species which occur in this habitat, *Cladonia portentosa, C. uncialis* and *Vaccinium vitis-idaea*, were affected by N in heathland at 5-10 kg N_{tot} ha^{-1} yr^{-1} (Emmett et al., 2011). The CL range extends slightly higher than this to 15 kg N_{tot} ha^{-1} yr^{-1}, but the evidence was considered consistent with the current CL. However, these species are infrequent and/or localised within the habitat, so this evidence was not considered relevant.	No	No	No evidence
43. Transition mire, ladder fen and quaking bog (upland)	10-15	No	There is no UK evidence related to this specific habitat class.	No	No	No evidence
44. Upland habitat assemblage/mosaic of habitats or vegetation types	None	No	There is no CL for this specific habitat class.	N/A	N/A	No CL
45. Wet heath (upland)	10-20	Yes	A UK N addition experiment (Ruabon) has found sensitivity of bryophytes and lichens to wet deposited N additions of 30 kg and above (Carroll et al., 1999) (Pilkington et al., 2007) and changes in plant tissue and soil chemistry (Pilkington et al., 2005) (Edmondson et al., 2010) (Field et al., 2013). Liverworts also responded to low levels of N addition, declining above 20 kg N (Edmondson et al., 2010). These observations are also reflected in spatial surveys, both broad-scale (Maskell et al., 2010) and targeted (Edmondson et al., 2010); (Field et al., 2014; Southon et al., 2013), (Payne et al., 2014). The surveys report overall declines in species richness with many highlighting the particular sensitivity of lower plants. Curvilinear response relationships are common, with more rapid declines in species richness below the upper-end of the critical load range and falling species richness above 10 kg N_{tot} ha^{-1} yr^{-1}. Increases in the cover of grasses was also observed (Southon et al., 2013). Much other work in the grey literature also supports these findings, in particular Stevens et al. (2009), which highlights many individual species responses observed in a number of UK national datasets. UK survey work also found declines in *Cladonia portentosa* and *Hylocomium splendens* above 17 kg N_{tot} ha^{-1} yr^{-1} (Field et al., 2014). However, the bryophytes *Leucobryum glaucum* and *Odontoschisma denudatum,* and *lichens Cladonia portentosa, C. verticillata* and *C. uncialis,* were affected by N in Upland wet heaths at 5-10 kg N_{tot} ha^{-1} yr^{-1} (Emmett et al., 2011). These rates are below the CL.	No	Yes	CL may be too high
46. Yellow saxifrage bank	5-10	No	There is no UK evidence related to this specific habitat class.	No	No	No evidence

CSM / CL Habitat Type	Critical Load	Relevant UK evidence	Notes	Evidence of no effect, or an effect only above CL?	Evidence of an effect below CL?	Outcome
47a. Wet woodland (excluding alluvial and bog woodland)	10-20	No	There is no UK evidence related to this specific habitat class.	No	No	No evidence
47b. Alluvial woodland	None	No	There is no CL for this specific habitat class.	N/A	N/A	No CL
47c. Beech woodland	10-20	No	There is no UK evidence related to this specific habitat class.	No	No	No evidence
47d. Acidic oak woodland	10-15	Yes	Differences in the epiphytic lichen and bryophyte assemblages between sites with 10-18 kg N_{tot} ha^{-1} yr^{-1} and sites with 11-53 kg N_{tot} ha^{-1} yr^{-1} have been demonstrated in Atlantic oak woodland in northern Britain (Mitchell et al., 2003), providing support for the current CL.	No	No	Consistent
47e. Dry acidic birch woodland	10-15	No	There is no UK evidence related to this specific habitat class.	No	No	No evidence
47f. Oak-bracken-bramble woodland (W10)	15-20	No	There is no UK evidence related to this specific habitat class.	No	No	No evidence
47g. Base-rich deciduous woodland (W8/W9)	15-20	No	There is no UK evidence related to this specific habitat class.	No	No	No evidence
47h. Native pine woodland	5-15	No	There is no UK evidence related to this specific habitat class.	No	No	No evidence
47i. Yew woodland	5-15	No	There is no UK evidence related to this specific habitat class.	No	No	No evidence
47j. Wood pasture and parkland	None	No	There is no CL for this specific habitat class.	N/A	N/A	No CL

CSM / CL Habitat Type	Critical Load	Relevant UK evidence	Notes	Evidence of no effect, or an effect only above CL?	Evidence of an effect below CL?	Outcome
47k. Broadleaved deciduous woodland (general)	10-20	Yes	Identification of N impacts in woodlands is complex due to effects of the tree canopy in intercepting N deposition, the degree to which woodlands are managed, and the confounding influence of deer browsing. Countryside survey data, covering ca. 800 deciduous woodland plots across the UK, found that decreased ground vegetation species richness and graminoid cover and increased forb cover between 1998 and 2000 was correlated with increasing N deposition (Carey et al., 2008). In addition, Pitcairn et al (2009) showed that woodland (mixed conifer and deciduous) ground flora (in terms of tissue N and overall Ellenberg N score) changed along four N deposition gradients going away from intensive livestock units. However Kirby *et al* (2005) studied changes in a national sample of semi-natural British woods from 1971-2001 and found no overall shift in species towards more fertile/eutrophic assemblages and no change in mean Ellenberg fertility score but specific changes in plant species cover and abundance *did* appear to be influenced by N deposition.	No	No	Consistent
47x. Bog woodland	5-10	Yes	Five species which occur in this habitat, *Cladonia portentosa, C. uncialis, Cetraria aculeata, Leucobryum glaucum* and *Vaccinium vitis-idaea* were shown to be affected in heathland at a rate of 5-10 kg N_{tot} ha^{-1} yr^{-1} (Emmett et al., 2011). Canopy interception is unlikely to be substantial in this open woodland type, so this evidence was considered to be relevant for bog woodland and to provide supporting evidence for the current CL.	No	No	Consistent
47y. Lowland juniper and box scrub	15-25	No	There is no UK evidence related to this specific habitat class.	No	No	No evidence
47z. Dry lowland scrub (not juniper or box)	10-20	No	There is no UK evidence related to this specific habitat class.	No	No	No evidence

Appendix B. Guidance on using the Factor 1 spreadsheet to generate Exceedance Score

N Decision Framework: Guidance Notes to Users
[WP1_FrameworkSpreadsheet.xlxs]

Purpose: To obtain an Exceedance Score for the degree of exceedance of N critical loads for CSM habitats, taking into account uncertainty in N deposition and critical loads for CSM habitats, based on "National/Theoretical Evidence"

- **Enter the N deposition for your site or feature.**
  - Use the "Search by Location" tool on APIS (www.apis.ac.uk) to obtain values of N deposition, selecting the correct broad habitat category for your CSM habitat.
  - Enter the grid reference location of your specific feature of interest, if it is available, otherwise enter a site grid reference location. In APIS, use the 'Check Grid Reference' button to check that the grid reference is correct (e.g. does not fall in the sea for coastal sites)
  - If your site contains both woodland and non-woodland habitat features you will need to look up two N deposition values: one for any woodland habitat and one for any non-woodland habitat. Enter these values into cells C2 (woodland) and C3 (non-woodland) of the spreadsheet.
  - If you have specific information on the N deposition for your feature/site AND information on the uncertainty, these can also be entered instead of the national modelled N deposition.

- **Select the correct CSM habitat type in the spreadsheet.**
  - Use the filters (columns A, B, C) in the spreadsheet to select the appropriate CSM habitat type.
  - Note that in some cases the CSM habitats are split into sub-categories (column C) according to the critical loads that can be applied to them. For example, "Humid dune slacks" (6) is divided into "Humid dune slacks (calcareous)" (6a) and "Humid dune slacks (non-calcareous)" (6b), and either habitat 6a or 6b should be selected.
  - Further guidance in selecting the appropriate habitat is given in the "Notes for users" (column D), and the corresponding habitats in other classifications can be found in:
    - Column G: National Vegetation Classification (NVC)
    - Column H: Habitats Directive Annex 1 habitats
    - Columns I&J: EUNIS class(es) and names
    - Columns R&S: JNCC NCL codes and names
    - Columns T-W: SSSI reporting features by country
    - Columns X-Z: JNCC reporting categories and SSSI interest codes and names

- **Read off the Exceedance Score (Factor 1 score) for your CSM habitat from column E.**
  - The "Factor 1" score giving the Exceedance Score for each habitat will be automatically generated and will appear in column E.
  - Remember to update the N deposition values when assessing a different site/feature or a different location within a site.
  - Note column F shows the modified CL range (taking account of uncertainty) which is used in the calculations.